Soil Carbon and Organic Farming

A review of the evidence on the relationship between agriculture and soil carbon sequestration, and how organic farming can contribute to climate change mitigation and adaptation.

November 2009

Soil Association

Credits

Grateful thanks are given to The Greenpeace Environmental Trust, The HCD Memorial Fund and to English Nature (now Natural England) for their financial support for this work.

Acknowledgements

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With thanks for advice and information received from: Peter Melchett, Ian Alexander of Natural England, Dr Julia Cooper of Newcastle University, Kathleen Hewlett, Eric Hewlett, Professor Pete Smith of University of Aberdeen, Rob George, Francis Blake, Phil Stocker, Pat Bellamy of Cranfield University, Martin Peck and Dr Francis Rayns. Special thanks are due to: Richard Young,

Comments

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> ***"Nearly 90 percent of the technical mitigation potential of agriculture comes from soil carbon sequestration … Many agricultural mitigation options, particularly those that involve soil carbon sequestration, also benefit adaptation, food security and development. These options involve increasing the levels of soil organic matter. This would translate into better plant nutrient content, increased water retention capacity and better structure, eventually leading to higher yields and greater resilience… "*** *FAO, November 2009.*[1]

KEY POINTS

- Based on a review of the evidence, this report concludes that **soil carbon sequestration – achieved through the widespread adoption of organic farming - would substantially reduce greenhouse gas (GHG) emissions and make agriculture more resilient to the effects of climate change.**

- The soil carbon impacts of agriculture are ignored by current GHG accounting systems, which means that the GHG emissions of agriculture have been greatly under-estimated, the emissions of organic farming greatly over-estimated, and the real potential of soil carbon sequestration overlooked. According to IPCC scientific advisers, about 90% of agriculture's GHG mitigation potential resides in improving soil carbon levels.

- A review of all available comparative studies in this report indicates that, on average, **organic farming produces 28% higher soil carbon levels than non-organic farming in Northern Europe, and 20% for all countries studied** (in Europe, North America and Australasia). This represents a soil carbon sequestration rate **of about 560kgC/year for each hectare of cultivated land converted to organic farming in the UK**, for at least the next twenty years.

- On this basis, we conservatively estimate that the widespread adoption of organic farming in the UK would **offset at least 23% of UK agriculture's GHG emissions**. And, as a separate estimate, if agriculture was globally converted to organic farming best practices, this could potentially offset around **11% of all global GHG emissions**, each year for at least the next twenty years.

- Critics have been too quick to dismiss soil carbon sequestration on the basis that the rates of sequestration tend to diminish twenty years after a switch to improved practices. It is the next twenty years that are in fact critical in policy terms for delivering major GHG reductions. Moreover, carbon sequestration still continues thereafter, albeit at lower rates, for a hundred years or more.

- Soil carbon sequestration by organic farming practices - because the accumulated carbon is in the organic form of humus - also has the lasting benefit of improving soil structure and quality. This will improve climate adaptation by reducing the impacts of flooding, droughts, water shortages and desertification, thereby also improving global food and water security.

- A review of the scientific evidence on the factors and biological processes of soil carbon accumulation indicates that organic farming increases soil carbon levels by: producing additional sources of organic matter, creating organic matter in forms that are more effective at producing soil carbon, integrating

crop and livestock systems, and by increasing the proportion of vegetation cover which promotes the soil's micro-organisms that stabilise soil carbon.

- Grass-fed livestock have a critical role to play in minimising carbon emissions from farming and this must be set against the issue of methane emissions from cattle and sheep. Grasslands for grazing livestock, whether permanent pasture or temporary grass on mixed farms (which account for most UK organic cultivated land), represent vitally important soil carbon stores. Already, each year in the UK, 1.6 million tonnes of carbon (representing a hidden additional 12% of the UK's agricultural GHG emissions) are being released into the atmosphere because of the net conversion of permanent grassland to cultivated arable land. Advocates of a shift from red meat to grain-fed white meat to address the methane issue could therefore find this has the perverse effect of exchanging methane emissions for carbon emissions from the soil and the destruction of tropical habitats (to produce soya feed), as well as having a far reaching impact on our countryside, wildlife and animal welfare.

- On the basis of these important benefits for GHG mitigation and climate adaptation, soil carbon sequestration should be maximised **by agricultural and climate policies** in four main ways:

1. Soil carbon impacts should be fully accounted for and considered in climate policy and agricultural GHG accounting systems, in line with IPCC recommendations and including overseas impacts.
2. National and global strategies for large-scale soil carbon sequestration should be adopted based on a major expansion and development of organic farming, with a parallel approach to improve non-organic farming.
3. Work to define a sustainable diet (as is being championed by the Council of Food Policy Advisors and the Sustainable Development Commission) should take account of soil carbon impacts including the importance of grass-fed livestock in conserving existing soil carbon stocks in permanent grasslands and in raising the soil carbon level of cultivated land via temporary grass leys on mixed farms.
4. The major national and global carbon source 'hot-spots' should be also directly addressed. For the UK, this means drastically reducing imports of beef, soya and palm oil, reversing peatland drainage, and returning the cultivated fenlands (lowland peaty soils) to rotational arable/grass ley farming.

SUMMARY OF THE REPORT

Importance of the soil carbon store for climate policy (Chapter 2 and Section 4.1)

- **Soil is a major store of carbon**, containing three times as much carbon as the atmosphere and five times as much as forests. About 60% of this is in the form of organic matter in the soil.

- Soil carbon losses account for a **tenth of all the CO_2 emissions** by human activity since 1850. However unlike the losses of carbon from the burning of fossils fuels, which account for two-thirds, the soil carbon store can be recreated to a substantial extent. This would remove large amounts of previously emitted carbon from the atmosphere, offsetting current greenhouse gas (GHG) emissions.

- The principal component of the soil carbon store is **humus, a stable form of organic carbon** with an average life-time of hundreds to thousands of years.

- The annual rates of change in the soil carbon levels of cultivated land that are produced by agricultural practices are usually small in percentage terms - hence the importance has often been overlooked, but they are **very significant in terms of tonnes of carbon** taken up (or emitted) at national and global level – as shown by the potential effect of widespread organic farming, below.

- Soil carbon sequestration also provides a **rapid and timely GHG mitigation 'win' for climate policy targets** since carbon sequestration starts as soon as the positive practices are adopted and about half of the total amount that will be sequestered occurs within the first twenty years. This is critical as drastic GHG reductions are required within the next two decades. Soil carbon sequestration still continues thereafter, albeit at lower rates, for a hundred years or more.

- Soil carbon sequestration compares **very favourably to other major land use options**. It has been estimated that a global afforestation programme would take over twenty years just to offset the emissions from the establishment of the plantations, before positive carbon sequestration starts. Likewise, the large-scale production of biofuels in tropical regions for the EU's targets are predicted to produce severe soil carbon consequences and so maybe a negative GHG balance for decades.

- In addition to substantially reducing GHG emissions, as the accumulated carbon is in the organic form of humus, a major increase in soil organic carbon levels also has the lasting benefit of improving soil structure and quality. This will improve **climate adaptation** by reducing the risks and impacts of flooding, drought and water shortages, and would protect the large area of vulnerable agricultural land in semi-arid areas from desertification, thereby improving global food and water security.

Inadequacy of the current agricultural GHG accounting systems (Section 4.2)
Soil carbon is probably **the most important climate aspect of agriculture**. According to IPCC scientific advisers, it represents almost 90% of agriculture's GHG mitigation potential. Yet, current GHG accounting and assessment methods omit to include and make transparent the soil carbon impacts of agriculture:

- **Official figures greatly under-estimate the GHG emissions of agriculture**. In the UK, for example, there is an estimated average of 1.6 million tC being emitted each year from the conversion of grassland to arable land, but this is being reported in the 'LULUCF' (Land Use, Land Use Change and Forestry) sector in the UK's GHG inventory, not under 'agriculture'. With the carbon losses from the fenlands also omitted, this doubles the figures for UK agriculture's CO_2 emissions (officially 1.8 million tC/yr) and would make CO_2 account for a quarter of agriculture's GHG emissions. (See 4.2)

- The basic **IPCC guidelines for accounting for soil carbon losses or gains from agricultural management** are not being implemented by the UK or indeed by most countries. So, for example, any soil carbon losses resulting from the declining proportion of arable farms that use temporary grass leys or livestock manure are also not being accounted. (See 10.2)

- Also, the major soil carbon impacts of Europe's food and agricultural systems abroad are being excluded even though these are often directly related to practices and policies in the UK: the **large carbon losses resulting from the on-going conversion of tropical habitats to agriculture**, occurring in South America to supply soya for the intensive livestock sectors and to supply beef in response to the falling UK self-sufficiency in beef (now an annual shortfall of 300,000t, resulting partly from dairy intensification), and the destruction of high-carbon peatlands in SE Asia to produce palm oil (widely used as an ingredient in industrial, processed foods in the UK and other countries).

- In addition, most Life Cycle Assessments of the comparative climate impacts of organic and non-organic farming to date have failed to take account of the soil carbon benefits of organic farming (including the LCA study by Cranfield University for the UK Government). So, **practically all existing estimates greatly over-estimate the net GHG emissions of organic farming**.

- **Grass-fed livestock have a critical role to play in minimising carbon emissions from farming and this must be set against the issue of methane emissions from cattle and sheep**. Grasslands for grazing livestock, whether permanent pasture or temporary grass on mixed crop and livestock farms (which account for most UK organically farmed cultivated land), represent vitally important soil carbon stores. Advocates of a shift from red meat to grain-fed white meat to address the methane issue could find that this has the perverse effect of exchanging methane emissions for carbon emissions from the soil and the destruction of tropical habitats (to produce soya feed), as well as having a far reaching impact on our countryside, wildlife and animal welfare.

Current agricultural soil carbon losses and trends in the UK and Europe (Sections 4.2 & 4.4)

- The current trend in soil carbon levels of agricultural soils is unclear. Large-scale European soil surveys indicate that arable soils are losing topsoil carbon, but deeper sampling provides different results. In the UK, the overall trend is unknown as only the top 15cm of the soil has been monitored.

- Two large-scale surveys have found that UK arable soils are overall losing topsoil carbon. However, according to one survey, the losses are mainly occurring from just part of the arable area and land that has been under cultivation for a long time shows little change in topsoil carbon levels. Changes in ploughing depth mean that changes could well have occurred in the lower soil levels.

- The evidence for UK grasslands is inconsistent, with one large-scale survey having found large, widespread topsoil carbon losses and another topsoil survey having found little change.

- According to a recent European Commission report, grasslands have the potential to be sequestering large amounts of carbon on an ongoing basis. In the UK, the potential sequestration has been calculated to be 670kgC/ha/year, which, if true, would offset all the methane emissions of beef cattle.

- The full extent of soil carbon losses and the influence of agriculture is currently being obscured by **short-comings in methodology.** Soil surveys only evaluate part of the soil carbon store and routinely omit changes in the lower soil layers, in soil depth, and land classifications categorise large areas of grazing land as 'non-agricultural'; these aspects are all affected by farming practices. (4.4)

- Soil carbon modelling studies also currently suffer from serious flaws, in particular the assumption that soil carbon input levels are proportional to crop yields - which is clearly unsuitable for assessing organic farming practices, but also the lack of subsoil and biological components. (See Section 4.4)

The biological processes of agricultural soil carbon accumulation (Chapters 2 & 7)

- Most fresh organic matter is decomposed in the soil and rapidly releases it carbon as CO_2, and only a small proportion of the soil carbon input is converted to humus (stable soil carbon). It is often assumed that the main determinant of soil carbon levels is simply the quantity of organic matter inputs to the soil. However, biological factors – that are influenced by agriculture - affect the amount of the carbon input that is converted to stable soil carbon, and can increase the proportion from a few per cent up to 60%:

- Key to building the soil carbon store is good soil structure and the process of **soil aggregation**, whereby the soil's mineral particles are clustered into 'aggregates' which stabilises humus by encapsulating part of the humus inside the aggregates so that it is protected from degradation.

- **Soil living organisms** play a major role in soil aggregation: the soil particles are glued together by the polysaccharide gums produced by soil microorganisms, by the networks of fungal hyphae in the soil, and by the activity of earthworms.

- **Plant roots** are a further key aspect and probably more important than the over-ground part of plants. As well as providing carbon from their biomass, roots supply almost as much carbon to the soil by a continuous release of exudates, root hair turnover and root cell sloughing. Also, the carbon from roots lasts over twice as long in the soil as the carbon from plant stems and leaves.

- Another factor is the **biochemical composition** of the organic matter: (i) the level of resistant compounds such as lignin, and (ii) the carbon to nitrogen (C:N) ratio. Nearly all of the carbon in residues with a C:N ratio higher than about 32:1, such as straw, is lost by microbial respiration.

- Different plant types affect the above properties differently: arable crop residues are relatively poor at forming soil carbon, legumes are better, and grass is very good. **Grass** has many characteristics that promote soil carbon levels: a high root density, resistant biochemicals, fine root hairs that promote soil aggregation, and high mycorrhizal fungal levels which increase soil aggregation. (See 7.1)

- Organic matter types that have undergone some microbial digestion are also good at producing high, long-term soil carbon accumulation, i.e. **farmyard manure (FYM) and compost**. (See 7.2 & 7.12)

- The rough proportions of carbon that are converted to soil carbon increases by type as follows: **straw – 5-7%; legumes – 17%; FYM – 23%; compost –50%** (if used without N fertiliser). (See 7.5)

Current farming practices that affect soil carbon levels (Chapter 5 & Chapter 7)

Arable soils have the lowest soil carbon levels of all major land types in Europe. There have been several developments in agricultural practices that are likely to have reduced soil carbon levels and are keeping levels low. The main ones for the UK are as follows, and they are all associated with the intensification and specialisation of agriculture:

- **Abandonment of mixed farming** with temporary grass alternating with arable crops (5.1, 7.1);
- The **reduced spreading of animals manure**: only 22% of the UK's cultivated area now receives manure of any kind (including sewage sludge) (5.2, 7.2);
- The wide production of **liquid slurry** instead of solid farmyard manure (with straw), which does not have the same qualities, because of the intensification of livestock production (5.3, 7.3);
- The **reliance on inorganic fertiliser**, which means farmers are no longer dependent on using organic matter for fertility and which reduces the size of crop root systems (5.4, 7.8);
- The introduction of modern **short-strawed cereal varieties**, which has reduced not just the amount of straw produced but also the size of crop root systems (5.5, 7.5);
- The **ploughing-up** of permanent grassland which releases from 23 tonnes (in England) to 90 tonnes (in Scotland) of carbon per hectare (5.6);
- A high increase in the numbers of **grazing cattle and sheep** because of earlier government incentives, which caused over-grazing of UK grasslands (5.8, 7.11);
- The move from **grass to grain-fed livestock systems** which means there is now a large 'ghost' area of low-carbon arable land abroad supporting the UK's livestock sector and major carbon losses occurring from the destruction of tropical habitats to supply soya and a shortfall in beef (5.9, 7.9).
- The production of **maize silage** for winter cattle feed instead of grass (silage or hay), which causes soil degradation (5.10).
- Due to the continued **cultivation of the fenlands** in the UK, it is estimated that two-thirds of the peaty areas of East Anglia that existed in 1985 will be lost by 2050 (5.14).

Two other agricultural practices are not normally cited as likely factors but we suggest these may be having an effect on the soil carbon levels of grassland, and urge they be better researched:

- **Grassland 'improvement'** is a package of practices that involves the ploughing-up of permanent grassland, re-seeding with commercial grass mixes, and usually regular inorganic fertiliser treatment and repeated cultivation and re-seeding at intervals thereafter. The grass is thus managed intensively like a regular crop and this may affect the ability of grass to produce higher soil carbon levels. (5.12)

- The **use of avermectin wormers** – farmers now routinely use these persistent insecticidal drugs to control parasites in grazing animals, but research shows that they reduce the natural rate of dung decomposition. We ask whether this practice could be disrupting the cycling of carbon and the production of stable soil carbon in grassland, and so affecting grassland soil carbon levels. (7.14)

The comparative effects of organic farming and policy significance (Chapters 6 & 8)

This report presents the results of the largest, most comprehensive and most detailed review of the soil carbon effects of organic farming to date.

- A **review of 39 comparative studies of organic farming covering over 100 individual comparisons** undertaken by the Soil Association, including controlled trials and farm surveys, shows that organic farming produces higher soil carbon levels than non-organic farming on cultivated land, and that this effect is substantial in terms of climate change.

- Organic farming produces an estimated **average of 28% more topsoil carbon per hectare than non-organic farming in Northern Europe** in c.15 years, and **20% more for all countries reviewed** (in Europe, US and Australasia) in c.12 years, based on the studies reviewed.

- Using standard accounting methods, it is estimated that this represents an average soil carbon sequestration rate **of about 560kgC/year (or 2 tonnes of CO_2/yr) for each hectare of cultivated land converted to organic farming in the UK**, for the next twenty years at least. A similar soil carbon sequestration rate of 550kg/ha/year was found for four US farming trials. (8.2, 8.2)

- On this basis, it is conservatively estimated that the widespread adoption of organic farming in the UK would increase the UK's arable soil carbon store by a total of 64 million tonnes of carbon, at least. This would **offset 23% of UK agriculture's current official GHG emissions** each year, for at least the next twenty years. (See 8.3)

- At a global level, assuming a higher possible sequestration level of 1tC/ha/year for organic farming best practices (including composting and agro-forestry), widespread organic farming could potentially sequester 1.5 billion tC per year. This would **offset about 11% of all anthropogenic global GHG emissions** for at least the next twenty years. (The global impact is greater than in the UK because the ratio of the area of cultivated land to total GHG emissions is much higher). (See 8.4)

- These +28% / +20% figures and the UK carbon sequestration potential estimate are presented as *current best estimates of the soil carbon benefits of organic farming based on the current available data*, for use by policy makers and the industry. The global estimate is speculative and *intended to be illustrative*. As further data becomes available, these estimates are expected to be improved.

Methodology used for the calculations

The results of all the studies where data was available (but excluding the results of biodynamic farming which tend to have higher levels than standard organic farming), were averaged to produce an average percentage difference for organic farming soil carbon levels compared to non-organic farming, (i) for Northern Europe (+28%), and (ii) all studies (+20%). The annual carbon sequestration potential of organic farming in the UK was then calculated by applying the +28% increase to official figures of the soil carbon stocks of cropland (tC/ha) and dividing this by twenty to provide an estimated average sequestration rate (560kgC/ha/yr) for twenty years after organic conversion.

For accuracy, the averages were calculated from the absolute data, not the percentage differences (to avoid any possible bias from higher increases occurring in lower soil carbon soils). For the UK estimate, to be conservative, the +28% figure for Northern Europe was used (instead of the slightly higher UK figure); the increase was applied to the soil carbon stock data for England (rather than the higher UK cropland figure); the increase was only assumed to apply to the top 18cm of the soil (the estimated average sampling depth of the studies; although IPCC methodology normally applies differences to the top 30cm); and the increase was assumed to occur over twenty years (instead of the estimated fifteen year average period of the studies; twenty years is the standard IPCC accounting period).

For the global sequestration potential estimate, a much simpler and more speculative approach was taken for illustrative purposes, as comparative data is not available for most countries and using a single soil carbon stock figure would be inappropriate. An average carbon sequestration figure of 1tC/ha/yr was assumed to apply to the global area of cultivated land to give a total sequestration figure of 1.5 billion tC/yr. It was assumed that a higher figure than the UK figure of 560kgC/ha/yr is realistic and reasonable considering the very wide potential of organic farming practices at a global level (e.g. composting and agro-forestry sequester particularly high levels of carbon) and the fact that current soil carbon data does not account for all differences (destruction of tropical habitats etc.)

- A sectoral analysis found that with these rates of carbon sequestration, the soil carbon benefit of organic farming is estimated to offset **44-72% of the GHG emissions of organic arable crops, and 29-39% of the GHG emissions of organic white meat** (pigs and poultry meat), at least for at least twenty years, giving a lower carbon footprint for organic farming than non-organic farming.

Other aspects of the soil carbon benefits of organic farming (Chapters 6 & 8)

- The review shows that organic farming also increases soil carbon levels in **semi-arid areas**. These account for much of the world's food production. These soils tend to have very low soil carbon levels (many under 0.5%) and are close to the threshold of desertification. Even small increases in organic matter will protect these soils. For the five studies in more arid regions, there were 12%, 13%, 52%, 10% and 138% higher soil carbon levels for organic than non-organic farming. (Section 6.1)

- Controlled trials show that **biodynamic farming** tends to produce even better soil carbon results than standard organic farming (at least 25% higher levels for all studies reviewed). Biodynamic farming is a special type of organic farming that uses composting and certain plant compounds. (6.1)

- The soil carbon benefit of organic farming probably works out greatest for **horticulture**: the soil carbon differences appear to be greater than for arable crops – due to the particularly low soil carbon levels of non-organic horticulture and the common use of composting by organic growers, and the GHG emissions of this food type are the lowest of all foods. (Section 8.5)

- Several studies indicate that organic farming also increases the soil carbon level of the **subsoil**. As this contains around half of the total soil carbon store and also the more resistant half of the soil carbon store, this effect would be particularly important, if confirmed to be common. (Section 6.6)

Summaries of individual soil carbon studies of organic farming (Section 6.2)

The report summarises many of the individual soil carbon studies of organic farming. This highlights the variety of conditions studied, describes some of the specific findings from the studies and provides further insights into the nature of the soil carbon effects of organic farming. For instance:

- A ten-year trial of ten 'Mediterranean' cropping systems by the **University of California, ('LTRAS'**) found that the organic system "disproportionately accumulated" soil carbon relative to its carbon input, converting eight times the estimated biomass carbon input than the equivalent non-organic system. The organic system started with one of lowest levels of soil carbon, but sequestered 560kgC/ha/yr in the top 15cm and ended with by far the highest of all the systems. All systems were cropped in a two-year rotation, with the organic system having alternating maize and tomato.

- In a comparison of a field under organic management and a field under non-organic management on an arable farm in Italy (**Marinari *et al*, 2007**), the researchers found, "considerable changes in SOM structure" on the organic field, with 55% greater humic C content in the upper soil layer. In the organically managed field, SOM mineralisation was concentrated on the 'labile' carbon fractions (i.e. water soluble organic compounds and microorganisms), while in the non-organic field there was mineralisation of the 'soil native SOM' (i.e. of the humus that constitutes the soil carbon store).

- The results of the **FiBL DOK trial in Switzerland** indicate that the greater soil carbon accumulation produced by compost more than compensates for the carbon lost during the composting process. Exactly the same 7-year crop rotation was used for all the treatments, but the biodynamic plots produced the highest soil carbon levels, even though it received 20% less soil carbon input from compost, then either the standard organic and 'integrated' plots received from uncomposted manure.

Reasons for the higher soil carbon levels of organic farming (Chapter 7)

- The soil carbon benefit of organic farming results from the fact that the system is based on **inputs of organic matter to the soil and its decomposition by soil microbial activity.** This releases nutrients for crop production (replacing the use of inorganic fertilisers) and, at the same time, this process also produces humus (stable soil carbon) which raises the soil's carbon level.

- A review of the scientific evidence on the factors and biological processes of soil carbon accumulation indicates that the key aspects of organic farming that produce higher soil carbon levels are:

1. The production of **additional organic matter sources** on farmland (grass leys, green manure crops), normally without reducing the area of farmland that is in food production;
2. The production of more organic matter in **forms that are more effective** at producing humus and raising soil carbon levels (grass, legumes, root systems, composting, and farmyard manure instead of slurry and straw), instead of relying just on arable crop residues which tend to be rapidly mineralised;
3. The common **integration of crop and livestock production** which ensures that much more livestock manure is produced in FYM form (with straw) instead of slurry and that much more of the collected manures are applied to the cultivated land, and the use of temporary grass in the rotation;
4. The **greater vegetation cover** and less bare soil (use of grass leys, more weeds, green manure /cover crops), which provides a greater and more continuous supply of the root exudates that provide a food supply for the soil's micro-organisms which build the soil carbon store.

Some specific practices of organic farming are:

- Use of **grass/clover leys** – in the UK and much of Europe, organic farming uses temporary grass leys in the crop rotation of 1-4 years in length. Organic farmers include clover in the leys, which is not so common among non-organic farmers, but which also has soil carbon benefits. (7.1)

- **Conversion of straw to FYM** – in industrial farming systems based on continuous cropping, arable crops residues are often the only source of organic matter. However, these are very poor at forming soil carbon. In organic systems, the straw is used for livestock bedding and thereby converted to farmyard manure, which is effective at promoting soil microbial activity and carbon build up. (7.5)

- Use of **green manure crops** – these are plants that are grown and then later ploughed into the soil without harvesting just to add organic matter to the soils. They are often grown for just a few months in the spare time between the main crops, such as over-winter. (7.4)

- **Larger root systems** – organic farming produces a higher root biomass, according to one study 72% more per hectare. The use of decomposing plant residues in the soil for fertility in organic farming promotes the deeper growth of crop roots than surface-applied inorgranic fertilisers. (7.6)

- Organic farming uses a variety of different practices. However, higher soil carbon levels tend to be an inherent benefit of organic farming, as, unlike inorganic fertiliser-based farming, the factors that organic farming relies on to provide fertility, are the same factors as those which build soil carbon levels: high and regular organic matter inputs, soil microbial activity and good soil structure.

Further considerations of the soil carbon effects of organic farming (Chapter 6)

- **These estimates are conservative.** The +28%/+20% average soil carbon increases with organic farming and the estimate of the UK carbon sequestration potential of organic farming, are conservative as they are only based on the differences in the topsoil carbon content of cultivated soils (which is all that most studies measure). They do not include:

1. The overseas carbon savings of organic food and farming, including an increase in the soil carbon levels of the large area of overseas arable land that provides feed for the UK's livestock sectors and the farmland that produces imported foods, and a reduced destruction of tropical habitats.
2. The increase in agricultural soil carbon storage that would result from the almost certainly greater percentage of farmland that would be in permanent grass with widespread organic farming.
3. Any increases in topsoil depth or subsoil carbon content with organic farming - the few studies to have looked at these have found increases in these aspects as well (perhaps due to more extensive crop root systems and larger earthworm populations).

4. Any higher soil carbon levels of organically managed permanent grassland (as found by the three comparative studies to have looked at organic and non-organically managed grasslands).
5. Any biodynamic farming studies – this is a special type of organic farming that tends to produce higher soil carbon levels than standard (non-biodynamic) organic farming.
6. The significant potential for further developing organic farming practices in line with its principles to further increase its capacity to build soil carbon, such as by the wider use of green manure crops, composting, and the use of non-agricultural organic matter sources, such as food and paper waste.

Answering concerns about agricultural soil carbon sequestration and organic farming

The report addresses in detail a number of concerns that have been raised about agricultural soil carbon sequestration and about the soil carbon impacts of organic farming (Chapter 9):

- **Ploughing:** a concern that the common use of ploughing in organic farming could be a weakness are answered by a number of trials in Europe that show that the depth of cultivation has no effect on the overall soil carbon levels of organic farming. Ploughing is used to incorporate organic matter into the soil; with sufficient inputs, increases in ploughing depth can even increase topsoil depth. (9.1)

- **'Min-till' and 'no-till':** reduced soil cultivation is the main non-organic farming option put forward for raising soil carbon levels, but its effects have been greatly exaggerated. According to government scientific advice, the soil carbon gains are minimal in the UK. Reduced tillage is effective in maintaining soil carbon storage in semi-arid regions where carbon is being lost by erosion and by the use of fallow periods, but otherwise there is no clear evidence that it increases carbon levels over the whole soil profile, and certainly not to the extent of organic farming. Moreover, the carbon is then in a relatively unstable form, and any soil carbon gains may fully be offset by higher soil N_2O emissions.

- **Relationship between soil carbon input levels, agricultural yields and soil carbon levels:** the report challenges a commonly held assumption that agricultural yields are one of the main determinants of soil carbon levels and that the use of inorganic fertiliser increases soil carbon levels. E.g. in the US, organic farming yields are similar to non-organic farming, but soil carbon levels are higher. Organic farming produces organic matter sources other than crop residues and also improves the biological conditions for soil carbon accumulation: studies show organic farming can produce two to eight times as much soil carbon per unit of biomass carbon input then non-organic farming.

- **Soil microbial activity**: the higher soil microbial activity of organic farming is a benefit and does not mean that stable soil organic matter is more liable to being broken down. There is a positive association between soil carbon levels and soil microbial levels because it is soil microorganisms that (i) produce the humus, and (ii) protect humus against degradation, by aggregating the soil particles.

- **Additionality**: one concern is whether organic farming produces additional soil carbon or whether the higher levels are largely a result of organic farmers using organic materials from non-organic farms, such as manure. In fact, there is relatively little use of non-organic farming materials by organic farmers in the UK, and other factors appear to explain much or most of the differences. Also, organic farmers have a choice of strategies and US evidence shows that there is no soil carbon difference between organic systems that might rely on external inputs and those that do not. (9.6)

- **Reaching equilibrium:** sceptics have been quick to dismiss soil carbon sequestration on the basis that the rates of sequestration tend to diminish twenty years after a switch to improved practices. But it is the next twenty years that are critical for delivering major GHG reductions. Moreover, carbon sequestration still continues thereafter, albeit at lower rates, for a hundred years or more. (9.8)

- **Security of soil carbon sequestration:** there is a concern that soil carbon gains are insecure and may be lost rapidly if the positive practices are abandoned. This is not a key issue, as the focus should be on improving agricultural soil quality indefinitely. Nevertheless, soil carbon gains seem sufficiently secure: if the practices are abandoned, the half-life of the accumulated carbon is from 10 to 130 years, and if organic farming builds carbon in the subsoil, the gains are even more secure.

Soil carbon and adaptation to climate change (Section 10.2)

- Soil humus levels determine the soil's water-holding capacity and drainage rates. Low soil carbon levels are likely to exacerbate the impacts of climate change, by increasing the risk and severity of water shortages, droughts and surface-water flooding. Conversely, higher soil humus levels should improve all these aspects.
- For instance:
  - in the UK, organic farming uses 26% less irrigation water per tonne of potatoes (partly due to more efficient irrigation practices).
  - a US trial found that in drought years, organic maize crops yielded 33% more than non-organic maize, and organic soya yielded 78% more than non-organic soya.
  - during torrential rains in 1999, water capture in the organically managed plots of the same trial was double that of the non-organic plots.
- Improvements in the drought resistance of agricultural crops will be particularly beneficial for the food security of drought-prone regions of developing countries.

Recommendations (Chapter 11)

- On the basis of these important benefits for GHG mitigation and climate adaptation, soil carbon sequestration should be maximised **by agricultural and climate policies** in four main ways:

1. Soil carbon impacts should be fully accounted for and considered in climate policy and agricultural GHG accounting systems, in line with IPCC recommendations and including overseas impacts.
2. National and global strategies for large-scale soil carbon sequestration should be adopted based on a major expansion and development of organic farming, with a parallel approach to improve non-organic farming.
3. Work to define a sustainable diet (as is being championed by the Council of Food Policy Advisors and the Sustainable Development Commission) should take account of soil carbon impacts including the importance of grass-fed livestock in conserving existing soil carbon stocks in permanent grasslands and in raising the soil carbon level of cultivated land via temporary grass leys on mixed farms.
4. The major national and global carbon source 'hot-spots' should be also directly addressed. For the UK, this means drastically reducing imports of beef, soya and palm oil, reversing peatland drainage, and returning the cultivated fenlands (lowland peaty soils) to rotational arable/grass ley farming.

- More specific recommendations are provided for the expansion and development of organic farming, such as the promotion of the soil carbon benefit of organic farming, targeting of conversion support at the specialist arable and horticultural farms and the fenlands, the extension of farm stewardship schemes to include a soil carbon component, the greater use of public procurement schemes and other initiatives to develop the organic food market, and more R&D investment.

1. Introduction to soil carbon and climate change

" A large proportion of the mitigation potential of agriculture (excluding bioenergy) arises from soil carbon sequestration, which has strong synergies with sustainable agriculture and generally reduces vulnerability to climate change, " IPCC, Working Group III, 2007.[2]

The single most important aspect of agriculture in relation to climate change is currently the most overlooked aspect: the soil carbon store. Most considerations of agriculture's impact on the global climate have focused on its emissions of greenhouse gases (GHGs) - methane and nitrous oxide, as well as energy use and the potential of converting land from food production to bioenergy production. However, the increase in carbon dioxide levels in the atmosphere is the main cause of climate change and the full extent to which agriculture has contributed to this is a neglected area.

Concern about carbon dioxide emissions has focussed almost exclusively on the energy sector. This is not surprising as the burning of fossils fuels has contributed two-thirds of the total CO_2 emissions by human activity since 1850. Soil carbon losses caused by agriculture have, however, contributed a tenth of the total. And, according to IPCC scientific advisers, almost 90% of the GHG mitigation potential of global agriculture now residues in improving soil carbon levels.[3]

While this has yet to be recognised by most policy makers, attempts to reduce the carbon footprint of agriculture are likely to fail … or simply be unambitious. When it comes to tackling the carbon footprint of farming, aspirations are low, indeed much lower than for other sectors of the economy. The 2020 target for agriculture in the UK's Low Carbon Transition Plan is just a voluntary 6–11% greenhouse gas reduction, compared to mandatory 20–40% targets in all other sectors of the economy.[4] Furthermore, without action on soil carbon levels, depleted soil carbon (organic matter) levels will exacerbate the most serious impacts of climate change that face societies and threaten future food security: flooding, drought and water shortages.[5] Low soil carbon levels can also limit the maximum level of crop yields.[6]

Importantly, the very low soil carbon levels of today's cultivated land are not an inevitable consequence of agriculture, as this report will show. Unlike the carbon released from fossil fuels, the soil carbon store has the potential to be restored to a substantial degree, if appropriate practices are adopted. This would remove large quantities of carbon from the atmosphere every year for at least two decades (and lower amounts thereafter until a new soil carbon 'equilibrium' level is reached). Action to increase soil carbon levels would therefore contribute substantially to the efforts to cut GHG emissions rapidly [7] and avoid dangerous atmospheric CO_2 increases, while at the same time reducing the impacts of climate change.

37% of the earth's land area is used for agriculture[8], which means agriculture is one of the main influences on soil carbon storage. Farming practices have a well-established ability to change soil carbon levels. The annual rates of change on cultivated land are often very small in percentage terms (often less than 1% of the total soil carbon per hectare per year). As such, the significance of changes in soil carbon levels has been overlooked in the past. However, any year-on-year gains or reductions are usually very significant in terms of the annual tonnes of carbon taken up or emitted at a national and global level, and certainly in Northern Europe[9].

So far, the loss of soil carbon due to agriculture is largely being ignored by climate policymakers and analysts. Very large estimates of annual soil carbon losses from the conversion of grassland to arable land are included in the UK's greenhouse gas inventory. However, these are not being openly declared as agricultural emissions. The IPCC's guidelines for accounting for soil carbon changes due to agricultural management practices are not being implemented in Europe, which means that almost all the other potentially major soil carbon impacts of agriculture are not reported at all. In addition, the rapid and large-scale clearance of tropical habitats in the southern hemisphere, for conversion to agriculture, is releasing enormous amounts of soil and biomass carbon to the atmosphere every year. These are classed as emissions by those countries. However, these carbon losses are a direct result of the large-scale importation of livestock feed, beef and food ingredients by Europe and other countries and, as such, they are very much a consequence of the food industry and agricultural practices and policies of the UK and rest of the northern hemisphere. Currently, soil carbon is excluded from most 'Life Cycle Analyses' of the climate impacts of farming (such as, the assessment of organic and non-organic farming by Cranfield University for the UK Government[10]) and from the current food 'carbon labelling' initiatives[11]. Soil carbon is therefore mostly not being accounted for, which means that important agricultural and climate policy decisions are being made without consideration of this critical dimension.

Recent assessments for the UK Government indicate that, with current non-organic farming systems, the potential to sequester carbon is limited. It has been argued that, although soil carbon levels can be increased on non-organic farms with the adoption of certain farming practices, as the extent of the changes that could be achieved is small, the Government has been advised not to focus heavily on soil carbon storage as a way of reducing greenhouse gas emissions.[12] For example, the most popular option that has been put forward, minimum tillage, would achieve less than a 1% increase in the UK, according to the latest scientific advice.[13] However, this position is contrary to the large body of evidence - set out in this report - that shows that the soil carbon levels of cultivated land *can* be greatly increased.

Much more optimism in soil carbon storage has recently been shown at a European level, however.[14] In September 2009, EU Agriculture Commissioner Mariann Fischer Boel called on European farmers to cut agricultural GHG emissions by at least 20% by 2020, primarily by storing carbon in the soil.[15]

In this report, we review the general relationship between agriculture and soil carbon levels, and present the large body of comparative evidence on the soil carbon impacts of organic farming – an approach based specifically on building soil organic matter. The review is based on the available evidence, which is still limited in many important areas. It reviews the issues mainly from a UK perspective, but it attempts to address issues relevant to a wider European and global sphere as well. From the different experience and perspective of organic farming, we have attempted to give prominence to and challenge some issues that we felt have been overlooked in previous analyses, but which seem central to the subject of agriculture and soil carbon. We are therefore aware that our conclusions in some places may not match the common views on the subject. We recognise that this is a developing area of work and hope this report will lead on to further debate of the issues raised.

This report concludes that organic farming, by its different techniques, produces substantially higher soil carbon levels than non-organic farming as an inherent product of the system. Additional practices have the potential to increase these gains still further. The average level of difference found is such that the increase in soil carbon from the wider adoption of organic farming, would offset a significant proportion of UK agriculture's greenhouse gas emissions, and of all GHG emissions globally.

Given this large potential for removing atmospheric carbon and the general importance of soil organic matter in other respects, the ability of organic farming to increase soil carbon levels is put forward in this report as an important addition to the policy case for wider organic farming. A wide expansion of organic farming is proposed as a powerful strategy for greenhouse gas mitigation.

This report reviews:

- the evidence on the current status of farmland soil carbon levels in the UK and Europe,
- recent developments in agricultural practice that are likely to be responsible for low soil carbon levels,
- the body of comparative scientific evidence on organic farming and soil carbon levels,
- the biological factors and practices of organic farming that appear to be producing the differences,
- an assessment of the total carbon sequestration potential of organic farming at a UK and global level, and the extent to which this would offset greenhouse gas emissions, and
- analyses of various current concerns about the case for increasing soil carbon with organic farming.

2. The soil carbon store: humus and a living soil

> *"Soil is one of the building blocks of life. Good quality soils are essential for a thriving farming industry, a sustainable food supply, and a healthy environment. Britain's soils hold more carbon than all the trees in Europe's forests - and their protection is critical if we are to successfully combat climate change."*
> Hilary Benn, UK Environment Secretary, 24 September 2009[16]

Soil is a major store of carbon, containing three times as much carbon as the atmosphere (2,500 versus 760 billion t C) and five times as much as forests and other vegetation.[17] About 60% of this is organic carbon, in the form of organic matter in the soil (1,500 billion tC).[18] The large size of this store means that soil carbon changes can have significant effects on the level of atmospheric CO_2. For instance, each 1% increase in average soil organic carbon levels could in principle reduce atmospheric CO_2 by up to 2%.[19]

As farming is the main land use in the UK (77% of the land area[20]) and also in Europe, the effects of agriculture on soil carbon levels are key to maintaining or increasing this carbon store. In the UK, to a depth of one metre, there is an estimated 738 million tonnes of carbon contained within the country's cultivated soils and 3.9billion tC held in the grassland area (including peatlands, see Box 1).

Typically, soil contains about 45% minerals (soil particles), 25% water, 25% air and 2-10% organic matter. The soil carbon is held in the soil's organic matter, which comprises:

1. freshly deposited and undecomposed organic matter (such as, dead plant roots and leaves);
2. temporary compounds from the process of decomposition;
3. the blackish-brown soil substance called humus[21] (stable soil carbon); and,
4. living organisms (earthworms[22], arthropods, molluscs, nematodes, fungi, protozoa and bacteria).[23]

The principal component of the soil carbon store is **humus**, a stable form of organic carbon.[24] All of the carbon in the soil originally comes from the atmosphere and was captured by plant photosynthesis and converted into plant material. Once the plant material is no longer attached to the plant, such as fallen leaves, the fresh organic matter is decomposed by the action of soil organisms and rapidly releases most of its carbon within a couple of years. But part resists biological action and remains in the soil as humus which persists for, on average, hundreds to thousands of years[25], forming the soil carbon store (with only a small amount at any one time breaking down into carbon dioxide and other simple compounds).

Earthworms and other macro-invertebrates do the initial physical breakdown of organic matter (in their absence, the process takes much longer). Macro-invertebrates, especially vertical-burrowing worms like the common earthworm, also incorporate organic matter into the soil.[26] Fungi and microorganisms then take over. The final product of the decomposition of fresh organic matter is humus. This is a colloidal[27] complex of stable organic compounds.[28] As humus has undergone some digestion, it contains a higher proportion of organic compounds that are resistant to decomposition than the original organic matter, in particular lignin[29] (a hard substance contained in the cellulose of plant cell walls).[30]

The soil's humus level represents the underlying level of the soil's carbon store: while the levels of the other SOM components – fresh and decomposing organic residues, and microbial populations – go up and down depending on whether fresh organic matter has recently been added, the level of humus changes much more slowly. As fresh organic matter is the source of all the humus, generally **the more organic matter** that is introduced to the soil (which can be either by plants growing in the soil or by applying additional organic matter to the surface), the more the soil carbon level rises[31], although a certain amount is needed just for the level to remain stable.[32] However, whether or not, and to what extent, soil carbon accumulates is more complex than this: the *proportion* of carbon in fresh organic matter that is converted to stable soil carbon varies greatly, from 0 to over 60%[33]. This proportion depends on the nature of the organic matter and then on the stability of the resulting humus, which in turn depends on the soil conditions. These aspects are determined by the management system.

The soil's living organisms play a major role in building the soil carbon store by the important process of

soil aggregation, whereby part of the humus is put into a more stable condition and protected from releasing its carbon.[34] The soil's mineral particles are clustered into 'aggregates' by the binding effect of: the polysaccharide gums produced by soil microorganisms[35], networks of fungal hyphae in the soil[36], some humus compounds[37], by the activity of earthworms[38] and by plant root systems. The aggregates encapsulate a portion of the humus and protect it from microbial degradation.[39] This change in the soil's structure also makes soil resistant to erosion. There is therefore generally a correlation between the soil carbon level and soil aggregation.[40] Humus stability also depends on the soil's clay content. Humus combines intimately with clay particles and this enables aggregation, so clay soils are more able to aggregate and retain humus than sandy soils.[41]

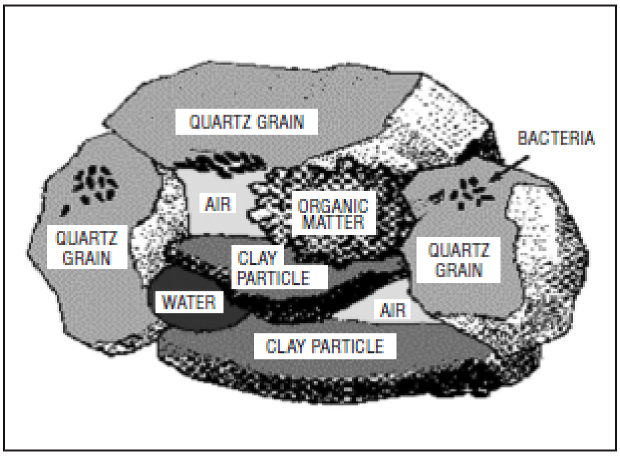


Figure 1 illustrating soil aggregation: clay and humus bond to create a stable soil aggregate (clump) that contains pore spaces to hold organic matter, water and air.[42]

A further key aspect of the soil carbon store is **plant roots**, a factor often overlooked.[43] Efforts to improve soil carbon levels usually focus on the level of above-ground crop residues, but many researchers now suggest root systems are more important.[44] As well as providing carbon from their biomass[45], roots supply almost as much carbon again from a continuous release of root exudates, root hair turnover and root cell sloughing[46] which play an important role. Moreover, the carbon from roots lasts over twice as long in the soil as the carbon from plant stems and leaves ('shoots').[47] This is for several reasons:

- roots have twice as much of the resistant compound lignin as 'shoots';[48]
- roots promote soil aggregation: roots physically enmesh soil particles and bind them together by the root surface compound mucilage, the root exudates support microbial populations (which promote aggregation), and the networks of mycorrhizal fungal hyphae that form around roots bind particles;
- protection against decomposition of the soil carbon in the complex ecosystems of the root hair zones;
- the carbon that is derived from root hairs growing inside the soil aggregates is protected; and,
- the deeper distribution of root carbon in the soil.[49]

Yet, another factor that influences the amount of humus produced is the **biochemical composition** of the organic matter. This means not only, (i) the level of resistant compounds such as lignin, but also (ii) the carbon to nitrogen (C:N) ratio[50]. These account for the fact that different organic matter materials have very different 'soil carbon conversion rates.' The amount of the carbon input that is converted to stable soil carbon ranges from just a few per cent of the carbon in straw or other arable crop residues (the organic materials that non-organic farmers mainly rely on), to 17-60% for some other organic materials (such as, legumes and compost).[51] Soil C cycling is linked to N levels[52] because decomposing microbes need both carbon and nitrogen as a food source, and the process of decomposition involves a reduction in the C:N ratio from that of the organic matter (between 13:1 and 100:1) to that of SOM, which is relatively constant at around 10:1[53]. Organic residues with a C:N ratio higher than about 32:1 do not provide enough N for efficient decomposition, and most of the carbon tends to be lost by microbial respiration.[54]

So, by decomposing and converting fresh organic matter into humus, incorporating organic matter into

Box 1 **Size of the UK and EU soil organic carbon stores**

The UK's soil organic carbon (SOC) store:

- The UK has the third largest SOC store in the European Union, after Sweden and Finland, because these countries have large areas of peatland[55] which are mostly carbon[56].
- The UK's soil carbon store is around 7 billion tonnes of carbon (from 4.6 to 9.8 billion tC).[57]
- To 1m depth, an estimated 738 million t of carbon are held in the UK's cultivated ('arable') soils and 3.9 billion tC in grasslands (including 'improved' grass, rough grazing, heath and peatlands).[58]
- About 63% of the total carbon over 1m depth in the UK's cultivated soil is found in the top 30cm (about 465 million tC).[59]
- The amounts of soil carbon per hectare (tC/ha) depend on the soil type, being low in 'mineral'-type soils, and far higher in 'organic'-type (high-carbon) soils.
- In England, there is typically 77tC/ha in the top 30cm of a cultivated mineral soil and 96tC/ha in the top 30cm of grassland mineral soil; and 120tC/ha and 146tC/ha over 1m depth respectively.[60]

The EU's soil organic carbon store:

- In the European Union (EU27), there are around 75 billion t of organic carbon in the soil.[61]
- About 80% is in mineral soils, with higher amounts found in the northern parts of Europe.[62]

(Note, references to the 'soil carbon' store generally just refer to soil organic carbon).

Box 2 How much carbon does the soil contain?

- It is generally assumed that almost 60% of the soil's organic matter, on a dry basis, is made of carbon ('soil organic carbon').
- A factor of x1/1.74 (0.575) is used to convert a quantity of soil organic matter (SOM) into the quantity of soil organic carbon (SOC) contained in a sample.[63]
- Soil organic carbon is measured either in grams of organic carbon per kilogram of soil, or as a percentage of the soil by weight (for example, a SOC level of 30g/kg or 3%).
- SOC measurements include the soil microbial biomass, which accounts for just a few per cent of the total SOC.[64]
- The plough-layer of arable soil commonly contains 1-3% organic carbon in the UK.[65]

Box 3 Humus – its relationship to the soil carbon store

Humus is the end-product of decomposition and is that part of the soil's organic matter which is stabilised and accounts for the underlying soil carbon store of a given soil. The total amount of soil carbon at any time is the sum of the carbon in each of the soil organic matter components: organic matter in the process of decomposition, soil living organisms and humus. However, the amounts of decomposing organic matter and microbes rise and fall rapidly depending on whether fresh organic matter has recently been added, and only a small portion of fresh organic matter is converted to humus (the rest is lost by microbial respiration). So, the level of humus - stable soil carbon - only changes fairly slowly over time. Humus itself is further stabilised by the structural process of soil aggregation. So, to increase underlying the soil carbon store, it is necessary to focus on increasing soil humus levels and improving soil structure.

the soil, protecting carbon within aggregates, and mediating the cycling of carbon, **the soil's living organisms** play a central role in the soil carbon store.

Soil aggregation has other valuable functions: it gives the characteristic crumb structure of healthy soils which enables soil to resist compaction and water to percolate, allowing rainwater to drain into soil. Aggregation also provides pore space in the soil that holds water, so better aggregation increases the soil's water storage capacity, sustaining plants between times of rainfall. Thus, the soil carbon store also plays an essential role in the other soil functions that will become of greater importance to agriculture and wider society as climate change progresses: the resistance of agriculture to intense rainfall and droughts.

Farm management cannot change the type of soil that exists (the clay content), but it can influence all these other aspects that determine soil carbon levels: total soil carbon inputs, soil aggregation, the presence and size of root systems, the biochemical type of organic matter inputs (lignin content and C:N ratio), and the level and diversity of soil living organisms.

While the objective for climate policy is to increase the level of 'soil carbon', it needs to be appreciated that the development of the soil carbon store is about *biological* processes, i.e. the formation of stable humus, not inorganic chemical flows of 'carbon'.[66] So far, the level of carbon input to the soil has been a main focus of attention. But the extent to which this can change the long term soil carbon level depends on the extent to which biological activity in the soil is able to turn the carbon input into stabilised humus. Attention therefore also needs to be focussed on other important aspects of agricultural management, such as the type of organic matter input and soil biological health.[67]

3. Why might organic farming produce a different level of soil carbon?

> *"Because of the heavy reliance on natural soil fertility and disease suppression, soil organic carbon and soil organic matter quality is a crucial component in organic farming, more than in any other farming system."* Technical report to the European Commission on soil organic matter, in 2004.[68]

Organic farming is, as its name implies, organic matter farming. The source of fertility is not inorganic fertilisers which - with some limited exceptions[69] - are prohibited in organic farming, but organic matter, specifically the decomposition of organic matter in the soil by living organisms. Organic matter inputs, a biologically active soil and good soil structural quality are therefore essential in organic farming[70] and the focus of the organic farmer's efforts. These processes provide nutrients and water to the growing crops, but they are also the same factors as those which build the soil carbon store (see Chapter 7).

Good soil management is not an obligatory objective in organic farming simply because of an inability to use the inorganic alternative. The organic movement has a positive interest in promoting soil humus and soil life because of discoveries by the organic farming pioneers of an important relationship between soil health and human nutrition. In natural systems, soil microorganisms mediate the complex nutrient and water flows that support plants. Soil microbes therefore supply most of the trace minerals in the food chain (including the human diet). Organic farming is based on the view that it may be better for the nutritional value of the crops[71], and so the health of people, to feed these natural microbial processes by providing organic matter inputs to the soil, than to by-pass them by feeding crops *directly* with inorganic fertilisers. In other words, a fundamental tenet of organic farming is to 'feed the soil, which feeds the crop.' (This does not just refer to applications of organic matter, such as manure, but includes direct organic inputs to the soil by plants, such as grass). The early advocates of organic farming were also greatly concerned that the practices of industrial farming were degrading soils and therefore unsustainable. Practices were therefore developed which attempted to build soil organic matter levels by bringing together and developing the best of traditional and new practices, based on these principles.

This approach is the general reason why one would expect to find a higher level of soil carbon in organically managed soils. Like many of its objectives, however, the organic sector is still only part way to fully realising the potential of its approach, and one or two aspects of organic farming have also been held-up by sceptics as weaknesses (in particular, ploughing).

The most well known organic standards and practices that could affect the level of soil carbon differently to non-organic farming (positively or negatively) are:

- **Fertility-building periods in the crop rotation** – unlike the continuous cropping of much non-organic arable farming, organic crop production involves dedicated soil 'fertility-building' stages. UK organic crop production is generally based on mixed (crop and livestock) systems with 1-4 years of grass and legumes in each rotation to build soil organic matter levels.
- **Non-use of inorganic N fertiliser** – instead of using inorganic nitrogen (N) fertilisers, nitrogen fertilisation is achieved by growing legumes which naturally fix nitrogen in organic form.
- **A living soil** – instead of water-soluble fertilisers, organic farming relies on the activity of soil organisms, such as symbiotic mycorrhizal fungi, to provide nutrients from the soil's organic matter.
- **Additions of organic matter** – organic farmers frequently add additional organic matter to the soil, such as farmyard manure or by specially growing and ploughing-in 'green manure' crops.
- **Use of composting** – organic horticultural farmers regularly compost, rather than applying the animal or plant remains directly to the soil.
- **Use of ploughing** – most organic farmers in the UK rely on deep ploughing of the soil, while many large non-organic arable farmers have now adopted shallow 'minimum tillage'soil cultivations.

Although organic farming is often discussed in terms of its practices, and that is also the case in this report, it is not the individual practices that set apart organic farming, but the basic approach and choice of practices. The practices used by organic farming are not exclusive to organic farming and nearly all will be used by some non-organic farmers. However, in practice, because of its basic approach, the organic farming sector is characterised by relying on particular types of practices and avoiding others, and thereby usually uses a different balance of practices to the non-organic farming sector. A couple of practices - the reliance on legumes for nitrogen and the general non-use of agrochemicals – are common to all organic farmers, and are untypical of non-organic farming in the West. Beyond this, however, organic farmers have a choice of other practices and use different practices in different parts of the world and for different enterprises. However, the practices selected are usually ones that promote aspects of the basis of organic farming: the decomposition of organic matter for fertility. As non-organic farmers are not fully relying on this source or are not intentionally trying to optimise it, while they may use some of the practices that are characteristic of organic farming, they are not normally using them to the same extent and, in many cases, hardly at all. It is this choice of certain types of practices driven by the fundamental approach of organic farming that determines the effects of organic farming (not the unique use of specific practices).

It should be noted that organic farming is totally different to the practice of leaving land 'fallow' - uncropped for a season, a medieval European practice that has also been used more recently in the Great Plains of the USA after the devastating soil carbon losses of the 1930s Dust Bowl[72]. This practice does not use plants to build soil organic matter or legumes to fix nitrogen.

The importance of soil carbon to organic farming and the ability of the system to build up soil carbon levels have already been noted by researchers and policymakers. In its position on organic farming, the Food and Agriculture Organisation (FAO) said, "Organic agriculture contributes to mitigating the greenhouse effect and global warming through its ability to sequester carbon in the soil. Many management practices used by organic agriculture (e.g. minimum tillage [more common among organic farming abroad], returning crop residues to the soil, the use of cover crops and rotations, and the greater integration of nitrogen-fixing legumes), increase the return of carbon to the soil, raising productivity and favouring carbon storage."[73] During the compilation of a 1980 report on organic farming, the US Department of Agriculture found little evidence of soil erosion on organic farms and noted that many of the practices were those highly recommended by the USDA for soil management.[74]

As a result, many researchers have recommended an increase in organic farming, among other measures, in order to increase agricultural soil carbon levels.[75] However, until now the level of the soil carbon differences and the sequestration potential of conversion to organic farming have been unclear, especially in Europe. An early estimate cited in a 2003 report by the European Climate Change Programme ranged widely from 0-1.98tC/ha per year.[76] A 2008 paper by an EU-funded research project on agriculture and climate change (PICCMAT) gives a more specific estimate: "With regard to CO_2-sequestration in soils, organic agriculture can achieve high carbon gains … In particular, in Northern European countries, conversion from conventional to organic farming would result in an increase of soil organic matter (from 100 to 400kg/ha/year)."[77] However, this is almost certainly based on a modelling study[78] – see Section 6.5. This report presents new estimates of the carbon sequestration potential of organic farming, based on the largest and most detailed review of comparative soil sampling studies carried out to date.

4. Soil carbon losses from agricultural land

Large historic soil carbon losses around the world have contributed to the past carbon dioxide emissions by human activity that are now causing climate change. These losses are considered to be mostly due to the global expansion of agriculture, rather than to management methods. However, our analysis below suggests that farm management practices have also been very important, with the widespread adoption of inorganic fertiliser as the primary source of fertility last century being a major indirect cause. It is not clear whether soil carbon levels are still falling on long-established arable land in Europe, or are now stable. However, there are still major on-going losses from at least two agricultural sources: the conversion of temperate grasslands to arable land and tropical habitat destruction for the expansion of agriculture. The total of all these soil carbon losses - both historic and current - indicate the large scale of the potential for re-building the soil carbon bank with improved land management practices.

4.1 Historic soil carbon losses and causes

The conversion of natural ecosystems to agriculture has released enormous quantities of carbon into the atmosphere by the loss of vegetation (clearance of forests and scrub) and by losses of soil organic matter. The world's soils are estimated to have lost around 44 billion tonnes of carbon (Tc) since 1850.[79] This accounts for about 10% of all the emissions of carbon by human activity since 1850 – see Box 4.

Box 4 Breakdown of all carbon emissions by human activities since 1850[80]

Primary cause:

• Fossil fuel burning	65.5%
• Vegetation losses by clearance for agriculture	19.3%
• Soil carbon losses by conversion to cultivated cropland	9.7%
• Deforestation for timber & fuel wood collection	5.5%
•	
TOTAL:	100%

(Derived from Marland *et al*, 2006; Houghton, 2003; Houghton, 1999. Other greenhouse gases are not included.)

These historic soil carbon losses have resulted from the cultivation of forested land and grasslands, which causes the loss of 25-30% of the organic carbon in the soil (about half of that contained in the top 20-30cm).[81] This releases 10-50t of soil carbon per hectare of forest or permanent grassland that is converted to cropland.[82] Some areas have lost particularly large amounts: for instance, in the US, some Midwestern soils that were composed of up to 20% carbon in the 1950s, are now just 1-2% carbon.[83]

The figure of 44 billion tC is not the total amount of carbon lost from the world's soil, however. Most of Europe's farmland was converted from forests long before 1850[84], so Europe's soil carbon losses are mostly excluded (Europe accounts for less than 4% of the figure[85]). Globally, the area of cultivated land increased four-fold from 1850 to 2000, but there was already a large area of cultivated land in 1850 (320 million ha).[86] Additionally, the 44 billion tC estimate assumes that the conversion of natural grasslands or semi-arid areas to agricultural grazed pasture does not produce any soil carbon losses on the basis that it is still grassland and not generally cultivated[87], which is unlikely to be right in many cases[88]. Carbon losses from peatland drainage have also not been fully included.[89] Also, no allowance has been made for the effects of changes in agricultural management practices[90], so the actual soil carbon levels are likely to have varied much more between regions and over time than has been assumed.[91] Allowing just for the additional losses from the land that was cultivated before 1850, suggests that around another 10.6 billion t of soil carbon had been lost, taking the total global historic loss of soil carbon to about 55billion tC.[92]

On the positive side, researchers estimate that between a half and two-thirds of all the carbon that has been lost from agricultural and degraded soils can be returned by appropriate management practices,[93] a sequestration potential of 27-37 billion t of carbon. The analysis in the rest of this report supports this.

The cause of these global soil carbon losses are normally blamed on the global 'expansion' of agriculture, implying that the losses were a largely inevitable result of having to dedicate enough land to producing food to feed the world's population. Alternatively, some of the losses are blamed on 'changes in land use.' For example, the recent historic soil carbon losses in the UK are mainly attributed to the widespread ploughing up of permanent grassland that occurred from the 1940s onwards, during World War II and afterwards.[94] Over 95% of the UK's ancient chalk grassland were ploughed up and converted to arable land, or became 'improved' grassland by being ploughed and replanted with rye-grass 'mono-cultures' and treated with nitrogen (N) fertiliser. This, and most of the drainage and conversion of wet grasslands (salt marsh) to arable land, happened during WWII and during a second phase from 1960 to 1980.[95]

However, another perspective is to say that a large part of these soil carbon losses were a result of the specific farming practices that were being used. Throughout history, societies have struggled to maintain the fertility of their cultivated soils and avoid erosion (the final stage of soil degradation). Over time, various practices were developed in different regions to help maintain soil organic matter levels. However, during the last century, most farmers were largely released from this requirement to maintain SOM levels.[96] In other words, it is likely that the introduction of inorganic fertilisers may indirectly have been one of the main causes of the recent past soil carbon losses, by enabling the abandonment of traditional farming practices that had previously protected soil carbon levels.

In the UK, the period of intensification of crop production included the move from mixed to arable-only farms during WWII onwards, and the steady increase in inorganic nitrogen (N) fertiliser use from the 1960s[97] on both arable and grassland. Before the widespread availability of inorganic fertiliser, agricultural productivity had been completely dependent on the soil's organic matter levels and good structure for fertility. In other words, farming was dependent on the maintenance of humus levels, and this was the focus of many farming practices. Nevertheless, in practice, for various reasons UK agricultural productivity was widely restricted due to circumstances, and these methods were only fully applied to part of the land. The introduction of manufactured inorganic 'mineral' fertiliser, however, meant that farmers now had direct access to plant nutrients in agrochemical form (or rather, to the narrow nutrient range responsible for crop yields: N,P,K). Soils were now only needed as a substrate for the receipt of inorganic nutrients, and both humus levels and the soil's living organisms became largely redundant to agriculture's immediate needs. This led to the abandonment of the traditional soil humus protection practices. This was noted by the UK Government in its 1970 report, "Modern farming and the soil," in which it highlighted how practices such as the use of farmyard manure, green manures and temporary grass/clover leys had declined and it linked this to a gradual decline in SOM levels.[98]

These fundamental changes in modern agricultural practice came about because of the uptake of inorganic N fertiliser. For example, the use of N fertiliser enabled specialised arable-only farming systems to replace the mixed crop-and-livestock systems that existed before, and which had supplied manure for spreading on the cultivated soils and had rotated the land between crop and livestock/grass production. It enabled the simplification of crop rotations and use of monoculture systems. N fertilisers also reduced the level of soil carbon inputs by leading to a reduction in the size of crop root systems. Many other modern developments, such as the introduction of maize silage production with its bare soils, higher animal grazing levels on grassland and the widespread use of pesticides are also likely to have reduced soil carbon levels in recent decades. These agricultural developments are summarised in Chapter 5, and the biological processes by which they affect soil carbon levels are considered in Chapter 7.

Finally, as briefly mentioned, it is important to note that prior to the adoption of inorganic fertilisers, the productivity and soil management potential of traditional practices were actually far from being fully realised. In practice, UK farmland management was widely restricted by economic and local circumstances and a lack of political support for UK agriculture. Competition with imports and low prices for agricultural products meant that much land was managed in a very unproductive way, and in some regions productivity was curtailed by low soil phosphate levels.[99] To this extent, the application of good soil management methods today with widespread organic farming, now further developed and modernised, would be the first real opportunity for the full, wide realisation of 'organic farming' methods.

4.2 Current soil carbon losses and trends in the UK and Europe

Arable soils have the lowest soil carbon levels of all major land types in Europe. The European Commission has estimated that 45% of European soils have low organic matter levels, principally in Southern Europe but also in areas of the UK, France and Germany.

However, the question of whether the UK and Europe's agricultural soils are *still* losing carbon is a complex area with conflicting views and the situation is far from clear. The situation is summarised here, with more detail and analysis provided in Annex I. Key points of confusion are that there appear to be differences between the trends in all soils and just arable soils, between trends in the overall arable soil carbon store and that of the majority of arable land, between trends in the topsoil and the subsoil, that there are important methodological weaknesses in both the soil surveys and the modelling studies, and also that small on-going changes that may seem insignificant (say, losses below 1% of the total a year) are usually politically very significant. One thing is clear, however: with Europe's food and agriculture industry being increasingly reliant on tropical food and feed products, there are very large soil carbon losses occurring in the tropics due to natural habitat destruction.

Researchers have commonly considered that most modern, intensively managed arable land in Europe has reached a 'low but stable' plateau in their soil carbon levels. Nevertheless, European advisers have tended to the view that arable land is an overall source of carbon. In 2003, a European Climate Change Programme working group concluded, "there is evidence that under current agricultural practices, many European soils are losing organic carbon and thus constitute sources of atmospheric CO_2 rather than sinks."[100] In 2007, the European Commission valued the cost of Europe's declining soil organic matter at the large sum of €3.4-5.6 billion each year (£2.9-4.8 billion/yr).[101] Based on further evidence (surveys and modelling studies), European policymakers stated in 2008 that on-going reductions are probably occurring and, although they are small at a field level, if true, they are "very significant" in policy terms.[102] Europe's grasslands, on the other hand, are considered to be slowly sequestering carbon.

Having reviewed the studies on arable soil carbon levels, we can say that the trend and scale of change for long-established arable land and the majority of the arable land area remains unclear. There is good evidence that the *average* soil carbon level of arable *topsoils* is falling at significant rates in the UK and Europe, and that the UK's *total* arable soil carbon store is also falling. However, for the UK, the majority of this decline appears to be occurring in just part of the arable area – at least, according to one study.

The UK's total arable soil carbon store is almost certainly falling because there are very large soil carbon losses occurring from two categories of arable land: (i) arable land that was converted from grassland in the last few decades, and (ii) high-carbon organic soil types under cultivation, such as the fenlands (lowland peaty soils). These are both releasing large amounts of carbon, amounting to an estimated 1.9 million tonnes of carbon from the UK's arable area each year according to the UK's GHG Inventory - see Box 5. These are currently excluded from the official figures of UK agriculture's GHG emissions. But if they were included – as they should be – this would increase UK agriculture's total GHG emissions by 14%, double UK agriculture's CO_2 emissions (officially 1.8 million tC/yr) and would make CO_2 account for a quarter of agriculture's GHG emissions (ignoring for now other omissions from the official GHG figures).[103]

For the remaining arable land – UK mineral soils that have been under cultivation for a long time and for all arable land in Europe, it is *not* clear if there are any on-going changes in the overall soil carbon levels, and further, more precise research is needed.

The evidence comes from surveys and modelling. As soil surveys involve actual measurements, this information should in principle be more reliable than the modelling studies. However, both the soil survey evidence and the modelling evidence suffer from fundamental shortcomings that are obscuring the real effects of agricultural practices. For instance, most soil surveys only sample the topsoil layer. However, the *distribution* of soil carbon has probably changed in recent years due to changing farm practices, so changes in the topsoil may be being offset by changes in the lower soil levels. The overall trend cannot be determined without knowing the changes occurring in both the topsoil and subsoil. For the modelling studies, the key problem is that arable soil carbon levels are estimated on the basis that they are proportional to crop yield levels, an approach we challenge, while other significant factors are neglected. The various methodological flaws and their implications for interpreting the current evidence and for understanding the effects of agricultural practices on soil carbon levels are considered in Section 4.4.

Box 5 Arable soil carbon losses that are included in the UK GHG Inventory

Large losses of soil carbon from UK agricultural land are already included in the national GHG inventory. However, they are not accounted for in the GHG emissions of agriculture, but are reported separately under the 'Land Use, Land Use Change & Forestry' (LULUCF) sector.[104] This comprises:

1. Soil carbon losses of about 1.6 million tC/year net from the ploughing-up of grassland and expansion of cultivated land (after accounting for the gains from the smaller area of cropland converted to grassland).[105] Most of these losses are occurring in England and Scotland.[106]

2. Annual soil carbon losses of at least 264,000tC/year from the drainage and cultivation of the fenlands (lowland, drained organic-type soils) of England.[107]

Together, these account for an additional 1.9 million tC/year produced by UK agriculture. This would double the official figures for UK agriculture's CO_2 emissions (1.8 million tC/yr) and add an extra 14% to UK agriculture's total official GHG emissions (of 13.8 million tC/yr[108]).

This still excludes other agricultural soil carbon losses that are occurring in the UK, such as the very high continuing carbon losses from peatlands which have been drained and converted to 'improved grass', and any losses from other managed grassland.

For information, the UK and European evidence on soil carbon levels is summarised here. There have been six large-scale soil surveys in EU countries. Four surveys that sampled the topsoil only found that arable land is losing significant amounts of topsoil carbon (Belgium, Austria, and two in the UK). In contrast, surveys in the Slovak Republic and Denmark - which both measured a deeper soil profile and should therefore be more reliable, found the levels were declining or stable in Slovakia, and increasing in Denmark. See Box for details (and further details of the NSI soil survey are provided in Annex I).

There have also been four attempts to model soil carbon levels across Europe. These used models that simulate climate-vegetation-land dynamics and data on the relationship between climate, crop yields and soil carbon levels. Two of these studies concluded that Europe's arable soils are losing carbon (Janssens *et al*, 2005[109] and Zaehle *et al*, 2007[110]), one concluded that arable soils are in the range of slightly gaining or slightly losing carbon over the long-term (Smith *et al*, 2005[111]), and one concluded that arable soils are gaining carbon but not in southern England (Gervois *et al*, 2008). Details of these studies are provided in Annex I. The first two studies had similar findings to each other and to the national soil surveys. They suggest that Europe's arable soils are currently losing around 30 million tC/yr (for the EU25, Norway and Switzerland)[112], and that the average rate of loss is 237kgC/ha/yr, almost 0.3% of the total soil C per year. This lends some support to the findings of the surveys that Europe's arable topsoils are losing carbon. However, for the methodological reasons indicated, the findings of neither the surveys nor the modelling studies can be considered as reliable indicators of the overall changes in the UK arable soil carbon store.

The evidence is even more inconsistent for grasslands, with findings of large topsoil carbon losses occurring from the UK's grasslands since 1978 by the NSI survey of England and Wales (Bellamy *et al*, 2005), but no detectable change since 1978 according to the Countryside Survey of Great Britain[113]. Both surveys only measured the top 15cm of the soil and the sampling periods were similar[114]. The NSI survey found that the losses were not occurring consistently across the grassland area. Unmanaged grasslands (including upland grasslands, moorlands and bogs), which have the highest carbon levels of all soils, had the greatest topsoil carbon losses. However, grassland with lower soil carbon levels had gained topsoil carbon (managed grassland that originally had a SOC content under 5% and rough grazing land

Box 6 Surveys of the current soil carbon status of Europe's arable soils

There have been at least six large-scale soil sampling surveys of arable land in Europe. The results are summarised here:

Topsoil-only soil surveys:

1. **Belgium:** a large-scale survey of cultivated soils in the Flanders region (0-24cm, 1989-2000) found a mean **loss of 480kgC/ha/yr over 0-30cm** (and an estimated loss of 900kgC/ha/yr for 1m).[115]

2. **Austria:** national survey of cropland found a **loss of 240kgC/ha/yr over 0-20cm** (1965-1991).[116]

3. **UK:** a national survey in England, Wales and Scotland (Countryside Survey[117], 0-15cm, sampling in 1978, 1998 and 2007) found that the soil carbon level of arable and horticultural soils had **significantly decreased by almost 1% of the total each year** on average, from 1998 to 2007 (this period follows the NSI survey – see below). Over this time, the average soil carbon content fell 9.7% (from 3.1% to 2.8%). The level had also decreased over the long-term from 1978 to 2007.

4. **UK:** a national survey of England and Wales (National Soil Inventory[118], 0-15cm, initial sampling 1978-83, re-sampling 1994/95) also found that **arable soils (including rotational arable/grass) were overall losing carbon, with the data indicating an average loss of over 1% of the arable topsoil carbon store per year for mineral soils** (see Annex I)[119]. **However, arable soils with an initial SOC content under 2% had slightly gained carbon** (which may apply to around half the arable land in England[120]). Significantly, the carbon content of soils that were originally in, and maintained in, arable cropping were largely unchanged or increased slightly.[121] Cultivated soils with a SOC content over 2% were losing carbon, and the decline was greatest for those with the highest SOC contents (over 10% SOC).[122] The carbon losses were largest from soils which had been ploughed out of permanent grassland and peaty soils in cultivation (the English fenlands), while levels increased slightly for sandy soils and medium silts ("possibly reflecting regular livestock manure inputs to root crops on these soils").[123] For arable soils, there was a pattern of increasing losses with increasing soil wetness.[124] However, for both the NSI survey and Countryside Survey above, the very shallow sampling means that the results of these surveys are not reliable as indicators of the *overall* changes in the UK arable soil carbon store (over the whole soil profile).

Deep soil sampling surveys:

5. **Slovak Republic**: a national soil survey (1993 – 2002, 0-10cm and 35-45cm) found that **arable land had lost carbon** over the five years.[125] Most soil types had lost topsoil carbon, and there were also slight falls in the lower layer of most soil types. For a couple of soil types, however, a carbon gain in the lower layer had offset or reduced the overall fall. The SOC level of arable soils was mostly 1–1.8%. An earlier and longer monitoring study from 1970 to 2002, had found that the average SOC levels of arable land stayed roughly stable but fluctuated between 1.2% and 1.4%. Given this, it is not completely clear if the recent falls are indicative of a long-term downward trend.

6. **Denmark:** a national survey of arable soils (1986/87 – 1997/90, 0-50cm) found that the soil carbon level was **increasing by 177kgC/ha/yr** over 0-50cm.[126] This used the greatest sampling depth of all the surveys and there were major differences between soil types, management types, and soil depth. The soil carbon level had marginally decreased in the 0-25cm depth but, importantly, had increased significantly in the 25-50cm depth (+179kgC/ha/yr). It could not be established from the data if the differences were mainly due to soil type or management, but there were interesting differences relating to each. On average, the soil carbon level was falling on land receiving pig manure (-378kgC/ha/yr) or just inorganic fertiliser (-166kgC/ha/yr), but it was very substantially increasing on land receiving cattle manure (+897kgC/ha /yr). For loamy soils, the overall carbon content had decreased; these were mainly receiving inorganic fertiliser and no manure. In contrast, for coarse sandy soils, the carbon content had increased, especially at 25-50cm; the sandy soils had overall more grass and catch crops and were mainly receiving cattle manure.

with SOC contents originally under 10%). In contrast, a soil survey over a much deeper profile in the Slovak Republic found the soil carbon levels of grassland were slightly gaining for some soil types (by gains in the topsoil, rather than the subsoil) but were stable in other soil types.[127]

Other data gives a very positive picture of grasslands. According to some researchers, grasslands currently are or have the clear potential to be sequestering large amounts of carbon. Direct measurements suggest that grasslands are sequestering 450-800kgC/ha/yr (Jones & Donnelly, 2004).[128] Moreover, modelling of grasslands based on UK data for grass productivity and levels of manure deposition by grazing animals, and UK rates of decomposition, predicts that UK grasslands should be sequestering 670kgC/ha/year (Janssens *et al*, 2003). In total, this study estimated that UK grasslands should have a current carbon sequestration figure of 6million tC/yr, which is almost half of UK agriculture's annual GHG emissions.

This is a very significant issue given the topical issue of methane emissions of grass-fed livestock. If these sequestration figures were, or could be, correct, this would offset all the methane emissions of beef cattle and about half those of dairy cattle (methane emissions are equivalent to about 1,500kgC/ha for 2 dairy cattle/ha).[129] However, it is not clear whether this is occurring. The finding of falling or stable topsoil carbon losses by the two UK surveys implies that this is not occurring, unless it is being realised only in terms of higher soil carbon levels in the deeper soil layers and/or increasing soil depth. Certainly there are many agricultural reasons (not accounted for in the modelling estimate) why soil carbon losses rather than sequestration may be happening in grasslands - see next chapter. Clearly, more research needs to be undertaken on grasslands as a priority. If it were to be confirmed that grasslands have this potential, but that it is not occurring now, then steps would need to taken to put grassland management onto a much more positive course. Moreover, until it is established if grasslands indeed are or could be sequestering such amounts of carbon on an on-going basis, current assessments of the climate impacts of ruminant livestock, the GHG impacts of agriculture as a whole, and the debate on grass-fed versus grain-fed meat - none of which have taken this issue into consideration, to our knowledge - could well be very misleading.

The UK Government does not report any carbon losses from grassland in its annual GHG reports, even from peatland, although these could well be enormous, running into many millions of tonnes of carbon per year.[130] In Scotland, over 150,000ha of peatland are "severely affected" by drainage[131] and likely to be releasing very large amounts of carbon (see Section 5.14). The reason given for not reporting on peatlands is because, "methods for estimating emissions do not currently allow emissions from mineral and organic soils to be separate." This is despite the fact that the UK reports its carbon losses from organic soil types for cropland and that other EU countries with large peatland areas (Finland, Germany and Poland) manage to report their carbon losses from organic type grassland soils.[132]

Whatever the scale and distribution of soil carbon losses from Europe's cultivated soils and, if they exist, from UK grasslands, the reasons for the observed losses have been the subject of much debate. Possible contributors include climate change, the conversion of grasslands to arable land, the effects of agricultural management practices, drainage of peatlands (often for agricultural intensification), heather burning and environmental pollution. Climate change - i.e. rising temperatures, rising CO_2 levels, increasing drought and altered weather patterns - is a potential factor that would apply to all soils. Temperatures in Europe have risen in recent decades, even more than climate change modelling predictions.[133] However, the consensus among UK researchers is tending to the view that climate change is not having a major negative effect yet. For instance, at the most, only small losses of 67kgC/ha/ha for European arable land and half this rate for grassland are predicted by modelling the effects of climate change.[134]

According to one group of European researchers, Janssens *et al*, the soil carbon losses from arable land,"are probably because of changes in management practices such as a decrease in the application of organic manure to cropland."[135] For the UK, in line with the analysis of the NSI survey results, they suggest that the ploughing-up of permanent grasslands "during the past 20 to 30 years" may account for the losses. However, they suggest this specific cause cannot explain the losses from arable soils in the rest of Europe given that the main period of grassland ploughing-up was much longer ago than in the UK.

Further analysis by the National Soil Resources Institute (NSRI) of the UK NSI survey results supports the view of agricultural practices as the main cause. The application of a simple carbon model that tested the effects of climate change, land use/management, and environmental pollution produced the initial conclusion that, "the dominant driver of soil carbon losses was changes in land use/management, but climate change was responsible for part of the losses, and is likely to cause increased losses in future."[136]

In our view, this conclusion seems very reasonable given that there have been and continue to be many important developments in agricultural practice that are likely to have affected soil carbon levels and that there appear to be a good correlation between the timing of these developments and the soil surveys – see Chapter 5. Conversely, this conclusion also implies that agriculture has significant potential for rebuilding soil carbon levels with a change in farming practices.

The heavy carbon impact of the UK's and Europe's food and agricultural systems abroad must also be considered. The destruction of tropical habitats is a major global source of GHG emissions, releasing about 1.5 billion t of carbon each year from the soil and trees.[137] This accounts for about 12% of all global anthropogenic GHG emissions.[138] Alongside logging for timber, agricultural expansion to supply export markets is one of the main causes of these carbon losses, with the trade in palm oil, beef and soya being leading culprits.

Based on available information, we estimate that the international trade in palm oil - a common ingredient in processed foods - is the source of *at least* 150million tC per year[139], because of the huge losses of carbon being caused by the degradation of Indonesia's peatlands. We estimate that Brazil's beef exports account for carbon losses of around 20-35 million tC each year from deforestation of the Amazon.[140] Beef imports by the UK are an unrecognised consequence of the intensification of dairy farming, and this impact may overwhelm any 'carbon savings' from the increased efficiency of milk production.[141] We do not yet have a figure for the carbon losses related to imports of soya, but it must be substantial. 60-70% of the economic value of soya in international markets is the soya 'meal' that is used for animal feed (the rest is for food use)[142], so 60-70% of the carbon losses of soya production should be attributed to livestock and the trend towards intensive, grain-fed meat and dairy systems. (Boxes 7 and 8)

The UK and Europe as a whole are important importers of these products. By sourcing directly from regions where habitats are being cleared (palm oil from South-east Asia, beef and soya from South America) and also just by fuelling the global demand for these products even when they are not imported directly from these regions (beef and soya), our food and agricultural systems are responsible for a part of these carbon losses.

Until now, these 'land use change' GHG emissions have not been included in any assessments of the GHG impacts of agriculture, including national GHG inventories and 'LCA' studies of organic and non-organic farming. A new report for WWK UK and the Food Climate Research Network (FCRN) has now evaluated these emissions and shown they would raise the food and farming sector as a proportion of the UK's total consumption-related GHG emissions from 19% to 30%.[143]

In conclusion, large amounts of carbon are being lost in the UK due to the conversion of grasslands to arable land, and in tropical areas due to habitat destruction as a consequence of the industrialisation of food production in Europe, including the trend from grass- to grain-fed meat. None of these losses are yet included in official figures of agriculture's GHG emissions. However, while topsoil carbon levels appear to be widely falling across Europe, whether significant overall soil carbon changes are widely occurring on UK and European farmland that has been under cultivation for a long time cannot yet be established from the current evidence. Further research and analysis is needed. The developing consensus is that the main cause of any observed carbon losses on farmland is agricultural land use and/or management.

Importantly, several developments in agriculture have been identified that are keeping arable soil carbon levels low and some of these *may* be depleting topsoil depth or subsoil carbon levels, and thus overall levels, in long-established arable land. The following chapter explores the effects of current practices.

Box 7 Soya imports - Carbon losses from destruction of the Brazilian Cerrado

The 'Cerrado' savannahs of Brazil are now one of the largest global sources of soya.[144] This natural habitat covers 20% of the area of Brazil – 2 million km^2 - and is being destroyed faster than the Amazon rainforest, particularly for soya production.[145] Since the 1960s, there has been a huge expansion of large-scale agriculture and over half the area has now been converted to farmland.[146] This development is causing huge soil carbon losses. The habitat has been compared to an upside-down forest. According to the Worldwatch Institute, the Cerrado stores large quantities of carbon as the vegetation is adapted to droughts and has very extensive root systems. It is estimated that a hectare of Cerrado contains about two-thirds as much carbon as a hectare of Amazon rainforest.[147] In addition, over a million hectares in the Amazon rainforest are used to produce soya[148] and deforestation linked to soya has been continuing.

Beef imports - Carbon losses from destruction of the Amazon

Few people realise that a falling domestic beef supply is a driver of the destruction of the Amazon. The Amazon is the world's most important forest carbon store[149] and plays a large role in the stability of the Earth's climate. But it is being rapidly destroyed and 80% of this destruction is due to cattle ranching[150], partly for export. Brazil's beef and veal exports rose six-fold in volume from 1998 to 2008 and Brazil is now the largest beef exporter, supplying almost a third of the global beef market in 2008.[151] Tragically, rainforest clearance is often carried out in preference to using the existing pasture land, as this costs about half as much as restoring previously cleared land to productive use which requires fertilisation and water resources.[152] This means that the destruction of the Amazon has not been driven simply by a growth in demand for beef, but just by the *existence* of the global beef market. We estimate that Brazil's beef exports currently account for carbon losses of around 20-35 million tC from the Amazon each year.[153]

According to Greenpeace, the growth in Brazilian beef exports over the last decade has compensated for falling beef production in the EU and Russia.[154] In recent years, the UK has gone from a state of self-sufficiency in beef to being only 80% self-sufficient in 2008 and is now importing around 300,000 tonnes of beef each year.[155] UK imports are forecast to continue growing to at least 2013.[156] The reason, according to a recent industry report, is because of a 38% fall in the supply of beef from the English dairy herd from 1990-2007, and this is partly because of the development of higher-yielding dairy systems in the UK.[157] In England, half of the beef is produced from the excess calves from the dairy herd and half from the specialist 'beef suckler cow' herd.[158] Intensification of dairy farming results in higher milk yields per cow but it also increases the metabolic stress of the cattle and shortens their productive lives, which means more of the calves have to be reared as dairy 'replacements', rather than being available to rear for beef. UK dairy cattle now produce milk for an average of just three lactations.[159]

In 2008, the UK was one of the top importers of processed beef from Brazil[160] (meaning prepared, ready cooked or tinned beef, e.g. for use in ready meals, such as lasagne and meat pies[161]). In 2009, Brazilian beef imports to Europe were restricted (due to Foot and Mouth cattle disease)[162] and most imports were sourced elsewhere. However, whatever the origin of the imports, the UK and Europe nonetheless account for a large portion of the global beef market that is driving the destruction of the Amazon.[163]

Action to protect the Amazon is now being taken by and against the Brazilian soya and beef industries[164] and the Brazilian Government has announced plans to substantially reduce the rate of Amazon deforestation.[165] Whether this happens remains to be seen, however.[166] According to an investigation by Greenpeace, the Brazilian Government has been investing heavily in the country's beef industry and had plans to double the country's share of the global beef market by 2018.[167] Additionally, over 90% of recent Amazon deforestation has been carried out illegally.[168] And, anyway, as long as the global demand for soya and beef continue to exist, initiatives to save the Amazon are only increasing the pressure on the valuable Cerrado region which is mostly unprotected.[169] So, there may be little reduction in carbon losses even if Amazon deforestation is curtailed.[170] The solution must therefore be for the UK and all importing countries in temperate regions to significantly cut their reliance on soya and revert to *non-tropical* sources of animal feed. In practice, this means reversing the trend of intensification of dairy farming, reversing the expansion of pig and poultry factory farming, halting imports of intensively produced chicken and pork, and re-investing in grass-based livestock systems on the large areas of existing farmland.[171]

Box 8 Palm oil – Soil carbon losses from peatland destruction in Indonesia

The use of palm oil by the food processing industry is one of the foremost global causes of carbon emissions by deforestation[172], due to the large-scale establishment of palm oil plantations on carbon-rich tropical peatlands and the associated burning and drainage of these peatlands. Much of this takes place in Indonesia which holds the global record for GHG emissions from deforestation.[173] Palm oil plantations account for about 32% of Indonesia's emissions from deforestation[174], which means that the trade in palm oil is the source of *a minimum of* 150million t of soil carbon losses per year.[175] Palm oil production has also been linked to large-scale deforestation in Colombia, Ecuador, Brazil, Central America, Uganda, Cameroon and elsewhere.[176]

By 2030, demand for palm oil is expected to be double that of the year 2000, according to the FAO.[177] Already over half of Indonesia's forested peatland has been cleared, and further huge expansion of palm oil plantations is underway and planned in the peatlands.[178] This is a huge threat. Indonesia's peatlands store 37billion tC and are among the worlds most concentrated soil carbon stores. The peatlands of Riau province, for instance, hold an average 3,650tC/ha.[179] This compares to the average palm oil yield of just 3.7t/ha/yr.[180] Each tonne of palm oil grown on peatland results in the release of 2.7-19t of carbon.[181]

Palm oil is widely used in industrial, processed foods in the UK and other countries[182], such as for making margarine (palm oil is used in 'healthy' margarines as a replacement for hydrogenated fats), bakery products (such as, bread and pastry)[183], instant soup and ice cream.[184]

As the emissions are not attributed to the importing countries (e.g. EU member states[185]) and as Indonesia is a developing country, the emissions are not subject to reduction under the Kyoto Treaty.[186] Another problem is that the global trade in palm oil is a commodity market, meaning that buyers cannot identify the origin and choose only sustainably produced palm oil.[187] Also, most food manufacturers are not openly labelling palm oil in the ingredients list of foods, usually listing it simply as 'vegetable oil.' This means that – unless consumers avoid all processed foods - it is almost impossible for people to avoid buying foods made with palm oil even if they want to. In other words, market forces are completely unable to operate at the moment.

4.3 Future soil carbon changes

The potential vulnerability of the soil carbon store to climate change is another major subject of debate. This is a highly complex and uncertain area.

There is concern that soil carbon losses may accelerate in future because the rate of microbial breakdown of soil organic matter is expected to increase with rising temperatures. A doubling of the soil respiration rate for each 10°C warming has been found to apply over periods of a couple of years, but the effects may increase even more over longer time-scales as the more stable humus components start to be affected.[188] This climate effect is only expected to occur in regions with sufficient soil moisture to allow higher microbial activity, which includes Northern and Eastern Europe (but not Southern Europe).[189] In addition, heat and drought stress will act to reduce plant growth and organic matter deposition. At the same time, the higher atmospheric CO_2 levels should promote plant growth. Current theory is that, in temperate zones, this "CO_2 fertilisation effect" will more than offset the negative effects of increased soil respiration and drought and it is therefore believed that organic matter deposition will increase. Modelling based on this concept suggests that climate change will have little overall effect on soil carbon levels in Europe.[190]

However, considerable work remains to be done on the reliability of the models and data, so this prediction of minimal change must be treated with great caution. For example, many climate-carbon-cycle models use fixed factors for the rate of soil respiration increase with temperature rise, despite the research suggesting that the rate of increase will probably accelerate.[191] Also, the CO_2 fertilisation factors being used in most of the modelling studies so far, were derived from small-scale enclosed-condition studies conducted over 20 years ago, and there is now evidence that they are probably very over-optimistic - see below.[192] Additionally, the models do not account for the fact that plant growth would be constrained by the availability of soil nutrients. Analysis of US forest data has failed to find a significant growth response to current higher CO_2 levels[193], and some researchers have now concluded that the 'CO_2 fertilisation effect' may be limited, such as by limits in soil fertility[194]. The models also do not consider the fact that other plant stresses will be increasing in future. These aspects all suggest that current predictions of little change in soil carbon levels are far too optimistic.

On the other hand, "realistic models dealing with the turnover of subsoil C need to be developed," according to researchers at Rothamsted.[195] An initial such model "strongly suggests" that other models that treat the top metre of the soil as a single homogenous layer *over-estimate* soil carbon losses due to global warming. As the subsoil contains the highly resistant half of the soil carbon store and is affected by farming practices (ploughing depth, root depth etc.), this is important for properly evaluating the effects and future potential of different agricultural systems on the soil carbon store.

Perhaps the most concerning weakness of the current soil carbon models is, according to the Centre for Terrestrial Carbon Dynamics (CTCD), "the lack of a biological component, i.e. how soil fauna will respond to future climates and how this will affect soil carbon fluxes." [196] Given that soil carbon is a product of biological processes and different farming systems affect these processes in different ways[197], this omission may be critical. The basic knowledge about the climate impacts on soil life is still inadequate. For example, according to the same source, "the biological significance and relevance of the most critical C-turnover parameter" used in the models, the 'Q10' value, representing the change in soil respiration rates of the different soil carbon components in response to temperature, "is not sufficiently understood."

As mentioned, recent work has indicated much lower levels of future plant growth and soil C input. Using Free-Air Concentration Enrichment (FACE) technology, large-scale field trials by the University of Illinois and others in fully open-air conditions have shown that the CO_2 enhanced growth is only *half as much* as previously thought for C_3 crops[198] (wheat, soya and rice) and *no* growth increase occurs in C_4 plants (maize, sorghum and C_4 wild grasses) as these plants are already 'CO_2 saturated'.[199] Moreover, when the phytotoxic effects of ozone and other future stress factors are included, a *reduction* in growth is predicted. Ozone reduces the level of photosynthesis and levels are expected to rise about 20% by the middle of the century in many temperate and tropical areas.[200] Very high temperatures, such as in the '40s can also reduce photosynthesis. Plants transpire less in elevated CO_2 levels, and while this improves leaf water content, they will be less able to maintain a cooler temperature. Also, while small increases in CO_2 may increase plant growth, at the projected very high increases in CO_2 (e.g. 60% increase), growth should fall again.[201] All these factors will affect future plant growth and biomass deposition in the soil.

Another point is that the modelling studies have to date only addressed mineral soils, not the impacts on the organic-rich soils that make up most of the UK's carbon store, as these soils were not covered by the models so far.[202] Current predictions have therefore, for example, not allowed for the fact that peaty soils are sensitive to falling water tables and if rising temperatures cause peat soils to dry, they could lose more soil carbon.[203] There seem to be conflicting views on whether the temperature sensitivity of soil carbon decomposition is also higher for peaty soils[204], which could be another cause of rising future carbon losses.

Given all this, nothing can be presumed now about the impact of climate change on soil carbon. This uncertainty about the future could be seen as an argument against investing in the soil carbon store. However, the soil's organic matter level is so important – such as for climate adaptation - that whatever the conditions, the optimisation of this resource surely remains a necessity. Despite the many uncertainties, the positive example from the Danish soil survey shows how much might be gained with the right approach. Despite average European temperatures having risen slightly, the carbon content of arable soils receiving cattle manure was nevertheless increasing by an impressive 900kgC/ha/yr.

4.4 Shortcomings in the current methodology for assessing soil carbon losses and causes

The studies on soil carbon levels are generally only assessing part of the soil and the likely changes. There are several methodological short-comings in the research so far that are obscuring the full extent of soil carbon changes and the real impact of agricultural practices. These shortcomings are summarised below, first for the soil surveys and then the modelling studies.

All of the following five points on survey methodology apply to the UK's NSI survey and many of the other European soil surveys. The first three issues also apply to the body of comparative studies of organic and non-organic farming soil carbon levels.

1. <u>Soil carbon content below the topsoil layer</u>

In most soil surveys, only the topsoil or part of the topsoil is sampled (0-25cm), sometimes just 0-15cm (e.g. the NSI study). This means that the surveys are only capturing the changes in half of the soil carbon store: 40-60% of the total soil carbon over 1m depth occurs below 25cm.[205] Moreover, the lower soil layers - below the ploughing depth of cultivated soils - is where there is less risk of mineralisation[206]. The mean age of the humus at 60-80cm is several millennia, meaning this carbon is extremely stable.[207]

The subsoil is therefore a very important part of the soil carbon store for climate policy, and it is essential to assess the trends and effects of management here. The issue of sampling depth is particularly important for agricultural soils because of the use of cultivation which mixes the soil over the depth of the plough-layer (typically, 8-9 inches/20-22cm for conventional 'mouldboard' ploughs), and because changes in management practice can produce a different distribution of carbon over the soil profile.

Deep soil sampling is vital for identifying the effects of ploughing depth, an aspect of agriculture that has changed significantly in recent decades (with both deeper ploughing and shallow cultivation practices having been widely adopted by different parts of the industry). There are also differences between the organic and non-organic farming sectors, with more use of deep ploughing by organic farmers in the UK and probably in all northern Europe (though not necessarily in all other countries). With shallow soil sampling, an increase in ploughing depth will give the impression of a decline in soil carbon levels even if the total amount of soil carbon is actually unaltered.[208] This is because deep ploughing tends to mix the topsoil with the lower-carbon content soil below, so an increase in ploughing depth is likely to dilute the topsoil carbon content over time. This is may account for some of the arable soil carbon losses observed.

Likewise, in arable regions where shallow cultivation methods have been adopted (typically areas with large, specialist arable farms and very low soil carbon levels), shallow sampling will give the potentially false impression of a small increase in soil carbon levels, as this practice concentrates the organic residues at the surface without necessarily changing the total amount of soil carbon (contrary to common perception, see Section 9.2). This could account for some of the small topsoil gains observed in arable land with the lowest topsoil carbon levels in the UK NSI study, and this may be obscuring subsoil and possibly overall carbon losses.

The soil carbon levels in the lower soil layers are also affected by other agricultural practices. Soil organic matter deposition by plant roots and incorporation by earthworm burrowing[209] can extend far below 30cm. Where conditions and the plant variety allow, for instance, the roots of crops can grow several feet deep.[210] This is especially important given the amount of research that now suggests that root systems contribute more to the soil carbon store than above-ground plant biomass.[211] Soil carbon changes below the topsoil may therefore be occurring because of changes in the size of root systems or earthworm populations. These aspects are also important for comparative evaluations of organic and non-organic farming. For example, the depth of crop roots tends to be reduced by the use of inorganic fertilisers (see Sections 7.6 & 7.8), as the nutrients are concentrated near the surface. In one comparative study of cultivated soil, significant differences in soil carbon levels occurred down to 60cm.[212]

This shows that the 0-15cm sampling of the NSI and Countryside surveys is a serious flaw, and the real scale of changes in the UK agricultural soil carbon store remains unknown. Unfortunately, this is a common problem and most soil carbon studies to date have used fixed-depth shallow sampling. The current body of evidence therefore probably mis-represent the impacts of agricultural management and under-represents the comparative effects of organic farming. Future research should be done using deeper sampling[213], with information gathered on ploughing depth[214] and any changes in ploughing depth.

2 Changes in soil carbon storage due to erosion or soil build up

Most surveys just measure the percentage of the soil that is carbon (SOC %) and do not measure the soil depth or topsoil depth. However, the soil carbon store also increases or decreases if there is a change in the depth of the topsoil or total soil depth. Soil/topsoil depth will increase if the conditions allow soil build-up to occur (which is possible with degraded arable soils) and will fall if soils are suffering from erosion or being degraded. This factor is likely to have changed in recent years.

For instance, the depth of ploughing determines the depth of incorporation of organic matter and can therefore influence the depth of the topsoil. Interestingly, if a significant increase in organic matter inputs takes place at the same time as deeper ploughing depths being adopted, then the topsoil depth may increase, as was found by a detailed arable soil survey in a Belgian province[215]. In such cases, there may *or may not* be a change in the topsoil SOC content[216] - the percentage of the topsoil that is organic carbon. The rest of the soil carbon increase can occur as an increase in the topsoil *depth*. This possible interaction between ploughing and topsoil depth is currently a missing dimension in the comparative studies of organic and non-organic farming.

Erosion by wind or water means that the total quantity of soil is being physically depleted. A large amount of soil - but a proportionately smaller amount of carbon – is lost this way. A 1999 NSRI survey for the Government found that 44% of land in England and Wales is prone to erosion[217] and that annual losses of arable topsoil are some 2.2 million t.[218] If all eroded soil has a normal carbon content, this would suggest a further 53,000t of carbon, or so, is being lost each year from the UK's arable land.[219] However, the amount of carbon lost by erosion is lower than indicated by the quantity of eroded soil,[220] because eroded soils are generally the most degraded and likely to have lower carbon content than average. It is also not known how much of the carbon in eroded soil is released as CO_2. About 20% of the organic carbon in eroded sediment is thought to be oxidised immediately[221], but much of the rest is washed into watercourses and only released over long timescales.[222] The annual quantities may nevertheless still be significant since river estuaries emit considerable amounts of carbon to the atmosphere.[223]

While the scale of CO_2 emission by soil erosion is unclear, it is a contributor to some degree and accounting for erosion is particularly important for agricultural soils with very low carbon levels, such as in semi-arid regions, as these cover a large area and are especially prone to degradation by erosion but are responsive to improvements in management.[224] In dry areas of the world, about 70% of the land is considered to be degraded.[225] However, erosion can also be an issue in intensively managed arable soils and in upland grassland areas where there has been over-grazing, as is the case in the UK.

Although most studies only sample a fixed depth of soil, importantly, some comparative studies have looked at topsoil depth and found it to be greater under organic farming than non-organic farming.[226] At the moment there is no information on how common this is, how much this adds to the soil carbon benefit of organic farming, whether this reflects changes in the relative depths of the topsoil and subsoil layers or if the total soil depth is also different between organic and non-organic farming, and what the causes are (whether due to differences in erosion rates, ploughing depth or other factors that promote soil build-up in organic farming). To complete the information on the comparative soil carbon effects of organic farming and the effects of agricultural management in general, data is therefore needed on the trends in topsoil depth, and the average difference in topsoil and subsoil depth between organic and non-organic farming.

3. Soil density

The common non-measurement of the soil's bulk density is another way in which the effects of agricultural management are not being properly taken into account. This may be distorting the results of some soil studies where they are reported in tC/ha, by giving the impression of lower soil carbon levels than actually exist. Healthy, well-structured soils have a low bulk density. However, if there has been widespread soil compaction, such as due to heavier machinery, more autumn cultivations or over-grazing (all developments that have occurred), then the soil samples - which are all of the same depth in most soil surveys - can include a greater proportion of soil from the deeper layer. These have lower average carbon contents than uncompacted soils, so would give the impression of lower soil carbon levels and thus soil carbon losses, irrespective of whether this is really the case.[227] Measurement of soil bulk density is therefore needed to control for these effects. (This is not to suggest that compaction itself is not also a concern: it is a serious type of soil degradation, and by reducing soil structural quality, aeration and root growth, it can lead to a reduction in soil organic matter levels.)

4. Classification of much grazing land as 'non-agricultural'

Land use classifications also appear to be obscuring the contribution of agriculture to soil carbon losses. In the NSI survey, rough grazing was classified as 'non-agricultural' land, and this is the case in other studies. A SEERAD paper, "Review of the contribution to climate change of organic soils under different land uses"[228], dismisses any role of agriculture in the carbon level of Scotland's organic soils by saying few of these soils are farmed and their land use is restricted to forestry and rough grazing. Indeed, in some reports all grazed land is referred to as 'non-agricultural' and only arable land is classed as 'agricultural.'

This is highly misleading as grazing is very much an agricultural activity and the UK's grasslands are the largest part of UK agriculture's soil carbon store. As a consequence, the various aspects of grassland management that can affect soil carbon levels may not be receiving as much attention as the management practices of cultivated soils, including: the various impacts of grassland 'improvement' which means replanting with commercial grass varieties, use of inorganic fertiliser and occasional soil cultivations; grazing intensity (which increased significantly in the UK between 1976 and 2000[229]); and possibly, the wide use of livestock worming drugs (see Section 7.14 for details). Therefore, much of the soil carbon changes observed in 'non-agricultural' land may well be due to agricultural practices.

(According to the UK's Centre for Ecology and Hydrology, this situation originates from the fact that the classifications were traditionally made by ecologists who defined land according to the main plant species. The absence of domestic crop plants tended to result in grassland being classed as non-agricultural.[230])

5. Classification of 'arable land'

The classification of 'arable land' may also be obscuring the impacts of intensive agricultural management. This category normally includes both continuously cropped arable land (typical of intensive 'industrial' arable farms) and arable land that is part of a rotation that includes a temporary grass ley, as used in organic and many traditional mixed non-organic farms.[231] As grass leys are a key way of raising the soil carbon levels of cultivated land, this is hindering the correct identification of the normally lower soil carbon content of all-arable farming. This is valuable missing information. It is therefore recommended that future soil surveys distinguish between all-arable and rotational arable/grass ley land.

Additionally, the FAO's classification of land – which is used by some soil carbon modellers – includes grass silage as 'cropland'.[232] Given that grass has particular benefits for soil carbon storage (see 7.1), that grassland normally has substantially higher soil carbon levels than arable land, and the common use of grass silage, this could well be distorting some estimates of arable soil carbon levels and trends.

There are also important limitations with soil carbon modelling studies. Inevitably, the estimates they produce are only as good as the data and assumptions that they use. At the moment, we have identified several methodological shortcomings that suggest, in our view, that most of the current modelling approaches do yet provide reliable estimates of the comparative soil carbon effects of organic farming or farmland soil carbon trends in general. For some examples of modelling studies and some of their respective flaws, see section 6.5 and Annex I. The use and development of soil models is, however, very valuable for challenging assumptions and for driving analysis, debate, the collection of new data and, thereby, overall understanding of agricultural soil carbon issues. For this reason, we fully support continued investment in the models and their use. We do, however, caution against any reliance on the models for policy purposes, particularly regarding decisions about the direction of agricultural development, unless their conclusions are clearly backed up by direct soil sampling studies.

6. The assumption that soil carbon input levels are proportional to crop yields

Our greatest concern about the modelling studies is that they are mainly based on the concept that the soil carbon input to farmland - and thereby soil carbon levels - is proportional to the crop yields, with often little consideration of the direct effects of agricultural management practices.[233] We understand that this is based on the results of long-term controlled trials, which show a correlation between yields and soil carbon levels *if* other factors are constant, for the reason that higher crop yields also generally mean higher crop residues (root, stubble and straw biomass).

However, many other agricultural management factors affect soil carbon inputs and soil carbon levels, Soil carbon inputs can come from many other sources in agriculture (rotational grass, manure, green manure crops etc.) and indeed, in 'good' farming systems (meaning good for soil quality), there *will* be additional, non-crop sources. These contributions need to be taken into account. The type of organic matter input is also important, as different types have different 'carbon conversion' rates (rate of conversion of soil carbon inputs to stable soil carbon). These management factors do not affect soil carbon inputs and crop yield levels in similar ways, and these factors also do not stay constant: they vary between different systems and as agricultural systems develop. There are also interactions between the different management factors, such as apparent effects of inorganic fertiliser use on root biomass (see Chapter 7). Given the probably dominant role of roots in the soil carbon store, how farming systems affect the quantity of root biomass, such as, from the use of inorganic fertiliser or legumes for fertility, and from the use or non-use of rotational grass, is a particularly important aspect that seems inadequately addressed by the modelling studies. According to one study, the omission of other management factors is "owing to the lack of consistent data to parametize such" effects.[234]

This issue is particularly important for assessments of organic farming or of the practices used by organic farming. Organic farming has very variable effects on crop yields (e.g. for arable crops, organic farming yields are much lower than non-organic yields in Europe, but are close to non-organic in the US[235]), but it has fairly consistently positive effects on soil carbon levels (Chapter 6). Thus, an assumption that soil carbon inputs mainly relate to crop yields is totally inappropriate for assessing organic farming. This issue also greatly undermines the reliability of the current modelling assessments of agricultural soil carbon trends (see Annex I for more details). The relationship between crop yields, soil carbon inputs and soil carbon levels are further explored near the end of this report, in Sections 9.3, 9.4 and 9.7.

7. No separate subsoil carbon component in the soil models

Other shortcomings of modelling studies were described and/or illustrated by example in the previous section on "Future soil carbon changes", and are only briefly listed here. The lack of a subsoil carbon component in the models is highly important given the longer life-time of the subsoil carbon store and the indications that organic farming often increases subsoil carbon levels (see Chapter 6).

8. Lack of a biological component in the soil models

The lack of a biological component may be important and especially for assessments of organic farming, given the differences in the soil microbial level/activity, soil respiration rates and soil microbial respiration rates found in organically managed soils – see section 9.5 on mineralisation rates.

9. Use of inaccurate data

Some of the data used may be inaccurate. For example, modelling studies may use some data derived from laboratory studies which do not represent real conditions, e.g. on the 'CO_2 fertilisation' effect of climate change. It is of particular concern that there is almost no relevant data from organic farming systems, so most attempts to model the effects of organic farming would be using non-organic production data, such as of the 'shoot' and root biomass levels. This could be very inaccurate (e.g. see Section 7.6).

10. Exclusion of organic soil types

This is particularly relevant for the UK, which has large areas of peatland in agricultural use.[236]

5. Developments in agricultural practice that may have reduced soil carbon levels

This is a review of the main changes in agricultural management which are likely to be causing the low soil carbon levels of arable land and any soil carbon losses from UK grassland. These are all associated with the intensification and specialisation of agriculture. The biological soil mechanism by which these practices affect soil carbon levels is considered in more detail in Chapter 7.

1. <u>Abandonment of mixed farming with temporary grass</u>

One of the main reasons for the long term fall in soil organic carbon levels of English arable soils has been attributed to the movement away from mixed farming rotations, into permanent arable cropping.[237] Mixed systems include both temporary grassland and cultivated land in their rotations, which is important as grassland has many benefits for soil carbon accumulation.

Traditional UK farming practice was to have some fields on the farm growing arable crops continuously (with often a leguminous crop in the rotation to maintain soil fertility), whilst other fields were in permanent grass. Then, from the 1930s onwards, arable-ley farming systems using short-term grass leys were introduced.[238] In these systems, the cultivated land underwent some years in a temporary grass/clover 'ley' in each rotation. However, the intensification of crop production in the UK meant a large-scale move from mixed to arable-only farms and the alternation of short-term leys with arable cropping was progressively abandoned again. This occurred in two main phases, during WWII and in the early 1970s when the UK joined the EEC. UK agricultural census data shows that the area of farmland in arable/ley rotations halved from 30% to 14% between 1969 and 1997.[239] The loss of mixed farming is also cited as a likely reason for the soil carbon losses in some cropland areas in Belgium.[240]

The positive effects of grass leys might also explain the interesting findings of the ten-year national Danish survey of cultivated soils[241], which measured a much deeper soil profile than other national soil surveys, 0-50cm. There was a large increase in the soil carbon levels in the sandy soils and this was mainly in the deep 25-50cm layer, in contrast to the loamy soils which were overall losing carbon. This deposition of carbon below 25cm might, perhaps, be explained by the fact that the coarse sandy soils had more grass in the rotation than the loamy soils (or else due to an increase in the depth of ploughing – see point 10.).

2. <u>Reduced spreading of animal manure on arable land</u>

The second key negative outcome of the loss of mixed farming and the intensification and specialisation of the industry is the reduced use of animal manures. The spreading of manure on cultivated fields declined between 1978 and 2003[242] and is likely to be an important factor in the current low soil carbon levels. UK non-organic crop production is now commonly on large specialised, continuously cropped farms which do not have livestock to provide manure for spreading, or the benefit of the direct deposition of manure by livestock during the grass stage of the crop rotation. Farms in the main arable regions such as the East of England generally do not even have access to manure from other farms either.[243] A Government survey indicates that now only about 22% of the UK's cultivated land is receiving animal manure (of any sort, including biosolids), with 40% of the cultivated land on mixed farms, but just 14% on the UK's specialist cereal farms.[244] Moreover, the trend is still downwards.

Manure is also only applied on about 20% of non-organic horticultural land.[245] As well as industry specialisation, an additional reason is that most Farm Assurance Schemes in the UK ('Little Red Tractor' logo) prohibit the application of manure while growing horticultural crops and for the previous three years.[246] Meanwhile, for most of the specialised intensive livestock farms, the large quantity of slurry they produce is commonly treated as a waste product, as these farms usually have insufficient land to use the manure fully as a carbon resource (especially the case in the pig and poultry sectors).

Reference is sometimes made to the greater use of biosolids (treated sewage sludge) being applied on UK arable land now, and indeed 1.5-4 million tonnes are applied on farmland each year[247]. Nevertheless, this still accounts for just 3% of the total quantity of animal manure applied[248] and this is anyway included in the percentages cited above for cultivated land receiving manure (though as it is not spread on the same piece of land year-after-year but is usually rotated around the land, the proportion of farmland receiving biosolids is greater than the area in any one year.[249]) There is no potential to increase the amount further as practically all is now being applied, with only 1% going to landfill[250].

3. Move from production of farmyard manure (FYM) to slurry

Another important development is that much more animal excreta is now produced in the form of liquid slurry rather than solid farmyard manure. A report for the European Commission suggests that this may be one reason for the declining SOC levels found in Western Europe and the Mediterranean.[251]

Again, this occurred because of the specialisation and intensification of livestock production, in the UK and Europe.[252] This involved a move away from the use of straw as bedding, which produces farmyard manure, to the housing of cattle on concrete or slatted floors, which results in the production of slurry. With the change away from mixed farming systems throughout the UK to mainly grass regions in the West, and separate specialist arable regions in East, many livestock producers now have little on-farm or local straw supplies to use as bedding. In addition, the intensification of livestock production meant that there is now much more indoor housing of livestock, with more grasslands cut for silage and less use of outdoor grazing. Thus, slurry production has also increased at the expense of manure being freshly deposited on grasslands.

Currently about 90 million t of animal manures are applied each year to farmland in the UK[253], potentially a huge soil carbon resource. But about half of this is slurry. By volume, about 45% is cattle slurry, 41% is cattle FYM, 3% pig manure, 3% is biosolids, and 2% poultry litter/manure.[254] In the dairy sector, three times as much manure is now produced in slurry form as solid manure form; while for the beef sector, about 30% of the manure from the housing is now in slurry form.[255]

Livestock manure is well established for having soil carbon benefits, and is an integral part of natural grassland systems (which have high soil carbon levels). Slurry, however, is a different biochemical product and does not seem to have the same positive effects. The researchers of the eleven-year Belgian survey of cropland, which found annual soil carbon falls of 480kgC/ha/yr for 0-30cm depth[256], gave the widespread move from solid-manure to slurry-based housing systems as a main reason for the fall.

4. Use of inorganic fertilisers and other agrochemicals

For many indirect reasons, inorganic fertiliser use is likely to result in low soil carbon levels. In the UK, N fertiliser is applied to most cultivated land and also widely to 'improved' grassland. Fertiliser application rates were particularly high in the UK from the early 1980s to the early 1990s[257] (which might therefore account for some of the widespread topsoil carbon losses of UK grassland observed in the 25-year NSI survey, which covered this period), but have since been declining. The average UK application rates are now 147kgN/ha on cultivated land and 69kgN/ha on managed grassland, applied on 91% and 58% of cultivated land and the managed grassland area respectively.[258]

Additionally, the three hundred or so pesticides that have been introduced into non-organic farming – comprising insecticides, nematicides, fungicides, molluscides, herbicides, livestock worming drugs – may well have had a negative effect on the ability of soils to support living organisms and store carbon.

5. Reduction in the level of the non-yield crop biomass

With the increase in yields, the amount of crop residues being returned to the soil has reduced.[259] This has resulted from the breeding of new varieties developed for higher yields and also to counter the negative effects of using NPK fertilisers. From 1975 to 1990, modern "short-strawed" cereal varieties were introduced and growth regulators to shorten the stems were increasingly applied in the UK[260], replacing older cereal varieties which had grown up to six feet tall.[261] Although little straw was being directly incorporated into the soil at that time (straw and stubble burning were widespread practices in the UK), this should nevertheless have reduced the amount of organic matter that was being returned to the soil via FYM and means there is less crop residue available to incorporate now that straw burning is banned. Probably more importantly, the crop root biomass has also been reduced considerably. The root depth of old crop varieties was substantial (wheat – six feet and very dense; oats – four feet; cauliflower – mostly two feet but some to four feet[262]).

These changes were a consequence of breeding varieties that produced higher grain yields by reducing the growth of the rest of the plant. Agricultural crop yields increased between 1978 and 2003 by 1.45% per year[263], and this trend is mainly attributed to improvements in the 'harvest index' – the amount of grain produced relative to straw and stubble.[264] However, the move to shorter stems was also made to address the undesirable effects of NPK fertiliser use, which makes cereal crops much more liable to 'lodging' (flattening by heavy rain or strong wind, which causes a loss of yield). For these reasons, semi-dwarf genes were introduced into cereal varieties, but these genes also reduced the size of the root system.[265]

There will also have been contributions to this trend from: the reduction in weeds during the cropping season and over winter from the increased use of herbicides[266], the reduced shedding of grain from cereal ears, and the huge increase in the efficiency of combine harvesters which means there is less spilt grain.[267]

On the other hand, the 1993 ban on straw and stubble burning in the UK[268] means that most large arable farmers are now incorporating their straw and stubble into the soil. This would have added a couple more tonnes of organic material per hectare[269], helping to increase the soil carbon levels of much of the arable area by a few per cent (of the total) over the next two decades.[270] This could have contributed to the findings of the NSI survey of arable soils in England and Wales: that the carbon levels of soils which were initially arable land and stayed as arable land, had remained stable or slightly increased from when they were first sampled (1978-83) to when they were re-sampled (1994-95). Around 15 million t of carbon are potentially returned to the UK's arable soils each year in straw, stubble and chaff.[271]

6. Ploughing-up of permanent grassland – just 'legacy' effects or also management effects?
The single largest cause of on-going soil carbon losses in UK arable soils is ascribed to the continuing effects of earlier conversion of the land from permanent grassland.[272] It is well established that the ploughing-up of permanent grassland causes large soil carbon losses, and that soil carbon levels fall substantially for several decades after this change. For instance, in a UK trial, the SOC level fell by a third over 30 years before stabilising at the level for arable soils.[273]

In the UK, as well as the earlier periods of ploughing-up during WWII and during the 1970s (after the UK joined the EU in 1973), there has been a 4.5% reduction in the area of permanent grassland over 20 years old since 1990, a loss of 589,000ha.[274] In the 1990s, an average of 96,000ha of long-term permanent grassland was ploughed-up and converted to cultivated land each year, and only 83,500ha was converted the other way.[275] For each hectare of grassland that is being ploughed up and converted to arable land, there is an average loss of carbon ranging from 23tc in England to 90tC in Scotland.[276] A clear decline in the area of permanent grassland has also been observed in Western Europe (EU13).[277]

Land ploughed out of grass during the Second World War will have been in crop production for almost 70 years and the soil carbon levels are probably hardly declining now. However, land ploughed out of grass during the 1970s, and all grass converted since then, will still be losing significant amounts of carbon each year. In fact, official figures indicate this is the cause of net losses of about 1.6 million tonnes of carbon each year (after excluding the carbon gains from the smaller area of cropland converted to grassland), which is all occurring from the UK's arable area.[278] This is equivalent to 12% of UK agriculture's GHG emissions.[279] Importantly, this category of agricultural soil carbon losses is included in the UK GHG Inventory. But, until now, this source has been classed as a 'land use' change (not a management effect) and so is reported as 'LULUCF' sector emissions and not part of agriculture's GHG emissions.[280] These trends and soil carbon losses are projected to continue for the foreseeable future.[281]

However, *such* a large effect and period of 'legacy' after the ploughing-up of pasture should not be considered inevitable, as the effects depend on the agricultural management practices that are used afterwards and how well they protect soil carbon. For example, in an 18-year study of the comparative effects of organic farming on ploughed-up grassland in Sweden, the soil carbon levels fell 55% less under organic than non-organic management and appeared to have stabilised after just 13 years (see Section 5.6).[282] This is a large difference. In other words, maybe around half of the 'legacy' effects of this 'land use change' is not inevitable and should instead be ascribed to the new *management* regime, and thus to some of the management factors described in this review. While this is not how this subject is discussed, this is actually how the IPCC guidelines advise soil carbon changes be estimated: by considering the types of the previous and the succeeding management regimes (including many of the factors addressed in this review) and their associated soil carbon levels.[283] In other words, agricultural management practices should be considered partly responsible for the c.1.6 million tC of UK emissions from this source.

7. Change in ploughing depth and intensity

There is a widely accepted view that ploughing causes soil carbon losses because it inverts the topsoil and exposes more of the soil organic matter to oxidation.[284] There has been a steady increase in ploughing depth with modern, more powerful machinery, from the traditional 4-6 inches to typically 8-9 inches now in the UK. There has also been an increase in the intensity of soil cultivation, with practices such as pan-busting, de-stoning and ridging for intensive, heavily irrigated carrots and potatoes, for example.[285] It is therefore suggested that this may have caused widespread soil carbon losses in cultivated soils. At the same time, however, in the 1970s and 1990s, many large specialist arable farmers in England adopted shallow cultivation practices in place of ploughing.[286] Scientific advisers have suggested that this could have marginally increased English arable soil carbon levels, by less than one per cent (of the total).[287]

However, the evidence on the effects of ploughing on soil carbon levels is notably inconsistent and - apart from the small scale of the observed effects in the UK - the routine use of shallow soil sampling depths unfortunately means that the overall effects of ploughing depth have probably often been misidentified by researchers (see Section 5..7). There are indications that ploughing often just re-distributes organic matter into the deeper soil layers, but does not necessarily reduce the total amount of soil carbon stored. While many studies have found that ploughing decreases the long-term storage of carbon in soils[288], others have found that it has no significant effect, especially when the entire depth of the soil profile is considered[289]. This is further supported by the gathering evidence that shallow cultivation practices (like 'minimum tillage') - which have been claimed to sequester significant amounts of carbon – mainly just concentrate the crop residues on the surface and also do not necessarily increase the soil carbon store over the whole profile (see Section 9.2).

A calculation of soil carbon balances in Germany even concluded that an increase in the ploughing depth can substantially *increase* the arable soil carbon store. With an increase in the plough-layer from 25cm to 35cm on 16 farms, soil carbon was estimated to have increased by up to 16tC/ha on loess soils under crop production and up to 26tC/ha on sandy soils under livestock production (Neider & Richter, 2000[290]). The findings of a large-scale arable soil survey in Belgium appear to support this, showing that if a greater ploughing depth is adopted at the same time as a large increase in organic matter inputs to the soil, then the depth of the topsoil will increase accordingly and produce an overall increase in arable soil carbon stocks.[291] There were similar results in a national Danish survey - with a soil carbon increase in the lower layer of sandy soils (25-50cm deep), though here the role of ploughing depth can only be guessed at.[292]

Thus, the increase in ploughing depth may mostly just be distributing the carbon over a deeper profile and not reducing the overall amount of soil carbon (especially in cases where ploughing is being used to incorporate organic matter). However, further soil surveys using deeper sampling and the collection of data on ploughing depth may be needed to confirm if this is generally true, as it may still be that an increase in the depth of ploughing can reduce soil carbon levels in common non-organic farming situations where organic matter inputs to the soil are minimal or the soil carbon levels are very low.

8. High livestock numbers on grasslands

Excessive livestock numbers over-graze and degrade the land, and this has been a serious problem in the UK. For a prolonged period, livestock farmers' subsidy levels were coupled to their livestock numbers by the provision of livestock 'headage' payments - Government or EU payments for each individual cattle or sheep. This was a major driver in taking the UK's livestock grazing levels above what is considered the 'ecological carrying capacity' of the land. This factor is particularly important in the UK, which has the largest breeding flock of sheep in the EU (the total UK flock was 34 million in 2007[293]). In Wales, the areas most at risk from erosion are in the uplands, with over-stocking by grazing animals being considered a prime cause.[294] In Scotland, erosion by over-grazing is considered one of the most common types of physical damage to soils.[295]

Prior to joining the EU, farmers in the UK uplands were already receiving headage payments to support farming in these regions. However, the introduction of the EU headage payments with the Common Agricultural Policy (CAP) led to a huge 38% increase in breeding ewes and 56% increase in beef cattle in the English upland hill regions between 1976 and 2000.[296] The payments for sheep were highest in the upland regions, and especially in the 'Severely Disadvantaged Areas', which gave a particularly great incentive for higher sheep numbers in the uplands.[297] Another important driver of sheep numbers was the long advance announcement of the introduction of sheep quotas in 1993 (which then limited payments of the Sheep Annual Premium Scheme to the amount of quota held by farmers). This led to farmers greatly increasing their sheep numbers, to be in a more advantageous position in advance.[298]

UK sheep numbers have already fallen significantly, from a total of 43 million in 1993-2000 to 34 million in 2007.[299] Over-grazing problems should continue reducing as all the EU headage payments have now been replaced by the 'Single Farm Payment Scheme' in 2005/06. This 'decoupled' farm subsidy levels from livestock numbers, encouraging farmers to reduce their stocking rates.[300] Defra statistics show that the number of grazing beef cattle and sheep in the UK fell by 2% a year in 2006, 2007 and 2008.[301] The total number of livestock has also decreased in Western Europe since 1990.[302]

9. Move from grass to grain for feeding cattle

As the non-organic cattle sector has intensified production, there has been a move to a greater use of grain to feed dairy and beef cattle, and less use of grass. Non-organic dairy farming has been increasingly using feed grain to raise milk yields per cow[303]. Even for upland beef and sheep production which relies more on grazing than the dairy sector, supplementary feed of concentrates (high-energy/protein feed substances) and cereal grain are being used.[304] UK livestock farmers now buy 21-22 million t of animal feed each year[305], practically all of which is produced from arable crops (cereals, soya and oilseeds). The dairy sector accounts for the largest portion of this UK animal feed market – 40% in 2005.[306] Thus, there is a large 'ghost' area of low carbon arable land producing grain for the UK's 'grassland' livestock sector. Much of this production occurs abroad (soya and maize) and, in the case of soya, there are also major soil carbon impacts resulting from natural habitat destruction (see Section 4.2).

10. Production of maize silage, in place of grass silage, grazing or hay

The area of maize grown for silage has increased markedly in the UK, from around 20,000ha in the 1980s - when maize was introduced as a main crop[307] - to about 120,000ha in 2002[308]. This may increase further as more cold-tolerant varieties are introduced[309] and if temperatures rise[310]. The crop has gained in popularity as an alternative to grass silage for feeding cattle over-winter.[311] However, maize production often causes serious soil quality problems. According to a 2001 report for Defra[312], assuming this is still the case, nearly all maize in the UK is grown with a wide row spacing (60-75cm, to accommodate harvesting machinery) which, with the use of herbicides to kill weeds, leaves a large area of bare soil between the plants. Additionally, for a large part of the year, maize fields are left bare, with little or no vegetation.[313] So, there is an overall very low level of vegetation cover in maize fields, and the soils often degrade so much that serious erosion occurs[314], a clear indicator of the loss of soil organic matter.

It might also be considered that silage maize production may contribute to lower soil carbon levels for the reason that most of the above-ground part of the plant is harvested and not returned to the land. However, long-term studies indicate that this aspect of maize production is probably not significant.[315]

Grass for silage is probably greatly preferable because of the many soil carbon benefits of grass. It has been suggested that the widespread production of grass silage in place of hay removes more residue from the land, and so may decrease grassland soil carbon stocks.[316] However, this is very unlikely to significantly affect the benefits of grass, which are mainly associated with the root systems (see 7.1).

11. Increase in factors causing erosion and bare soil

As well as over-grazing in the upland grasslands, many factors are likely to have caused an increase in erosion and the general level of bare soil in arable areas:

(i) general degradation of soil structure because of the loss of soil organic matter levels and compaction (from heavier machinery, more autumn cultivations and over-stocking by livestock);

(ii) an increase in the amount of bare soil as a result of: the steady move to autumn sowing and a consequent reduction in over-winter cereal stubble, more continuous arable cropping with short or no grass leys, the reduction in weed levels (during the cropping season and over-winter) from the increased use of herbicides[317], the recent phasing-out of set-side (also reducing the area of over-winter stubble), greater production of maize (severe erosion occurs on autumn-sown fields in some areas as the soil is exposed in periods of peak rainfall.[318]);

(iii) a reduction in boundary windbreaks resulting from: the increase in field sizes, loss of livestock from arable areas, and the more intensive cutting of hedges in place of traditional management.

12. 'Improvement' of permanent grassland

Within the remaining 11.6 million ha of UK permanent grassland[319], much of the 'rough grazing' pasture has been ploughed-up and converted to 'improved' grassland in recent decades (see point 6). A main driver of this was the set of policy incentives to intensify livestock production (see point 8). Grassland 'improvement' involves ploughing-up the land, re-seeding with commercial grass mixes[320] that better support livestock, and then usually regular inorganic fertilisation, and often repeated cultivation and re-seeding at intervals thereafter.[321] The grass thus becomes managed more intensively like a regular crop, enabling more productive use (silage or hay production, or fattening sheep).

The state of knowledge and policy treatment in this area is currently very confused. On the one hand researchers acknowledge that with the large carbon stocks of permanent grassland, there are "potentially large losses" of carbon occurring from grassland improvement.[322] Certainly, this is an explanation for the large topsoil carbon losses from the UK's grasslands with higher soil carbon levels found by the NSI survey.[323] Yet, there is considered to be little relevant research on the impact of grassland improvement[324] and there is no estimate of these losses in the UK GHG Inventory. Recent attempts to rectify this lack of evidence with controlled studies were based on a narrow investigation of just the effects of cultivation[325], rather than a much more relevant investigation of the effects of the whole package of 'improvement' (i.e. also with N fertiliser, commercial grass varieties and more intensive grazing/cutting).

Meanwhile soil carbon modellers and policymakers are taking the opposite approach and assuming that 'improvement' *increases* grassland soil carbon levels due to the higher productivity of the grass and an assumed higher soil biomass input. Under the IPPC soil carbon accounting guidelines, a 14% increase in grassland soil carbon storage is assumed to occur with the use of N fertiliser or high-yielding grass species, over unimproved grassland (as long as grazing levels are not excessive).[326] However, while these factors mean more grass is produced and removed as silage or by livestock grazing, based on our review of the indirect effects of inorganic fertiliser and modern plant varieties, and the survey evidence, we suggest that they may be reducing overall soil carbon input levels. For instance, 70 to 75% of the root biomass of grasslands is located in the top 15cm of the soil[327], which was the depth measured by the NSI survey which found large soil carbon losses were occurring (except for grasslands with the lowest soil carbon levels, which perhaps includes most of the grassland that had been 'improved' some time ago.)

13. Use of avermectin wormers and other veterinary medicines

Dung decomposition is an important stage in the carbon cycling of grassland systems. However, farmers in the UK and many other countries now routinely use avermectin drugs for internal parasite control in grazing animals. These are strong, persistent insecticidal drugs. Though administered internally, some of the drug passes through the animal and continues to be active in the deposited dung where it has been found to affect the rate of dung degradation by living organisms.[328] Avermectins and other drugs used on dairy farms can also be present in slurry and spread to land. There is therefore a question whether this could have contributed to the significant reductions in topsoil carbon levels observed by the NSI survey of the UK's grasslands.

14. Drainage and extraction of peatlands

The degradation of 'organic' soils (high carbon content) and especially peatlands, is probably the largest source of soil carbon losses in the UK. Naturally, undisturbed peatlands steadily accumulate carbon, i.e. they are carbon sinks.[329] However, drainage, cultivation, peat extraction and other activities that aerate the soil cause the carbon to oxidise and be released. Deep peats contain over 5000t of C/ha[330], so degradation produces very large carbon losses. Overall, the degradation of the UK's upland peatlands may be releasing many millions of tonnes of carbon each year[331], but this is not in the UK's GHG inventory.

One of the factors in the expansion of the drainage of blanket bog and wetland was the drive to 'improve' land so more livestock could be reared. Once drained, the indigenous vegetation was ploughed and replaced by 'improved grassland'. As well as the policy-driven incentives for farmers to intensify their livestock production (see point 8)[332], drainage and improvement was also encouraged by Government grants. Over 150,000ha remain "severely affected" by drainage in Scotland, but major initiatives are now underway in many areas to restore peatlands and re-establish natural conditions.[333]

At the moment, the only carbon losses from drained peatlands that are included in the UK's GHG Inventory, are those from the drained *lowland* wetlands in England. These 'fenlands' were drained many years ago for agricultural use but still release carbon on a continual basis. It is estimated that England's 150,000ha of fenland are releasing over 264,000t of carbon each year.[334] This is based on UK-specific estimates of very high losses of 12.8tC/ha/yr from the 24,000ha of 'thick peat' (over 1m deep; 21% carbon content) and losses of 1.1tC/ha/yr from the remaining 'thin peat' (12% carbon).[335] It is estimated that two thirds of the peat areas of East Anglia Fenland of about 240 km^2 in 1985, will be lost by 2050.[336]

The IPCC's standard emission factors for drained organic soils in cool temperate and boreal regions[337] are soil carbon losses of 250kgC/ha/yr if the land is kept as permanent grassland, but *twenty times more* if the land is being cultivated: 5tC/ha/yr. (The respective factors for tropical and sub-tropical regions are far higher: 5tC/ha/yr and 20tC/ha/yr).[338] In other words, it is considered that the use of drained organic soils for arable or horticultural production causes far higher emissions than if the land is kept in grass and used for rearing livestock. Thus, any decline in ruminant farming in the fenland areas (including the loss of mixed to all-arable farming), has probably led to a large increase in these soil carbon losses.

Lastly, the removal of peat for agriculture, gardening or fuel use is also a source of carbon losses, as all the stored carbon is eventually released.[339] In UK agriculture, most peat is being used for ornamental pot plants and we believe little is used by the glasshouse food sector which, for non-organic production, uses rock-wool or other sterile materials, not peat or soil.[340] Although they do not include the other impacts of agriculture on soil carbon storage, the Tesco and Carbon Trust/BSI food carbon footprint labelling standard[341] includes any agricultural use of peat by allocating the carbon loss over a 20 year period.[342]

6. Results of the comparative studies on the soil carbon levels of organic farming

6.1 General findings of the comparative studies of organic and non-organic farming

Soil carbon levels vary considerably according to the soil type, climate, management and stage of the crop rotation. However, there is strong scientific evidence that organic farming generally produces higher soil carbon levels than non-organic farming for cultivated soils. This Chapter reviews all of the comparative soil carbon studies of organic farming that we could find and is the largest, most comprehensive and most detailed review of the comparative soil carbon levels of organic farming, we believe.

There have been at least 39 published comparative studies of organic and non-organic farming soil carbon levels carried out in different countries.[343] In 32 and a half, the soil carbon levels were higher under organic farming than non-organic farming, ranging from +8% to +325% (in one trial, only one of the two organic systems produced a higher level, hence the 'half'). In at least 15 of these studies, covering 42 individual comparisons, the higher levels were reported as being statistically significant.[344] There were three and a half studies where there was little difference between organic and non-organic farming (-4% to +2%), and three studies where we were not able to identify the results. In the only study to have found a lower level (-4%), the difference was not statistically significant. Basic details of most of the studies are presented in the table below, with the soil carbon difference between the farming systems shown where known. See the 'Notes to review and table of comparative studies' for further details of the approach taken for the review. In addition, the results of the studies are presented in much more detail in a table at the end of this section and most of the studies are individually summarised in Section 6.2.

All the studies were based on actual soil sampling and include twelve long-term trials of organic and non-organic farming and at least 17 surveys of organic and non-organic farms. Two are UK studies (Armstrong Brown *et al*, 2000; Gosling & Shepherd, 2005). As best we could establish, all of the studies are of arable or horticultural land (including rotational arable/grass systems), i.e. they represent cultivated soils. In a few studies, the organic systems were 'biodynamic', a special form of organic farming that accounts for a small proportion of organic land. Five studies were excluded from the review that had been included in some earlier reviews but did not provide relevant comparative data (egg. in one, most of the 'organic' land had not yet converted to organic farming). In addition to all these studies, there have been at least two non-comparative long-term monitoring studies of organic farming soil carbon levels and three studies where the comparative levels were modelled, rather than measured (Sections 6.4 and 6.5).

All of the comparative studies reviewed were all carried out in Europe, the US and Australasia. Based on the studies for which soil carbon content data was available, but excluding the biodynamic farming results, we have calculated the average soil carbon difference between organic and non-organic farming. The result is that, for the studies in this review, **organic farming has on average 20% higher soil carbon levels** than non-organic farming for cultivated land (based on 81 comparisons from 20 studies). **For Northern Europe alone, organic farming has 28% higher soil carbon levels** on average, based on the studies from the UK, Netherlands, Sweden and Germany (8 studies, 38 comparisons). For the UK alone, the average difference was 33% higher soil carbon levels (2 studies, 20 comparisons).

The greater difference for organic farming in Northern Europe may be due to three reasons:

(i) the length of time under organic management was longer for the Northern European studies, about 15 years compared to only about 12 years for all studies of standard organic farming;

(ii) carbon accumulation is generally greater in wetter than drier soils, because of slower oxidation rates under wet soil conditions;[345]

(iii) there may be greater differences between organic and non-organic farming practices than in the other regions reviewed (e.g. in the UK, most organic arable production is based on mixed crop and livestock systems, while most non-organic arable farming is based on continuous cropping. In some other world regions, while there are other important differences between the systems, both organic and non-organic farming use continuous cropping or both use mixed systems).

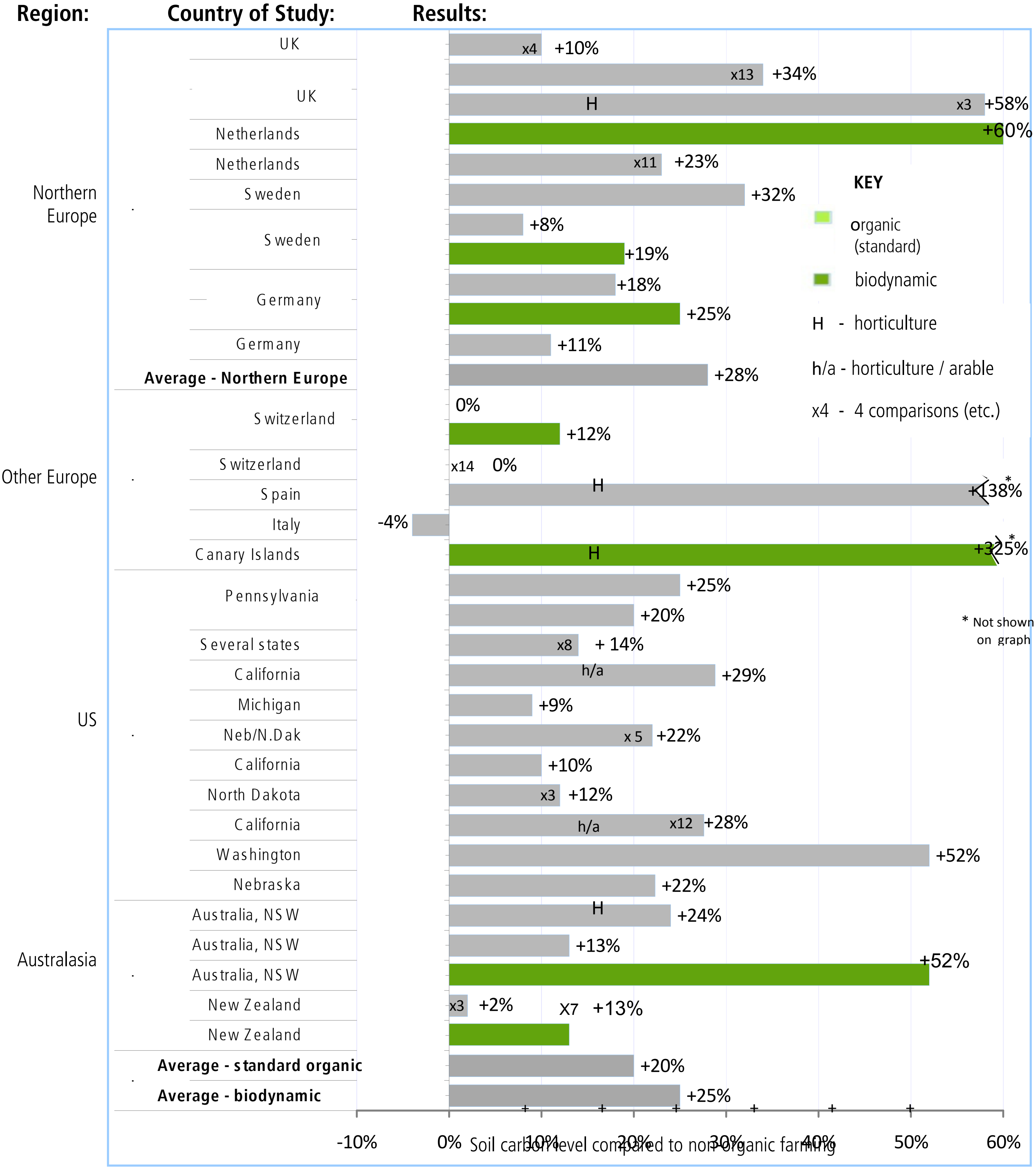
Table 1 : summary of the comparative studies on soil carbon levels under organic and non-organic farming, with the soil carbon content difference shown where known, grouped as (1) controlled long-term trials and (2) surveys of commercial farms and short-term trials; presented in chronological order:

Long-term comparative trials (six years or more)	**Trial duration, years**	**Organic soil C level, vs. non-organic**[346]	**Reference**
Grass to crop conversion, Sweden	18	+ 32%	Kirchmann *et al*, 2007[347]
FiBL 'DOK' trial, Switzerland	28	+ 0%, +12%	Fließbach *et al*, 2007[348]; Mäder *et al*, 2002[349]
IBR Darmstadt, Germany	18	+ 18%, +25%	Raupp & Oltmanns, 2006[350]; Raupp, 2001[351]
Vegetable trial, Andalusia, Spain	6	+ 138%	Melero *et al*, 2006[352]
Rodale Institute, Pennsylvania, US	21	+ 25%,+ 20%	Hepperly *et al*, 2006[353], Pimental *et al*, 2005[354]
Survey of 9 farming trials, US	10	+ 14% (x8)[355]	Marriott & Wander, 2006[356]
University of California 'LTRAS', US	10	+ 29%	Kong *et al*, 2005[357]
Michigan University, US	9	+ 9%	Robertson *et al*, 2000[358]
'K-trial', Sweden (1958-1990)	33	+ 8%, +19%	Raupp, 1995b[359], Granstedt *et al*, 2008[360],
SAFS cropping trial, California, US	8	+ 10%	Clark *et al*, 1998[361]
Germany (1979- 1988)	10	+	Diez *et al*, 1991[362]
Nebraska, US (1975 - 1982)	7	+ 22%	Fraser *et al*, 1988[363]

Surveys of organic & non-organic farms, and short-term trials		
1 farm with split management, Italy	- 4%	Marinari *et al*, 2007[364]
4 pairs of organic and non-organic fields, England	+ 10% (4 comparisons)	Gosling & Shepherd, 2005[365]
1 pair of biodynamic & non-organic fields, Netherlands	+ 60%	Pulleman *et al*, 2003[366]
30 pairs of organic & non-organic farms, England	+ 34% (13 arable comps) + 58% (3 hort. comps)	Armstrong Brown *et al*, 2000[367]
19 organic & 26 non-organic farms, Netherlands	+ 23% (11 comparisons)	Pulleman *et al*, 2000[368]
14 pairs organic & non-organic cereal fields, Switzerland	0% (14 comparisons)	Oberholzer *et al*, 2000[369]
Trial of organic and non-organic farming, Germany	+ 11%	Friedel *et al*, 2000[370]
Trial of vegetable production, 1992-95, NSW, Australia	+ 24%	Wells *et al*, 2000[371]
5 pairs organic & non-organic farms, Nebraska/N. Dakota	+ 22% (5 comparisons)	Liebig & Doran, 1999[372]
Pair organic & non-organic mixed farms, NSW, Australia	+ 13%	Derrick & Dumaresq, 1999[373]
1 pair of organic & non-organic farms, Iowa, US	+	Gerhardt, 1997[374]
3 pairs of organic & non-organic farms, North Dakota, US	+ 12% (3 comparsions)	Gardner & Clancy, 1996[375]
Organic & non-organic tomato farms, California, US	+ 28% (12 comparisons)	Drinkwater *et al*, 1995[376]
3 pairs organic & non-organic mixed farms, New Zealand	+ 2% (3 comparsions)	Nguyen *et al*, 1995[377]
7 biodynamic & 9 non-organic farms, New Zealand	+ 13% (7 comparsions)	Reganold *et al* ,1993[378]
1 pair organic & non-organic farms, Washington, US	+ 52%	Mulla *et al*, 1992, Reganold 1988[379]
5 pairs organic & non-organic fields, 1985-87, Germany	+	Capriel, 1991[380]
Biodynamic & non-organic avocado plantations, Tenerife	+ 325%	Garcia*et al*, 1989[381]
Biodynamic, organic & non-org. vegetable trial, Germany	+	Abele, 1987[382]; Koepf, 1993[383]
A biodynamic & non-organic cereal farm, NSW, Australia	+ 52%	Forman, 1981[384]

AVERAGE of study results	
• For organic farming in Northern Europe only:	**+ 28%** (8 studies, 38 comparisons)
• All non-biodynamic organic farming:	+ **20%** (20 studies, 81 comparisons)
• Biodynamic farming comparisons only:	+ 25% (8 studies, 14 comparisons)

Figure 2 Organic farming soil carbon levels compared to non-organic farming –summary of studies



References, in order:

Northern Europe: UK, Gosling & Shepherd, 2005; UK, Armstrong Brown *et al*, 2000; Netherlands, Pulleman *et al*, 2003; Netherlands, Pulleman *et al*, 2000; Sweden, Kirchmann *et al*, 2007; Sweden, 'K-trial'; Germany, IBR Darmstadt trial; Germany, Friedel *et al*, 2008

Other Europe: Switzerland, FiBL 'DOK' trial; Switzerland, Oberholzer *et al*, 2000; Spain, Melero *et al*, 2006; Italy, Marinari *et al*, 2007; Canary Islands, Garcia *et al*, 1989

US: Pennsylvania, Rodale Institute FST trial; US, Marriott & Wander, 2006; California, 'LTRAS' trial; Michigan, Robertson *et al*, 2000; Nebraska/North Dakota, Liebig & Doran, 1999; California, Clark *et al*, 1998; North Dakota, Gardner & Clancy, 1996; California, Drinkwater *et al*, 1995; Washington, Mulla *et al*, 1992; Nebraska, Fraser *et al*, 1988

Australasia: Australia, NSW, Wells *et al*, 2000; Australia, NSW, Derrick & Dumaresq, 1999; Australia, NSW, Forman, 1981; New Zealand, Nguyen *et al*, 1995; New Zealand, Reganold *et al*, 1993

Notes to the review and table of comparative studies

- The objective was to evaluate the real impacts of existing organic farming practices, compared to existing non-organic farming practices, using the results of studies that sampled organically and non-organically managed land and, when drawing conclusions, to be conservative when making assumptions (unless stated otherwise).
- Breakdown of the 39 comparative studies reviewed (note, eleven studies involved several comparisons, which is not taken into account here). In the middle column, the range in brackets represents the results of the 28 studies for which we have data (of which 24.5 studies found a higher level of +8% or more, and 3.5 studies found little difference). The 8 studies for which we only know that organic farming produced a higher level are included in the ‘higher level’ group.

Type of study		**Result, comparative soil carbon level of the organically farmed land (OF)**		**Decade study published**	
Long-term trial:	12	OF has higher level (+8% or more):	32.5	In the 2000s:	16
Farm survey:	17	OF has lower level (-5% or less):	0	In the 1990s:	16
Short-term trial:	3	Little difference (-4% to +2%):	3.5	In the 1980s:	7
Type unknown:	7	Difference unknown:	3		
Total:	39	Total:	39	Total:	39

- The previous table presents all 39 studies in the review except four for which we have no details other than that they found higher soil carbon levels with organic farming (Petersen *et al*, 1997[385]; Pomares *et al*, 1994[386]; Labrador *et al*, 1994[387]; and Goldstein & Young, 1987[388]), plus three which were not published in English and we do not know the results (Welp, 1993[389], which is reported to have found that organic farming produced a greater soil carbon increase, and two 1989 studies where no statistically significant differences are reported).[390]
- In the table, a ‘+’ sign only indicates that the organically managed soils had higher carbon levels, but we have not been able to find out the size of the difference. Northern Europe’ refers to all studies from UK, Netherlands, Sweden and Germany (there were no studies from other Northern European countries).
- Five studies were excluded from the review. Four of these had been included in some earlier reviews but they did not provide representative results of the real impacts of organic farming: the ‘organic’ and ‘non-organic’ land were clearly unrepresentative in two farm surveys (Shepherd *et al*, 2002[391]; Løes & Øgaard, 1997[392]), one was an experimental plot fertilisation trial (Bullock *et al*, 2002[393]) and one a soil incubation study (Breland & Eltun, 1999)[394]. In addition, a study of just two years of organic management was excluded (Werner, 1997[395]).
- For accuracy, the averages cited were calculated from the absolute soil carbon level data (for all studies and comparisons for which data was available), not by averaging the percentage differences of all the comparisons. This was to ensure that the results were not biased by any occurrence of increasing or reducing differences with increasing soil carbon levels. Analysis nevertheless indicated that the comparative soil carbon level of organic farming (in percentage terms) seems to be relatively independent of the soil carbon level (or else possibly that a potential for greater differences with high-carbon soils is countered by a greater likelihood of horticultural production on low-carbon soils in which organic farming tends to produce greater soil carbon differences).
- No. of biodynamic studies & comparisons: 4 of the studies for which results were available were exclusively of biodynamic farming; another 4 studies included both standard organic and biodynamic farming (including a single biodynamic comparison in the study by Nguyen *et al).* This total of 8 studies on biodynamic farming provided 14 comparisons on biodynamic farming. However, some of the organic farms in the farm surveys (especially the larger surveys) may have included a few biodynamic farms that were not identified as biodynamic (i.e. the number of biodynamic comparisons might actually have been more than 14.)
- Influence & inclusion of biodynamic studies: this has little effect on the average differences. For N. Europe, there is no difference in the average if the biodynamic studies are included or not (the average is +27.9% if the 3 biodynamic comparisons are included along with the 35 ‘standard’ organic comparisons, and +28.0% if they are excluded). Similarly, for all studies, inclusion of the 14 biodynamic comparisons only raised the average from +19.5% to +20.5%. This was important to check as biodynamic comparisons accounted for 16% of the total comparisons for which there was soil carbon level data (14 of 95), which is probably more than (i) exists currently, (ii) may exist in future, and also (iii) biodynamic methods could be a way to increase soil carbon levels.
- Number of comparisons used: in the couple of cases where there was a difference in the number of organic and non-organic farms being compared, we used the number of organic farms. For example, for the Armstrong Brown *et al*, 2000, study, we counted the 13 organic arable farms vs. 21 non-organic arable farms as ‘13 comparisons.’ The only exception was for the horticultural comparisons for this study, where we counted the 9 organic vs. 3 non-organic horticultural farms as only ‘3 comparisons.’ This was to ensure that the influence of these high horticultural results (+58%) was not disproportionate (horticulture accounts for only about 3% of UK cultivated land; if we had counted all 9 organic horticulture results as ‘9 comparisons’, this would have been too high a proportion of all the comparisons) and also because a sample of just three non-organic farms means this comparison has a much higher uncertainty than if there had, say, also been 9 non-organic farms.

The review is based on **the percentage difference** in the soil carbon levels of organic and non-organic farming and mostly on soil carbon content data, not on the differences in the amounts of soil carbon stored (tC/ha). This is because most studies only report on the soil carbon content (the proportion of soil that is carbon), not on the absolute amounts. Additionally, this is the most relevant information for soil carbon/greenhouse gas accounting purposes: current accounting methods (egg. the IPCC soil carbon guidelines) are based on applying the percentage soil carbon differences that have been found to exist between different farming practices to databases of the standard soil carbon stocks (tC/ha) for each area.

Many of the studies carried out in the 1990s and 1980s were very briefly reviewed in some earlier reports[396]: the 2003 scientific review of the environmental benefits of organic farming in support of Defra's Organic Action Plan[397], a 2002 paper on soil organic matter by Shepherd, Harrison and Webb[398], the review of the environmental impacts of organic farming in Europe, Stolze *et al*, 2000[399], and a review of comparative soil studies on biodynamic farming by John Reganold.[400] None of these reports, however, presented the results in much detail and there was no previous attempt to calculate an average.

We did not identify the climatic conditions for all of the studies. However, for the five studies that were reported as being in **more arid regions** (semi-arid or with frequent dry periods), organic farming had positive soil carbon effects in all cases. There were 12%, 13%, and 52% higher soil carbon levels than non-organic farming in three arable farming studies (two in the US and one in Australia), 10% higher levels in a vegetable/arable trial in the US, and 138% higher levels in a vegetable trial in Spain.[401] This is significant as Mediterranean soils, for example, often have low or very low SOM content (many less than 0.5% organic carbon) and are close to the threshold of degradation and desertification. Even small increases in organic matter will take them back from this point and protect these soils.[402] This is important because much of the world's food is produced in semi-arid areas (often with irrigation)[403] and about 70% of the land is considered to be degraded in dry areas of the world.[404] Moreover, even for low-carbon soils, the rate of soil carbon sequestration produced by organic farming can be substantial. For example, in the US vegetable/arable trial by Clark *et al*, 1998, the soil carbon content was almost 1% and the organic system produced just 10% higher soil carbon levels than the non-organic systems after eight years, but this still gave a good estimated soil carbon sequestration rate over this time of +546kgC/ha/yr.[405]

Only three studies that we know of have measured **organic grasslands** (Shepherd *et al*, 2002; Armstrong Brown *et al*, 2000; Pulleman *et al*, 2000). All of these were in Northern Europe and all found higher soil carbon storage in organic than non-organically managed grassland. We assume they were all studies of managed ('improved') permanent grasslands, but this is not stated. From the published data, we estimate that the organic grassland had an average higher soil carbon level of at least +15% in these cases (16 comparisons, 3 studies).[406] However, the data in at least two of the studies is likely to have underestimated the difference (for instance, in one, the non-organic fields had been in grass for many more years than the organic fields). Whilst this preliminary evidence is very encouraging (differences in this sector would be highly significant given the large area of grassland in the UK and globally, and the higher soil carbon levels of grassland), a sample of just three studies is too small to draw conclusions. We therefore recommend that much more comparative research of organic grassland be undertaken, of all types (including unimproved, rough grazing land) and with at least the whole topsoil depth sampled.

The average figures found by this review probably **under-represent the full soil carbon benefit** of organic farming. Except for the Swedish 'K-trial', they mostly only represent the differences in the carbon *content* (%) of the *topsoil*, which is generally all that is measured. As such, they do not capture differences in carbon levels of the subsoil, which contributes almost as much soil carbon as the topsoil[407], where the carbon is longer-lasting, and where organic farming also appears to make a difference, even if not in all cases[408]. They also do not include differences in topsoil depth or total soil depth, such as due to differences in the rates of erosion or soil build-up. Additionally, most of the farms in the studies would not have been in organic management for a long time (only 12 years for the +20% difference for all of the studies of standard organic farming) and their soil carbon levels were therefore likely to still be increasing (increases usually continue to occur for over 100 years, though about half of the total increase is normally occurs in the first 20 years[409]. In addition, several of the studies were controlled trials which, although these help in investigating important issues, they often reduce the differences that exist between organic and non-organic farming in reality, such as by sometimes using exactly the same crop rotations; in comparison, the surveys of actual organic and non-organic farms should be more reliable for the purposes of this review. Any differences in permanent grassland soil carbon levels are also excluded.

Also, the +20% overall average figure is strongly affected by the large number of Swiss results, where little differences were found (in contrast to the more 'industrial' farming systems of Northern Europe and the US, non-organic farms in Switzerland are often mixed farming systems and are relatively similar to organic farming systems.) Finally, it should be noted that these results represent the effects of *current* organic farming practices, not the maximum potential for soil carbon storage with organic farming - there are many practices available to improve levels further.

Of the 39 comparative studies in this review, ten monitored the **changes in the level of soil carbon over a long-term** (at least six years). All of these were controlled experimental farming trials. Organic farming performed better than non-organic farming in every case, except in the Swiss FiBL DOK trial, where only one of the two organic systems performed better. In eight of these, organic farming produced an increase in soil carbon over the period of the study. In the other two, the organic system produced a smaller fall in soil carbon than the non-organic system (the 18-year Swedish trial; and the FiBL DOK trial, where one of the two organically managed plots produced a fall and the other was stable). Including also the two UK long-term monitoring studies, this means eight of the total of twelve long-term monitoring studies that we know of found that the soil carbon level increased over time with organic farming (four of the six long-term trials in Europe[410] and all four of the US long-term trials that monitored the changes[411]). The levels in the two UK monitoring studies remained stable (see end of this section).

Eight of the studies in this review involved 'biodynamic' organic systems. **Biodynamic farming** uses all the normal organic standards and practices but it always involves composting, as well as the use of special 'preparations' of fermented plant material and mineral compounds. Although it is only used by a small proportion of organic farmers, at least in the UK, biodynamic farming produces even more soil carbon than standard organic farming. This is shown by the much better results of the biodynamic system in the three trials that included both standard organic and biodynamic farming (FiBL DOK trial, IBR Darmstadt trial, and Swedish 'K-trial'). The overall finding of this review was that, for the 14 biodynamic farming comparisons, biodynamic farming produced an average soil carbon increase of 25%, compared to just +20% for standard organic farming. However, this finding is compounded by the fact that over half of the biodynamic comparisons were in New Zealand (7 comparisons) and Switzerland (1 comparison), where the differences between organic and non-organic farming are much smaller than in other regions (limiting the soil carbon differences), and the average length of biodynamic management in the biodynamic studies reviewed was 18 years, which is much longer than the 12 years for the standard organic farming studies (and would have increased the average difference found for biodynamic farming).

The results for many of these 39 comparative studies are described in **more detail** in the following table and in the next section. Some care should be taken when comparing the results from different studies. Confounding factors are whether the farms are arable or horticultural, and whether the organic farms are standard organic or biodynamic. Both organic horticultural production and biodynamic practices tend to produce larger soil carbon differences, probably because of the use of composting. In addition, when comparing findings from different countries, it should be borne in mind that there are differences in the design of organic and non-organic farming systems in different parts of the world. For instance, much of North American organic farming is fundamentally different to the mixed organic farming systems normally used for arable production in the UK. In most if not all of the US trials studied, the organic systems involved continuous cropping with a significant use of winter cover or other annual green manure crops, and no grass ley periods in the rotation.

Table 2 :Details of all studies for which results were available:

Study (No. of comparisons are as follows: All: 105 (with soil C content data - 95) N.Europe: 38 (" " " " - 38) Standard: 91 (" " " " - 81) Biodynamic: 14 (" " " " - 14)	**Trial/ farm survey (H) = horticul.**	**Soil carbon content results, %**			**Soil sampling depth, cm**	**No. years of organic farming** (at time of sampling)	**Description of non-organic rotation**, if similar (or differs) to the organic more than may be normal or expected.
		Organic farming	**Non-organic farming**	**Difference (organic vs. non-org.)**			
Northern Europe:							
UK - Gosling & Shepherd, 2005	farm	2.27 x 4	2.06 x 4	+10.2% x 4	30cm	15-54 yrs	2 of 4 were mixed systems
UK - Armstr.Br. *et al*, 2000 Arable:	farm	2.37 x 13	1.77 x 13	+33.9% x13	10cm	1-15+yrs	
Horticulture:	" (H)	2.38 x 3	1.51 x 3	+57.6% x 3	"	"	
Netherlands - Pulleman *et al*, 2003	farm	1.4	0.87	+60%	20cm	70 yrs	Same rotation w. grass ley
Netherlands - Pulleman *et al*, 2000	farm	1.31 x 11	1.06 x 11	+23.2% x11	15cm	6.3-13.5	
Sweden - Kirchmann *et al*, 2007	trial	2.5	1.9	+31.6%	topsoil	18 yrs	Diverse rotation w. gr/cl ley
Sweden - 'K-trial' Organic:	trial	2.03	1.83	+ 8.1%	60cm	32 yrs	Same rotation with gr/cl ley
(average of 3 soil layers) Biodynamic:	"	2.20	1.83	+18.5%	"	"	" " " "
Germany - IBR Darmstadt. Organic	trial	0.93	0.79	+17.7%	25cm	18 yrs	Same rotation w. clover ley
Biodynamic:	"	0.99	0.79	+25.3%	"	"	" " " "
Germany - Friedel *et al*, 2000	trial	3.50	3.15	+11.1%	25cm	22-23 yrs	Same rotation with gr/cl ley
(Average for N.Europe:		*1.97*	*1.54*	*+27.9/28.5%*	*18cm*	*c.15 yrs)*	
Other Europe:							
Swiss - FiBL 'DOK' trial. Organic:	trial	1.33	1.33	0%	20cm	21 yrs	Same rotation, manure use
Biodynamic:	"	1.49	1.33	+11.8%	"	"	" " " "
Swiss - Oberholzer *et al*, 2000	farm	2.22 x 14	2.21 x 14	+0.45% x 14	20cm		'Integrated' management
Spain - Melero *et al*, 2006	trial (H)	2.15	0.90	+138.3%	15cm	6 yrs	Same vegetable rotation
Italy - Marinari *et al*, 2007	farm	1.34	1.40	- 4.3%	35cm	7 yrs	
Canary Islands - Garcia *et al*, 1989	farm (H)	5.68	1.33	+325.4%	25cm	5 yrs	Avocado plantatations
US:							
Penn - Rodale Instit. 'FST' Manure:	trial	2.5	2.0	+25%	15cm	21 yrs	(Continuous soya/maize)
Legume:	"	2.4	2.0	+20%	"	"	" " " "
Marriott & Wander, 2006	trial	c.1.40 x8	c.1.24 x8	+14% x 8	25cm	10 yrs	
University of California 'LTRAS' trial	trial (h/a)	n.a.	n.a.	+28.8%	15cm	10 yrs	Same maize/tomato
Mich. Uni - Robertson *et al*, 2000	trial	1.09	1.00	+ 9%	7.5cm	9 yrs	Same maize-wheat-soya
Neb/N.Dak - Liebig & Doran, 1999	farm	n.a	n.a	+21.7% x 5	30.5cm	17 yrs	
California - Clark *et al*, 1998	trial	1.02	0.93	+10.2%	30cm	8 yrs	
N.Dak - Gardner & Clancy, 1996	farm	n.a	n.a	+12.2% x 3	15cm	10+ yrs	
California - Drinkwater *et al*, 1995	farm(h/a)	1.25 x 12	0.98 x 12	+27.6% x 12	20cm	4-10 yrs	Both tomato/other crop
Washington - Mulla *et al*, 1992	farm	1.37	0.90	+52.2%	15cm	c.20 yrs	Similar wheat/pea rotation
Nebraska - Fraser *et al*, 1988	trial	n.a	n.a	+22.3%	30cm	6-7 yrs	(Continuous maize)
Australasia:							
Australia, NSW - Wells *et al*, 2000	trial (H)	1.85	1.49	+24.2%	10cm	3.5 yrs	
NSW - Derrick & Dumaresq, 1999	farm	1.21	1.07	+13.1%	15cm	29 yrs	Both mixed farms with ley
Australia, NSW - Forman, 1981	farm	1.43	0.94	+52.1%	10cm	7 yrs	
New Zealand - Nguyen *et al*, 1995	farm	c.3.32 x3	c.3.26 x3	+ 1.8% x 3	15cm	7-8 yrs	All farms mixed with ley
New Zealand - Reganold *et al* ,1993	farm	4.84 x 7	4.27 x 7	+13.3% x 7	10cm	8-18 yrs	
OVERALL AVERAGES:							
All organic farming:		*2.12*	*1.76*	*+20.5/23.8%*	*19cm*	*c.13 yrs*	
Standard organic farming only		*1.90*	*1.59*	*+19.5/21.0%*	*19cm*	*c.12 yrs*	
Biodynamic farming only:		*3.60*	*2.87*	*+25.4/42.0%*	*17.5cm*	*c.18 yrs*	

Notes: Systems are known or assumed to be arable or mixed arable/livestock, except where indicated: H = horticulture, h/a = horticulture/arable. Shading indicates a biodynamic farming study/comparison; in addition, one of the three organic farms in Nguyen *et al*, 1995, was biodynamic. The average soil carbon difference is calculated in two ways: 1) from the difference in the average organic and average non-organic soil carbon levels (e.g. 2.12/1.76 x 100 = 20.5%; giving the overall impact on the topsoil carbon store; these are the results cited elsewhere in the report), and 2) by averaging the % differences of all the comparisons listed in column 5 (i.e. giving the average impact at any one site). Both methods produce similar results for Northern Europe and Standard (non-biodynamic) organic farming (indicating that soil carbon level has little influence on the comparative soil carbon level of organic farming). However, note that soil carbon content data is missing for ten of the comparisons, so the average figures calculated by the first method for 'All' and 'Standard' organic farming do not represent all of the comparisons listed here (unlike the second figures presented for the second method). nab. = data not available (results were only available in tC/ha). If the % difference does not correspond exactly to the data shown, the figure cited by the researchers was used, if different, or it was derived from more accurate data given by the researchers (e.g. more decimal places or tC/ha results). In the first column, 'organic' written above 'biodynamic' refers to standard, non-biodynamic organic farming. In the last column, the description of the non-organic farming crop rotation refers to the main crops and the words 'same', 'both' or 'all' (which means the organic and non-organic systems were *both* as described) does not imply a non-use of cover crops in the organic rotation; no description implies unidentified commercial rotations or simpler crop rotations than on the organic land (i.e. the difference is as expected, from a UK perspective). For more explanation, see earlier 'Notes to the review and table of comparative studies' and the study summaries (section 6.2).

6.2 Results of individual comparative studies

In this section, the studies are individually summarised to give an idea of the variety of conditions studied, insights into the nature of the differences and causes, and to highlight some of the specific findings of the studies. The long-term trials are presented first and then the surveys of commercial farms. Also, European studies are presented first, then US studies and then studies from Australia and New Zealand.

It should be noted that some of the trials are somewhat special situations (at least not from a UK perspective). In the FiBL and IBR Darmstadt trials, the inorganic fertiliser-treated systems are not typical industrial non-organic crop systems (though the 'integrated' system in the FiBL trial is typical of Swiss farming).[412] In these trials, the same diverse crop rotation was used for both the organic and non-organic plots and included a temporary grass or clover ley. Such rotations are typical of organic farming, but non-organic farming arable rotations are normally simpler and, at least in the UK, the majority do not use grass or clover (non-organic farmers use inorganic N fertiliser instead of N-fixing clover). Similarly, in the Swedish 'K-trial' the crop rotations were exactly the same and included a grass/clover ley. This means that these trials are mainly just comparisons of the effects of adding organic matter (manure, compost) versus using inorganic fertilisers, but are not really full 'systems' comparisons of typical organic and non-organic farming (at least from a UK perspective). As grass and clover are a key source of organic matter in organic farming, the soil carbon differences found in these trials would be expected to be less than between average organic and non-organic farming in Europe. In addition, it should be noted that the 18-year Swedish trial, summarised below, followed the impacts of ploughing up established grassland, so a fall in soil carbon levels would be expected even under organic farming management.

An 18-year trial of the effects of organic and non-organic mixed farming after ploughing up unfertilised grassland in southern Sweden, **Kirchmann *et al*, 2007** (1980 to 1999), found that the soil carbon levels fell under both systems but much less with organic farming.[413] The topsoil organic carbon (SOC) content declined from 27 to 25gC/kg of soil in the organic system over the 18 years (a fall of only 8.5%), and appeared to have largely stabilised in the last five years at 32% more than the non-organic topsoil. In the non-organic system, the topsoil carbon fell over twice as much, from 24 to 19gC/kg soil (-21%). The soil was a sandy loam, with 13-14% clay content. Both systems used a diverse six-year crop rotation with a year of grass/clover (non-organic) or clover (organic) and mouldboard ploughing. But the organic system also had leguminous cover crops and received solid cattle manure (average of 15t/ha every three years), while the non-organic system received inorganic fertiliser, herbicides and cattle slurry (average of 30t/ha every three years, with a dry matter content half that of solid manure). The non-use of herbicides meant that the weed biomass was 1-3t/ha dry matter greater in the organic system than the non-organic system.

Overall, the organic system was estimated to have an over 40% higher soil carbon input (3.8tC/ha/yr vs. 2.6tC/ha/yr, including root residues and the continuous root carbon supply).[414] Both systems had been designed to represent dairy production (i.e. much or most of the crops were for cattle feed). In the organic system used, however, manure was applied at a level 50% higher than could be supported by the level of feed crops produced[415] (the organic arable yields were 50% lower and the grass/clover yields 18% lower per hectare, than the non-organic system). Also, in the organic system, for some reason, the straw was incorporated in the soil and extra straw was bought in for the animal bedding (the authors acknowledge that this was not normal organic farming practice - usually enough of the straw would be removed to provide the bedding[416]), while in the non-organic system, some of the straw was removed for bedding[417]. However, modelling indicated that even if these external inputs were eliminated so that the organic system was using a lower, self-sufficient amount of straw and manure, it would still eventually produce a 25% higher final soil carbon level than the non-organic system produced.[418] (See Sections 4.4 and 9.3 for more details and our concerns that current models may under-represent the effects of organic farming).

It is not clear how long the land had been in grass in this study, but it is likely to have been a long time.[419] This study confirms that the ploughing-up of permanent grassland should be avoided, but also indicates that organic farming is much better at protecting the soil carbon store after such an event.

The Järna Institute carried out the **33-year 'K-trial' in Sweden** from 1958-1990. Eight fertilisation treatments were evaluated, using the same four-year crop rotation with a one-year grass/clover ley. The 'organic' plots received raw manure (30t/ha or 45t/ha every two years), the biodynamic plots received composted manure (30t/ha or 45t/ha before composting, every two years) and three rates of mineral NPK fertiliser were trialled (including 'medium' – average 58kgN/ha, and 'high' – average 117kgN/ha). The soil was sampled at three depths (0-60cm); it had a 27-33% clay content. The carbon levels increased under most plots over the trial. After 32 years, in 1989, the biodynamic plots had the highest soil carbon levels, then the organic plots and then the inorganically fertilised plots, as follows in Table 3.[420]

Table 3: Comparison of soil carbon % after 32 years at three depths on the different plots.

Soil carbon %, after 32 years.	Organic (K3)	Biodynamic (K1)	NPK fertiliser, 'medium' (K7)	NPK fertiliser, 'high' (K8)
0-10cm	3.1	2.9	2.6	2.5
25-35cm	2.1	2.4	2.0	2.3
50-60cm	0.9	1.3	0.9	0.6
(Average of above)	*(2.03%)*	*(2.20%)*	*(1.83%)*	*(1.80%)*

The total amount of organic carbon to a depth of 60 cm, including all the soil between, was calculated to be 146Ct/ha for the organic raw manure treatment, 160tC/ha for the biodynamic (K1) and 135tC/ha for the non-organic treatment.[421] The organic treatment had therefore produced 8.1% more soil carbon and the biodynamic treatment 18.5% more, compared to the inorganic fertiliser treatment, over the whole 60cm profile after 32 years.[422] This meant that the average annual carbon sequestration rate was over 300kgC/ha for the organic treatment and about 800kgC/ha for the biodynamic treatment (K1).[423] The researchers have concluded that, "Organic and biodynamic farming has the capacity to be an important carbon sink to reduce the surplus of carbon dioxide in the atmosphere."[424]

The Institute for Biodynamic Research, **IBR**, **long-term trial in Darmstadt**, in the Rhine Valley, Germany, which started in 1980, compared land receiving composted manure ('organic' and 'biodynamic) with inorganic fertiliser, at three N input levels on a sandy soil. The biodynamic treatment involved all of the biodynamic preparations.[425] All three systems had the same diverse crop rotation with a clover ley. After both ten[426] and eighteen years, the soil carbon levels were highest for the biodynamic plots, then the organic plots and then the mineral fertiliser plots. Overall, the two higher application rates of compost ('medium' and 'high') produced significantly higher levels of soil carbon, while the inorganic fertiliser did not produce any increase in soil carbon. The SOC levels after eighteen years were: non-organic: 0.79%; organic: 0.93%; and biodynamic 0.99% (0-25cm soil depth, medium N fertilisation rate)[427], so the organic plots had 18% higher levels than the non-organic, while the biodynamic plots had 25% higher levels.

The 28-year **Swiss 'DOK' trial by FiBL** (Research Institute of Organic Agriculture), from 1978 to 2005, compared the effects of four different treatments: organic farming (application of slightly rotted farmyard manure & slurry[428]), biodynamic (composted manure & slurry, with biodynamic preparations), 'integrated' non-organic[429] (inorganic fertiliser, manure & slurry) and 'intensive non-organic' (only inorganic fertiliser). All plots were in the same diverse 7-year crop rotation with a two-year grass/clover ley. The non-organic plots also received pesticides, and there was more mechanical weeding in the organic plots.

The soil carbon levels in the top 20cm fell under all the treatments over the first ten years, except on the biodynamic plots where they stayed roughly stable over the trial. After 21 years, at the end of the third rotation, the soil carbon content had reached practically the same level in the organic, integrated and 'intensive non-organic' plots (1.3%), but was higher on the biodynamic plots (1.5%).[430] There were differences in the average soil carbon losses under the different treatments over the trial. However, except for the biodynamic plots, this was simply because there were different starting soil carbon levels, so the differences cannot be considered a product of the different treatments (and we are therefore not citing them).[431] The biodynamic and 'intensive non-organic' plots, however, started with the same 1.6% soil carbon levels: over 28 years, the level fell by an average of 207kgC/ha/yr on the 'intensive non-organic' plots, while there was a small gain of 42kgC/ha/yr on the biodynamic plots.[432] (The starting soil carbon levels were lower for the organic and integrated plots, c.1.5% and 1.4% respectively.[433])

After 21 years, the soil carbon levels were also measured over the whole soil profile, 0-80cm, and showed significant differences down to 60cm, amounting to a total of 16.7tC/ha more in the biodynamic plots than the integrated plots (127.8tC/ha vs. 111.1tC/ha; we do not have data for the other two treatments).[434] This is a total difference of 15% over the whole soil profile (slightly more than the 12% difference for 0-20cm). The researchers state that, for reliable data on soil carbon storage levels, ideally "the whole soil profile down to a depth, where no changes are observable, should be analysed" and measurements of the bulk density should also be taken.

The better results from the biodynamic treatment is interesting given that it received an average soil carbon input of only 1.8tC/ha/yr from the compost, while the organic and integrated plots received 2.2tC/ha/yr from uncomposted manure/slurry.[435] However, the organic matter input to the soil from the grass leys and crop roots/stubble would also have varied between the plots in response to the different treatments. Whatever the process, the FiBL trial shows the benefits of composting: the fact that the manure and slurry was composted before being applied (and in conditions of no agrochemicals) resulted in the highest soil carbon levels. This appears to confirm the organic movement's long-held view that, in most agricultural situations, composting builds soil organic matter to a greater extent than when the same organic matter is applied to the soil straight (or even slightly rotted). It is interesting to note that while about 20% of the carbon was lost in the composting process in this case [436], greater total soil carbon accumulation was produced because the already humified carbon was more stabilised.

It is not clear why the topsoil carbon level fell on most of the plots. One factor could be the previous management regimes[437], but the researchers say, "there is no evidence so far that the residue return or manure input before the start of the experiment was markedly higher than after." [438] Another possibility is if the organic system caused the soil carbon to be distributed more deeply[439], so different results might have been found if a deeper sampling depth had been used. The soil type (loess[440]) could also be factor.

A six-year trial of organic and non-organic vegetable production in a silty loam soil in semi-arid conditions in Southwest Spain (**Melero *et al*, 2006**[441]), found organic management significantly increased the total soil carbon, soil microbial biomass and enzymatic activity of the soil, as well as producing a 66% higher yield. The soil organic carbon content (0-15cm depth) of the organic plots started at 1.3% SOC before conversion in 1995, and was an average of 2.2% in 2000 and 2001 (69% increase in five years), while only 0.9% on the non-organic plots. So, the organic plots ended with 138% higher soil carbon levels (statistically significant). This was considered a "particularly important" result as agricultural soil "organic matter" levels are normally less than 1% in Andalusia, the region of the study. The same vegetables were grown on the organic and non-organic plots (one to three types each year, of: lettuce, cauliflower, potatoes, strawberries, onions, carrot, leek, broccoli, broad bean and melons, except for two years when no crop was grown). On the organic plots, as well as receiving 'vegetal' compost at amounts (30-50t/ha) that gave similar N rates to the inorganic fertiliser applied on the non-organic plots, the broad bean plants (grown in 1999/2000) were left in the soil after the harvest and used as a green manure, whereas they were removed on the non-organic plots. Irrigation and mouldboard ploughing were used on all plots.

The long-term "Farming Systems Trial", **FST, by the Rodale Institute in Pennsylvania** compared continuous organic and non-organic arable production. The non-organic maize/soya system represented a typical commercial arable system in North America[442], the 'manure-based' organic system represented a typical organic dairy farm[443] (2-3 months aged manure was applied two in five years), and the 'legume-based' system represented a grain-producing organic farm. The organic crop rotations were more diverse, with other legumes (such as red clover or hairy vetch) and rye cover crops, as well as maize and soya.[444]

The organic systems produced significantly higher soil carbon levels in the top 15cm. After 21 years, (1981-2002), organic farming had increased the topsoil carbon levels by 28% for the organic dairy and 15% for the organic arable system, while the non-organic arable system produced only a (statistically non-significant) 8.6% increase[445] and did not show an overall rising trend (the levels rose, fell back and rose slightly – see Figure 3). Over 21 years, the soil carbon content of the topsoil increased from about 1.9% to 2.5% and 2% to 2.4% in the organic dairy and arable systems respectively while rising from about 1.85% to 2.0% in the non-organic system.[446] Over 21 years and for 30cm depth, the average level of annual soil carbon sequestration was calculated to be 981kgC/ha/yr and 574kgC/ha/yr for the organic dairy and arable systems respectively, and 293kgC/ha/yr for the non-organic system.[447] This gives 281kgC/ha/yr and 688kgC/ha/yr more carbon sequestered by the organic systems than the non-organic, over the whole trial.

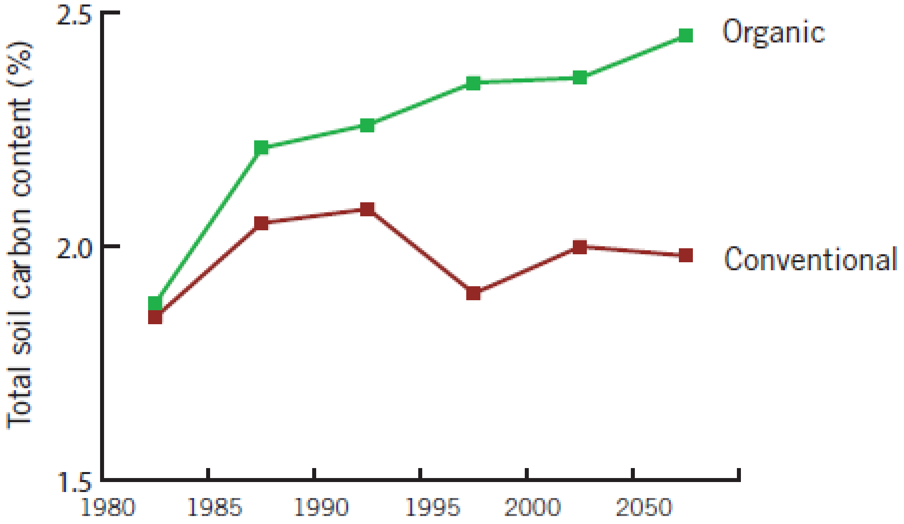


Figure 3: Graph from P.Hepperly, The Rodale Institute.[448] (It is not specified in the source, but the 'Organic' line appears to represent the average of the organic dairy and grain systems. '2050' should presumably be '2005.')

In recent years, the situation appears to have diverged more: soil carbon levels have remained high in the organically managed plots and reached a total increase of about 30% over the 29 years[449], while in the non-organic plots, in 2006, the levels had fallen back to the starting level (1.8%).[450] On average, the soil carbon levels in the organic systems rose by about 0.75% of the starting levels each year.[451] Interestingly, the yield levels of the three systems were similar (6.4-6.6t/ha for maize, 2.2-2.5t/ha for soya[452]).

In 2004, the soil carbon levels were measured down to 70cm. Statistically significant differences were found between the organic and the non-organic systems down to 30cm. For 0-10cm depth, the SOC levels were 2.51%, 2.45% and 2% for the two organic systems and the non-organic system respectively; for 10-30cm, the SOC levels were 0.75%, 0.86% and 0.5% respectively; for 30-50cm, they were 0.35%, 0.45% and 0.35% respectively; and for 50-70cm, they were all 0.20% (i.e. no difference).[453]

The researchers believe that the trials show that winter cover crops are very important in building up soil carbon in organic systems.[454] However, analyses showed that the soil carbon differences were not caused by different levels of above-ground soil carbon input, as these were similar in all of the systems.[455] [456] Earlier, the researchers suggested that the differences may arise from the different types of organic matter applied, with manure and the biochemically different plants of the organic systems causing more of the carbon input to be converted to humus and/or producing more root biomass, than just the arable crop residues in the non-organic system. For example, in the organic arable system, maize accounted for 48% of the returned organic residue but only for 12% of the increase in soil carbon, meaning the other plants grown (e.g. legumes) had higher soil carbon retention rates.[457] More recent research has suggested that the main value of the cover crops is probably in providing a much more continuous vegetation presence in the organic systems, which enables the development of high levels of soil mycorrhizal fungi (see 7.4).[458]

A ten-year trial of ten 'Mediterranean' cropping systems by the **University of California, ('LTRAS', Kong *et al*, 2005**[459]) found that the organic system "disproportionately accumulated" soil carbon relative to its carbon input. From 1993 to 2003, it sequestered 560kgC/ha/yr in the top 15cm, and increased the soil carbon store by 33% in this layer, which was several times better than any of the nine non-organic systems (the difference in the final levels was statistically significant). All systems were cropped in a two-year rotation. The organic system had alternating maize and tomato, a leguminous winter cover crop and received composted manure. It started with one of lowest levels of soil carbon (17.2tC/ha, 0-15cm) but ended with by far the highest of all the systems (22.8tC/ha), 29% more than the equivalent non-organic system ('conventional–maize-tomato', CMT). The soil carbon changes on the nine non-organic systems ranged from annual losses of 350tC/ha to gains of 60kgC/ha/yr. The two non-organic systems that were also cropped with maize/tomato produced either a marginal fall of 10kgC/ha/yr ('legume-maize-tomato', also with a leguminous winter cover crop, but no compost) or a slight increase of 40kgC/ha/yr (CMT, only inorganic fertiliser). The organic system converted 6.3% of its estimated biomass carbon input to the soil to SOC, which was eight times that of the equivalent non-organic (CMT) system at just 0.8%.[460]

A survey of soil samples from nine farming systems trials across the US (**Mariott & Wander, 2006**[461]) concluded that, "organic management significantly increased average SOC concentrations," by an average of 14% above non-organic farming over 10 years for the top 0-25cm (11 comparisons; the difference between the systems was statistically significant). The differences between organic and non-organic farming were consistent across the sites and there was little difference between the effects of 'manure & legume-based' organic systems and 'legume-only' organic systems. Six of the trials had been established for 6 or more years, and three for just three to five years. (Note, the survey included the Rodale Institute's FST trial and the University of California's LTRAS trial.)

A nine-year crop trial from 1991-1999 by **Michigan University** (**Robertson *et al*, 2000**[462]) found that organic farming built 80kg C/ha/year[463] in the top 7.5cm (only this depth was measured). It ended with a soil organic carbon level of 1.09% in this layer, compared to 1.00% for the non-organic system with conventional tillage, which had no change in soil carbon. The organic system had a winter cover crop but no manure or composts were applied. Both systems were continuously cropped with a maize-wheat-soya rotation. The researchers ascribed the carbon sequestration in the organic system to the winter cover crops, which added 1 to 2t/ha of plant biomass to the soil in two out of three years. They noted that, "soil carbon storage in surface horizons provides a conservative estimate of the in situ CO_2 sequestration … Ignored are potential changes in … soil C deeper in the profile due to root decomposition." We assume that had the soil been measured to a greater depth than 7.5cm, the results would probably have been even more favourable for the organic farming system. (Note, we have not reported on the no-till non-organic system, as the finding of high carbon sequestration with this system would have been mostly a product of the fact that only the top 7.5cm of the soil was measured. In practice, it is likely that there would have been little effect as found by studies which have measured the whole soil profile.[464])

An eight-year trial in California ('Sustainable Agriculture Farming Systems'; **Clark *et al*, 1998**[465]), found that organic farming produced a small but "significantly greater" total carbon level over a 30cm soil depth after two crop rotations (1988 – 1996), than the two non-organic 'conventional' cropping systems. The systems were representative of farms in the semi-arid, irrigated farmland of California's Sacramento Valley. The difference was +10.2% over the 30cm; 1.02% vs. an average of 0.93% for the two non-organic systems[466], which produced similar results to each other. Interestingly, the difference existed only in the 0-15cm layer (at the 15-30cm depth, the level in the organic system was marginally lower than in the non-organic systems, though this was not statistically significant). It was calculated that the organic farming system had produced a soil carbon sequestration rate of 546kgC/ha/yr since the start of the trial in the top 15cm, compared to just +12kgC/ha/yr for the nearest non-organic farming system (four-year rotation). The organic system used a four-year rotation, composted poultry manure (4-7t dryweight/ha every second year) and winter cover crops. The two conventional systems were: a four-year rotation with the same four main crops as in the organic farming system, and a simple two-year tomato/wheat rotation. The tillage types were similar (disking and rotary cultivators) but more frequent in the organic system.

In a seven-year trial in Nebraska (1975 - 1982), **Fraser *et al*, 1988**[467] found the organic farming system produced 22.3% more soil organic carbon over 30cm than a non-organic continuous maize system, ending with 69.7tC/ha vs. 57tC/ha (average of last two years). The differences were statistically significant over 0-15cm deep, but there was no difference at 15-30cm. 'Minimum tillage' (disking) was used in both the organic and non-organic systems as the primary soil tillage method, which may help explain the lack of a difference in the deeper soil layer. The study is presented as an investigation of, "conventional and organic management" and the tillage practices are described as standard for the region.

As well as the trials, there have also been several comparative studies of commercial organic and non-organic farms, including two UK studies, both of which found higher levels of SOM on the organic farms. In 2001, in a Defra-funded study (**Gosling & Shepherd, 2005**[468]), the soil was sampled to 30cm depth on four organic arable farms in England and compared with the soil on adjacent non-organic arable farms, or on the same farm if they were using parallel systems. The organic farms had been organic for between 15 and 54 years, were mixed systems and typical of the regions in which they were located. Two of the non-organic farms were also mixed (with dairy cattle) and two stockless. For each organic farm, samples were taken from fields at two contrasting stages of the rotation: fields in the 'high-fertility' stage (at the end of the grass ley period or immediately after) and in the 'low-fertility' stage (end of the arable phase). The soil carbon levels of the organic farms were: 23.8gC/kg soil for the high-fertility samples and 21.6g/kg for the low-fertility samples.[469] The average of the two organic results, 22.7gC/kg, versus 20.6g/kg for the non-organic samples, means that the organic farms had on average 10% more SOC than the non-organic farms. However, only one organic farm actually had a higher soil carbon level, and at two of the sites, the conventional fields had very slightly more organic carbon than the organic[470].

The modest difference was probably due to the fact that half of the non-organic samples were from mixed farms (one of which was applying a large amount of manure), which would have under-represented the average difference between organic and non-organic farming in the UK. Non-organic dairy farms probably account for the main remaining mixed farms in the UK non-organic sector and, being often more intensive with higher stocking densities than organic dairy farms, would often be applying large amounts of manure to their arable fields. However, the counter side of this is the greater area of all-arable land producing food and feed grain that is not receiving manure. On reflection, it seems that this study was not intending to assess the general differences between organic and non-organic farming (the purpose of this review), but was intended to study the one-on-one conversion effects, which is subtly different.[471] Nevertheless, the study is included here to ensure different types of non-organic farm are included.

In 1992, **Armstrong Brown *et al* , 2000** surveyed 30 pairs of neighbouring organic and non-organic farms over a wide area in south-eastern England and found much higher soil carbon levels on organic arable and horticultural farms (0-10cm). The 13 organic 'arable' farms had on average 34% more topsoil carbon than the 21 non-organic arable farms (c.2.4% versus 1.8% SOC[472]). The nine organic horticultural farms had similar soil carbon levels to the organic arable farms, but 58% more than the 3 non-organic 'horticulture' farms (c.2.4% versus 1.5%). The researchers attributed these differences to the use of grass leys in the organic arable rotations, the frequent use of manure, and the slightly lower tillage intensity of the organic horticultural farms. The researchers also found the topsoil depth was 5% less in the organic than the non-organic arable soils, but 13% greater in the organic horticultural soils (33.4cm vs. 29.7cm).[473] Interestingly, the seven organic farms with permanent pasture[474] had an 11% lower topsoil carbon level than the five non-organic farms with permanent pasture (2.8% versus 3.1% SOC). However, the topsoil was twice as deep on the organic pastures (42cm versus 20cm on the non-organic pasture), implying that overall more soil carbon was being stored in the organic pasture. This shows that for grasslands, it is important to sample the whole topsoil depth. No results were statistically significant.

A study of two fields in the Netherlands that had been under organic (biodynamic) and non-organic arable management for 70 years each (**Pulleman *et al*, 2003**[475]), found that the topsoil carbon level was 60% higher on the organic field than the non-organic field, 1.4% versus 0.87%[476] (0-20cm, the difference was statistically significant). The soil aggregation level was also significantly higher. However, the organic field had a 20% higher soil clay content which would probably account for some of the difference. It was estimated that the non-organic system produced a total above-ground organic matter soil input of 6.3t/ha/yr of dry matter, while the organic system supplied 6.9t/ha/yr. Both systems had the same type of rotation with a 2-3 year grass ley, which was typical for the region, and both were deep-ploughed. But unlike the non-organic system, the organic field received farmyard manure (10t/ha), slurry (10t/ha) and no pesticides. Most of the straw for the farmyard manure was imported (so the organic system was not totally self-sufficient in carbon input, but the straw was converted to FYM which has a better effect).

A survey of 45 fields with the same soil type (loamy, 17-25% clay) in a large agricultural region in south-western Netherlands (**Pulleman *et al*, 2000**) found that, "organic management increased SOM content" (the differences were statistically significant for farms that had been organically managed over the previous 3-7 years). Samples were taken at 15cm depth from 15 fields in 1996 and 30 fields in 1998. The eleven arable fields that had been organic for over three years had 23% higher soil carbon levels on average than the eight non-organic arable fields (1.31% vs. 1.06% SOC, respectively).[477] The length of organic management of these farms was from 3 to over 31 years (average range 6.3-13.5 years).[478] The three organic grassland fields that had been in grass for over a year had 14% more soil carbon than the eleven non-organic grass fields, 2.12% vs. 1.86% SOC. Two of these three organic fields had only been in grass for one to three years, while most of the non-organic fields had been in grass over seven years.

In 1993 and 1994, **Friedel *et al* (2000)**[479], sampled the soil of organically and non-organically managed plots on an experimental farm in Southwest Germany. The organic plots had 11% higher soil carbon levels (3.50% vs. 3.15%, 0-25cm, not statistically significant). The soil was high clay-content, 70%, and the farms had been managed organically/non-organically since 1972. The modest[480] size of the difference was ascribed to the fact that all the plots had the same 7-year crop rotation with cereals, peas, and grass/clover, and only differed in the type of applied fertilisation (inorganic fertiliser or cattle manure) and the use of biodynamic preparations on the organic plots. Both plots were deep-ploughed (25cm).

In a three-year farm survey of 5 pairs of fields in Germany (**Capriel, 1991**), both the organic and non-organic farms showed a decrease in soil carbon levels over the period, but the levels decreased less under the organic systems. The soil was only measured to a depth of 15cm.

In 1997 and 1998, in Switzerland, **Oberholzer *et al* (2000**), compared the soils of 14 organic winter cereals fields with the soil from adjacent non-organic fields growing the same crop. As in the Swiss FiBL DOK trial, the organic and non-organic fields had the same soil carbon levels (on average 2.22% vs. 2.21% SOC, respectively). Like the FiBL trial, the non-organic farms were also using 'integrated' management, which is common in Switzerland and normally means they are mixed farming systems and more similar to organic farming than more 'industrial' farming systems. However, the soils were only sampled to 20cm depth, so any differences in the deeper soil layers would not have been identified.

In a side-by-side comparison of a field under organic management for seven years and a field under non-organic management on an arable farm in Italy, the soil was sampled at two depths (5-20cm, 20-35cm) (**Marinari *et al*, 2007**).[481] The SOC level was marginally lower on the organic field (average 1.34% SOC versus 1.40%), which was not statistically significant.[482] However, both fields had been left fallow in the year of sampling (2001) and the previous year, which may have reduced any differences. Nevertheless, the researchers found, "considerable changes in SOM structure" on the organic field, with 55% greater humic C content in the upper soil layer, and a slightly higher level of 'pseudo-stable' organic substances in the lower layer. Detailed analysis indicated that in the organically managed field, SOM mineralisation was concentrated on the 'labile' carbon fractions (i.e. water soluble organic compounds and microorganisms; the former are likely to be from decomposing organic residues[483] and root exudates[484]), while in the non-organic field there was mineralisation of the 'soil native SOM,' i.e. of the humus that normally constitutes the soil carbon store. The researchers suggested that, in this case, the organic system needed more time to raise the soil carbon level (for instance, perhaps there were differences in the starting soil carbon levels of the two fields). The management practices were representative of organic and non-organic farming in the region. Both fields were ploughed (30-40cm) and the organic field received 8t/ha of animal manure.

On Tenerife in the Canary Islands, a 6 hectare biodynamic avocado plantation was sampled and compared to 31 non-organically managed plantations (**Garcia *et al*, 1989)**.[485] Over 0-25cm, the soil organic carbon level of the biodynamic plantation 325% greater, than the non-organic plantations (c.5.7% vs. 1.3% SOC content[486]; this difference was statistically significant). This result is particularly impressive given that in the year of sampling (1986), the biodynamic plantation had completed only five years under biodynamic management. The biodynamic plantation was fertilised by biodynamic compost (made from plant residues and manure), pine leaf mulch and cow urine.

Liebig & Doran (1999)[487] compared soils of five field pairs from four organic farms and five non-organic farms - three field pairs in Nebraska and two pairs in North Dakota, matched by soil type. The organic fields had consistently higher soil organic carbon levels in the top 30.5cm, 22% more on average (+4%, +36%, +26%, +35%, +13% respectively; the differences were statistically significant at three locations). The organic farms contained 12.6tC/ha more than the non-organic farms in this layer. Topsoil depth was also measured in Nebraska and was higher on the three organic farms, 2-15cm more (9-43% more).
Interestingly, the organic farm which had the smallest soil carbon *content* difference in the top 30.5cm (+4%) had the largest *topsoil depth* difference, 50cm versus 35cm for the non-organic farm. Accounting for the slightly lower topsoil bulk densities of the three organic farms, the greater topsoil depth could have increased the amount of topsoil carbon stored by these farms by about 40%, 5% and 5% per hectare respectively.[488] Given that, in the first and last of these organic farms, the topsoil depth was more than 30.5cm, this would have increased the average soil carbon difference between the organic and non-organic farms above the +22% and +12.6tC/ha result reported for the top 30.5cm. (The subsoil carbon contents and total soil depths would be needed to calculate the exact difference this makes to total soil carbon storage). This study shows that if only a small difference in SOC % is found between an organic and non-organic farm (as found by a few of the other comparative studies that used shallow sampling and did not measure topsoil depth), that does not on its own mean that organic farming has not produced a higher soil carbon storage level. Researchers should therefore always attempt to measure topsoil depth.

The greater level of soil carbon on the organic farms was attributed to more diverse crop rotations (e.g. all included alfalfa, while the non-organic farms used standard simple arable rotations), grass ley periods, additions of organic matter and less frequent tillage (though the tillage types were mostly the same as the non-organic farms). In addition, the organic farms in three of the five comparisons were using composted manure. The organic farms had been managed organically for an average of 17 years.

Gerhardt (1997) compared two adjacent farms matched by soil type in eastern Iowa[489], USA, and found significantly greater topsoil SOC content and depth on the organic farm.[490]

In 1990 and 1991, **Gardner & Clancy** (**1996**[491]), took soil samples (0-15cm) from three organic farms in North Dakota, US, and compared them with the soil from three non-organic farms representing dominant practice in the region, with similar soil and enterprise types. The organic farms had an average of 12% higher soil carbon levels[492] (two had higher levels but one had less and was suffering from water erosion on the slopes). In addition, the organic farms had an overall average 12% deeper topsoil[493], though the differences were inconsistent (-10cm, +20cm, 0cm) and most of this was offset by the lower soil bulk densities. The organic farms used green manure crops and/or regular applications of farmyard manure as well as crop rotations, and had near-continuous crop cover and a greater diversity of crops. They had been managed organically for at least a decade.

The University of California studied 20 organic and non-organic tomato-producing farms in California (**Drinkwater *et al,* 1995**). The region, Central Valley, is one of the USA's top tomato-growing regions. Three-quarters of all organic farms in the region with over half a hectare of tomatoes were included in the study, while the non-organic farms were representative of the area. The organic farms were mixed vegetable and orchard farms, while the non-organic farms were divided between large tomato/arable farms and small-scale vegetable/orchard farms. Tomato fields were sampled in 1989 or 1990 to 20cm depth. The 12 organic fields that had been managed organically for four or more years had an average 28% higher SOC level than the ten non-organic fields with similar soil types (1.25% vs. 0.98%).[494]

As well as the carbon inputs from crop residues and root exudates/turnover that were produced in both systems, the organic farms had additional carbon inputs from a variety of other sources: cover crops, leguminous residues, off-farm residues (manure and compost) and weed biomass. Additionally, because the organic farmers maintained plant cover in the fields outside the cropping season, while the non-organic farmers normally had a bare fallow by using herbicides and/or cultivation, "additional C inputs occurred in the ORG [organic] fields through root exudation/turnover during the rainy [4-7 months uncropped] season." The researchers concluded, "Thus, accumulation of SOM in ORG cropping systems could indicate either greater total C inputs or greater retention of soil C during decomposition."

In the Palouse region of Washington State, much higher soil carbon levels have been found on a long established organic farm[495] than on an adjacent non-organic farm. This is a dryland region with a steep topography that has traditionally suffered high rates of erosion due to the use of conventional tillage and the soil surfaces being left bare over-winter. **Mulla *et al* (1992)** sampled the soil to 15cm depth at different locations along the boundary of the two farms up the slope of a hill. The soil organic C content was "significantly higher" on the organic farm than the non-organic farm, an average of 52% more (1.37% vs. 0.90%). Reganold, 1988 also reported very much lower rates of erosion on the organic farm: 7.8t/ha vs. 20.4t/ha.[496] In 1987, Reganold *et al* reported in *Nature* that the organic farm also had a 16cm deeper topsoil, attributed to greater erosion on the non-organic farm. The differences were attributed to differences in the crop rotations and tillage practices.[497] Both farms used a wheat/pea rotation with occasional summer fallow, but the rotation was a bit more diverse on the organic farm.

A short-term trial of vegetable production in New South Wales, Australia (**Wells *et al*, 2000**[498]), found that the soil organic carbon levels "increased strongly" (by 55%) on the organically managed land over four cropping seasons, and ended 24% higher than on the land managed by conventional means ('District Practice'). The SOC levels were 1.85% and 1.49%, respectively. However, the soil was only sampled to 10cm, the trial period very short (3½ years, 1992 to 1995) and the difference was not statistically significant. The researchers remarked that, "Conventional vegetable farming often involves repeated tillage, frequent exposure of soil to rainfall and excessive use of fertilisers, pesticides and irrigation water. These practices can result in severe damage to soil structure." They considered that the rapid response of the soil (15% clay) to the management system, "reflects the intensity of horticultural production." The organic system used legumes, rotations, cover crops, compost and minimum tillage, while the non-organic system used continuous vegetable cropping, poultry manure, agrochemicals and multiple tillage. Farmers were consulted in the design of the systems to ensure they were, "consistent with commercial practice."

Derrick & Dumaresq (1999), studied the arable soils of an organic mixed farm and a neighbouring non-organic mixed farm in dryland New South Wales, Australia, taking samples in three consecutive years (1991-1993). The soil carbon level was 13% higher on the organic farm than the non-organic farm (1.21% vs. 1.07% SOC; not statistically significant), though it was only measured to 15cm depth. The organic farm was long-established (since 1963) and the non-organic farm was a typical wheat/sheep farm of the region. The organic system used an eight-year rotation with a six-year grass/clover pasture period, while the non-organic system used a six-year rotation with a three year clover pasture period.

A comparison of adjacent fields from a biodynamic and a non-organic farm on a clay-loam soil in New South Wales, Australia, found that the biodynamically managed field had significantly higher soil carbon levels than the non-organic farm (**Forman, 1981**). The soil carbon level was 52% greater (1.43% vs. 0.94% respectively, 0-10cm). The seven-year old biodynamic farm used a crop rotation of wheat/rye /fallow/wheat/fallow/wheat/wheat. The eleven–year old non-organic farm used a simpler wheat/wheat/ fallow rotation, and had been in pasture for about 35 years previously.[499]

Nguyen *et al* (1995), compared the soil from three mixed organic farms (one biodynamic) and three mixed non-organic farms in the Canterbury region (South Island) of New Zealand, the main cereal-growing region of the country. The total carbon levels in the top 7.5cm were exactly the same in the cropping phases (3.23%) but slightly higher on the organic farms in the pasture phases (3.53% vs. 3.33%). There was no difference over 7.5-15cm[500], suggesting that the organic farms had only around 1.8% more soil carbon overall than the non-organic farms.[501] Differences between the systems may be limited in this region, as the non-organic farms are commonly mixed systems with grass/clover (or were at the time). The organic farms, which had been converted 7-8 years before, had longer grass/clover phases in their rotations than the non-organic farms (half vs. an average of 30% of the time). Organic farms in the region do not have a ready supply of farmyard manure to apply to the arable land as the livestock are not housed in winter but grazed year-round, which is why they use longer pasture phases for soil fertility.

In 1990 and 1991, 10cm deep soil samples were taken from 7 biodynamic and 9 adjacent non-organic farms matched by soil type on the North Island of New Zealand (**Reganold *et al*, 1993**; Reganold,1995[502]). There were significantly higher levels of 'total carbon' in most of the biodynamic topsoils than the non-organic (averaging 4.84% vs. 4.27%, i.e. 13% more). The biodynamic soils also had significantly thicker topsoils, 22.8cm vs. 20.6cm (11% more), though this was partially due to having significantly lower soil densities (7% less). The biodynamic farms had been managed biodynamically for 8 to 18 years. The study concluded that the, "biodynamic farms proved in most enterprises to have soils of high biological and physical quality: significantly greater in organic-matter content and microbial activity, more earthworms, better soil structure, lower bulk density, easier penetrability and thicker topsoil."

6.3 Other surveys of organic farming soil carbon levels

Two other farm surveys have attempted to look at the effects of organic farming soil carbon levels. Neither provide representative data on the comparative effects of organic and non-organic management of cultivated land, so they were not included in our review of comparative studies. The first study, nevertheless, has useful findings on the value of mixed farming systems and provides some tentative data on the effects of organic farming on grassland soil carbon levels.

A Defra-funded survey compared the soils of converted and unconverted fields of 19 mixed organic farms, 4 organic stockless farms, and 6 predominantly grassland organic farms in England (**Shepherd *et al*, 2002**[503]). Though this appears to be presented as a comparative study of organic and non-organic farming[504], the study was not actually designed for this purpose. Most of the 'non-organic' soil samples in the study came from unconverted fields on the organic farms, not from normal non-organic farms (farmers entering organic management often convert their farms to organic progressively over a period of years, so many still had a few unconverted fields; others had separate parcels of land that had not been converted with the rest of the farm).[505] This is important as converting farms (especially ones which have already converted), and therefore the land on these farms, are often unrepresentative of the non-organic farming sector generally – see below.[506] Just as importantly, the study excluded the most characteristic and probably largest difference between organic and non-organic farming in the UK, the use of mixed systems, by separately comparing the land in mixed systems from the land in stockless systems. This invalidates the study for the purposes of this review. This study therefore contrasts with the comparative studies included in our review which, as far as we could establish, were clearly intended to represent commercial organic/non-organic farming practice[507] and which used dedicated non-organic farms/systems for the non-organic sample.

The sampling was carried out in 1999/2000, using the same methodology of sampling the 'high' and 'low' fertility stages of the organic crop rotations as Gosling & Shepherd, 2005, used. There was no difference between the average topsoil carbon levels of the organic and non-organic fields on the mixed farms (2.5% SOC, 0-20cm), or the organic and non-organic fields on the stockless farms (1.8% SOC, 0-20cm). For the grassland farms, however, the topsoil carbon levels were 16% higher on the organic than the non-organically managed grassland (5.2% vs. 4.5%, 0-8cm; statistically non-significant), and there was a 14% lower soil bulk density (significant). As might be expected, there was a highly negative correlation between the soil carbon content and the soil bulk density.

These result of 'no difference' between the organic and non-organic fields of the cultivated land clearly does not represent the soil carbon differences between organic and non-organic management in the UK, as the influence of mixed systems was excluded by the specific use of separate groups for the mixed and stockless systems. In contrast, the majority of UK non-organic arable production is in continuously cropped stockless systems, while most organic crop production is on mixed farms (mixed systems are generally the most viable organic arable system for agronomic and economic reasons). Mixed farming systems are normally associated with higher soil carbon levels. Additionally, the management of the 'non-organic' fields was probably somewhere between typical organic and typical non-organic and cannot be assumed to represent the non-organic sector generally.[508] For the grassland farms, however, as this was a direct comparison (no division into system types), the results may be more reliable, although presumably conservative given that most of the 'non-organic' sample was not from the mainstream non-organic sector. The ability of the study to identify differences was also limited as the sampling depth was only 20cm for the cultivated land, and just 8cm for the grassland.

Despite these limitations, the finding that organic mixed farms had 39% more topsoil carbon than organic stockless farms strongly confirms the importance of mixed farming systems for high soil carbon storage. This indicates that UK organic stockless systems (which form a small proportion of the total area of organic cultivated land in the UK) do not generally share the soil carbon benefits of most organic farming. According to the researcher, the lower levels on stockless arable farms may be partially because there is some transfer of straw from stockless farms to mixed farms[509] (for livestock bedding). However, our research shows that straw is of relatively little benefit, unless it is converted to manure (see section 7.5), which suggests that this practice would be benefiting the mixed systems, but not significantly affecting the stockless systems. The soil carbon effects may also be different for stockless horticultural operations. Organic horticultural holdings are likely to be using composting (and in some cases biodynamic methods), which would be expected to improve soil carbon levels.

The finding that there was no difference in the soil carbon levels of the converted and unconverted fields is presumably because most farmers who have so far converted in the UK, especially the main 'early wave' of those converting, were already using mixed systems. Many also had more similar attitudes to organic farmers, then those who had gone down the intensive stockless conventional route and whose systems have diverged from organic farming. There would still have been a benefit from these mixed farmers maintaining their high carbon levels with organic farming, especially as many were close to being economically unviable and might otherwise have sold up and the farms converted to intensive stockless systems. The majority of the remaining non-organic arable farmers are now stockless. Some of these farmers are now converting to organic farming, mostly into mixed systems of some type. However, barriers to entry into organic farming remain for these stockless farmers and it is important that these are addressed as this offers the greatest potential for realising the soil carbon benefits of organic farming.

A six-year monitoring study was also carried out on twelve farms that were converting to organic farming in Norway (**Løes & Øgaard, 1997**).[510] The farms were sampled in 1989 and 1995. There was a significant (roughly 30%) increase in the total carbon level of those sites which had had less than 1.7% carbon in 1987, and the researchers concluded that "organic dairy farming may increase" the carbon level of soils with a low carbon content. However, half the farms had still not been certified as organic in 1995 and only four had been certified for three or more years by then, so we are not convinced that the findings represent the effects of organic farming. Overall for all samples, the average subsoil carbon content increased by 8% (20-40cm) over this time, but there was no increase in the average carbon level of the topsoils (0-20cm).

6.4 Other long-term monitoring studies

As well as the long-term comparative studies, there has been some long-term monitoring of soil carbon levels just on organic farms. In the two published UK studies that we are currently aware of, the soil carbon levels have remained steady. In a survey of two sites in Aberdeen, with different soil types and climate, mixed organic farming maintained the soil organic matter levels from 1992 to 2003, with the level at one site staying stable at 6% organic matter (i.e. c.3.4% SOC) and very slightly increasing at the other site around a level of 9% (c.5% SOC).[511] (The average of these is 4.2% which is, for information, higher than the average soil carbon content of Scottish arable soils of around 3.6%.[512]) Both sites were previously in mixed non-organic farming, so the change to organic management would have involved a much smaller difference than a change from continuously cropped land. However, the fact that no differences were found might also be because only the top 15cm of the soil was sampled.

Another survey measured soil organic matter levels on organic vegetable systems in Warwickshire and Lincolnshire for 10 years after organic conversion.[513] It has not so far identified any significant changes, even at one site which has now been monitored for over 14 years[514]. This could relate to the previous management of the land (organic farming would only produce a soil carbon increase if the previous management had kept the soil at a lower soil carbon level). However, the systems are also stockless and would not be expected to build as much soil carbon as mixed organic farming.

In the few cases that we know of where soil carbon levels have been monitored by UK organic farmers or researchers for private use, it has generally been reported that SOM levels are remaining stable under organic farming (two instances[515]), though in one case they are increasing year-on-year. There is a view among organic farmers and researchers who have taken a particular interest in this issue that there is good potential for substantially increasing soil carbon levels above current organic farming levels.

In the UK case where levels are reported to be rising, the organic farmer is using composting specifically to increase his soil humus level. Regular soil tests show that carbon levels have increased from an average of 3-3.5% to 4% (a 25% increase), even though the land was under intensive arable production which would be normally expected to result in stable or falling soil carbon levels.[516] Soil carbon is even rising on land that is under continuous cropping. This has been achieved simply by applying small amounts of good quality compost for over 20 years, using material from the farm and some local sources (no manure is brought from other farms). Moreover, in the acre of glasshouse, where the farmer has been applying high levels of compost, the soil carbon level has increased from 2.3-2.9% to 10.5-11%, a four-fold increase. This would probably normally be considered almost impossible under current soil theory.

6.5 Modelling studies of organic and non-organic farming

There have also been three studies where the soil carbon differences were calculated by soil models. While these are useful tools, they do not provide direct data on the differences between organic and non-organic farming like studies that actually measure the levels by soil sampling. So we have not included these in our main review of comparative studies. These models attempt to simulate the effects of the complex biological processes behind soil carbon dynamics. However, with the exception of the REPRO model, we believe most of the current soil models do not yet account for the different relationships and soil biological conditions of organic farming.

A survey and greenhouse gas emissions inventory of the cropping systems of 18 organic and 10 non-organic farms in Bavaria, Germany, used the REPRO model to calculate that the organic farms were building an average of 402kgC/ha/year, while the non-organic farms were losing 202kgC/ha/year (Hülsbergen & Küstermann, 2008).[517] (Earlier references have reported different figures, though with the same general result).[518] The REPRO (REPROduction of soil fertility) model simulates carbon and nitrogen dynamics of the soil–plant–animal–environment interface, and has been validated with long-term data from an experimental farm in Bavaria operating organic and non-organic systems since 1992.[519]

In the study, Kirchmann *et al*, 2007[520], the researchers had 32% measured higher soil carbon levels on the organically managed land than the non-organically managed land, in a long-term trial (see Section 6.2). Using modelling, they showed that the final equilibrium (steady-state) soil carbon levels of the organic system would be 58% higher than the non-organic system, 19gC/kg versus 12gC/kg. Modelling also predicted that even if the carbon inputs of the organic system were adjusted to be proportional to the organic crop yields (so that the system was not using any 'imported' straw), organic farming would still produce 25% higher soil carbon levels than the non-organic system.[521] In addition, modelling was carried out to evaluate the effects of other scenarios. It was predicted that *if* the non-organic system also used three cover crops and solid manure (instead of slurry) like the organic system, then it would also produce higher soil carbon levels. Furthermore, because of the higher crop yields and thus assumed higher crop residue levels, the modelling predicted that such a modified non-organic system could produce even higher soil carbon levels than organic farming (13% more). Unjustifiably, on this theoretical basis and despite their positive findings for organic farming, the authors said, "Thus, we conclude that organic farming systems are not an option to sequester C in the soil under Swedish conditions"!

These modelling results may well be inaccurate and have under-estimated the impacts of organic farming. The crop carbon inputs were not derived by measuring the residues actually produced by each system in the trial, but were estimated from the crop yields using standard values from literature for the relationship between yield and residue levels (presumably from non-organic systems). See comments on this issue regarding the next study, below. In addition, the Kirchmann *et al* may have over-estimated the effects of straw incorporation[522], which research shows has only a small effect on soil carbon levels (see Section 7.5). Also, the modelling was only carried out for the top 30cm of the soil, ignoring the subsoil.

Finally, a 2002 Danish study modelled the long-term effects of organic and non-organic crop management on cultivated land.[523] Three scenarios were modelled: arable, pig and dairy/beef production, using representative crop rotations for organic and non-organic farming. With the CENTURY soil model and data from a long-term farming trial in Denmark, for both loam and sandy soils, the researchers predicted an increase in soil carbon under organic farming of 100-400kgC/ha/year during the first 50 years. The levels were lowest for organic systems that used slurry (Denmark has a large excess of pig slurry) and largest for organic systems using farmyard manure ('straw-manure') at the same N level as the slurry. The latter sequestered from 250kgC/ha/yr to 400kgC/ha/ha/yr; this treatment would be more typical for the UK. In contrast, they predicted reductions of about 35kgC/ha/yr (on loam soils) or negligible change (c.-5kgC/ha/yr on sandy soils) under non-organic farming.[524]

Although this is an interesting study and gives positive results for organic farming, several shortcomings suggest that it may not be reliable. The model did not account for the fact that organic fertiliser (as opposed to inorganic fertiliser) is considered to increase the root:shoot ratio, which would affect the below-ground organic matter deposition (see Sections 7.5 and 7.6). The study also assumed that the level of crop biomass added to the soil relates linearly to the level of crop yield. This would not be at all correct for a comparison of organic and non-organic farming, either for the root or straw biomass (see 9.3)[525]. So, the study did not pick up on the positive differences in crop biomass that would be expected under organic farming and may also have been wrongly influenced by the lower yield levels of organic farming. The study additionally assumed that non-organic systems use diverse crop rotations with a year of grass in the rotation which is not typical in the UK, and so the small predicted soil carbon decline under non-organic farming may not be enough for UK conditions. The model also only covered the top 20cm of soil, and thus excluded changes in topsoil depth and the subsoil. These points are all likely to have underestimated the comparative level of soil carbon storage of organic farming. In addition, though the soil management practices and the crop rotations used in the study represented typical organic farming practices, the farm trial from which the dataset was derived was apparently a non-organic trial that had been comparing the effects of different fertilisation treatments and the effects of crop rotations over time. It is unclear how well this data would match the integrated impacts of all organic farming practices.

6.6 Discussion and recommendations

Overall, this review of comparative studies indicates that organic farming produces an estimated average of 28% more topsoil carbon per hectare of cultivated land than non-organic farming in Northern Europe (over a period of about 15 years and a depth of about 18cm), and 20% higher levels for all countries reviewed in Europe, US and Australasia (over a period of about 12 years and a depth of about 19cm). These estimates are for standard, non-biodynamic farming and include findings of higher levels in semi-arid regions. Based on the studies in this review, biodynamic farming produces about 25% higher soil carbon levels than non-organic farming, but this is likely to be an under-estimate as explained in section 6.1. Organic horticulture seems to produce greater differences than organic arable farming, and there are initial indications that organic grasslands also have higher soil carbon levels than non-organic grassland.

This review has also highlighted certain issues. As should be expected, there are indications of a relationship between the percentage difference and the length of period under organic management. For instance, the modest difference of only +10% found at the end of the eight-year trial by Clark *et al* (1988) may simply be due to the relatively short length of the trial. After all, on an annual basis, a +10% difference after eight years is similar to the +25% difference found by the Rodale Institute for a dairy (manure and legume-based) organic system over 21 years compared to non-organic farming. This shows that it can be misleading to look at the size of the differences found, without also considering the length of time under organic farming.

Another interesting point is that the studies cover a **variety of organic farming practices**, and higher soil carbon differences are found for different types. From a UK perspective, it is widely felt that grass leys and mixed farming systems are crucial for achieving higher soil carbon levels and that this is a key benefit of organic farming (e.g. this is borne out by Shepherd *et al*, 2002). However, looking at the whole body of studies from all regions, it is clear that organic farmers use different strategies in different regions and for different enterprise types (arable or horticulture) and it appears that generally all types are successful: mixed farming with grass leys and manure use, legume/cover crop-only based systems, and systems relying more on composting. This implies that it is the basic approach of organic farming that is important for the soil carbon benefits – the reliance on organic matter for supplying fertility, but how this is achieved is flexible in practice. In the few regions where organic farming produces only a small or no soil C benefit (such as, Switzerland), it seems to be due to the use of similar practices by the non-organic sector: in these cases, non-organic farms were also using mixed farming systems, similar diverse rotations and organic fertilisation. (There were, however, no regions where non-organic farming systems were relying on legume/cover systems or composting.) Therefore, the soil carbon benefits of organic farming should be ascribed to the *system* of organic farming, rather than to specific practices of organic farming.

As well as the +28%/+20% greater topsoil carbon contents, the review also shows that organic farming is associated with **greater topsoil depth**. Although part of this will be accounted for by the lower soil densities of organic farming, this should nevertheless increase the soil carbon benefit of organic farming. Six comparative studies looked at topsoil depth and all found the topsoil was on average deeper under organic farming (though not in every individual case):

1. Armstrong *et al*, 2000 found that the topsoil depth was 13% greater on the organic horticulture farms (+4cm) and double in organic grassland (+21cm) in England than on the non-organic horticulture/arable farms respectively, but was 5% lower on the organic arable farms (-2cm) (no differences were statistically significant).
2. Liebig & Doran, 1999, found a 2-15cm greater topsoil depth on three organic farms in Nebraska (+43%, +9%, +9%, compared to the non-organic farms), only part of which might be due to a lower topsoil bulk density (which was 3-4% less over 0-7.6cm depth).
3. Gerhardt,1997, found a significantly greater topsoil depth on an organic farm in Iowa, US.
4. Gardner & Clancy, 1996, found an overall average deeper topsoil on three organic vs. non-organic farms in North Dakota (-21%, +89%, 0%), though most was offset by the lower soil bulk densities.
5. Reganold *et al*, 1993, found a statistically significant 11% increase in topsoil depth with biodynamic farming, partially due to a 7% decrease in bulk density, in New Zealand.
6. Reganold, 1987, found a 16cm thicker topsoil on the organic farm than an adjacent non-organic farm in Washington State (the same farms studied by Mulla et al, 1992).

The review also shows that organic farming is associated with higher carbon content levels in the **deeper soil layers** in many cases. This was found by five studies. In Pennsylvania, the Rodale Institute trial found organic farming had higher soil carbon levels than non-organic farming down to 30cm (+60% for the 10-30cm layer, little difference below this). In this case, it is not clear if this was due to greater topsoil depth or greater subsoil carbon content. The Swedish K-trial found that organic farming produced little difference in the 25-35cm layer, but there were differences in the 50-60cm layer: the organically managed plots had a 50% higher subsoil carbon content than the non-organic plots when a high rate of inorganic fertiliser was used in the non-organic system (while the biodynamically managed plots had a 50-100% higher level in this layer when either medium or high fertiliser rates were used by the non-organic system). In Switzerland, the FiBL DOK trial found a significantly higher soil carbon content for the biodynamic compared to the non-organic 'integrated' system down to 60cm (+15%). Increases in both topsoil and subsoil carbon content with organic farming are also reported for Welp, 1993, and Diez *et al*, 1991.[526] Two US studies found no difference in the 15-30cm layer between organic and non-organic farming, but did not sample more deeply than this (Clark *et al*, 1998, and Fraser *et al*, 1988).

A way in which the studies could have over-represented the soil carbon benefit of organic farming is if any of the organic systems were using **external organic matter inputs**, like manure. In such cases it then has to be asked how much of the difference was simply due to the 'import' of extra carbon from the non-organic farming sector. This question is examined in detail in section 9.6. While this is an issue in some cases, an interesting finding from this review is that organic farming appears to produce similar soil carbon differences *whether or not* it is using external inputs. In the US, there is little difference between organic systems that use 'manure & legume' based systems - which may be relying on external inputs - and 'legume-only' systems, which it can be fairly certain are not relying on external organic inputs (see results of the Rodale Institute trial, and the Marriott & Wander trial survey). This indicates that the differences are explained by factors inherent in organic farming, rather than the use of external inputs. As regards this issue, it is also important to consider that the estimates of the soil carbon differences derived from this review are very conservative and likely to be under-estimating the impacts in other respects (length of time under organic management, topsoil depth, subsoil carbon content etc.)

To consider the possible effects of other factors, we carried out a rough analysis of the uncertainties in our findings of +28%/+20% higher soil carbon levels - see Box. This produced very wide ranges for the possible effects of organic farming, but still strongly supported the conclusion that organic farming produces higher soil carbon levels than non-organic farming, on cultivated soils. In this analysis, our findings of +28% and +20% average differences of for Northern Europe and all studies respectively, falls well within the range and in the lower end of the 'likely range'. These +28%/+20% findings and this analysis still exclude other important soil carbon benefit of organic farming – the larger area of permanent grassland and reduced tropical habitat destruction, as well as the possibly higher soil carbon levels of organically managed grasslands. Overall, we are therefore confident that our findings of +28%/+20% higher soil carbon levels for organic farming are reasonable and conservative. These figures are presented as current best estimates of the soil carbon benefits of organic farming based on the current available data, for use by policy makers and the industry.

As further data becomes available, these estimates are expected to be improved. As well as just gathering more data from more locations, future work should also be designed to address the areas of uncertainty. In particular, we recommend that future comparative research addresses:

- differences in topsoil depth
- differences in subsoil depth & content
- consideration of the contribution of carbon imported from the non-organic farming sector
- differences in carbon losses from destruction of tropical habitats
- differences in the area and soil carbon levels of permanent grassland (improved and rough grazing).

Box 9 Analysis of uncertainties

How accurate are these findings of +28%/+20% average higher soil carbon levels of organic farming likely to be? This analysis considers what effect taking account of factors that may have been omitted or mis-represented in the review could have on the estimates. Various factors are listed below, and the table shows estimates of the minimum and maximum effect they could have on the +28/+20% figures for Northern Europe (N.E.) and all studies reviewed (All), respectively. For instance, if '+5' is indicated, this means we consider that the factor could increase the +28% figure by 5%, to +33% higher soil carbon levels than non-organic farming. The estimates were informed by available information – see notes.

The +28/+20% average findings could be under-estimates:

1. If, as the land was only a limited period under organic management (an estimated15/12 years), this means that the organic farms are still building soil carbon and would have a higher level after, say, 20 years and, an even higher long-term difference when the land nears near equilibrium state, say at 100 years (no. 8 in table). The lower estimates addresses the possibility that many organic farms in the surveys had been farming extensively for long before they had converted (this is likely in the UK) and, over 100 years, the lack of very long-term comparative data and the possibility of a reduced carbon sequestration potential in future climatic conditions.
2. If, for N.Europe, of the 38 comparisons, the use of exactly the same rotations with a ley in 6 comparisons, plus another 3 with similar rotations/systems, has under-represented the differences.
3. If organic farming also produces greater average topsoil depth (and which is not all offset by lower soil density): NE – assume no effect (insufficient evidence available).
4. If organic farming produces a higher average carbon content in the subsoil and lower soil layers.

The +28/+20% average findings could be over-estimates:

5. If some organic farms are 'importing' carbon from non-organic farms (e.g. manure or straw).

The +28/+20% average findings could be over-estimates:

6. If there has been positive or negative development of organic or non-organic farming, since these studies were carried out (e.g. for non-organic farming in UK, straw incorporation, lower inorganic fertiliser use, further reduction in mixed farming, or increase in the area of maize).
7. If the review did not include a representative proportion of cultivated organic soil types, and the effect on these soils are more or less than for mineral soils.

Assumed addition /reduction to the +28% /+20% higher soil C level of organic farming.	1. Over 20 years	2. Rotation	3. Topsoil depth	4. Subsoil	5. C imports	6. Development	7. Organic soils	**TOTAL over 20 years**	8. Over 100 years
N.E.+28% +*minimum*	+5	+2	-	+0	-15	-10	-10	**0%**	+5
+28%+*maximum*	+10	+4	-	+30	0	+10	+10	**+92%**	+36
All +20% +*minimum*	+5	-	+5	+0	-10	-10	- 5	**+5%**	+5
+20% +*maximum*	+15	-	+15	+30	0	+10	+ 5	**+95%**	+31

Summing the low and high ends of these ranges, gives a maximum possible range for Northern Europe of: 0 to +92% over 20 yrs (and +5% to +128% long-term). We therefore suggest a likely range of: +18 to + 74% over 20 years (+/-30% of the range around the mid-point of +46%). And for all studies of standard organic farming: 5 to +95% over 20 yrs (and +10% to +126% long-term). We therefore suggest a likely range of +23 to +77% over 20 years (+/- 30% around the mid-point of 50%).

Explanatory notes of the calculations for the analysis of uncertainties

1. Over 20 years: For the maximum estimates, the increase was assumed to be linear. So, for Northern Europe, if +28% was produced in 15 years of organic management, then 20/15 x +28% = +37% would be achieved after 20 years, i.e. an additional +9% on top of the +28%. On this basis, we suggest a minimum-maximum range of +5% to +10%. Similarly, for all regions studied, if +20% is produced in 12 years, then 20/12 x +20% = +33% would be achieved in 20 years, i.e. an additional +13%. So, a range of +5% to +15% is assumed. This also allows for some inaccuracy in our estimate of 15 and 12 years as the average period of organic management in the studies reviewed.

2. Use of similar/same rotations: if the difference was underestimated by an assumed average 30% in these 9 cases (of 38 total comparisons), then the actual comparative effect would be greater by 30/70 x 9/38 x +28% = +2.8%. So, a range of +2% to +4% is assumed. Also, the Armstrong Brown *et al*, 2000, survey was mostly outside the main East of England arable region, so may well have over-represented the proportion of mixed farms in the UK non-organic sector, which would make its findings under-estimates – this is not considered.

3. Topsoil depth: The data from the three US studies of standard organic farming that measured topsoil depth was used. It was assumed that part of the increase in topsoil depth was simply due to a lower bulk density (first 3-4% in the case of Liebig & Doran, 1999). For the lower estimates, it was assumed that the remaining extra topsoil was replacing subsoil with a C content of half the topsoil; for the upper estimate, it was assumed that the remaining increase in topsoil was all additional soil. So, for the three results in Liebig & Doran, the greater topsoil depth was estimated to increase the comparative soil C level by an extra: +20 to +40%; +2 to +5%; + 2 to +5%. For the three results in Gardner & Clancy, the difference in topsoil depth was estimated to add +1% to +2%, on average. For Reganold, 1987, the extra 16cm was assumed to add from +20% to +40%. Summing these, gives from +6.7% to +13.7%. So, a range of +5% to +15% was assumed.

4. Subsoil: in the UK, the 30-70cm layer of cultivated soils contains 37% of the total carbon in the top1m (see Chapter 2). However, the +28%/+20% estimates are based on the top 18/19cm on average, so at least 47% of the soil carbon store is excluded in these estimates, i.e. the increases could be double if the lower soil layers are included and the increases are similar in size to the topsoil, which is roughly in line with the studies to have looked at the lower layers. So, a conservative minimum-maximum range of 0-30% is assumed over 20 years.

5. C imports: For N.Europe the 'minimum' estimate is informed by the results of the Swedish study Kirchmann *et al*, 2007, which estimated that if C imports from other farms were excluded, then the long-term C benefit of organic farming fell from an increase of +58% to +25%, i.e. a reduction of 56%. 56% x +28% = +15.7%, i.e. a reduction of 12% on the +28%. So, a minimum estimate of -15% was assumed. However, it seems unlikely that in practice, an organic farmer that was using carbon imports from another farm would not adjust if this was no longer an option; for instance, they might replace the carbon from imported manure/straw by growing more cover crops, using paper waste etc. So, for both N.Europe and all studies, the 'maximum' estimate (0%) is informed by two US studies which found that different organic farming systems have almost the same soil carbon levels: Marriott & Wander (the 3 'legume-based' organic farming systems were measured to have 2% higher soil carbon levels on average than the 6 'manure & legume' based organic farming systems, implying that the possible use of imported manure/straw by the latter had no positive effect compared to the alternative organic system) and the Rodale Institute FST trial (which found that the legume-based system had 4% lower soil C levels than the 'manure & legume' based system; a non-statistically significant difference).

6. Development of organic or non-organic farming – educated guess of +10 to –10%.

7. Organic soils - 20% of Europe's (EU27) soil carbon store is in peaty soils, the rest in mineral soils. About 16% of Europe's peatland area is in agricultural use (grassland & cropland).[527] Educated guess of +10 to –10%.

8. Over 100 years: Normally half of the total carbon that would be sequestered over 100 years is sequestered in the first 20 yrs in temperate regions.[528] So, for N. Europe: if organic farming produces +37% in 20 years, it can be assumed it produces 2 x +37% = + 74% as the maximum in 100 years, i.e. an additional +46% on the +28%, or an extra +36% over the estimate for 20 years. So, a minimum-maximum range of +5% to +36% is assumed. All studies reviewed: if organic farming produces +33% in 20 years, then it produces 2 x +33% = + 66% as the maximum estimate in 100 years, i.e. an additional +46% on our +20% finding, or an extra + 31% over the estimate for 20 years. So, a minimum-maximum range of +5% to +46% is assumed. These are conservative, as they do not consider increases in the topsoil depth and lower soil layers over 100 years.

7. Main factors in organic farming that increase soil carbon levels

> *"Organic agriculture can achieve high carbon gains through the use of green and animal manures, soil fertility-conserving crop rotations with intercropping and covering cropping, as well as by using composting techniques."* PICCMAT Consortium (of EU soil & agricultural scientists), June 2008.[529]

Main factors in organic farming systems

Organic farming derives its fertility from a healthy, living soil with high humus levels. Inorganic fertilisers are prohibited and the success of the system is based on good soil management to maintain, and ideally progressively enhance, soil humus and living organism levels.[530] Organic farming therefore involves many practices that protect and build up soil carbon levels[531], including ones: that promote the overall carbon input to the soil, that increase the supply of more resistant organic matter inputs, that promote soil aggregation and the retention of carbon in the soil, and activities which help protect the soil from erosion.

The various soil processes that determine the accumulation of soil carbon are complex and still incompletely understood. Based on research and understanding so far, the main aspects and practices of organic farming which maintain and build up soil carbon are these:

7.1 Dedicated soil fertility-building stages & grass/clover leys

Unlike most non-organic farming, organic farming normally involves regular periods dedicated to building soil fertility by increasing soil organic matter levels. In the UK and much of Europe, this is through the use of 'mixed' crop and livestock systems that are based on alternating cropping and grass/clover 'ley' periods in a 4-8 year crop rotation.[532] During the grass/clover ley stage of an organic rotation, which is from 1 year in length (in the fens) to 4 years, organic matter is produced by the growth of the grass and clover, which is then afterwards incorporated into the soil by ploughing. (The ley stage is also the main period of the rotation during which nitrogen is biologically fixed). The grass growth, including of the root systems, is also promoted by grazing with livestock, or by cutting for hay or silage production.[533] There are also some stockless organic arable and horticultural systems in the UK, which use grass/clover leys (or other long-term green manure crops) for building soil organic matter, but without livestock grazing.

Long-term UK trials show that grass leys have positive effects on cultivated land. For example, after 36 years, an arable-ley system comprising a three-year grass ley in a six-year crop rotation produced an 18% higher topsoil carbon level than a six-year rotation of five years arable cropping and one year grass for hay (Rothamsted 'ley-arable experiment', 1949-2002, soil with 25% clay content). In another study, after 33 years, a three-year grazed grass-clover ley in a five year rotation produced a 40% higher topsoil carbon level than continuous arable cropping (Woburn 'ley-arable experiment', 1938+, 12% clay soil).[534] The accumulated soil carbon can also last a fairly long time: the half-life (length of time for half to decompose) of the soil carbon sequestered from ryegrass residues has been reported to be about 25 years.[535] The survey of several UK organic farms by Shepherd *et al*, 2002, confirmed the importance of mixed (rotational arable/grass) farming systems for higher soil carbon storage: it found that the 19 mixed organic farms (which account for the majority of organic cultivated land in the UK) had 39% higher topsoil carbon levels than the 4 organic stockless farms (2.5% vs. 1.8% SOC, 0-20cm).

As well as using grass, organic farmers include clover in their grass leys, which is not so common in the non-organic sector. The clover replaces the role of N fertiliser in providing N inputs to the soil which promotes the productivity of the grassland and can thereby increase the organic matter inputs and promote soil carbon storage.[536] In addition, however, grass and clover have many specific features that promote soil carbon accumulation. These are plant types that naturally contribute large amounts of organic matter to the soil.[537] And, importantly, because grass has a high 'root-to-shoot' biomass ratio (as an adaptation to livestock grazing[538]), the organic matter is particularly in the form of the root systems, meaning the soil carbon supply should be of a more stable form.[539] For example, while roots contribute typically only 24-31% of the non-yield biomass of cereal crops, it is over 50% in grasslands – see Table 4 in Point 6. Grasslands have high root densities and soil carbon levels in the top layer of mineral soils.

Also, the organic matter may be deposited at deeper levels by grass than other agricultural plants (though our information is inconsistent here[540]), where the soil carbon store is even more stable.

The biochemical make-up of grass is also important: the resistant carbon-containing root compound suberin has been found to be a major contributor to soil carbon levels in grasslands.[541] Additionally, both grass and clover have higher levels of the resistant compound lignin than arable crops.[542] Compared to arable crops, grass and clover are also much more effective at promoting soil aggregation[543], allowing a portion of the soil carbon to be protected from degradation. The reason may be the larger root systems and continuous presence of the grass plants on the land, which means there is a larger and more continuous supply of carbon in the root zone (such as, in the root exudates). This promotes microbial levels and means there is a greater and more continuous production of the polysaccharides gums that cause aggregation of the soil mineral particles.[544] Grass and clover are also plants that particularly associate with mycorrhizal fungi, the hyphae of which also bind the soil particles into aggregates.[545] Grass roots also produce abundant fine root hairs which grow into the soil aggregates, depositing organic matter inside, where the carbon will last longer.[546] In this way, temporary grass leys and clover leys[547] provide major soil carbon benefits for cultivated soils in mixed farming systems.

7.2 Regular additions of animal manures

Other organic matter is regularly introduced in organic farming by additions of animal manure, green manure crops, and occasionally brought-in non-agricultural organic waste. The use of animal manure does not increase the overall amount of carbon supplied by organic farming (as the carbon derives from the plants eaten by the animals) but manure has a different biochemistry to plant matter and improves soil aggregation and microbial levels, improving the overall accumulation of soil carbon in farming.

Animal manure is used much more widely in organic farming, with more applied on the cultivated land than in non-organic systems. Organic farms are typically mixed farms, so manure is deposited by the livestock at each grass ley stage of the crop rotation, as well as on permanent grazed grassland. Additional farmyard manure (FYM) is available from the livestock housing and spread by organic farmers on the grass leys and the cultivated land. The rate of application varies considerably, but we estimate that UK organic farmers typically apply about 10-15t of FYM once every three years. Some organic farmers, however, use more: many organic dairy farmers spread FYM every year on the pastures close to the farmhouse which they are cutting for silage. Higher rates might also be spread on some organic horticultural land. The maximum application rate allowed under the organic standards is 28t/year.[548]

Being mostly mixed farming systems, organic arable farmers generally have their own source of FYM, which is an important resource that is used strategically to promote the whole farm's fertility. Manure does not have the same role in the non-organic sector because of: (i) the use of inorganic fertiliser, (ii) the specialisation of the industry into separate arable and livestock sectors, and (iii) the prohibition on using manure on much (maybe most) non-organic horticultural land (see Section 5.2). The non-organic farming sector almost certainly produces a larger amount of manure per hectare of grassland (having higher stocking rates and more indoor housing) but, including the greater area used for grain feed production, the amounts produced per ha of all farmland may be similar. Crucially, however, the manure of non-organic cattle farmers is mostly applied on permanent grassland and little reaches the cultivated land.

Animal manures are not simply recycled plant carbon. The grazing of grass and deposition of manure is part of the natural carbon cycle of grasslands, and this may assist the ability of grasslands to stabilise humus and produce high soil carbon levels. Manure is a different biochemical product to grass leaves and stems. Also, if grass leaves have similar effects to the above-ground parts of other plants then it would be relatively poor at forming stable humus[549], compared to the roots of grass and other organic matter types.

It is well established that the regular spreading of farmyard manure is effective at increasing soil carbon levels.[550] Having passed the digestive tract, manure is enriched with compounds that are resistant to microbial degradation: for example, the lignin content of FYM is 25%[551], compared to only 6.2% for ryegrass leaves and stems[552]. In total, about half of the organic matter in FYM is considered to be resistant to decomposition and about 2% is mummified organic matter.[553] FYM also binds soil particles and improves soil aggregate stability[554], helping soil carbon levels to rise (this quality is more effective in clay soils, which are more conducive to aggregation, than sandy soils). This is partially because manure greatly stimulates soil microbial levels (through its physical effects on the soil and by providing a good nutrient source for soil micro organisms[555]), which is important for promoting soil aggregation (see point 7). Animal manure also promotes earthworm activity in cultivated soils[556], which can in turn improve aggregate stability.[557]

A Defra review of UK studies found that cattle FYM increases soil carbon levels by an average of about 15kgC/ha/yr per tonne (freshweight).[558] This is around 75kgC/ha/yr for a 5t/ha/yr application rate. Also, an average of 23% of the carbon in the FYM is converted to soil carbon.[559] These studies might well have under-estimated the typical conversion rate of FYM in the UK, however[560], and the rate for organic farming might possibly also be different (maybe higher) due to the different soil conditions. Presumably a similar relatively high carbon conversion rate applies to fresh manure that is deposited by grazing livestock. For farmyard manure collected from the livestock housing, however, most is stored before being applied and half the carbon initially present can be lost over this time (e.g. a loss of 58% in four months of storage of organic FYM in one study).[561] Once this is accounted for, the percentage of the starting level of carbon in fresh FYM that is converted to soil carbon is, after storage and application, about 10%.[562]

The soil carbon effects of FYM appear to be very long-lasting. In a long-term UK trial on clay soil, almost half the extra SOM that had accumulated from just 20 years of FYM application still remained 130 years after the applications had stopped.[563] This indicates that on clay soils, FYM produces SOM that is very resistant to microbial decomposition.[564] On a sandy loam, the half-life of accumulated SOM from FYM application was only 20 years.[565] Though much less, this is still positive as it is normally assumed that soil carbon losses occur more quickly than this.[566] Additionally, manure promotes the soil's trace mineral supply, which helps the growth of grass and crops and this may increase the overall soil carbon input.

The IPCC guidelines for estimating soil carbon changes attribute the highest soil carbon level for arable land if it is regularly receiving manure: according to the default factors, manure use is estimated to produce a 30% higher soil carbon level than any other positive management practice.[567]

As well as greater use on cultivated land, the use of manure in organic farming offers a few additional potential benefits for soil carbon. Organic manure seems to have a higher carbon content than non-organic manure, 22% more per tonne according to one UK study, though the difference reduces somewhat when the manure/FYM is stored (to 5-18% more).[568] Another benefit is the greater use of outdoor grazing in organic livestock systems, than in the non-organic farming sector where more grass is cut for silage to feed housed livestock. (A study by Newcastle University, for example, found that, grazing provides around twice as much food for dairy cattle on organic farms than on non-organic farms.[569]) This could be very beneficial as directly deposited manure has up to twice as high a carbon content as stored manure (about half the carbon content is lost over four months of storage).[570] Also, manure from the housed livestock in the non-organic sector may not be spread as widely and evenly over the farm as the manure (both deposited and spread) is in organic farming, as manure is much less of an important nutrient resource for a non-organic farm so convenience will be more of a factor in where it is applied.

Additionally, a long-term UK trial (the 33-year 'Ley-arable experiment' at Woburn) found that the positive effects of FYM were greater in an arable-ley farming system then in a continuously cropped system, suggesting a possible further soil carbon advantage for organic farming. In this trial, the regular use of FYM at 38t/ha/yr every five years (mean of 7.5t/ha/yr) produced an additional 18% increase in the topsoil carbon level of plots in an arable-ley rotation, on top of the increase produced by the ley, while it just produced a stable soil carbon level and avoided carbon losses on continuously cropped plots. In total, this gave around 45% higher soil carbon level after 33 years from the use of grazed grass leys plus FYM application, than a continuously cropped system without either grass ley or FYM use.[571] This could be because manure has been found to have greater effects on grass than on arable land: UK studies of the application of manure (cattle slurry and broiler litter) found that 32-39% of the carbon was retained in the topsoil, half as much again as the studies of arable soils found (23%).[572] Ideally, the effects of FYM would be tested in organic farming conditions to confirm and evaluate all these effects.

7.3 Animal manure more in FYM form, than slurry

Another advantage of organic systems is that solid manure forms a larger proportion of the animal excreta produced than in the non-organic sector, where more is in the form of liquid slurry which is typical of industrial livestock systems. This is because organic livestock systems are much more likely to use straw-based housing. Straw bedding produces farmyard manure, a drier, denser manure product than slurry, and it appears to be much better for building soil humus. In the organic dairy sector, although many farmers are using slatted floors, many have cubicle housing for milking cows with straw bedding or sand, and straw yards for dry cows.[573] In the beef sector, while some non-organic farmers are using indoor slatted-floor rearing systems[574], few organic farmers are and straw or wood shavings are used instead.

Slurry is not associated with the same positive effects of solid (farmyard) manure. For example, in contrast to the large increases in topsoil carbon levels from long-term FYM application (35t/ha/yr or more) in the trials at Rothamsted and Woburn in the UK[575], there was a decline in topsoil carbon levels with the use of 25t/ha/yr of dairy slurry in the long-term trial at Askov in Denmark. The researchers of the Danish trial commented that, "well managed, straw-rich FYM may be more beneficial to SOM build-up than slurry that is low in bedding materials and stored anaerobically."[576] And, the 10-12-year national Danish arable soil survey found that land receiving cattle manure was gaining an impressive 900kgC/ha/yr (over 0-50cm depth), while land receiving pig manure (mainly slurry) was losing the most of all soils, -380kgC/ha/yr. The researchers stated, "It seems that manure from pigs (mainly slurry) was not as efficient as cattle manure in increasing soil C storage."[577] In a Danish modelling study, the researchers concluded that, "The use of farmyard manure ("straw-manure") as opposed to slurry caused a significant increase in SOM content."[578] The researchers of an 18-year Swedish study of organic and non-organic farming (Kirchman *et al*, 2007) also considered that solid manure represents a "more stable carbon source" and "the use of solid instead of liquid manure … would increase SOC contents."

FYM and slurry are different products. FYM is typically 25% dry matter and slurry just 6%.[579] The lignin level of FYM (standard level 25%) is much higher than that of slurry (14.5%).[580] FYM also has a higher C:N ratio, ranging from 13:1[581] to 30:1[582] [583], compared to 8:1 to 13:1 for slurry[584] (close to the C:N ratio of SOM at typically 10:1[585]). Unlike the negative effects of a high C:N ratio for other organic residues, in a study of slurries of different C:N ratios, the soil organic carbon level, "appeared to be substantially higher in equilibrium state" for the slurry with the highest C:N ratio.[586]

Likewise, non-organic farms are also more likely to use poultry manure which is less likely to contribute to soil carbon increases since it is rapidly mineralised[587], compared to the more slowly decomposing organic matter sources of solid ruminant manures, legumes and composts used by organic farmers.[588]

7.4 Green manure crops: adding biomass, greater vegetation cover & use of legumes

'Green manure' crops, such as winter cover crops, are also very important in organic farming[589] and are noted for increasing soil carbon levels[590]. These plants are grown and ploughed into the soil without harvesting, specifically to build soil fertility. In organic mixed farming systems, as well as the fertility-building grass/clover ley (effectively a long term 'green manure' crop), green manure crops are also often grown for short periods of a few months in the spare time between the main crops, such as over winter.

Green manure plants include leguminous plants, such as vetches, that naturally fix nitrogen, as well as, like all plants, fixing carbon. They also include so-called 'lifters', bulky or deep-rooting plants that take up and store nitrogen and carbon as they grow. While the plants grow and when the plants are later ploughed into the soil and the tissues decompose, they add additional organic matter to the soil and improve soil aggregation (and also release the fixed nitrogen for the next crop).[591] In stockless organic farming systems, where livestock are not grazed in the fertility-building ley part of the rotation, then N-fixing legumes are used for the main ley (such as, red clover or lucerne[592]). In continuous cropping stockless organic systems, such as those used in North America, short-term green manure crops replace the long-term leys of UK systems (since soya, which is a legume, can be grown as an N-fixing main crop).

The inclusion of green manure crops in the cropping season raises the soil carbon level of arable land. In the US Rodale trial, the use of green manure crops (legumes and cereal rye) in the organic arable system, produced a 15% increase in soil carbon after 21 years, compared just to an 8.6% increase in the inorganically-fertilised non-organic system which relied just on arable crop residues. (The level of above-ground soil carbon input was the same in both systems; see Section 6.1). In the UK, a (non-organic farming) trial found that an annual green manure crop produced a 14% higher soil carbon level after just six years on continuous arable land, than the use of inorganic fertiliser, and 35% of the carbon from the green manure crop was retained in the soil.[593] However, as that the soil carbon retention rates in this trial for FYM and straw were double the average rates found by a Defra review[594], (unless those are underestimates[595]) a more typical UK level might perhaps be closer to half this, i.e. about 17%.

Green manure crops provide several different benefits for soil carbon. They supply additional soil carbon input.[596] In addition, they appear to have a higher soil carbon conversion rate than arable crops. This is likely to be due to the lower C:N ratio of legumes than arable crop residues and a greater effectiveness in promoting soil aggregation. The amount of humus (stable soil carbon) that is formed is related to the C:N ratio of the crop residue.[597] Most fresh plant materials have around the same carbon content (40%) but different N levels.[598] Unlike arable crop straw, legumes, being N-rich, have C:N ratios that are generally lower than the 'break-even' level of about 32:1[599] that appears to be needed for a high soil carbon retention rate. The C:N ratios reported for legumes range between 13:1[600] and 32:1[601]. There is a linkage between N levels and soil carbon cycling[602] due to the fact that decomposing microbes need both C and N as a food source, and the decomposition of plants involves a reduction in the C:N ratio from that of the plant to that of SOM (C:N of about 10:1[603]) and the microbial biomass[604] (C:N of 8:1). The difference is accounted for by the loss of carbon as CO_2 due to microbial respiration. Legumes provide sufficient N levels for the microbes to efficiently decompose the residues, so that not too much carbon is lost by respiration.[605]

Green manure crops also promote soil aggregation. This has been attributed to the promotion of fungal mycorrhizal levels and perhaps also to the different microbial populations that these plants support (see point 7).[606] There seem to be two reasons for this. The use of green manure crops provides a more continuous plant host presence over the year for soil fungi, while in non-organic arable farming, the soil is often bare for significant periods (especially over winter).[607] In addition, leguminous green manure crops have been found to be more effective at promoting soil aggregation than arable crops, such as wheat, barley and maize (indeed some studies found that arable crops decrease aggregate stability)[608]. This is probably because the use of legumes for soil fertility often increases soil microbial levels (bacteria and fungi), which is considered to be due to the greater below-ground supply of nutrients for soil microorganisms than surface-applied inorganic fertilisers.[609] As explained in Chapter 2, soil aggregation protects SOM from decomposing bacteria, assisting soil carbon retention and accumulation.

Green manure crops are not, however, as good as grass for producing aggregate stability.[610] It has been noted that only have a short-term effect on aggregate stability after they are ploughed-in, as the level of fungal hyphae and polysaccharide production declines soon after incorporation.[611] (This may be less true of organic systems than non-organic systems, as the general conditions in organic farming are more conducive to maintaining high levels of living soil organisms).

The reliance on leguminous plants for fertility in organic farming (such as, clover in the UK), rather than inorganic fertiliser, therefore appears to be a significant advantage of organic farming over non-organic farming, for soil carbon levels. The use of additional short-term green manure crops (over and above the grass/clover ley period) is not, however, as common as it probably should be in the organic sector and this is an area with much more potential. We estimate that perhaps only around a third of UK organic farmers are growing short-term green manure crops, although this compares to virtually no non-organic farmers doing so.[612] In the US, surveys by the Rodale Institute suggest that about 75% of organic farmers are using cover crops, compared to only about 2% of non-organic farmers.[613]

7.5 Straw management

In current industrial arable systems, based on continuous cropping and inorganic fertiliser use, arable crop residues (root, stubble and straw) are often the only available source and form of soil carbon input.[614] More use of straw is not an option for increasing the low soil carbon levels of cultivated land, as most large arable farmers are already incorporating their straw in the UK. What is significant, however, is that the application of straw is a relatively poor way of converting plant carbon into soil carbon. While the incorporation of cereal straw usually produces slightly higher soil carbon levels than if it is not applied (though not always), straw stands out for having a much lower rate of soil carbon production per unit of carbon than other agricultural organic materials. This situation contrasts with organic farming where there are several other sources and forms of organic matter, and straw is generally converted to and applied to the soil in a more effective form, as FYM or mushroom compost, rather than as straw.

Some aspects of organic farming affect the quantity of straw produced compared to non-organic farming. Organic farming promotes the level of straw and stubble produced, in relation to crop yield. As organic farmers do not use herbicides, they achieve some of their weed control through the nature of the crop growth. They tend to select taller strawed cereal varieties to shade out weeds, and varieties that branch sideways to cover the ground surface ('tiller') and so smother weeds before growing upwards, and they may use a higher seed sowing rate to increase the crop density. Organic farmers also do not use plant growth inhibitors, which are widely used in non-organic cereal farming to standardise the height of the crop for harvesting[615] and to reduce the risk of lodging which is increased with N fertiliser use[616]. Nevertheless, while the straw:grain ratio may be higher in organic farming, as non-organic farming produces much higher cereal yields than organic farming in Europe[617], the total amount of straw and crop stubble produced by organic farming may not be greater than agrochemical based systems.

In the UK, the amounts of straw produced by non-organic farming are about 3.5t/ha for wheat, 2.75t/ha for barley and 1.5t/ha for oilseed rape.[618] A recent review of English studies for Defra found that cereal straw incorporation usually produces a soil carbon increase (though not in all cases).[619] However, it is unlikely that any differences in the amount of straw produced between organic and non-organic farming are a major factor in the systems' soil carbon level differences as straw is probably contributing relatively little of the soil carbon in organic systems.

Studies constantly show that little of the carbon in straw is converted to soil carbon, 0 to 13% for studies in the UK[620] (which confirms farmers' perceptions[621]). According to the Defra review, the average 'biomass carbon to soil carbon' conversion rate of cereal straw in the UK is only 7%.[622] A similarly low conversion rate for arable crop residues/straw of around 5% has been found in North America, with many long-term studies having reported that cereal residues had no effect on soil carbon levels – see Box 10. This low carbon conversion rate of straw must therefore be one of the main reason why soil carbon levels in industrial arable systems are so low. (Note, these were not trials of organic systems, and it would be interesting to know if the carbon conversion rate of straw is any higher in organic farming.[623])

Based on current understanding, there appear to be two main reasons for this. Firstly, straw is the above-ground part of the plant, which is anyway considered to be relatively poor at forming stable soil carbon compared to root systems (see next point 6). Secondly, cereal straw has a very high C:N ratio of around 100:1 for wheat and barley straw and 60:1 for maize, oats and rye.[624] This is well above the 32:1 ratio that is the approximate limit for attaining the maximal rate of soil carbon conversion from plant matter. In effect, this means that straw provides insufficient nitrogen[625] for efficient microbial decomposition, and most of the carbon is lost by microbial respiration during the process of reducing the C:N ratio of the straw to that of SOM (c.10:1), or else carbon is lost from existing SOM being mineralised to supply the N.[626] [627] (See previous point on green manure crops for details.)

Given this, the different form in which the straw carbon is applied in organic farming is a benefit of organic (and mixed non-organic) systems. Large non-organic arable producers generally chop and leave the straw on the fields, while mixed non-organic farms usually bale and remove the straw for use on the farm as livestock bedding or animal feed, or for sale. Of the 7 million tonnes of wheat straw produced in the UK, about 40% is returned directly to the soil (straw and stubble burning has been illegal since 1993).[628] As only a small percentage of the carbon in this straw is being converted to soil carbon (about 7%), this means that there is a large loss of the soil carbon input in non-organic all-arable systems.

Box 10 Studies of arable crop residue to soil carbon conversion rates in North America

Arable crop residue carbon to SOC conversion rates range between 0% and 21% in North America, according to the following ten studies. If a rate of zero is assumed for the five studies which reported 'no effect' or a negative effect, including Soon, 1998, and for the Kong *et al* study, and a rate of 17% is used for Rasmussen & Collins, 1991, this gives an **average SOC conversion rate of 5.0%** for arable crop residues for these ten North American studies.

The following are cited in Kong *et al*, 2005[629]:

1. Horner *et al*, 1960 - a crop residue carbon to SOC conversion rate of **8.7%** for a continuous wheat system in Washington.
2. Rasmussen & Smiley, 1997 - a **14.8%** residue carbon to SOC conversion rate for a wheat-fallow system in Oregon.
3. Rasmussen & Collins, 1991 - a **14-21%** crop residue carbon to SOC conversion rate.
4. Kong *et al*, 2005 - a 7.6% crop residue to SOC conversion rate for 10 cropping systems in California, which includes the results of an organic system; the rate for the seven non-organic cropping systems (excluding the two 'control' systems which did not use any type of fertilisation) was effectively **zero** (0.36%) – see Chapter 6.

According to Rasse *et al*, 2005[630], "Several long-term studies [mostly of maize and wheat] have reported that SOC contents remained unchanged or were decreased by the addition of shoot residues to cropped soils as compared to the root contribution alone (Campbell *et al*, 1991; Clapp *et al*, 2000; Reicosky *et al*, 2002; Soon, 1998)":

5. Campbell *et al*, 1991 - 30 years of wheat straw restitution to soils **did not change** the carbon content of the soil in a trial in Canada.
6. Clapp *et al*, 2008 - a **400kgC/ha fall** in the SOC level from 13 years of maize shoot restitution in an unfertilised system, in Minnesota.
7. Reicosky *et al*, 2002 - a 30-year US experiment found that the restitution of maize stalks versus removal for silage, with low and high fertiliser use on continuous maize production, produced **"virtually unchanged"** SOC contents.
8. Soon, 1998.

Also:

9. Laford *et al*, 2009 - **"no difference"** in SOC levels between straw removal or retention after 50 years of a fallow/wheat/wheat rotation in Canada (fertiliser was used in one of the two cases of straw retention).[631]
10. Duiker & Lal, 1999 - a 7-year study found a **8-10%** wheat straw carbon to SOC conversion rate in Ohio, using varying residues application rates of 0-16t/ha/yr.[632]

Notes: (i) we have not checked these studies in detail and are not sure in each case if the conversion rates reported also reflects the SOC increase level, or if some existing SOC was mineralised in the process of producing these retention rates, in which case the net conversion rates would be lower than reported; and (ii) reports by researchers of a 'lack of difference' or 'no effect' are sometimes misleading, as researchers often report this when they find differences (even politically significant differences) that are not statistically significant (i.e. when they cannot be scientifically proven to be caused by the practice being tested, which could be because the difference was just a chance effect or because it was indeed caused by the practice but the study design did not enable this effect to be identified, such as due to using a low sample size).

In organic farming, the straw tends to be used for livestock bedding and thus converted to farmyard manure (FYM) before being applied. Alternatively, where organic arable farmers have access to this market, the straw is sold to mushroom producers (organic straw is very valuable for organic mushroom production[633]) and converted to compost. Under the terms of 'mushroom compost agreements', the compost is afterwards returned to the organic farmer[634], and applied to the land.

These two types of organic matter, FYM and compost, both increase soil carbon levels (see points 2 and 9) and, significantly, have much higher 'soil carbon conversion rates' than straw: 23% for FYM in the UK and around 50% for compost in the UK in the absence of inorganic N fertiliser (see points 2 and 11). This is presumably partially due to the much lower C:N ratios of FYM and compost (ranging from 13:1 to 30:1 for FYM, and 40:1[635] for mushroom compost), so they avoid the problems that straw faces in this department. Even after accounting for the carbon that is lost during the storage of FYM and the composting process, these materials still have higher overall biomass carbon to soil carbon conversion rates, of 10% and 40% respectively[636], compared to straw's 7%. Assuming this is right, this means fresh FYM is about 3 times as good, stored FYM 40% better, and compost around 5.7 times as good at producing soil carbon as using straw is directly, per unit of straw carbon.[637]

This difference in effectiveness is supported by the results of the couple of comparative farming trials where the soil carbon input levels were analysed (see Sections 6.2). In the US Rodale trial, the organic system which used manure and green manure crops (and no agrochemicals), produced a *three times* greater soil carbon level increase per unit of above-ground soil carbon input, than the non-organic system which relied just on the crop residues from continuous arable cropping (note, the green manure crops will also have contributed to the difference). Similarly, in the University of California trial, the organic system, which used composted manure and green manure crops (and no agrochemicals) produced an *eight times* greater SOC increase per unit of biomass carbon input than the equivalent non-organic system which was just relying on crop residues (in this case, maize and tomato, not just cereal residues).[638]

Thus, the different management of straw in organic farming means more carbon is converted to soil carbon for each tonne of straw produced than in non-organic farming (perhaps 1.4 to 4.5 times as much).

7.6 Greater, deeper root systems

A few aspects of organic farming increase the level of roots in the soil and also result in the roots extending more deeply into the soil, where less mineralisation[639] takes place. This may be an important contributor to the higher soil carbon levels of organic farming. Almost all of the comparative studies, which found a 20-30% higher level for organic farming, were just based on the soil carbon contents of the topsoil. Five studies, however, also found that organic farming is associated with greater topsoil depths, and five others found that the higher soil carbon levels of organic farming extend into the subsoil[640], where the soil's carbon content is lower (less carbon per kg of soil) but is much more stable.

Many researchers now suggest that root systems are the dominant influence on the soil carbon store.[641] As explained in Chapter 2, roots supply carbon both in their biomass and continuously in the form of root exudates[642], root hair turnover and root cell sloughing[643]. Also, the carbon derived from roots is over twice as stable as carbon from the above-ground parts of a plant.[644] For example, in the Rodale Institute trial of a US organic arable system, a study of the vetch cover crop[645] found that the roots comprised only 20% of the plant's biomass[646] and only 16% of the biomass carbon input to the soil when ploughed-in. However, five months later, all but 13% of the shoot-derived carbon had been mineralised, but 49% of root-derived carbon was still in the soil and forming just over half of the soil carbon derived from the vetch.[647] Moreover, twice as much root- as shoot-derived carbon was in the more stable aggregate fraction of the soil carbon, where the humus is encapsulated in mineral particles and protected from degradation.[648]

Roots are also a key contributor of the carbon in the subsoil, where the soil carbon is much more stable. There is a large increase in the age of the carbon with soil depth[649], with a mean age of several thousand years for humus at 60-80cm.[650] Therefore, any increase in the subsoil carbon store is very significant for long-term carbon sequestration. In the topsoil, most fresh organic matter is rapidly mineralised, but a portion (including of the root exudates) bonds to the soil's mineral particles which then inhibits their degradation. It is suggested that this process may be much more significant in the subsoil where the soil carbon levels are low and there are more mineral particles available for bonding.[651]

This greater stability and depth of root carbon means roots may make a larger contribution to the soil carbon store than above-ground plant biomass.[652] This could be particularly the case in organic systems.

Organic farming tends to produce larger, deeper root systems. One study (Haas & Köpke, 1994) estimated that organic farming produces the same levels of biomass carbon in total (including harvested crops, cover crops, and a small amount from weeds), but it increases the root biomass to above-ground biomass ratio substantially. The study data suggests that (with an estimated 62% greater level of crop root biomass in the organic system, plus smaller contributions from cover crops and weeds), roots contribute 27% of the biomass carbon of crop plants in organic farming, but just 16% in non-organic systems.[653] This suggests organic farming provides 72% more root biomass carbon per hectare than non-organic farming.[654] Moreover, this study did not include the large root carbon input supplied by the grass leys in mixed organic farming systems or the continuous root carbon supply which may be as much again as the carbon inputs from root biomass[655], which would increase the differences still further.

The biggest reason for the greater amount of roots in European mixed organic farming is probably the regular use of grass ley periods which, as explained, produce much more root biomass than arable crops – see also table (note, the continuous root carbon supply is excluded from this data, so the total root carbon supply from each crop may be around double the figures shown). Also, organic farmers usually include deeper-rooting species in their grass.[656] In contrast to non-organically managed grassland, which usually involves grass 'mono-cropping' with just ryegrasses and additions of N fertiliser, organic farmers usually sow a mixture of clover and grass and sometimes other species. Clover may increase the amount of grassland roots considerably, as indicated in the table. UK organic farmers commonly use white clover but often use red clover which is deeper rooting. Other deep-rooting species are often planted in organic grass mixtures and crop rotations as well, such as, chicory or lucerne in the UK. Chicory, for example, is reasonably common in organic sheep pasture and organic vegetable production.[657] In the US, organic farmers grow the deep-rooting legume alfalfa to feed dairy cattle, which has tap roots that can grow to 20 feet.[658] These plants deposit organic carbon into the subsoil.[659]

Root biomass carbon as a percentage of all plant biomass carbon inputs to the soil, by crop type

	Total non-yield biomass carbon, t/ha/yr	Above-ground crop residue carbon, t/ha/yr	Root biomass carbon, t/ha/yr	Root biomass C as a % of total	(Crop yield to which the data applies, t/ha/yr)
Grassland:					
• Grass-clover mix, 2nd year	4.07	0.95	**3.12**	77%	(7.83)
• Temporal grass mix, 2nd year	3.74	1.66	**2.08**	56%	(4.46)
Arable crops:					
• Winter wheat & straw	3.92	2.97	**0.95**	24%	(5.04)
• Winter barley & straw	3.08	2.13	**0.95**	31%	(4.99)
• Winter rape & straw	5.18	3.72	**1.46**	28%	(2.57)
• Silage maize	2.19	0.63	**1.56**	71%	(32.17)
• Maize (corn) & straw	4.44	3.36	**1.08**	24%	(5.75)
• Soya & straw	1.77	1.09	**0.68**	38%	(1.92)
• Potatoes	0.95	0.62	**0.33**	35%	(19.39)
• Sugar beet	0.38	0.18	**0.20**	53%	(49.95)
Legume:					
• Alfalfa, 2nd/3rd/4th year	2.97-3.28	1.03	**1.94-2.25**	65-69%	(10.83)

Table 4 showing mean total crop residue and root biomass carbon level for various crops. Derived from table in Annex II, Baritz *et al*, 2004, Task group 5 Land Use Practices and SOM[660]. Note, this data is presumably from non-organic farming systems, but the yield levels are lower than UK yields (14-58% less[661]) and also, for many crops, lower than organic yields in the UK and northern Europe[662], so this only *indicates* the comparative levels of carbon between the crop types (not absolute levels). Also, these figures exclude the continuous root carbon supply (exudates/root hair turnover/root cell sloughing) and therefore the full root carbon inputs may be around double the quantities shown.

Deep-rooting plants are important in organic farming for several reasons: they improve the soil quality (breaking up plough-pans[663] and make the soil friable to a deeper depth), they increase the trace mineral level of the pasture for the livestock, increase the soil's trace mineral supply for the rest of the crop rotation, and they improve the drought-resistance of the grass. Moreover, as they make the soil healthy and fertile to a deeper depth, having deeper-rooting plants in the grass ley period promotes deeper rooting by the subsequent arable crops in the rotation.

Anther reason for the deeper root systems is understood to be a consequence of not using inorganic fertiliser.[664] When inorganic fertilisers are used, the nutrients are concentrated in a shallow layer at the soil surface, so the crop root growth is also then shallow. In organic farming, the nutrients are distributed over a much deeper soil profile as they result from the decomposition of plant roots (from the grass ley and N-fixing plants) and ploughed-in organic matter. This means the crop roots generally grow more extensively.

Thirdly, many organic farmers also grow green manure crops between the main crops, increasing the total production of root carbon over the year by around 15%, according to one source [665] (see point 4).

Fourthly, weed levels are normally higher on organic farms, though this may be only a small contributor of root biomass carbon in many cases. For instance, in the comparison by Haas & Köpke, 1994, mentioned above, though weed levels were estimated to be five times greater in the organic than the non-organic system, the weed roots only contributed 2.4% of all the root biomass carbon produced by the organic farming system. On the other hand, in an 18-year Swedish trial of organic and non-organic faming, the weed biomass was "a significant component in the organic system," contributing an average of 1t/ha of dry matter (roots plus above-ground biomass), compared to the non-organic farming system, where the weed levels were "very low due to herbicide treatment." [666]

Additionally, the fact that organic farmers usually have a higher diversity of plant types in their grass leys[667] may help to increase overall biomass production[668] and thus the soil carbon supply, since each type occupies a different ecological niche which promotes overall productivity.

7.7 Higher level of living soil organisms

Organic farming promotes soil life. Many of the standards and practices have a positive effect. The Soil Association standards require that organic producers in general create conditions that are optimal for soil biological activity.[669] As a result, studies show that organic farming supports a greater abundance of organisms in cultivated soils, including more earthworms, mycorrhizal fungi and bacteria. Evidence is growing that this may be one of the main reasons for the higher soil carbon levels of organic farming.

The greater level of soil microorganisms does not itself account for the higher soil carbon levels of organic farming. Soil microbes commonly constitute only 1-2% of the soil carbon store in arable land.[670] But the activities of soil organisms are highly influential in the stabilisation of the soil carbon input, and thus the accumulation of soil carbon. Researchers have shown that there is a close positive association between soil microbial and soil carbon levels.[671] The polysaccharide gums produced by microorganisms[672] and the networks of hyphae of fungal mycorrhizae[673] bind the soil's mineral particles into aggregates, which then 'encapsulate' and protect humus against degradation[674]. The activity of earthworms also promotes soil aggregation.[675] Larger populations of earthworms (nature's ploughs) might also help distribute more soil carbon to the deeper layers (i.e. helping to explain the greater soil carbon in deeper layers found by at least five comparative studies of organic farming[676]), where the soil carbon is longer-lasting.

The mycorrhizal fungal level of the soil appears to be particularly important. Arbuscular mycorrhizal (AM) fungi have been shown to enhance soil aggregation[677] and recently a major portion of the soil carbon store (the insoluble humus, humin) has been identified as the glycoproteins produced by the hyphae of mycorrhizal fungi.[678] According to recent research into the biological mechanisms of soil carbon sequestration by the US Government and the Rodale Institute[679], the greater ability of organic farming to convert organic matter into stabilised soil carbon is especially related to the higher levels of fungal mycorrhizae and their ability to produce colloidal chemicals. The US researchers have also shown, "a strong relationship between the distribution of mycorrhizal fungi and carbon in the soil profile." [680]

Higher levels of mycorrhizal fungi are not just a by-product of organic practices, but are fundamental to the organic farming system. Rather than relying on the uptake of inorganic nutrients in the soil solution (the main crop nutrient supply mechanism when inorganic fertilisers are used), organic farming depends more on a different soil mechanism: the symbiotic relationship of crop plants with the naturally occurring arbuscular mycorrhizal (AM) fungi. The crop plants supply the fungi with sugars and in return receive an enhanced mineral and water uptake via the extensive hyphal network of the fungi, which act as extensions of the crop's own root system.[681]

This is important for the soil carbon store as, "the hyphal coating of mycorrhizal fungi is composed of a highly resistant glycoprotein, glomalin, that has been shown to accumulate in soils naturally becoming a significant portion of the total soil carbon reserve." [682] Glomalin has a low solubility and closely associates with clay particles, which means that it does not easily decompose and appears to have a strong influence in stabilising soil aggregation.[683] For example, it has been suggested that mycorrhizal fungi largely control the stabilisation of root-derived carbon in the soil.[684]

There are a large number of reasons for the higher levels and activity of living soil organisms in organic farming. It is probably due to the combined effects of:

- higher overall levels of soil organic matter inputs, including grass leys, which provide a food source to support soil organisms.[685] Hole *et al* (2005), for example, cite the addition of animal (and green) manures on organic farms as the principal factor, as they are an important food resource;
- the more continuous nature of the soil nutrient supply in organic farming. Specifically, the greater proportion of the time that the land is supporting plants (grass leys, more weeds, cover crops) means there is a more constant release of organic nutrients from plant roots, which is an important nutrient source and environment for soil microorganisms.[686] Root exudates feed soil microbes and most plants transfer organic nutrients to the symbiotic mycorrhizal fungi that closely associate with their roots[687].
- the more continuous host presence over the year for soil mycorrhizal fungi by the use of winter cover crops (in non-organic farming, the soil is often bare for significant periods);[688]
- in Europe, the regular use of grass leys in the organic crop rotation boosts soil mycorrhizal levels compared to continuously cropped soils;[689]
- the inclusion of legumes in the crop rotation increases soil microbial levels because they increase the below-ground supply of nutrients, compared to surface-applied NPK fertiliser;[690]
- the addition of manure which greatly stimulates soil microbial populations by its effect on the soil's physical characteristics and supply of readily available C and N;[691]
- greater diversity of plants grown in organic systems might promote soil microbial populations, as the different groups, such as bacteria or fungi, use different carbon sources as a nutrient source[692] and more plant diversity means a greater variety of such compounds[693];
- the non-use of fertilisers means organic crops are reliant on an active symbiotic relationship between roots and fungal mycorrhizae for nutrition, which might consequently be more active than in non-organic systems. In some conditions, inorganic N fertiliser can also reduce soil microbial populations and suppress their biological activity[694], and high levels can reduce earthworm populations.[695]
- the non-use of herbicides which have been found to suppress the activity of soil microbes responsible for N fixation and nitrification for 4-12 weeks[696] and can reduce total soil microbial populations[697];
- the prohibition of nearly all pesticides which provides a more favourable environment for living organisms. This minimises the harmful effects that these chemicals can have on non-target

organisms.[698] For example, earthworm populations can be negatively affected by certain pesticides[699];

- soil sterilisation methods, such as steam sterilisation, are prohibited for open organic fields;
- higher soil moisture levels, which can enhance the soil microbial level[700].

The evidence for higher levels of soil organisms in organic farming is summarised here.[701] At least nine of the comparative studies on soil carbon levels also measured soil microbial levels, almost all of which found higher levels with organic farming. The long-term Swiss FiBL trial found that the biodynamic system produced the highest microbial biomass, then the standard organic system, then the non-organic 'integrated' system, while the non-organic system receiving inorganic fertiliser had the lowest levels (all plots had the same crop rotation).[702] At end of the fourth crop rotation (1977-2005), the standard organic plots had a two-thirds higher soil microbial biomass than the integrated plots (40t/ha vs. 24t/ha).[703] As these had received the same amounts of manure/slurry but the integrated plots also received inorganic fertiliser and pesticides, this suggests that the agrochemicals had had a detrimental effect on the micro-organisms. Additionally, fungal mycorrhizal colonisation was 40% higher on the organic plots.[704]

A six-year Spanish trial, found a 117% higher soil microbial biomass on the organically managed plots (though no pesticides were used on the non-organic plots; Melero *et al*, 2006). An Italian study found a 70% higher soil microbial biomass in an organically managed field than an adjacent non-organically managed field (Marinari *et al*, 2007). A German study found 22% higher soil microbial levels on the organically than non-organically managed plots (using the same crop rotation; Friedel *et al,* 2000).

In an Australian trial of vegetable production, the organically managed plots had a 46% higher microbial biomass carbon level than the conventionally farmed plots (Wells *et al*, 2000).[705] A US study of five farm pairs, found a 44% greater soil microbial biomass on the organic fields than the non-organic fields[706], and microbial biomass carbon formed a higher proportion of the total soil organic carbon on the organic farms at four locations (Liebig & Doran, 1999). This study also found a higher level of earthworm activity on the organic farms.[707] A study of the rhizosphere (root zone)[708] of organic tomato plants on farms in California found that, although total bacterial and fungal abundances were similar, the organic rhizosphere soils had a greater microbial activity and greater abundance and diversity of actinomycetes (a group of bacteria that play an important role in the decomposition of organic matter and humus formation), than non-organic tomato plants (Drinkwater *et al*, 1995[709]). Some of the biodynamic farming studies have also reported higher earthworm levels: for example, a Dutch study found a 3.5-fold higher earthworm activity in the topsoil of a long-established biodynamic field than a non-organically farmed field (Pulleman *et al*, 2003).

US research in the late 1980s and early 1990s found that fungal mycorrhizae were much more abundant and active in organic than non-organic farming. Organically managed soils had far higher spore levels (up to 30 spores per 50cm^3 compared to 0-0.3 spores/50cm^3 in non-organically managed soils) and produced 2.5-10 times greater AM colonisation of plant roots.[710] Further research in 2006 and 2007 did not find such large differences[711], though the organic systems in the Rodale Institute trial had more AM propogules in the top 20cm of the soil than non-organic systems.[712] A seven-year trial in Nebraska found a 7.5% greater soil microbial biomass in the organic system over the 0-30cm soil layer than a continuous maize non-organic system (statistically significant), including higher levels of soil bacteria and fungi.[713] A comparative study of a biodynamic and non-organic vegetable field in New Zealand (Reganold, 1993) found a much higher number and mass of earthworms in the biodynamic fields: 175 earthworms per m^2 versus 21, and 86g/m^3 vs. 3.4g/m^3, which was attributed to the pesticide use on the non-organic farms.[714]

There is also information contained in the major review of comparative biodiversity studies of organic farming, Hole *et al*, 2005.[715] Five of ten studies on soil bacterial populations found higher levels on organic farms (the others found limited differences), and the three studies that reported on soil fungal levels found higher levels in organic arable fields than non-organic fields. Of 11 studies of earthworms on arable soils, seven found higher earthworm levels on organic than non-organic fields (three found no significant difference, one found lower levels). For example, Brown (1999) reported almost twice the abundance of earthworms and a higher species diversity in organic than non-organic fields.

7.8. Non-use of inorganic N fertiliser

The replacement of inorganic N fertiliser by biological N fertilisation methods in organic farming, avoids the negative knock-on effects of relying on inorganic fertiliser and also avoids any more direct effects. There is a lot of evidence that shows a general association between the use of N fertiliser and low soil carbon levels. Almost all arable land in the West is fertilised with inorganic N fertiliser but has low soil carbon levels. Several long-term trials in the UK and around the world[716] show that inorganic N fertiliser does not raise soil carbon levels (except minimally compared to totally unfertilised land[717]) and that levels remain low in the absence of positive soil management practices. In the Danish survey, which measured to 50cm depth, arable land receiving only inorganic fertiliser (and no organic residues) was losing 166kgC/ha/yr, contrary to the positive situation nationally.[718]

Previous considerations of the effects of N fertiliser have, in our view, been inadequate and potentially very misleading, as they have tended to consider the effects of inorganic N fertiliser use versus no N fertiliser use, or the effects of higher or lower N fertiliser applications, rather than comparing the alternative that is important from an organic farming perspective and the perspective of commercial agriculture, which is the use of inorganic N fertiliser versus the use of biological N fertilisation.

As argued in 4.1, the wide adoption of inorganic fertilisers led to the abandonment of a range of traditional land management practices which had previously maintained (to varying extents) the humus levels of cultivated land - such as, mixed farming systems with grass ley periods in the crop rotation and an on-farm supply of manure, and more complex crop rotations with legumes. Inorganic N fertiliser also contributed to the development of modern cereal varieties with semi-dwarf genes. This may be the largest overall impact of inorganic fertilisers on the soil carbon store.

But in addition, inorganic fertiliser has other indirect effects. The use of inorganic fertiliser tends to reduce the size and depth of crop root systems,[719] since the nutrients are then concentrated in a much shallower layer at the surface of the soil than in traditional and organic systems fertilised by decomposing plant roots and ploughed-in organic matter. Plant root growth is also promoted by conditions of soil N stress - Dutch researchers have therefore noted that soil carbon increases in grassland are actually lower when high rates of N fertiliser used, then when lower rates are used, due to the smaller root systems.[720]

There are also some suggestions from research that inorganic N fertiliser reduces the soil carbon sequestration rates that occur when organic matter is added to the soil, although it may also increase the rate in some situations, such as with very high application rates of organic materials or for applications of organic materials with high C:N ratios. The overall effect in commercial situations may be negative, but further research will be needed to confirm this.

A negative effect has been suggested by both US and recent UK research. Four UK trials on the effects of applying green waste compost to the soil found that the additional use of inorganic N fertiliser at standard rates was associated with a reduction in the average soil carbon sequestration rate by a third, compared to when compost alone was used.[721] The effect was inconsistent, however, with inorganic fertiliser being associated with a 55% reduction in the average sequestration rate for a compost application rate of 33t/ha/yr (freshweight), but with a 21% increase for a very high compost application rate of 50t/ha/yr.[722] However, as the sequestration rates per tonne of compost were generally lower at the higher compost application rate, the total average carbon sequestration achieved per hectare when N fertiliser was used with the higher compost rate was only equal to the result without N fertiliser at the lower compost application rate.[723] In other words, N fertiliser was not able to increase the maximum sequestration rate.

The negative effect of inorganic N fertiliser on the soil carbon gains from organic matter might be because in some conditions N fertiliser reduces microbial populations and suppresses their enzyme activity, which could then reduce the capacity of soils to aggregate and for soil carbon to accumulate. While many studies have found that the use of inorganic fertilisers does not have negative effects[724], depressive effects on soil microbial populations and their enzyme activity have been found to occur in some conditions, generally where the use is causing soil acidification and/or salt toxicity (Dick, 1992; Witter *et al*, 1993).[725]

Researchers at the University of Illinois have also claimed that intensive use of inorganic N fertilisers causes a direct reduction in soil carbon levels by increasing the rate of soil carbon degradation (Khan *et al*, 2007).[726] Continuous high inorganic fertiliser use in the oldest farming trial in the US resulted in a substantial decrease in soil carbon, of 12t/ha after 40 to 50 years, even though large amounts of plant biomass were being added to the soil. The researchers concluded that high levels of inorganic fertiliser promote the oxidation of soil organic matter and say this conclusion is supported by the results of numerous cropping trials in the US 'corn belt'. Other researchers have since challenged this claim[727], saying that some of the cases that Khan *et al* have cited in support of their claim do not actually indicate any negative effect of inorganic fertiliser. For instance, in the UK Broadbalk and Hoosfield trials – the longest continuous arable trials in the world, and where the crop stubble (but not the straw) was ploughed-in – the soil carbon levels on the NPK fertilised plots, though remaining very low, were nevertheless higher after 150 years than on the PK-only fertilised plots or the unfertilised plots.[728] We also note that, based on our review of the evidence, when the only soil carbon inputs are from arable crop residues, a decline in soil carbon levels (or no change from a low starting level) is not necessarily unexpected and could also be explained by the low soil carbon conversion rate of arable residues, not just by an effect of N fertiliser.

The positive effect of N fertiliser on carbon sequestration for the very high compost application rate, suggests that perhaps insufficient N levels were limiting the decomposition process for the high compost rates, and that in these conditions the extra N supply from the fertiliser outweighed any negative effects. Reay *et al* (2008) also recently reviewed evidence for the impact of N on soil organic carbon stocks, and found that the evidence is contradictory, with some studies suggesting that soil C may decrease under N enrichment, others suggesting no change, and others suggesting that soil C sinks may increase.[729]

Further research is needed to confirm if these indications about the effects of N fertiliser are true. This should be based on realistic organic matter application rates (50t/ha of compost seems very high[730]) and the effects of N fertiliser should be studied in comparison to *biologically N* fertilised systems, rather than in comparison to an absence of N fertilisation altogether which is not a relevant agricultural scenario. Establishing this is important: after all, if a higher soil carbon sequestration rate for organic matter additions normally applies in organic farming systems, this would then imply that the general ability of agriculture to sequester carbon is to some extent limited as long as there is widespread use of N fertiliser.

7.9 Grass versus grain feed for ruminant livestock – direct and indirect carbon impacts

The organic dairy and beef sector is grass-based and uses less grain feed than the non-organic cattle sector. Because ruminant livestock production is an important component of most UK organic farming, this provides a significant carbon benefit for organic farming as a whole, both in the UK and abroad.

UK livestock farmers buy 21-22 million t of animal feed each year[731], practically all of which is produced from arable crops (cereals, soya and oilseeds). The dairy sector accounts for the largest portion of this market – 40% in 2005 (followed by poultry – 37%, then pigs – 15%).[732] In other words, there is a large 'ghost' area of (low carbon) arable land supporting the UK's non-organic 'grassland' sector. In the organic sector, the temporary grass/clover leys in the crop rotation and the higher use of grass/less use of grain feed than in non-organic farming means that a greater proportion of farmland is kept as grassland rather than as arable land. In the UK, mixed organic farms typically have about 50% of grassland on the farm at any one time (25-40% on the few stockless arable organic farms). Thus, there is a better balance in organic farming, with a smaller area of low-carbon arable land and more higher-carbon grassland, than in non-organic farming. As much of the animal feed that supplies the UK livestock sector is produced abroad (soya and maize), this soil carbon benefit of organic farming extends abroad.[733]

Grassland normally has much higher soil carbon levels than arable land (see point 10). As well as the specific benefits of grass for soil carbon storage (point 1), compared to grass, grain crops have lower levels of lignin, smaller root systems in proportion to their total biomass, their production involves more land being bare of vegetation, and they tend to decrease soil aggregation.[734] If organically managed grassland also has higher levels of soil carbon than non-organic grassland (as three studies suggest[735]), than the soil carbon benefit of the greater proportion of grassland in organic farming is even greater. Organic farming reduces the amount of grain feed because the organic standards require that at least 60% of the diet of cattle and sheep is roughage. This means most of the diet is grass-based (i.e. fresh grazing, grass silage, or hay).[736] For example, research by Newcastle University found that, in summer, grazing provided the vast majority, around 84%, of food for dairy cows organic farms, compared to only 37% for non-organic dairy cows, and 34% of the diet of the non-organic cows was concentrate feed (silage was 29%).[737] (In winter, organic and non-organic dairy cattle diets are very similar.) Organic cereals and concentrates are also very expensive to buy[738], which probably further constrains their use by organic farmers. (Note, while this standard applies to all organic farming in Europe and similar standards exist in other countries, the exact diet of organic and non-organic cattle depends on the country.)

For pigs and poultry, which mainly eat grain and depend on arable land, it could be considered that there is conversely a soil carbon disbenefit with organic farming *if* the same levels of production are assumed. The higher soil carbon levels of organic arable production are a positive factor (the carbon sequestration after conversion to organic farming would initially offset some of the GHG emissions of organic chicken, pork and eggs). But organic pigs and poultry consume more grain than non-organic pigs and poultry: in free-range systems, pigs and poultry live longer and expend more metabolic energy than if they are raised in industrial indoor systems. The production of organic pigs and poultry therefore involves a larger area of arable land for each tonne of output. However, because of the prohibition on in-door factory farming systems in organic farming and the much greater cost of producing pigs and poultry in organic systems (using organic feed, slower growth rates etc.), widespread organic farming actually implies a large reduction in pig and poultry production[739] and thus in the amount of arable land used to produce feed for these sectors. An initial assessment by Reading University of the impact of widespread organic farming has suggested that the production of white meat would fall by around 70% in England and Wales.[740]

The other highly important dimension of the greatly reduced reliance on soya with organic farming is the reduced destruction of natural habitat in South America that is associated with soya imports (see Section 4.2). Organic farmers also use some imported soya for dairy, pig and poultry production (in addition to home-produced protein feed), but the carbon impacts are far less as less soya is used overall and the organic soya imported into the UK usually comes from South or Eastern Europe or China, not regions where major habitat clearance is occurring.[741] We do not yet have a figure for the likely reduction in these carbon losses with organic farming, but it may be substantial.

Additionally, there should be another major carbon benefit of organic livestock production. UK organic farming increases the domestic production of beef, which would help reverse the current completely unnecessary trend of increasing beef imports into the UK, which is contributing to the destruction of the Amazon (see Section 4.2). This is due to two factors. Firstly, UK organic arable production is based on mixed crop and livestock systems, so organic farming increases the overall production of ruminants. Secondly, organic farming improves the health and productive life of dairy cattle, which means that a greater proportion of dairy calves can be reared for beef instead of being needed as dairy cow replacements (in the UK, the average dairy replacement rate is once every three years[742], compared just once every 5 years for organic farming). Widespread organic farming in the UK would therefore increase the national beef supply substantially: according to a modelling study by Reading University, based on one scenario, widespread organic farming would result in a 68% increase in the UK's beef supply.[743] This would supply enough beef for the UK's own needs to bring an end to imports, and the excess could be exported to replace the production of 'unsustainable' beef in the Amazon that is currently supplying some other northern hemisphere markets, such as Russia, and which is a major cause of carbon losses.

(An rise in beef production would not, however, occur in all countries with widespread organic farming as organic systems are not based on mixed systems everywhere, non-organic farming is still based on mixed systems in some regions, and large amounts of beef in the Americas are being finished (fattened) in intensive grain-based feed-lot systems which would not be possible under organic farming.[744] The issue is just where global beef production should best take place and whether it should be by grass-based organic or more grain-based non-organic systems. The UK's climate is particularly well suited for grassland production and the per hectare yield difference between organic and non-organic farming in the UK is less much less for beef (c.15%), then for arable crops (around 33%[745]). So, for these reasons, and also the higher soil carbon stocks of grasslands, it makes sense to concentrate more on beef production in the UK. Overall, the organic movement advocates a reduction in red meat, by ending the current production based on grain-based systems and Amazon deforestation, to reduce the total GHG emissions of the beef sector.)

Along with most other soil carbon impacts, the soil carbon impacts of animal feed production are omitted from all Life Cycle Assessments of agriculture (e.g. Cranfield University's LCA study for Defra), as well as from the CALM farm carbon footprinting scheme and the Carbon Trust/BSI food carbon labelling scheme. The knock-on effects of dairy intensification on beef imports are also not yet being accounted for.

7.10 More permanent grass

The greater area of grass in organic farming includes higher average levels of permanent grass (on top of the much greater area of temporary grass that contributes to the higher soil carbon level of organically managed cultivated land).[746] This may provide a double soil carbon benefit. Firstly, permanent grassland has higher soil carbon levels than land in temporary grass leys. For example, a Dutch study found that permanent pasture contained three times as much soil carbon as non-organically managed arable-ley land and almost twice as much as organically managed arable-ley land.[747]

The official 'carbon stock' figures for grassland and cultivated land used for the UK's GHG Inventory suggest that each additional hectare of arable land converted to permanent grassland in the UK may provide on average, at least, an additional 26tC/ha – see Table 5 below (the levels are much higher for organic soil types, not shown).[748]

Table 5: UK soil carbon stocks for grassland and cultivated land to 1m depth, mineral soil types only[749]:

tC/ha	Grassland	Cultivated land	Difference
England	146	120	+ 26tC/ha
Wales	164	122	+ 42tC/ha
Scotland	246	154	+ 92tC/ha
Northern Ireland	276	215	+ 61tC/ha

In addition, it is believed that permanent grasslands in temperate regions should be steadily accumulating soil carbon under current conditions (i.e. they should be carbon 'sinks')[750], with the exception of drained peatlands. Results derived from direct measurements of soil carbon suggest a sequestration rate of 450-800kgC/ha of grassland.[751] If this were true for the UK's grasslands, then they would be sequestering 5-6 million tC per year and offsetting over a third of UK agriculture's GHG emissions.[752] The greater area of permanent grass in organic farming would mean an even higher level of sequestration (in proportion to the area of organic farming). It is not clear if the UK's grasslands are really sequestering carbon, however, and certainly the findings of the NSI soil survey - that the topsoil carbon content of all grassland types in the UK are overall significantly declining - suggest that perhaps they are not (though it did not measure changes in soil depth or bulk density, so is not reliable).[753] It might be that aspects of non-organic farming management are having a detrimental effect on the UK grassland soil carbon store, and that the differences between organic and non-organic management (such as, regarding the use of clover, grazing intensities and agrochemicals) might mean that organic farming has a more positive effect and may be able to realise some or all of this potential. The preliminary evidence from three studies indicating that organically managed grassland has higher soil carbon levels than non-organic grassland[754] supports this (see section 6.1). This is conjecture, however, and far more full soil profile research will be needed to establish the trends and factors affecting the UK grassland soil carbon store, and the comparative soil carbon levels and sequestration potential of organic and non-organic grassland.

7.11 Lower grazing intensity

In grasslands, the intensity and timing of grazing (and livestock species) can affect the amount of carbon that accumulates in the soil.[755] Soil carbon levels are often higher on optimally grazed lands than overgrazed (or ungrazed) lands.[756] This is because overgrazing reduces the growth and organic matter deposition of the grassland plants, changes the grassland species composition, increases the proportion of bare ground[757], and causes erosion.

Grazing intensity is recognised as an important factor in grassland soil carbon storage in the UK.[758] Evidence comes, for example, from a grazing intensification experiment on grazed acid grassland on organic soils in Wales, which resulted in a loss of carbon.[759] As well as the effects on the grass, heavy grazing also suppresses the growth of heather and other dwarf shrubs[760] which contribute to organic matter deposition in the heathlands and moorlands of the UK's hill regions. These are important ecosystems in the British Isles, and also in parts of Scandinavia, Alpine regions and other temperate upland regions globally.[761] According to a review of the pressures on UK moorlands (Holden *et al,* 2007), heather only grows at grazing levels below two sheep per hectare and the proportion of UK moorland in which stocking densities exceeded this rose from 29% in 1977 to 71% in 1987, as a result of CAP subsidies.[762] Incentives to increase stocking levels continued into the 1990s – see Section 5.8.

The organic standards require the stocking levels of grazing animals to be low enough to prevent poaching of the soil and over-grazing of the vegetation.[763] There are also upper limits on the livestock levels which help avoid the likelihood of over-grazing (at least in lowland areas). For example, in the UK, the maximum number of organic 'ewes and lambs' is an average of 15.7/ha; the maximum number of dairy cattle is 2/ha (for cattle of 500kg).[764] In contrast, a typical intensive non-organic farm may be stocking at 2.4 dairy cattle/ha.[765] Since 2005/06 and the end of the EU livestock 'headage' payments many non-organic farmers are now more extensive and similar in stocking levels to organic farmers.[766] However, total UK grazing livestock numbers have only fallen by 4% or 5% since 2005[767], so there is probably overall still a significant difference nationally.

7.12 Composting

Composting[768] is one of the best ways of increasing soil carbon levels, producing very high sequestration rates of 1-2tC/ha/yr in trials in favourable conditions. It is an ancient technique that, in modern times, was investigated and promoted by the UK Government agricultural researcher and pioneer of the global organic farming movement, Sir Albert Howard (1873-1947).[769] Historically low levels of compost were applied to farmland. There has now been a significant increase in use, with 480,000t of green waste compost applied to UK farmland in 2003/04, but it is still being used on a relatively small area.[770]

Composting is one of the best ways to improve the soil carbon store for many reasons:

1. It by far offers the highest soil carbon sequestration rate per hectare and per unit of carbon input of any of the main agricultural organic matter materials available;
2. There is a large source of non-agricultural organic material available for composting (e.g. green waste, food waste and paper waste), so there is a very large potential to increase overall soil carbon inputs to farmland, and at the same time help the UK meet its recycling targets;[771]
3. The composting of food waste that would otherwise be landfilled avoids the large methane emissions from landfill that is the largest source of methane in the UK[772], which greatly increases the overall 'carbon savings' of compost (and so of the whole food system);
4. Composting of green and food waste would also return phosphate and potassium back to the soil[773] (global mineral supplies of these valuable plant nutrients are gradually being exhausted and are rapidly increasing in cost[774]), as well as recycling other trace minerals back to the soil;
5. At an application rate of around 30t/ha/yr (freshweight), and as long as inorganic N fertiliser is not used, green waste compost offers as much carbon sequestration/savings per hectare as the conversion of farmland to woodland or biomass energy crops[775], but with the great advantage that the land can be kept in food production so this is not displaced elsewhere.

Composting of organic matter before application is routinely carried out in organic horticulture. Indeed, animal manures must be composted or stacked for several months before being applied to organic horticultural land[776] (to avoid any pathogenic contamination of the food. In the non-organic sector, manure use is simply prohibited on most horticultural land, preventing the possibility of using composted manure[777]). Crop plants can also be composted after harvesting (for example, cucumber plants produce excellent compost[778]). Composting is also a standard practice of biodynamic farmers.

However, composting is not widely used on organic arable and livestock farms, as there is no similar requirement and doing it on a large scale is not easy (possibly requiring investment in equipment and time for turning). Exceptions are the portion of organic arable farmers who are receiving mushroom compost from organic mushroom producers (see point 5), organic farmers bringing in green waste and, under Soil Association standards, the small proportion who are bringing in non-organic manure (see 9.6). Given its great potential for soil carbon storage and that it is really a key organic farming practice, efforts should be made to encourage and assist many more organic farmers to do composting.

Composted materials produce high levels of soil carbon accumulation, because the product consists of humic substances[779]. These are stabilised form of organic carbon[780] and also produce long-term stable soil aggregation as they are stable binding agents of the soil's particles.[781] (See Section 9.5 for details of the mechanism of aggregation.)

Trials show that composted material produces far better soil carbon results than most other types of organic matter.[782] For instance, in an 18-year UK trial, about 40% of the carbon was retained in the soil when compost was used, compared to 25% for FYM.[783] This was on a sandy loam soil so an even better result might be expected with clay soils.[784] In four recent medium-term trials in England, green waste compost application produced an average soil carbon conversion rate of 43%.[785] These results compare with the low carbon conversion rates of fresh, uncomposted crop residues (with a range of 2-21%).[786]

The benefits of compost were also studied in a nine-year trial (1992-2001) in the US by the Rodale Institute and USDA researchers.[787] This found that the application of compost just once every two or three years at levels sufficient for grain and vegetable production (at least 14t/ha dry matter every three years)[788], together with the use of cover crops, produced very high levels of carbon sequestration.[789] A compost made from cattle manure and leaves[790] and the cover crops produced a carbon sequestration rate of 2,363kgC/ha/yr, with the stored soil carbon increasing from 80t to 101tC/ha/yr over the trial.[791] The soil carbon level in the top 20cm increased significantly from 1.97% in 1992 to 2.5% in 2001 (a 27% increase over nine years). The carbon content of the compost was 31%. In contrast, the carbon levels in the plots treated with inorganic fertiliser fell by 317kgC/ha/yr, while the plots treated with raw manure increased by just 312kgC/ha/yr, although all plots had the same crop rotations and cover crops, all fertiliser types were applied at rates to supply the same estimated N availability, and all produced similarly high yields. Composting also reduced the N leaching rates by over 50% compared to the other treatments.[792] Further research showed that the addition of substances such as clay and calcium eliminate ammonia release and N leaching during composting.[793] Initial projections by the researchers, based on these trials and other values from literature, suggest that the use of compost can build 1-2tC/ha/yr.[794]

The comparative organic farming studies include a couple of further examples. The ten-year cropping trial by the University of California found a "disproportionate" level of carbon sequestration in the organic system, 560kgC/ha/yr, compared to no change in the equivalent non-organic system. The only management difference was the use of composted manure and no agrochemical use on the organic plots.[795] A trial of vegetable production on Australia found that organic farming using compost as well as other practices, resulted in a 55% increase in the soil's organic carbon levels in just four cropping seasons.[796] In the 28-year Swiss FiBL 'DOK' trial, the topsoil carbon levels fell in the plots receiving inorganic fertiliser or uncomposted manure, but the levels stayed stable in the biodynamic system where composted manure was applied, despite the amounts of above-ground carbon added to the soil being lower on those plots (the soil type in this case may have been unsuitable for higher carbon storage.) In addition, a US survey of farm pairs with similar soil types found that three organically managed fields that were receiving composted manure had greater soil carbon levels than non-organically managed fields (one had a 43% greater topsoil depth, the other two had 35% and 13% higher SOC contents respectively). These results were not, however, better than two organic fields in the survey that were not receiving compost, which also had higher SOC contents than the non-organic fields (+36%, +26%), but differences in topsoil depth were not measured for two of the organic fields that were receiving compost.

It is possible that composting in organic farming may achieve much higher sequestration rates than in non-organic farming. The sequestration results from the four English trials are interesting in that they varied greatly according to the level of compost applied and whether or not inorganic N fertiliser was applied. The average soil carbon conversion rate was 66% for a 33t/ha/yr compost application rate (21.6t/ha/yr dryweight), but was only 30-41% when a higher compost rate of 50t/ha/yr was used and/or when inorganic N fertiliser at standard rates was also applied.[797] N fertiliser was associated with a 55% reduction in the average soil carbon conversion rate for the 33t/ha/yr compost application rate, but with a 21% increase in the average sequestration rate for the higher 50t/ha/yr compost rate (though this did not achieve a better result than the lower compost application rate without inorganic fertiliser). This suggests that N fertiliser has some suppressive effect on the ability of organic matter applications to produce soil carbon sequestration, but that at high rates of compost application, N levels may be limiting the decomposition process and N fertilisation can have a positive effect. Presumably the higher soil carbon sequestration rate would apply to biologically N fertilised organic farming systems (we have only identified positive effects of the use of leguminous N-fixing plants) but this should be confirmed by research, as should these possible negative effects of higher compost applications and N fertiliser use identified here.

Overall, for these four trials, 33t/ha/yr of green waste compost without N fertiliser produced a very high average carbon sequestration rate of 2,070kgC/ha/yr, while when N fertiliser was applied, only the higher compost rate of 50t/ha/yr produced the same result (2,020kgC/ha/yr). Encouragingly, these results are higher than the carbon sequestration/savings that have been estimated for the conversion of arable land to woodland or biomass energy crops (willow), at up to 1,862 and 1,741kgC/ha/yr respectively.[798] However, 50t/ha/yr of compost seems unrealistic, not only because it is a large amount to source and apply, but any application rate above 36t/ha would risk breaching the 250kgN/ha/yr limits that apply to organic matter applications in the UK.[799] At the 33t/ha/yr compost rate (still a large amount to apply each year), the average sequestration rate when N fertiliser was used was only 880kgC/ha/yr in these trials. Although this is still a very good annual rate and means that composting should be encouraged on all farms, this does imply that the use N fertiliser may significantly limit the full potential of composting.

If agricultural materials, such as livestock manure or crop residues are used, it should also be borne in mind that a portion of the carbon is lost during the composting process (20% in one trial)[800], compared to if farmers apply the material fresh to the soil. However, even after accounting for this, a high proportion of the original carbon is still converted to soil carbon, about 40% assuming no use of inorganic fertiliser.[801]

In an interesting UK case, an organic farmer who has been applying small amounts of good quality compost (mix of 'greens' and 'browns'[802]) to his fields for over 20 years has increased his soil carbon level substantially (from 2.9-3.5% to 4% SOC), despite intensive and sometimes continuous arable cropping.[803] The compost is made of 30% manure, at least 30% green manures (mostly from the farm plus some local horticultural waste), wood chips and waste card. Given the fact that the soil in his greenhouse, where he has been applying much larger amounts, has now reached an impressive 10.4-10.9% SOC, which is getting close to the organic carbon level of his compost (c.12%), it appears that the soil carbon level of his fields will also continuing rising significantly (possibly eventually reaching 10-12%, it is conjectured).

Overall, the evidence so far suggests that the combination of composting and organic farming may be the most powerful way of increasing the soil carbon levels of arable land.

7.13 Additions of non-agricultural organic matter

Some organic farmers bring non-agricultural organic waste onto the farm, as an additional source of organic matter. This includes 'green' waste, food waste and waste paper. This helps replace the carbon (and minerals) that is removed from farmland by harvesting crops and provides the opportunity to increase the total amount of carbon sequestered by agriculture, especially as such materials are usually composted by farmers before they are applied.

7.14 Limited use of avermectin livestock wormers

The reduced use of wormers by organic livestock farmers, especially the minimal use of the avermectin group, may possibly help maintain soil carbon levels in grassland. Organic farmers mainly use the 'yellow and white' class of wormers which act in a different way to avermectins and are more benign (being digestive inhibitors, rather than neurotoxins). Avermectins are only used in cases of last resort. Additionally, horse manure should not be applied to organic land until 48 days after being produced, to avoid negative effects of veterinary drugs on soil life.[804]

Dung decomposition is an important stage in the carbon cycling of grassland systems. However, the modern use of wormers by livestock farmers has been shown to reduce the decomposition rate of dung. There is therefore a question whether this has contributed to the significant reductions in topsoil carbon levels found in the NSI survey of the UK's grasslands. A 2008 Defra report states, "Microbial and invertebrate activity and hence degradation of cowpats can be reduced by the presence of veterinary medicines" such as avermectins.[805] Additionally, avermectins and other drugs used on dairy farms can be present in slurry and spread to land, which might also be having effects. This issue has not so far been considered in the debate on agricultural soil carbon levels.

As well as supporting rich microbial populations, cattle dung supports over 200 species of invertebrates in temperate Europe which assist the conversion of cattle dung to soil humus.[806] UK research has shown that the natural rate of loss of organic matter from dung is between 0.7% and 2% per day (depending on the time of year).[807] However, farmers in many countries now routinely use drugs from the avermectin group for internal parasite control in cows, sheep, horses and pigs. There is now good evidence that this delays or prevents the normal decomposition of dung when there are residues of the drug in the dung.[808]

Avermectins are strong, persistent insecticidal drugs that are neurotoxins. Though they are administered internally, some of the drug passes through the animal and continues to be active in the deposited dung, killing or impairing the health of beetles, fly larvae, and other species that feed on the dung. The highest concentrations are in the first few days after treatment, but low levels can still be present in dung produced several weeks later.[809] It has been noticed that since the widespread introduction of these drugs, the levels of flies attracted to dung appears to have reduced considerably and dung also takes far longer to decompose than it used to.[810] Research has been undertaken to establish whether there is a significant effect by these drugs and there is now a growing understanding of the subject.

Several studies on the effect of avermectins in temperate regions have shown that there is an effect on dung degradation and probably a long-term effect, at least on a small-scale. An earlier review in 1998 of studies conducted in seven countries (including England, Scotland, France, Denmark and Germany), had concluded that despite evidence of initial reductions in insect colonisation and in the disappearance rate of dung after ivermectin or abamectin use, there was then no evidence of long-term adverse effects on the degradation of dung.[811] More recent studies, however, have strengthened the case for a long-term effect. A 2002 Danish study found that five common veterinary drugs reduce the decomposition of dung organic matter, and four had long-term effects. In this study, compared with dung from untreated cattle, the loss of organic matter was significantly lower in dung from heifers treated with the recommended doses of cypermethrin, fenbendazole, ivermectin, levamisole and spiramycin. When a decay model was applied to the data, all of the drugs, except spiramycin, resulted in significantly more organic matter remaining at infinite time[812], implying reduced long-term decomposition. A 2006 study by American researchers found that ivermection caused a lower decomposition rate of the organic matter in the dung.[813] Other studies indicate that veterinary antibacterials (such as tylosin) may also inhibit the decomposition of dung.[814]

Studies by the University of Bristol[815], which has been investigating the subject for 20 years, show that the dung of cattle treated with ivermectin does not decompose normally. In experiments, such dung remained "solid and compacted" after 42 days, while the control cowpats were crumbling. It is now known that avermectin binds tightly to the organic matter in the dung.[816] Although only some organisms are adversely affected by the drugs (dung-specific nematodes[817], for example, but not earthworms[818]), the process of decay depends on the activity of many species and the absence of any one can have strong effect on dung decomposition[819]. The effects of the drug can also continue in dung buried in the soil.[820]

There is still much important research that needs to be done to establish the scale of this effect, however. This is necessary because only some of the dung in grasslands will contain significant levels of residues at any time, and because several non-biological factors also affect the abundance of dung-feeding organisms (such as whether the weather is wet or dry), so the contribution of each factor has still to be determined. Additionally, the studies so far have only been looking at the effects on dung degradation, which is not the same as determining the effects on soil carbon levels. Even if it is found that there are only limited large-scale effects on dung degradation and most dung still eventually degrades, the nature of the delay and changes in the decomposition process may be changing the proportions of organic matter in the dung that is eventually decomposed and forms stable carbon to the soil, compared to the level that is eventually mineralised or washed away. At the moment, this aspect remains totally unknown. Given the large area of land that is being exposed to these drugs and the finding of politically significant levels of topsoil carbon losses each year from the UK's grasslands, this issue needs investigation.

7.15 Biodynamic farming standards

The additional practices used by the small subset of organic farmers that subscribe to biodynamic methods further increase soil carbon levels. Many studies indicate that these organic systems produce the best results.[821] For example, in the FiBL DOK trial, IBR Darmstadt trial and the Swedish 'K-trial', biodynamic methods produced better soil carbon results than standard organic farming and 12-25% higher soil carbon then non-organic farming (compared to only 0-18% more for standard organic farming in these trials; see section 6.2). Long-term comparative research by the Biodynamic Research Institute in Sweden since 1958 has documented an average annual increase corresponding to 500 – 800kg soil carbon per ha with biodynamic farming.[822] As well as composting, biodynamic farmers apply seven herbal 'preparations' to the compost and two 'preparations' of fermented plant material and mineral compounds to the soil. These treatments are claimed to enhance soil biological activity.[823] Biodynamic standards also require that food that is grown and harvested in accordance with lunar cycles.

7.16 Peat use

Peat use is an issue where organic standards and practices are no better than non-organic farming, and perhaps even somewhat worse. Under EU and UK organic standards, peat can only be used in horticulture (not as a soil conditioner in other agricultural sectors).[824] The Soil Association restricts peat use further to just horticultural propagation (i.e. the small quantities of compost used for seeds or cuttings, not the main crop production stage where soil is used, including in glasshouses), potted herbs and plants, and mushroom production. Moreover, for propagation, sustainable alternatives to peat should be used wherever possible.[825] The majority of UK protected crop growers are certified with the Soil Association.[826] However, these are not restrictions compared to the non-organic sector, as there is little peat used in the UK non-organic edible horticulture sector and non-organic market gardeners can raise their transplants in smaller modules, which uses less peat, as they can use liquid fertilisers freely[827]. Also, effective alternatives to peat-based composts for organic horticultural propagation in commercial situations have not yet been found (products like coir, for example, have not been found to be suitable).[828]

The Soil Association also prohibits peat cutting from peat bogs (except for a farmer's own domestic fuel use). Adding new drainage to recognised areas of significant conservation value is also prohibited and livestock cannot be allowed to overgraze valuable habitats, under Soil Association standards.

7.17 Agro-forestry in the tropics

The soil carbon benefit of organic farming also applies to organic food produced and imported from other regions of the world. In the humid tropics, agro-forestry is a good alternative to traditional slash-and-burn farming[829] or to modern intensive monocropped plantations, and it is a common technique of organic farming in these regions. Agro-forestry is the integrated production of perennial crops (trees or bushes) with annual crops, providing a sustainable production system of food and other products from the land. It has the major benefit of sequestering carbon both in the soil and an even larger amount in the vegetation. Over 20-25 years of establishment on degraded tropical land, such systems can sequester as much as 60 tonnes of carbon per hectare, 5-15t in the soil and 50t in the vegetation biomass.[830] This is an annual increase of up to 2.5tC/ha/year over 20-25 years, clearly an excellent method of addressing climate change. Many imported foods can be produced with agro-forestry methods, such as cocoa, coffee, tea, citrus fruit, tropical fruit (e.g. banana, papaya), coconut, nuts, avocado, dates and palm oil.

7.18 Prohibition of hydrogenated fats in organic food

As 30-40% of the economic value of soya is for food (the rest is for animal feed)[831], the use of soya for food is a large contributor to the clearance of natural habitats in tropical countries, and the associated soil and biomass carbon losses (see point 9 above). The prohibition on hydrogenated fats in organic foods ensures that the organic food sector is not a significant factor in this carbon source. Large quantities of soya are used by the food processing industry, which uses soya derivatives such as soya oil and lecithin. The main food product, soya oil, is commonly modified by the industrial process of 'hydrogenation' to produce hydrogenated fats for use in industrial foods, such as margarine and commercial frying fats.[832]

7.19 New Soil Association standard on palm oil and tropical deforestation

The use of soya is already greatly restricted in the organic sector by the grain feed limits and the ban on hydrogenated fats in organic food (see above). For palm oil, the Soil Association has adopted a new standard to avoid any deforestation being associated with palm oil used in organic products. From 2011, any organic palm oil or derivatives used in Soil Association certified products will have to be sourced from a list of approved sustainable suppliers who do not source palm oil from any land that was primary forest after 2006; a similar policy will apply to soya from a later date.[833] The Soil Association is therefore taking leading action on palm oil in the UK food industry, which is recognised as dragging its feet on this crucial issue.[834] It is hoped that other organic standards-setting bodies will follow suit. The fact that committed organic consumers tend to avoid processed foods is another important contribution.

Several practices of organic farming also **reduce the potential for erosion** of the soil and losses of carbon by this route. As well as the limits on grazing livestock numbers (see above), these are:

7.20 Better soil structure

The higher soil organic matter and soil microbial biomass levels means the soil particles are more likely to be aggregated into a healthy 'crumb' structure that is less susceptible to erosion. This is because, in such a condition, the soil particles are more stable[835] and the soil surface is more open, enabling water to percolate instead of passing over the surface and causing erosion[836]. For example, the FiBL trial found soil aggregate stability was 10 to 60% higher in the organic than the non-organic plots, and that there was a positive correlation between microbial and earthworm biomass and aggregate stability.[837] The Dutch study of a long-established biodynamic and non-organic field, Pulleman *et al*, 2003, found the soil aggregation level was significantly higher.

7.21 Winter vegetation cover

During the grass/ley period of the organic crop rotation, there is a good vegetation cover all year round. In addition, in organic farming, some cereals are under-sown with legumes which then remain after the cereals are harvested and act as a winter cover crop.[838] Winter cover crops protect the soil from erosion, by avoiding the development of rills and small gullies, and by providing food for earthworms, fungi and other soil organisms whose by-products increase soil particle aggregation.[839] The Soil Association standards require producers to maintain a protective cover of vegetation, such as a green manure or growing crops.[840] The non-use of herbicides also means there is a greater weed cover in organic farming.

7.22 Over-winter crop stubbles

The use of more diverse crop rotations and more spring crops means there is in less autumn sowing in organic farming. A higher proportion of organic arable crops are spring-sown, especially modern whole-crop forage mixes (peas and barley), as well as most peas and beans. As a consequence, there are more over-winter crop stubbles and less bare soil than in non-organic farming. The recent reduction in the use of 'set-aside' on non-organic farms (which was not normally used on organic farms), has further reduced the amount of over-winter stubbles on non-organic farms and the difference with organic farms.[841]

7.23 High proportion of uncultivated land

The use of grass/clover leys means that organic arable land in the UK is not cultivated for a quarter to half the time in each crop rotation. The higher permanent grassland percentage and uncropped field margins (for natural predators) further increase the proportion of the untilled area in organic farming.

7.24. More wind breaks

Organic farms have a greater presence of hedgerows and trees. This is because (i) due to the greater diversity of crops being grown, organic farms tend to have smaller fields and so a greater length of field boundaries; (ii) because boundary habitats support populations of the natural predators that control pests on organic farms; (iii) smaller fields enable the natural invertebrate predators living in the field margins to reach the field centres; and also because (iv) smaller fields enable a more precise grazing strategy which is used for internal parasite control and grassland management on organic farms[842]. The maintenance of wind breaks reduces the risk of soil erosion.[843]

7.25 Discussion and recommendations

Based on the evidence reviewed in this report, the main factors that determine agricultural soil carbon levels and the higher soil carbon levels of organic farming compared to non-organic farming, according to current understanding of the subject, can be summarised as follows.

Main factors that determine the soil carbon levels in farmland are:

1. Amount of organic matter input, per year (including root biomass and continuous root C supply)
2. Where the organic matter is applied (to low-carbon arable or horticultural land, or grassland)
3. Proportion of the plant biomass carbon input that is converted to soil carbon, which depends on C:N ratio, lignin level, and the root to above-ground plant carbon input ratio.
4. Level of soil aggregation to stabilise soil carbon inputs, which depends on fungal mycorrhizal levels, presence of grass and leguminous plants and overall extent of plant cover.
5. Depth of the organic matter input (because deeper is longer-lasting)
6. Protection against erosion

Main reasons for the higher soil carbon levels of cultivated land with organic farming are:

1. More above-ground biomass carbon input – in many, but perhaps not all, cases more organic matter input is made to the soil from both *applications* to the land (livestock manure, crop residues) and from growing plants (grass leys, green manure crops, and limits on grazing livestock levels to avoid overgrazing grasslands).
2. More root biomass carbon input – grass leys, larger crop root systems (from the use of decomposing incorporated plant residues instead of using surface applied fertiliser), and deeper rooting species.
3. More continuous root carbon supply – from the greater plant presence on organically managed land and less bare soil (use of grass leys, some weeds, green manure crops) and larger root systems.
4. Much more of the available organic matter is applied to cultivated land (FYM, grass leys in the crop rotation) - by using mixed farming systems with integrated crop and livestock components, and the lack of the prohibition on using manure on horticultural land that applies in the non-organic sector.
5. More use of the types of organic matter that convert a high proportion of the carbon input to soil carbon: FYM, green manure crops, root systems, and compost; and less reliance on straw and slurry.
6. Living soil and legumes to better aggregate soil – a more living soil resulting from the more continual supply of organic matter inputs to the soil (the greater plant cover providing a more continuous root carbon supply, and more regular organic matter applications to cultivated land) and from the non-use

of pesticides, which supports fungal mychorrizae and soil microbial communities; leguminous plants are used as the main fertiliser in organic systems instead of inorganic fertiliser.

7. Greater depth of SOM – incorporation of organic matter by ploughing, larger root systems, deeper-rooting plant species, and more burrowing earthworms.
8. Factors protecting against erosion – as well as the factors that promote soil aggregation (living soil and legumes), uncultivated stages in the rotation (grass leys), and more wind breaks (hedges etc.).

There is as yet little information on the relative significance of these factors. It appears that certain practices have major effects, in particular, grass leys/mixed systems, and composting. However, similar differences are reported for alternative systems, such as cover-crop based systems. This suggests that it is the fundamental approach of organic farming that is key. Organic farmers in different situations choose the strategy that works best for them, but the effects are generally to produce higher soil carbon levels as an inherent outcome of the system.

This is our attempt to explain the results based on the available evidence. We encourage all these areas to be investigated more. As research proceeds, the explanation of the higher soil carbon levels of organic farming can be refined and developed.

8. The carbon sequestration potential of organic farming

8.1 Introduction

To know the significance of these findings for climate change policy, the higher level of soil carbon of organic farming needs to be expressed in tonnes of carbon sequestered per year and in terms of how much this would offset the greenhouse gas emissions of agriculture (or total GHG emissions).

In this section, some previous calculations of the value of the soil carbon gains of organic farming at various locations are first presented. Then an estimate is made of the soil carbon sequestration potential of widespread organic farming in the UK, based on the results of our review of comparative studies and a standard method for calculating annual sequestration amounts. These show that the likely level of carbon storage and GHG offset produced by conversion to organic farming is very large. As more data is available from more studies from different regions and soil types, these estimates can be refined.

It is important to note that this benefit is related to the *conversion* of non-organic to organic farming, and it cannot be claimed that soil carbon sequestration will occur at the same levels on a long-term basis with organic farming. After a positive management change, soils build up carbon over a certain period until they stabilise at a new higher soil carbon level (there are a few exceptions, such as undisturbed peatlands which continuously accumulate carbon). The rate of sequestration is high for around 20 years (typically half of the total change over 100 years occurs in the first 20 years[844]) and then continues at progressively declining rates for a long time (for up to or over 100 years in temperate regions[845]), until the soil carbon level reaches the 'equilibrium' level for the new management regime.[846] Nevertheless, this front-loaded pattern of sequestration is a major benefit for climate change policy, which requires substantial reductions in atmospheric CO_2 levels to occur within the next couple of decades. And, importantly, the soil quality benefits of higher soil organic matter levels that will assist in climate adaptation are permanent.

Some care also needs to be taken in applying a percentage increase derived from just a limited number of regions to either a global level or to individual countries. The level of carbon stored in soils varies considerably, depending on the climate, soil type[847], starting level of carbon and the exact mix of farming practices employed at each site. As each site has a different current level of soil carbon, the percentage difference between organic and non-organic farming equates to different amounts of carbon in tonnage terms.[848] Additionally, while organic farming across the world operates to a common set of principles and practices – fertilisation by building soil organic matter levels, use of legumes, diverse rotations, non-use of inorganic N fertiliser - there are differences in the organic and non-organic farming practices and crop types used in each region, which could affect the comparative impact.

It is, nevertheless, standard accounting practice to identify a fixed soil carbon percentage increase (or reduction) for each relevant farming practice, which is then applied to standard figures for the soil carbon stocks at each location to produce annual sequestration amounts (see IPCC soil carbon accounting guidelines[849]). Given the wide spread of the positive evidence for organic farming, this approach should also be suitable for organic farming (although it is a system, rather than a single practice). The review of comparative studies in Chapter 6 showed that organic farming produces a substantial increase in soil carbon levels in many different temperate regions, and with different systems (e.g. continuous and mixed organic farming) and for different enterprise types (arable and horticulture). While there may well be some differences in the average level of the comparative impact between regions, there is not yet enough data to calculate separate averages for most regions. In Chapter 6, we therefore only calculated averages at a northern European and global level. In this chapter, the northern European results are applied to UK soil carbon data, and a simpler approach is taken for evaluating the possible impact at a global level.

The cultivated soils of Northern European should be particularly good candidates for carbon sequestration. Northern Europe has relatively carbon-rich soils[850], compared to the poor soils found in many other countries, and the potential for soil carbon sequestration is considered to be highest in humid-temperate regions[851] and for degraded soils[852] such as, arable soils[853]. Even small percentage increases in agricultural soil carbon levels in this region will therefore produce large amounts of carbon sequestration[854].

8.2 The soil carbon sequestration benefit of organic farming at specific sites

The researchers in six of the comparative studies, all trials, calculated the annual level of soil carbon sequestration (or loss) that was occurring with organic farming. The results are summarised in the table below (see section 6.2 for details of all studies).

Although useful, this data – particularly for 'all' studies - is inevitably less representative than the findings of our review of comparative studies in Chapter 6, which included a much larger number of studies and data from many commercial farms. Nevertheless, this provides an estimate of the average sequestration rate of organic farming in the US, of around 550kgC/ha/yr.[855] Interestingly, this is almost the same as the rate we estimate for the UK in the next section, based on the results of our review of comparative studies.

Location	**Study**	**Soil depth**	**Organic farming**, /ha/yr	**Biodynamic farming**, /ha/yr
Sweden	33-year 'K-trial'	60cm	300 kgC	800 kgC
Switzerland[856]	FiBL DOK trial	20cm	-123 kg C	42 kgC
Pennsylvania, US[857]	Rodale Institute FST trial	30cm	981 kgC	
" "	" " "	"	574 kgC	
California, US	Uni. of California 'LTRAS'	15cm	560 kgC	
California, US	Clark *et al*, 1998	15cm	546 kgC	
Michegan, US	Michegan University	7.5cm	80 kgC	
Average US:		**19.5cm**	**548 kgC**	
Average all:		**25.4cm**	**417 kgC**	**421 kgC**

Table 6 : the rates of soil carbon sequestration of organic farming found by various trials.

In three studies of organic farming, the researchers also calculated the greenhouse gas emissions of the systems and compared this to the rates of soil carbon being sequestered. The annual gain in soil carbon offset 39%, 87% and 27% of the annual GHGs emissions of organic farming, respectively:

1. In the nine-year crop trial by Michigan University, the 80kgC/ha/yr increase in soil carbon (derived from soil sample measurement) **offset 39%** of the greenhouse gases of organic farming (fuel use and soil nitrous oxide emissions), compared to none being offset in the non-organic system using conventional tillage.[858] As this study only measured the top 7.5cm of soil, the carbon sequestered over the whole soil profile would have been much more and probably more than enough to offset the entire GHG emissions of the organic system, which would be a very positive result indeed (for example, if it is three times as much for three times the depth, 0-22.5cm, this would be an offset of 117%).

2. In a study of two crop rotations of a German experimental farm (Scheyern), in Bavaria by the University of Munich, the annual rate of soil carbon sequestration was calculated using the REPRO soil dynamic model and validated by long-term data from the farm.[859] This was found to **offset 87%** of the GHG emissions of the organic system (for the crops only), making its overall Global Warming Potential (GWP) per tonne of output 80% lower than the non-organic farming system.[860]

3. In a survey and emission inventory of 28 commercial farms in Bavaria, the 402kgC/ha/yr of soil carbon that the 18 organic farms were estimated to be sequestering (using the REPRO soil dynamic model), was calculated to **offset 27%** of the organic farms' GHG emissions. This made their overall GWP per tonne of output 26% lower than the ten non-organic farms (estimated to be losing 202kgC/ha/yr).[861]

These calculations are not entirely satisfactory. The first used far too low a soil depth, and all were for crop systems only. The livestock sector has much higher GHG emissions, so these studies over-estimate the effects for organic farming as a whole. Also, none of these are UK estimates, which might produce different results, given the higher organic content of UK soils and the use of mixed farming systems for organic arable production in the UK.

8.3 UK estimate - the soil carbon sequestration potential of organic farming

This section calculates the carbon sequestration rates of UK organic farming and the level of offset this would be of UK agriculture's GHG emissions, based on the finding of a 28% higher average soil carbon level with organic farming in Northern Europe in Chapter 6. We have tried to be conservative in all assumptions.

The UK calculation was done as follows:

1. We used the +28% higher soil carbon level finding for Northern European cultivated soils from Chapter 6 (based on 8 studies and 38 comparisons), which was supported by the two UK studies (20 comparisons). The two UK studies actually gave a higher level, +33%, but this was only based on farms in England and we do not have data for the rest of the UK where soil carbon levels are higher. So, to be conservative, we used the lower figure for Northern Europe, which is also based on more studies and comparisons.

→ *We assume UK organic farming produces a 28% increase in the soil carbon levels of cultivated soils.*

2. The 28% increase was then applied to official figures for the arable topsoil carbon store, as used for the UK GHG Inventory, to produce a figure for the increase in units of tC/ha. To be conservative, we used the figures for England, rather than the higher figures for all UK cropland.[862] Also, we assumed that the increase only applies to the top 18cm of the soil, the estimated average sampling depth of the studies (even though it is likely that organic farming produces soil carbon increases over a greater depth and the IPCC methodology normally applies soil carbon differences to the top 30cm). We conservatively assumed that the amount of soil carbon in the top 18cm is in proportion to that contained in the top 30cm, but it is actually likely to be higher as the topsoil layer is probably not normally as deep as 30cm in arable soils.

→ *English cropland contains 67tC/ha for 0-30cm (for 'all' soils)*[863]
→ *Assume the top 18cm contains 18/30 x 67 = 40.2tC/ha.*
→ *So, the adoption of organic farming should produce 28% x 40.2 = average 11.26tC/ha increase.*
→ *At a UK level, the adoption of widespread organic farming would produce 11.26 x UK arable area of 5.7million ha*[864] *=* ***64.2million tC total sequestration potential at a UK level****.*

The total UK sequestration potential of widespread organic farming of 64 million tC in around 20 years is almost five times UK agriculture's official annual GHG emissions of 13.8million tC/year.[865]

3. To work out the annual rate of carbon sequestration, we assumed the total tC/ha increase is produced over twenty years and therefore divided the figure by 20. This was conservative as a higher figure would have been produced if we had used our estimated average length of time that the farms in the studies had been under organic management, of around 15 years (see table at end of section 6.1; 15 years was a very rough estimate: in the majority of cases, the studies only gave a range of years, so assumptions of the time period had to be made for most cases, e.g. using the mid-point of the range given). Twenty years was also chosen for consistency with the standard accounting methods: the standard IPCC accounting period for soil carbon level transition between different farm management regimes is twenty years.

→ *Assume the increase is produced over 20 years, so the average annual increase = 11.26/20* **=** *an* ***annual carbon sequestration rate of 563kgC/ha/yr*** *for 20 years.*
→ *At a UK level, 64 million tC increase over 20 years, is an annual increase of 64/20 = an* ***annual UK carbon sequestration potential of 3.2million tC/yr*** *for 20 years.*[866]

Interestingly, this estimated sequestration rate of +560kgCha/yr for UK organic farming is very close to the average finding of +550kgC/ha/yr from four US trials – see previous section 8.2. European soils with similar soil carbon levels would give similar carbon sequestration rates.[867]

4. Then, to illustrate the significance of this benefit, we applied the annual sequestration potential of 3.2milliontC/yr to the official figure for UK agriculture's greenhouse gas emissions of 13.8million tC.[868]

→ *This would offset 3.2/13.8 = 23.2%, i.e. an* ***offset equivalent to 23% of UK agriculture's current official GHG emissions for the next 20 years (and presumably a lower level thereafter).***

Encouragingly, a 23% offset with widespread organic farming is more than double the 6–11% greenhouse gas reduction target by 2020 that has been adopted for agriculture in the UK's Low Carbon Transition Plan.[869] It should be noted that this offset is only *equivalent to* 23% of agriculture's *current official* GHG emissions, since the 13.8milliontC figure is not the total figure of agriculture's emissions – it excludes current agricultural soil carbon losses, for example, and a different GHG emission figure would apply with widespread organic farming, though this has not yet been quantified – see below.

The carbon sequestration rate that is calculated depends heavily on all the assumptions made. We have tried to be conservative at every stage in this calculation. We thereby present this estimate of a 560kgC/ha/yr sequestration rate and 23% offset of UK agriculture's current official GHG emissions, as current best estimates of the soil carbon benefit of organic farming in the UK, based on current available data. If, however, future data were to show that, for instance, the 28% increase actually applies to the whole top 30cm of all arable soils in the UK, then the carbon sequestration level of UK organic farming would be *double* that of our estimates.[870]

This calculation represents the effects of newly converted organic farmland and is applicable to considerations of all further conversion of non-organic to organic farming. The figures are, however, probably higher than the sequestration rate and offset being achieved by the current UK organic sector. A proportion of existing organic farmland was converted over twenty ago and much of the land to enter conversion early on was believed to be in extensive, mixed farming systems before conversion. This land may be approaching or have reached its 'equilibrium' soil carbon level and not be sequestering more carbon, although it is still providing a soil carbon benefit by storing a higher level of carbon and providing a higher soil quality for climate adaptation benefits. These steady lasting benefits cannot be represented in these calculations. Land that was converted from typical non-organic farming systems in the last twenty years would, however, be sequestering the levels of carbon estimated here, we assume.

These sequestration figures presumably apply to most mineral soil types. However, for cultivated organic soil types, such as the fenlands, it is possible that the effect of organic farming may instead be to mostly reduce existing soil carbon losses. This is not specifically taken into account here, but if the annual amounts of carbon saved per hectare in these cases are similar (or higher) than the amounts sequestered on mineral soils, the overall effect should still be similar to the figures estimated here (or greater).

For arable land that was converted from grassland in recent decades and is releasing an estimated 1.6million tC/yr, it is possible that the adoption of widespread organic farming would cancel these emissions, which are being declared in the UK's GHG Inventory (see section 4.2). This is based on the assumption that, as indicated in section 5.6, organic farming roughly halves the soil carbon losses from ploughed-up grassland and that there would be no further ploughing-up under widespread organic farming. Assuming that the loss of 1.6milllion tC is accounted for by land at different stages of the transition, the effect of organic farming at any site would range from, a positive gain of 28% for soils which have practically reached equilibrium level, to cancelling further losses for those halfway through their transition, to halving the losses for those which have just been ploughed-up. In other words, organic farming could perhaps produce an annual 1.6milliontC saving, made up of up soil carbon gains of 800,000tC and avoided losses of 800,000tC. So, it could perhaps be assumed that these declared losses would be halted under widespread organic farming. This is without accounting for the fact that widespread organic farming would almost certainly *increase* the area of permanent grassland in the UK, i.e. reverse the current trend to some extent, which would produce further soil carbon gains.

These estimates are only for cultivated land and do not include a possible soil carbon benefit of organic permanent grassland. If organic farming also produces higher soil carbon levels in grassland, this could also be very significant as grassland has higher soil carbon levels than cultivated land and covers a large area of land in the UK. However, with just three comparative studies of grasslands so far (all in Northern Europe and all of which found higher soil carbon levels with organic farming – see section 6.1), it is too early to conclude that organic management raises grassland soil carbon levels. Nevertheless, to assess the potential significance of this, we can use the average difference from the three studies of 'at least 15%' higher soil carbon levels with organic farming. To be conservative, we assume that the increase applies just to the managed grasslands area (not rough grazing) and just to the top 20cm of the soil. However, we do not have a carbon stock figure just for managed grasslands and so use a figure for all grasslands which would higher, which would offset the conservative assumptions mentioned.

The calculation of this theoretical potential for grasslands can be made as follows:
→ to be conservative, we use the soil carbon stock figures for English grassland (rather than UK grassland), which is an average of 83tC/ha in the top 30cm.[871]
→ assume that the top 20cm of managed English grassland contains 20/30 x 83 = 55.3tC/ha
→ if an increase of at least 15% applies only to the top 20cm, this would be an increase of at least 0.15 x 55.3 = 8.3tC/ha+ in managed grasslands with organic farming.
→ across the whole UK managed grassland area of 6 million ha[872], this would mean another 8.3+ x 6 million = 49.8tCmillion+, i.e. an extra **at least 50million tC stored in the UK's grasslands with widespread organic farming** (theoretically).[873]
→ on an annual basis, if this increase is produced over 20 years, this works out at 8,300/20 = an annual carbon sequestration rate of **at least 415kgC/ha/yr,** and 50million/20 gives a **UK carbon sequestration potential of at least 2.5 million tC/yr** (theoretically).
→ 2.5million is an offset equivalent to 2.5/13.8 x 100 = **at least 18% of UK agriculture's GHG emissions** for 20 years (and lower amounts thereafter) (theoretically).

Much more research is needed to confirm the existence and level of a soil carbon difference on organic grassland, however.

Box 11 Grazing livestock – soil carbon vs. methane emissions

Grass-fed livestock have a critical role to play in minimising carbon emissions from farming and this must be set against the issue of methane emissions from cattle and sheep. Grasslands for grazing livestock, whether permanent pasture or temporary grass on mixed farms (which account for most UK organic cultivated land), represent vitally important soil carbon stores. Already, each year in the UK, 1.6 million tonnes of carbon (representing a hidden additional 12% of the UK's agricultural GHG emissions) are being released into the atmosphere because of the net conversion of permanent grassland to cultivated arable land – see section 4.2. Advocates of a shift from red meat to grain-fed white meat to address the methane issue could therefore find this has the perverse effect of exchanging methane emissions for carbon emissions from the soil and the destruction of tropical habitats (to produce soya feed), as well as having a far reaching impact on our countryside, wildlife and animal welfare.

The soil carbon impacts that need consideration in assessments of grass- and grain-fed meat are:
1. The soil carbon losses (and N20 emissions) of ploughing up grassland (23-90tC/ha in the UK)
2. The carbon losses and climate effects of habitat destruction in tropical regions
3. The question of whether grassland sequesters carbon on an on-going basis and, if this is not generally occurring now, whether it could do so under improved management, such as organic farming.
4. If organic grassland has higher soil carbon levels and the carbon offset value of this.
5. The climate adaptation benefits of higher soil carbon levels in grassland, than arable soils.

For example, if the levels of on-going carbon sequestration by grasslands are or could be as predicted, 670kgC/ha/yr[874], this would offset all the methane emissions of beef cattle and about half those of dairy cattle (methane emissions are equivalent to about 1,500kgC/ha for 2 dairy cattle/ha)[875] – Section 4.2

The above calculations have some important drawbacks. They have the advantage of including the livestock sector, and thus not over-estimating the overall soil carbon benefit of organic farming as the calculations by previous researchers of just organic crop system will have done (section 8.2). However, Defra's 13.8million tC figure for UK agriculture's GHGs is not a 'life cycle' figure and does not represent the full GHG emissions of UK agriculture. It excludes some UK agriculture emissions, such as from N fertiliser manufacture and UK agricultural soil carbon losses (ploughing-up grassland, fenlands and any losses from improved grasslands etc.). It also excludes the overseas emissions of UK agriculture, including from imported fertiliser and feed manufacture, and UK agriculture's share of the carbon losses from the destruction of tropical habitats. The 'life-cycle' figure for UK agriculture's GHG emissions is therefore far higher, and the offset percentage should work out lower.

However, unlike the previous studies of the sequestration potential mentioned in Section 8.2, the above offset calculation also does not the advantage of being based on figures for the GHG emissions of organic farming which should be lower, and would be helpful as that would show the value of the soil carbon sequestration of organic farming in terms of the overall carbon balance of organic farming. Taking a life cycle approach would, however, in principle have to include the soil carbon sequestered by imported organic feed production, the carbon gains from the greater area of permanent grassland and the reduced destruction of tropical habitats, which would all have the effect of increasing the level of the offset.

We have therefore taken another more detailed sectoral approach, presented on the next pages.

5. We have made sector-level calculations for organic production of arable crops and grain-fed livestock, assuming that organic farming sequesters 560kgC/ha/yr or 550kgC/ha/yr of soil carbon. For the grain-fed livestock sectors, we have taken account of the soil carbon sequestered by imported organic feed crops, as well as the carbon sequestered by UK organic feed crops. We then applied the relevant carbon sequestration figures to Cranfield University's 'life cycle' estimates of the GHG emissions of organic and non-organic farming (using their updated August 2007 results, not their 2006 published figures). These estimates exclude still the carbon gains from the greater area of permanent grassland and reduced destruction of tropical habitats, but they go some way to providing life-cycle estimates.

It is important to emphasise that Cranfield's figures over-estimated the GHG emissions of UK organic farming (even in their 2007 figures): they over-estimated organic farming energy use by using the wrong production system for organic arable production (they used stockless rather than mixed systems, which are the normal organic arable system in the UK and are more energy–efficient); and they over-estimated the N2O emissions of organic farming as they used the 1996 IPCC emission factors which effectively double-counted the nitrous oxide (N20) emissions from biological fixation (these emissions have been reduced in the new 2006 guidelines), which is important as N20 is the largest agricultural GHG.

(i) UK arable crop production

For UK crop production, we have assumed that organic farming sequesters 560kgC/ha/yr. To use the same units as Cranfield, we have converted this to a sequestration figure of 2,053kg CO_2eq/ha/yr.[876] We also reduced Cranfield's organic GHG figures slightly to conservatively account for their over-estimate of energy use for organic crops (based on analyses not presented in this report, we assumed Cranfield over-estimated energy use by 15% and then adjusted their 2007 figures accordingly = 'adjusted Cranfield').[877] We used current UK organic farming yields of 5.4t/ha for wheat and 28t/ha for potatoes. As there is currently almost no organic production of oilseed rape in the UK, we assumed a notional yield of 2.2t/ha.

This analysis shows that the **the soil carbon benefit of UK organic farming offsets 44-72% of the GHG emissions of organic arable crops**, for the first twenty years after organic conversion (with lower amounts thereafter) – see table. This would make the emissions of organic arable production just 30-60% of non-organic farming for about twenty years following conversion. As even these adjusted organic GHG figures are likely to be over-estimates (they haven't been adjusted for the new lower IPCC N20 emission factors, for example) and as our 560kgC/ha/yr estimate of the soil carbon sequestration level of UK organic farming is conservative, these figures are conservative and should be reliable.

Table 7: Calculation of the level of carbon offset of the GHG emissions of organic arable crops, for the first twenty years after organic conversion (GWP means Global Warming Potential, or 'carbon balance.'):

If UK organic farming sequesters **560kgC/ha /yr**	**Organic GHGs/t of product**, kg CO_2eq (Adjusted Cranfield, 2007)	**Area used to produce 1t of organic product, ha**[878]	**Soil carbon sequest-ration/t,** kg CO_2eq (col 3 x 2,017)	**Offset value of the soil carbon benefit**, As % of organic GHGs (col 4 / 2 x 100)	**Net organic GWP/t**, kg CO_2eq (column 2 – column 4) = **%** of non-organic GWP (Cranfield, 2007)
Wheat	607 kg	0.185	373	**61%**	234 kg = 39**%** of 600kg
Oilseed rape	1,273 kg	0.454	916	**72%**	357 kg = 29**%** of 1,220kg
Potatoes	167 kg	0.036	73	**44%**	94 kg = 59**%** of 160kg

(ii) UK grain-fed livestock production

To calculate the soil carbon benefit for organic grain-fed livestock production, for each sector, we calculated the area of UK/EU produced feed and the area of imported feed required to produce one tonne of organic livestock product, and then applied a carbon sequestration figure of 550kgC/ha/yr to this total area. We used organic yield data and assumed that organic dairy cows on average consume only 70% of the grain of non-organic animals (grass is a larger constituent of their diet), and that organic poultry for meat consume an additional 45% more grain and organic laying hens 6% more grain per tonne of output[879] (they consume more being free-range and slower-growing).

We assumed that 100% of soya feed and 69% of maize gluten feed[880] used in the UK would be imported (as currently), that this would come from the US or countries with similar organic yields and sequestration levels to the US, and that 1t of maize gluten requires 1.2t of maize to produce[881]. Also that, the yield of US organic feed production is 6% less than non-organic production (using data on the comparative yields of US organic arable farming [882], which gives organic yields of: soya - 2.7t/ha, maize - 8.4t/ha[883]). Note, if these assumed organic yields are too high, this only gives a more conservative offset figure.

We then applied these carbon sequestration amounts to Cranfield's 2007 GHG figures for organic farming, which gives the following estimates of the carbon offset of the soil carbon benefit of organic grain-fed livestock in the UK. A sequestration rate of 550kgC/ha/yr converts to 2,017kgCO_2eq /ha /yr.[884]

Table 8: Calculation of the level of carbon offset of the GHG emissions of grain-fed livestock from organic feed production, for the first twenty years after organic conversion:

If organic feed crop production sequesters **550kgC/ha/yr**.	**Organic GHGs /t of livestock product**, kg CO_2eq (Cranfield, 2007)	**UK/EU cereal & maize area + overseas soya & maize area to produce 1t of organic product, ha** (see Annex II)	**Soil carbon sequest -ration /t,** kg CO_2eq (col 3 x 2,017)	**Offset value of the soil carbon benefit**, As % of organic GHGs (col 4 / 2 x 100)	**Net organic GWP/t**, kg CO_2eq (column 2 – 4) = **%** of non-organic GWP (Cranfield, 2007)
Pigs	4,190 kg	0.159 + 0.434	1,196	**28.5%**	2,994 kg = 60% of 5020kg
Poultry meat	5,450 kg	0.281 + 0.774	2,128	**39.0%**	3,322 kg = 84% of 3710kg
Eggs (unit =20,000)	4,740 kg	0.096 + 0.495	1,192	**25.1%**	3,548 kg = 89% of 3970kg
Milk (unit = $1m^3$)	1,040 kg	0.004 + 0.028	65	**6.3%**	975 kg = 93% of 1050kg

This shows that the soil carbon benefit of organic farming **offsets an estimated about 29-39% of the GHG emissions of organic white meat production** (poultry and pigmeat), **and about 25% of the GHG emissions of organic egg production**, for about twenty years after conversion (with lower amounts thereafter). This would make the GHG emissions of organic poultry and milk production lower than non-organic production (instead of being possibly higher and similar, respectively), and would further reduce the GHG emissions of organic pig production below those of non-organic farming, to an estimated just 60% of non-organic emissions for about twenty years after conversion.

Several aspects of this calculation need refinement. However, several parts of the calculation are reasonably founded or conservative. The 550kgC/ha/yr soil carbon sequestration figure for organic farming is our conservative estimate for the UK based on our review of comparative studies, and from real carbon sequestration data from long-term organic farming trials in the US. Additionally, the calculation still excludes part of the soil carbon benefit of organic farming, including some feed (production of oilseed feed and imported feed used for home-mixing), the carbon gains from the smaller area of arable land and greater area of permanent grassland and the expected reduced destruction of tropical habitats which should result from a large overall reduction in white meat production and grain feed with widespread organic farming. An initial assessment by Reading University of the impact of widespread organic farming has suggested that the production of white meat would fall by around 70% in England and Wales.[885]

Also, in this calculation, we have not made any adjustments to account for Cranfield's over-estimates of organic livestock GHGs (as well as the use of more energy-intensive stockless arable systems for UK organic feed production and the over-estimates of N20 emissions, the assumption of organic maize yields of 55% of non-organic, rather than, say, the 94% for US organic maize; and their underestimate of the proportion of non-organic free-range eggs which would increase the non-organic egg sector emissions). So, these figures are probably underestimates and should thus be reasonably reliable.

For comparison with these scenarios for organic farming, there have been three analyses of the potential carbon sequestration that could be achieved by adapting non-organic farming in the UK, the most recent two of which have concluded that only limited amounts of carbon can be sequestered:

- A 2007 review of the scientific evidence for the UK Government of the soil carbon benefits of reduced tillage practices and organic matter additions concluded,"there is only limited scope for additional soil carbon storage /accumulation … over and above 'present day' normal farm practice," and advised that soil carbon storage should not be the justification for improving soil organic matter levels (Bhogal *et al*, 2007).[886] The estimates in this review suggest that the adoption of reduced tillage in the UK can only increase arable soil carbon levels by up to 1% (of the total), for the area affected.[887]

- A 2004 study calculated that the amount of carbon that could be sequestered by non-organic arable farming in England would be around 125,000tC/year (21kgC/ha/yr), if farmers adopt additional practices (conservation field margins, increased returns of crop residues and reduced tillage). This is less than 1% of UK agriculture's official GHG emissions (13.8milliontC/yr). In contrast, it estimated that the conversion of arable land to woodland or biomass energy crops (willow) would produce total carbon savings of 1,862 and 1741kgC/ha/yr respectively, half by soil carbon sequestration (and the rest by reductions in fossil fuel energy use and N_2O emissions) (King*et al*, 2004).[888]

- A 2000 analysis estimated that with a combination of measures, the best level of carbon sequestration achievable on the UK's arable land is a total of 6.1million tC/yr.[889] The analysis covered a broad set of options. As well as soil carbon sequestration, it included above-ground carbon storage gains and energy savings from growing energy crops on, "surplus arable land" (Smith *et al*, 2000).

As regards the last two studies, the concept of 'surplus arable land' or of converting arable land to non-food uses is highly questionable given that the UK is far from self-sufficient in cereals (millions of tonnes of bread wheat and animal feed grain are imported each year) and that climate change is likely to reduce global grain supplies[890] (probably especially if current, drought-susceptible, farming systems continue). A reduction in the UK's arable land would only lead to a greater import of cereals, some with possibly higher carbon emissions. Widespread organic farming in the UK would, in contrast, result in a rebalancing of farming with far less white meat production (as factory farming systems are not allowed) and a consequent lower demand for cereal feed[891], a greater area of grassland, and would also mean imported feed being organically produced – all with associated soil carbon benefits. Also, the last study may have been completed before the limitations of reduced tillage were widely known (see section 9.2), which was taken into account in the 2007 review. It should also be noted that organic farming also offers other GHG savings as well as carbon sequestration (e.g. a reduction in agricultural energy use by about 30%[892]).

These analyses for non-organic farming are also not exactly comparable to our estimates of the soil carbon benefit of organic farming in Northern Europe: they have partly or largely assumed that non-organic farmers would adopt additional practices or change their practices specifically to build soil carbon, instead of or besides the practices they currently use for their commercial needs, whereas this review has attempted to present the effects of *existing* organic management. The organic farming sector can also adopt many additional practices to increase its soil carbon sequestration ability. Additionally, there is the possibility of substantial additional unidentified soil carbon gains with organic farming (such as on grasslands and at the lower soil levels).

8.4 Global estimate - the carbon sequestration potential of organic farming

Importantly, at a global level, the ratio of arable land to annual greenhouse gas emissions is far higher than in Europe or the US. Therefore, estimates of the carbon sequestration potential of widespread organic farming are much higher at a global level. Additionally, there is potential for particularly high rates of carbon sequestration with organic farming in humid tropical regions (with agro-forestry, which sequesters up to 2.5tC/ha/yr in wood as well as in the soil[893]), than the average identified in this review for temperate regions. There are also the large carbon savings from the presumed reduced destruction of tropical habitats that should be taken into account (from a reduction in grain-fed livestock production).

However, comparative data is not available for most countries and using a single soil carbon stock figure would be inappropriate at a global level. So, for estimating the global sequestration potential of organic farming, we have taken a much simpler and more speculative approach for illustrative purposes. Considering the very wide potential of organic farming at a global level (e.g. using composting and agro-forestry) and the fact that current data does not account for all differences (destruction of tropical habitats etc.), we have assumed that a higher sequestration rate than the UK figure of 560kgC/ha/yr would be realistic and reasonable: 1tC/ha/year.

So, assuming an average sequestration rate of 1tC/ha/year (for both soil and biomass carbon sequestration) applies to the whole cultivated land area of 1.5 billion ha[894], we suggest that widespread **organic farming could potentially sequester 1.5 billion t carbon each year** for at least the next twenty years (5.5 billion tCOeq).[895] This would be a **reduction of 11% of the annual anthropogenic GHG emissions by human activities** (assuming no change in future emission levels).[896] Over twenty years, this would sequester a total of 30 billion tonnes of carbon, two-thirds of the estimated total historic loss of soil carbon since 1850[897].

The achievement of such a high level of carbon sequestration worldwide does not seem unrealistic. There is very wide potential for organic farming practices at a global level. As well as agro-forestry, high rates of carbon sequestration are possible with composting, and other good organic farming practices can be used more widely (such as, green manures). The expected reduction in carbon losses from the reduced clearance of tropical habitats for soya and beef production may be substantial. There is also the real possibility that the current comparative data is under-estimating the effects of organic farming, and there could be additional soil carbon benefits (from differences in topsoil depth, the subsoil, reduced erosion, the area and soil carbon content of grasslands, etc.). Moreover, additional carbon sequestration could achieved by the further development of organic farming in line with its principles, such as by using available non-agricultural wastes to increase organic matter inputs (paper waste, food waste etc.)

An annual saving of 1.5billiontC, or 5.5billion tCO_2eq, is equal to the current IPCC figure of the global GHG emissions of agriculture, of 5.1-6.1 billion $tC0_2eq$/year.[898] In other words, we suggest the soil carbon sequestration of widespread organic farming could potentially make agriculture officially carbon-neutral for the next twenty years, assuming similar GHG emissions with global organic farming. However, the

IPPC figure is not a 'life-cycle' figure and is an underestimate, as it excludes agricultural energy use and all other indirect agricultural emissions. And, organic farming reduces agricultural energy use[899] and probably also reduces N20 emissions (being more N efficient)[900]. As these aspects are not yet quantified, we cannot yet present the potential offset in terms of agriculture's global GHG emissions.

This estimate for organic farming compares very well to the global level of carbon sequestration that it has been estimated could be achieved by improving non-organic farming practices. There have been four earlier analyses of the carbon storage effects of a range of agricultural practices (excluding organic farming, we believe).[i] The results are a soil carbon sequestration potential of 0.38 - 1.2 billion tC/year.[901]

A more recent analysis of the *full* global potential for agricultural GHG mitigation (including methane and N_2O emissions), carried out to advise the IPCC, has estimated that the maximum reduction that is biophysically achievable for agriculture is 1.5-1.6 billion tC/year (Smith *et al*, 2007[902]). Almost 90% of this, 1.42 billion tC, would be through soil carbon storage (sequestration and fewer losses). This estimate of 1.5-1.6billion tC/yr, which is the same size as the carbon sequestration figure we have estimated for global organic farming, was based on a consideration of a broad range of agricultural measures including many that the organic farming movement advocates (use of legumes, cover crops, more organic matter additions, more perennial crops, less input-intensive systems, avoiding over-grazing, agro-forestry, restoration of peatlands and degraded farmlands). But it also includes options that are contrary to organic farming principles (more intensive livestock systems, more concentrate cattle feed and use of cattle hormones). There also has to be doubt about the reliability of the estimate as it was mostly derived by modelling the combined effects of the practices[903], rather than from direct field data. Also, for a couple of the practices, the case for emission reduction is questionable (reduced tillage and growing energy crops on 'spare agricultural land'). Accordingly, it may well be a significant under- or over-estimate.

The potential of organic farming also compares favourably to the level of carbon sequestration that could be achieved globally through forestry, which is estimated at 87 billion tC over 50 years[904]. While this is theoretically equivalent to 35 billion tC in 20 years, i.e. slightly over the 30 bn tC in 20 years for organic agriculture, the great advantage of *soil* carbon sequestration is that this would actually be achieved within the next 20 years. This is crucial as GHG emissions have to be substantially reduced within the next two decades.[905] Global carbon sequestration by new forests, however, can only bring long-term gains: it would take over 20 years to offset the emissions from the initial establishment of the plantations.[906]

Consideration should also be given to new, emerging soil carbon approaches if they can be complimentary or suitable for organic farming. For instance, biochar production may be an effective option, especially in hot countries where the conditions are more difficult for humus to build up than in temperate regions[907].

However, where agricultural approaches are not an intrinsic part of sustainable food production systems, great care should be taken to avoid global adverse side-effects (this is a risk where the financial opportunities for agri-businesses are large and divorced from ecological and social factors). This is now an enormous problem with the biofuel industry and Europe's biofuels policy. According to a 2008 report for the European Commission, "If the EU biofuel requirement is, as forecast, met by increased imports, there are serious implications for soil carbon stocks in the exporting countries. For example, the production of soybeans in Brazil and palm oil in Southeast Asia has expanded largely at the expense of tropical forest... If biofuels policy results in reduction of SOM, it will take many years or decades of biofuel production for the overall carbon balance to become positive. In other words, the increased production of biofuels will result in a significant surge of GHG emissions … The GHG balance would be negative for decades….."[908]

It is also important to note that the estimated 1.5billion tC/yr carbon sequestration potential of organic farming is not the full emission reduction that could be delivered. Apart from the fact that the full carbon sequestration potential of organic farming may eventually turn out to be higher, it does not include any

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[i] IPCC (1996, TAR); Lal , 2003 – 2004a); IPCC (2000; SR-LULUCF); and Manne & Richels, 2004

other GHG reduction that would be delivered by organic farming or any additional GHG mitigation options that could be adopted alongside, such as peatland restoration, or the many other changes that are advocated by the organic farming movement to reduce the climate impacts of the food system and that are synergistic with widespread organic farming (localised food economies, less meat consumption, less processed foods and more seasonal foods).

In other words, at a global level, the carbon sequestration of widespread organic farming alone may be similar to the maximum theoretical total GHG mitigation that it is estimated that all of agriculture could achieve without organic farming, but organic farming has some additional mitigation potential and it would facilitate the adoption of other complimentary options that can further reduce the total GHG emissions from the agriculture and food sector.

8.5 Discussion

The previous calculations show that the likely amount of carbon that would be sequestered by the adoption of widespread adoption of organic farming would significantly reduce agricultural GHG emissions (of almost 40% in the UK and more globally for at least twenty years), and that a provisional estimate of the GHG offset at a global level is around 11% (1.5 billion tC/year), for at least twenty years. These estimates are conservative, and the global estimate is in line with the view of IPCC scientific advisers that about 90% of agriculture's GHG mitigation potential resides in improving soil carbon levels.

These estimated carbon gains would be delivered as a by-product of an expansion of organic farming. To realise this, national and global programmes addressing technical issues and marketing etc. would be needed to ensure a very much wider uptake of organic farming, above the current modest pace of conversion. However, there is the advantage that an international framework of standards and regulation is already in place for organic farming, and that there is some market support, so there would therefore not be the need for a major framework of on-going targeted policy intervention, as would be required for many of the non-organic farming options to ensure that the required the practices were being continuously used. Also, widespread organic farming would deliver all the other policy benefits of organic farming, such as for climate adaptation, greater farmland biodiversity, more rural employment etc.

The soil carbon benefit of organic farming appears to work out greatest for field horticultural crops. This is because the soil carbon differences between organic and non-organic farming appear to be largest in this sector, the yield levels of organic and non-organic production are similar[909], and the GHG emissions of this food type are the lowest of all foods.[910] There are concerns about the soil carbon levels of non-organically managed horticultural land[911] as they are even lower than arable land[912], due to the large areas of bare soil and low residue returns of horticultural crops. For instance, the root length density of broad beans in the top 20cm of soil is just 0.8cm/cm^3 of soil compared to 12.2cm/cm^3 for winter wheat.[913] And, for example, most of the above-ground part of lettuce and vining pea plants are removed at harvest[914]. The practices used in the organic horticultural sector, however, tend to produce good soil carbon levels. Organic growers regularly apply manure or composts (which are especially good for soil carbon sequestration) and they use green manure crops to add more organic matter and reduce the amount of bare soil. However, the possibly greater use of peat-based composts by the organic market gardening sector for raising transplants may offset part of this benefit and should also be considered.

The comparative studies show there are high differences between organic and non-organic horticultural production: a UK, two Spanish, US and Australian study found 58%, 138%, 325%, 28% and 24% higher soil carbon levels for organic than non-organic production, respectively.[915] Going by the results of the UK study, organically managed horticultural land in Northern Europe appears to have similar soil carbon levels to organic arable land, but the per hectare benefit is more due to the low soil carbon levels of non-organic horticultural land. The two Spanish studies indicate that organic horticulture may be highly beneficial in arid regions. Since half of all vegetables and 95% of all fruit consumed in the UK are imported[916], from countries such as Spain, this aspect of organic horticulture is a very important consideration as regards the UK's GHG emissions (on a consumption basis). It is therefore perhaps a priority that soil carbon impacts

are included in the calculations of the 'carbon footprint' of horticultural crops, such as in the food carbon labelling schemes being developed by Tesco and the Carbon Trust/BSI for the UK government.
There also needs to be more comparative assessments of the level of soil carbon under organic and non-organically managed grassland. We currently have only three sets of comparative data for grassland, indicating greater topsoil carbon storage under organic management of 15% or more (see Section 6.1).[917] If organic farming indeed improves the soil carbon storage of grassland, and there are several reasons to think it can[918], perhaps especially in the deeper soil layers and in terms of topsoil depth, the total soil carbon benefit of organic farming would be much higher. This is the largest land type in the UK (11.5 million ha[919]), has higher soil carbon levels than arable land, and is suffering larger topsoil carbon losses than arable land in the UK.[920] Even just a 15% higher soil carbon level would offset over 50% of UK agriculture's GHG emissions (7 million tC/yr) for 20 years, so this could be very significant indeed. This would further reduce the carbon balance of organic dairy farming, and also reduce that of the red meat sector which has the highest GHG emissions of any sector but is so important to protecting the UK's existing soil carbon store. So, further research to establish the differences in this area is a priority.

It should also be noted that soil carbon calculations only account for part of the higher carbon storage capacity of organic farms. Organic farming also supports a larger non-crop biomass in the form of trees, hedgerows, wild plants and other farmland wildlife. For example, a scientific review of 66 published comparative studies in 2005 concluded that wildlife is on average 50% more abundant on organic farms.[921] Trees and hedges are partly promoted by the need for natural habitats to support the natural predator populations on which organic farming relies for pest control, but the organic standards often also promote trees and hedges directly (e.g. East African Standard, Pacific Organic Standard).[922] This higher living biomass constitutes another carbon store on organic farms, as yet unquantified and unaccounted for in current Life Cycle Assessments, farm carbon footprinting and food carbon labelling calculations.

Finally, if additional practices are adopted by organic farmers then the potential level of carbon storage by individual farmers and organic farming generally could be much higher. Examples of such practices, which are all based on organic principles, are: greater use of green manure crops, composting, more manure/less slurry production, more use of deeper-rooting plants and complex species mixtures in the grass ley, bringing in food waste or paper/card waste, biodynamic farming, inter-cropping (growing two compatible crop species in one field, which can double biomass production per hectare)[923], growing varietal mixtures[924], and agro-forestry. These offer huge potential for further increasing soil and also biomass carbon levels. Paper and card waste, for example, is a highly under-used carbon source in the UK, as currently most of the millions of tonnes of paper and card collected for recycling are not being applied back on the land; much is being exported and there are now ideas to use this material for energy generation in future. There is also a high level of food waste available. At least until recently, waste food (mainly vegetables) has been landfilled in the UK and was a very large source of the country's methane emissions. All of this should be being composted and returned to the land.

Planting more hedges and trees in available areas on the farm should also help, particularly if the establishment and management inputs are kept down: new hedges sequester around 2tC/km/yr and individual trees around 25kgC/tree/yr.[925] With woodland regeneration, in total about 300tC/ha is sequestered over 120 years (100t in the top 69cm of the soil, and 220t in biomass).[926] Newly planted woodlands, however, can take a long time before net carbon sequestration starts.[927]

Development and uptake of all these practices could be achieved through research support by the organic sector (e.g. pioneering farmers and the organic farming organisations) and/or by market or government campaigns and incentives. There is likely to be greater long-term interest in such practices than in the non-organic sector: soil organic matter enhancement is the basis of organic farming's productivity, so these practices may offer some yield and economic benefits and help improve the viability of organic farming.

9. Answering concerns about agricultural soil carbon sequestration and the contribution of organic farming

In discussions with different parties over a number of years, we frequently encountered a set of concerns about the potential to increase soil carbon levels. Some of these appeared to have originated from experience with non-organic systems, and they were discouraging a positive response to the ability of organic farming to raise soil carbon levels and of the potential of agricultural soil carbon sequestration generally. Two successive reviews for the Government, for example, have questioned the potential for increasing agricultural soil carbon storage (King *et al*, 2004 and Bhogal *et al*, 2007[928]), the most recent questioning the effectiveness of increasing organic matter applications and of reduced tillage practices. Other concerns were specific to organic farming and its effects on soil carbon levels.

This section considers these various concerns in turn. From our review of the comparative and general scientific evidence, we conclude that most of these concerns are unfounded. For instance, the fact that a problem exists in some circumstances (such as, industrial farming systems), does not mean that it is a fundamental problem of agriculture generally or that it applies to organic farming. Overall, the conditions for improving soil carbon levels are different and more favourable for organic farming.

9.1 Concern: 'Organic farming relies on ploughing which reduces soil carbon levels'

The use of ploughing is often held up as a concern in response to the claim that organic farming increases soil carbon, because ploughing is widely believed to reduce soil organic matter levels and degrade soils.[929] Ploughing is used to create a friable and aerated soil for good root growth[930], and to incorporate organic matter (such as grass leys and manure).[931] Organic farmers also use it to control weeds and promote humus build-up (by aerating the soil). A disbenefit, however, is that the disturbance of the soil promotes the loss of soil carbon in the ploughed layer, by breaking the soil aggregates that protect the soil carbon[932] which exposes more of the humus to the processes of mineralisation and oxidation[933]. However, this does not *necessarily* mean that ploughing reduces soil carbon levels, and it is not the case in organic farming.

Firstly, organic farming does not use at all as much ploughing as is widely assumed. Secondly, the evidence is clear that despite its use organic farming does not have negative impacts on soil carbon and its practices generally result in much higher soil carbon levels than non-organic farming. Thirdly, in organic systems, ploughing plays a positive role in building the soil carbon levels. Finally, there is now direct evidence that the use and depth of ploughing does not affect the soil carbon levels of organic farming (and perhaps also of non-organic farming in many conditions), at least in Northern Europe.

Organic farming relies on mechanical cultivation, and much of the time this means conventional deep mouldboard ploughing. Ploughing is widely used because it serves various purposes (though there is nothing in principle that requires it to be used in organic farming, if better results can be obtained otherwise). However, it is not used as frequently as is probably assumed. Most UK organic crop production is in mixed farming systems with rotational grass/cropping. Although the land is ploughed during each cropping season, organic arable land is under grass and not ploughed at all for around a quarter to a half of the time over the whole rotation.[934] This compares to non-organic crop production which is now widely based on continuous cropping, with the land ploughed either every year or, when min-till practices are used in the UK, ploughed (or subsoiled) every 3 or 4 years[935]. Additionally, there is a higher percentage of permanent grassland in UK organic farming, which is never ploughed.[936] Moreover, although this is not always the case, several researchers have observed that the soil cultivations are less intensive or less frequent on the organic farms they studied/in their region, than on non-organic farms, even in some US regions where reduced tillage has widely replaced the use of ploughing.[937]

Several trials have now investigated the use of deep ploughing in organic farming. Even if there remains a concern about ploughing in non-organic farming, these show that deep ploughing has no negative effect on soil carbon levels in organic farming in Northern Europe. Seven long-term organic farming trials in Germany compared different cultivation depths and intensities ranging from deep ploughing to 30cm, to no-till. They found no disbenefit from deep ploughing, just a different distribution of the carbon over the 30cm soil profile.[938] Similarly, in non-organic farming, while several studies have found that ploughing decreases the long-term storage of SOM[939], many researchers have found that ploughing has no significant effect, especially when the entire depth of the soil is considered (Deen & Kataki, 2003; Balesdent *et al*, 2000; Angers *et al*, 1997; Angers *et al*, 1995).[940]

Importantly, a study in Belgium has shown that if an increase in ploughing depth is adopted *at the same time* as a large increase in organic matter inputs to the soil, then the depth of the topsoil will increase and this will increase the overall soil carbon store. This comprised a detailed survey of 939 arable sites in the Belgian province of West Flanders[941]: there was a 25% increase in the soil carbon store over forty years which was explained by an eight-fold increase in slurry applications. The 25% increase was made up of a 17% increase in the topsoil SOC content plus an 8% increase by an increase in the topsoil depth. The latter was because of a 44% increase in the ploughing depth, from about 22cm to 32cm. (It is not known if the soil carbon store would have increased as much by a larger SOC % increase, if the ploughing depth had not increased at the same time as the increase in slurry applications, i.e. there is the possibility that the deeper ploughing depth allowed a greater increase in soil carbon storage than might have otherwise occurred). There were similar results in a national Danish survey - a soil carbon increase in the deeper layers of the sandy soils, though here the role of ploughing can only be guessed at.[942]

(These conclusions presumably only relate to mineral soil types and the cultivation of high-carbon 'organic' soil types will presumably cause a net loss of carbon even under organic farming, though perhaps much less than under non-organic farming.)

Importantly, even for the fragile soils of arid arable regions, such as exist in the Mediterranean and parts of the US and where tillage is particularly associated with soil erosion[943], organic farming produces higher soil carbon levels than non-organic farming (see section 6.1). It is not clear if this is despite the use of ploughing or if in many of these regions, like non-organic farming, organic farming generally makes less use of deep ploughing and relies more on shallow cultivation methods (minimum tillage or 'min-till'). Nevertheless, it is interesting that *even where* ploughing is used in such conditions, organic faming has been found to produce higher soil carbon levels than non-organic farming, according to a couple of studies. Mulla *et al* found a 52% higher soil carbon level and 62% lower erosion rate on the organic arable farm of a rolling dryland US region, despite the use of mouldboard ploughing on the organic farm after harvesting while the non-organic farm was left untilled after harvest (both used min-till methods before planting). Melero *et al* found a 138% higher soil carbon level with organic horticulture than non-organic management in the semi-arid conditions of southwest Spain; in this case, mouldboard ploughing was used on both the organic and the non-organic farms.[944]

Despite its common use of ploughing and other mechanical cultivation methods, the scientific evidence - as presented in this report - clearly shows that organic farming produces at least 20% higher average soil carbon levels on cultivated soils than non-organic farming. In a survey of nine US farming systems trials, the researchers concluded, "even though organic systems often involve intensive and frequent cultivation, they retain more SOC than conventional systems."[945]

Of the many organic farming practices that contribute to building soil carbon, ploughing is actually one. The grass ley stages in the rotation and the green manure crops are both very important for building soil carbon but they rely on ploughing to incorporate the plant matter into the soil. Additionally, by aerating the soil, ploughing promotes soil microbial activity and root growth, and so encourages humus build-up. Comparisons with shallow cultivation methods also indicate that ploughing has benefits for the subsoil carbon store below 30cm depth (see 9.2), meaning it helps distribute soil carbon to the deeper layers where the humus is much more stable. So, it can be argued that ploughing performs a positive function in producing the higher soil carbon levels of organic farming. This would be less true of non-organic crop systems which are much less likely to be introducing large quantities of organic matter when ploughing.

Overall then, the view that the use of ploughing somehow undermines the claims of higher soil carbon levels with organic farming is clearly invalid. From the organic sector's point of view, it is also worth mentioning that this concern never really made sense. Unlike non-organic farming, organic farming *relies* on maintaining and building up the soil organic matter level, as this is its source of fertility and productivity. If organic farming methods did degrade soils, organic farming would not be a viable system, and the practices would not have been adopted by the farmers and researchers who developed the system specifically to protect the soil against degradation and erosion. So, if ploughing is a weakness as regards soil carbon levels in temperate regions, it would be mainly in systems that do not introduce enough organic matter to the soil, in other words most inorganic fertiliser-based farming.

This concern appears to have been a response to the widely publicised claims of positive soil carbon effects with minimum tillage practices, although these are generally not standing up well to scientific scrutiny (see point 2). It may also be because of awareness of the past detrimental effects of ploughing. A large part of the past soil carbon losses has resulted from the ploughing-up of permanent grasslands. Additionally, ploughing has been a part of agriculture for hundreds of years[946] and it is believed that there have been gradual soil carbon losses from cultivated land throughout history[947]. However, there are other reasons why cultivated soils have lower soil carbon levels than naturally vegetated land, than just the ploughing of the soil. These reasons are the high proportion of bare soil in arable systems and because the plants are annuals, rather than permanent, and hence normally have smaller root systems.[948]

Such comparisons are also not really relevant to an assessment of organic farming. Ploughing-up grassland is not comparable to the on-going management of arable land. And, the effects of organic farming's use of ploughing are different to the historical effects of ploughing. Traditional ploughs were unlike those of today': horse-drawn ploughs were less wide and deep, and altogether less disruptive to the soil than modern 'full inversion' ploughing implements. However, traditional crop production did not involve all of the soil organic matter input practices that are used by modern organic farming. Historically, crop production involved either regular fallow periods or the land was continuously cropped. The use of short-term grass/clover leys in the crop rotation of mixed farming systems, one of the most important practices for promoting soil carbon levels, is a modern development that was not used in the UK until the 1930s.[949]

9.2 Concern: 'Organic farming does not use minimum tillage which sequesters large amounts of soil carbon'

Minimum and zero tillage[950] are widely practised in North and South America and Australia[951], where they were primarily adopted to conserve water.[952] 'Min-till' is now being used by many large arable farmers in the UK.[953] Recently, the practices have also been held up as a way for farmers to sequester significant amounts of soil carbon[954], with claims in the US that no-till builds up about 330kgC/ha/yr[955]. In the US, it is now suggested that this may offset much of the greenhouse gas emissions of farming.[956] With the industry's current enthusiasm for reduced tillage, it is sometimes even being claimed that non-organic farming may already, or can, build up more soil carbon than organic farming[957], and that organic faming is therefore not an ideal approach. Several problems have emerged with these claims.

The gains with reduced tillage are believed to come from the lower disturbance of the soil which retains the soil's aggregated structure[958], avoiding soil carbon oxidation and erosion[959]. Increase in soil carbon levels have been reported by many researchers. The reported effects are probably not as great as is assumed, however. A meta-analysis of 161 trials in various climatic conditions found that no- and min-till systems had an average of 2.1t/ha more soil organic carbon than conventionally ploughed soils (Alvarez, 2005).[960] This is not even an increase of 5% in temperate regions[961]. A meta-analysis of 80 studies of *just no-till* systems (Ogle *et al*, 2005) found that twenty years after conversion from conventional tillage, soils had 16% more organic carbon in temperate wet climates and 10% more in temperate dry climates. Thus, the claimed soil carbon benefits of reduced tillage are *no more than half,* and perhaps far less, than organic farming which is about 28% more than plough-based non-organic farming in Northern Europe (temperate, wet, cool climate) and 20% more overall, according to our review.

Moreover, it is now considered that the majority of these reported soil carbon increases from reduced tillage were actually largely an artefact of the sampling method.[962] The claims have mainly rested on measurements of just the topsoil.[963] But the soil carbon increase with reduced tillage is confined to the top 10-15cm, and sampling over deeper soil profiles does not really support the claims. The crop residues accumulate at the surface with reduced tillage, while ploughing moves the material down into the soil. Thus, the apparent gains in soil carbon found when only the topsoil is sampled often disappear when the whole soil profile is sampled (more than 30cm depth).[964] The different tillage systems therefore produce a different distribution but not necessarily a different amount of soil carbon. The research also implies that there is depletion of the subsoil carbon with no-till systems, which could be significant in the long-term as this is usually the more resistant half of the agricultural soil carbon store. This issue of distribution was unfortunately not considered by researchers for some time, resulting in very misleading conclusions.

As an example, in the nine-year trial by Michigan University (Robertson *et al*, 2000)[965], one of the farming systems was a no-till system. According to the researchers, this sequestered by far the most of any of the four systems, 300kg C/ha/yr, almost four times as much as the organic system, which was using "mechanical cultivation", 80kgC/ha/yr. They calculated that this offset 85% of the no-till system's annual greenhouse gas emissions, compared to only 39% being offset in the organic system. However, crucially, the researchers had only measured the top 7.5cm of the soil, thus greatly exaggerating the no-till soil carbon benefit and under-estimating the organic farming benefit. So, this conclusion was far from correct.

It has also emerged that many of the soil carbon gains of reduced tillage in the US were not actually due to a lower decomposition rate, but to the special circumstances of dryland agriculture. Reduced tillage is particularly recommended in semi-arid erosion-prone regions as it conserves water and strongly reduces erosion.[966] Previously, fallow-based arable rotations were commonly used in these areas to conserve soil moisture, for instance, wheat–fallow rotations used in semi-arid regions of the US. But bare fallow causes soil carbon losses and limits the productivity of the land. The introduction of reduced tillage practices improved soil water storage and enabled the fallow periods to be reduced and more crops to be grown. This both reduced the negative effects of the fallow periods and increased the crop residue inputs to the soil, overall increasing the soil carbon levels.[967] This impact is important but irrelevant to Northern Europe.

For the UK, with its greater need for ploughing to control weeds, there is the important problem that the soil carbon sequestered by reduced tillage is highly susceptible to being lost if the soil is later ploughed. This is because the accumulation of residues at the surface that occurs with reduced tillage produces a *different form* of soil organic matter. The sequestered carbon is not bound in stable organo-clay complexes as it is with stabilised soil humus, but is just contained as particulate organic matter in the sand-size soil fraction. This is easily and rapidly mineralised on ploughing[968], so any soil carbon built up under min/no-till over several years is liable to be oxidised and fall back to the starting levels if the land is ploughed.[969] For this reason, according to the IPCC soil carbon accounting guidelines, land should not be classed as subject to reduced tillage or no-till unless the practice is used continuously, since "even an occasional pass with a full tillage implement will significantly reduce" the soil carbon storage.[970]

A review of the scientific evidence on reduced tillage for the UK Government shows it is unclear whether these practices produce any soil carbon changes in the UK, and that any effect is marginal.[971] As some gains have been observed in UK trials[972], the authors concluded that their best estimate for now is that min-till probably builds some soil carbon initially, around 160kgC/ha/yr in the top 30cm in English and Welsh conditions (or 310kgC/ha/yr +/-180 for no-till, but few UK farmers use no-till[973]). There is no mention of whether the studies sampled to the soil to over 30cm or not, which is the key information. Nevertheless, the authors say that this level should anyway, "not be considered to be annually accumulative." Arable soils in England and Wales are still ploughed (or subsoiled) every 3-4 years to control weeds and disease and reduce compaction, and this may cause, "much (if not most) of the stored C" to be released again. This indicates that the effect of min-till is only very marginal in the UK, producing an average increase in arable soil carbon levels of less than one per cent of the total.[974] In addition, many studies, including a UK study, indicate that reduced tillage can substantially increase nitrous oxide (N2O) emissions, a far more powerful greenhouse gas than CO2.[975] This, "may *completely* offset" any soil carbon stored. At this stage, considerable uncertainty remains over the overall effects.

It should also be pointed out that the relevance of reduced tillage to the soil carbon debate is frequently overstated in the UK. Almost no-till is used, the system that offers the most gains. Moreover, well over half, and probably most, non-organic arable production in the UK is still based on regular ploughing. This is particularly the case in the wetter regions (North of England and Scotland), where susceptibility to soil compaction makes min-till practices less viable, but which is where more topsoil carbon is being lost from arable land.[976] Also, in Europe, rotations that include crops such as potatoes and beets normally require heavy tillage, so reduced tillage is only suitable for all-grain crop rotations.[977] Also all farmers using mixed systems will be ploughing to incorporate their grass, and farmers also plough to incorporate manure.

Therefore, based on the current evidence, the soil carbon benefit of min-till and no-till is smaller than has been claimed, and there may be little overall reduction in GHG emissions. The benefits and relevance is particularly limited in the UK. So, with the anyway proven and much higher soil carbon levels of organic farming, the general non-use of reduced tillage by organic farming clearly cannot be claimed to be a disadvantage. Nevertheless, for many farmers and particularly in drought-prone regions, reduced tillage presumably remains a good way to avoid soil organic matter losses through erosion, reduce soil compaction, conserve soil moisture and limit fuel costs.[978]

The reason why reduced tillage is rarely used by organic farmers in Northern Europe[979] is because the wet conditions mean weeds build up and become too difficult to control in the absence of ploughing or the use of herbicides[980], and because of the many benefits of ploughing (see point 1). However, it is worth noting that it is nevertheless attractive in principle to organic farmers, not necessarily for soil carbon reasons, but because ploughing has various drawbacks: it can cause the development of plough-pans[981] and soil compaction, and 'inversion' ploughing is detrimental to vertical burrowing (anecic) earthworms[982] and destroys the stratified layers of soil life that develops in an undisturbed soil. Some farmers and researchers are therefore experimenting to develop approaches for European conditions. For instance, an organic farmer in Wiltshire claims to have successfully developed a viable 'non-inversion' tillage system.[983]

Reduced tillage seems to be used a bit more commonly by organic farmers in the Americas. For instance in the study by Mulla *et al* (1992), both the organic and non-organic farms used min-till before planting (though the organic farm used ploughing after harvest). And, in the nine US farming trials surveyed by Marriott & Wander (2006), at least two of the organic farming systems were using min-till methods.[984]

The available evidence from the US shows that organic systems using reduced tillage produce even better soil carbon results than non-organic systems using reduced tillage. A seven-year trial in Nebraska of organic and non-organic systems in which disking was used as the primary tillage method in both systems, found a 22% higher soil carbon level over 30cm soil depth on the organic than the conventional system (Fraser *et* al, 1988). This tillage method was described as standard practice for the region.[985] A nine year US Government-funded trial compared three non-organic no-till systems with an organic min-till system (Teasdale *et al*, 2007, 1994 – 2002, Maryland). The location was a sloping, drought-prone site that was typical of region and of the conditions where reduced tillage practices are recommended. Due to its higher organic matter inputs, the organic system produced a much higher soil organic carbon level than the non-organic systems (the difference was statistically significant)[986] and a very high overall rate of carbon sequestration of 1,829kgC/ha/yr, compared to no increase in the conventional no-till system.[987] The organic system had 24% more soil carbon in the top 0-7.5cm and 44% more in the 7.5-30cm layer.[988] The researchers concluded, "These results suggest that OR [organic farming] can provide greater long-term soil benefits than conventional NT [no-till], despite the use of [minimum] tillage in OR." However, the organic system ended with severe weed problems and yielded 28% less maize.[989]

Since 2003, the Rodale Institute in Pennsylvania claims that it has developed an innovative and apparently successful organic no-till system. This is sequestering high levels of soil carbon and controlling weeds by the intensive use of cover crops which are rolled onto the ground.[990]

Nevertheless, in line with the evidence from non-organic farming, trials of reduced tillage in organic farming in Northern Europe show there is no soil carbon benefit over the whole soil profile, compared to the use of ploughing in organic farming. This was the finding of a review of seven long-term organic farming trials in Germany comparing different cultivation depths and intensities, from deep ploughing to no-till.[991] For instance, a nine-year organic farming trial compared the soil carbon levels over 0-30cm for four cultivation systems (ploughing to 30cm, two-layer ploughing with turning to 15cm and break-up 15-30cm, a less intensive version of the two-layer system, and min-till with a cultivator and rotary harrow to 30cm maximum). All the results were close (1.241% to 1.285% soil carbon content) and full ploughing to 30cm actually produced the highest soil carbon level (though the min-till system was very close).[992]

Therefore, it cannot normally assumed be that any positive soil carbon effects of organic farming using reduced tillage, compared to non-organic farming, is necessarily due to the effect of the reduced tillage. It may be just the effect of organic farming anyway, especially where the difference is similar in scale to the differences found generally in this review of comparative studies of organic and non-organic farming.

It should be noted, however, that the Swiss research organisation, FiBL, has reported positive results with a successful reduced tillage organic farming trial that started in 2002. After two and a half years, the reduced tillage system (using a chisel plough to 15cm) had produced a 7% soil carbon increase in the top 10cm and no change in the 10-20cm layer.[993] This gave a sequestration rate of 814kgC/ha/yr.[994] In comparison, standard mouldboard ploughing to 15cm depth showed no significant change in either layer.[995] More recently, in 2009, the researchers have reported a similar sequestration rate of 879kgC/ha/yr for the reduced tillage system and none of the ploughed system.[996] However, the sampling in this trial was only to 20cm, so the findings are questionable, especially as there was a 30% or so higher level of vertical burrowing earthworms on the ploughed plots[997], which may have distributed the soil carbon over an even deeper profile. The reduced tillage system also received almost 100kg/ha/yr more organic matter than the ploughed system.[998] The team will now be taking more detailed measurements on the whole of the soil profile in a new series of trials on several farms.[999]

Further research is needed of reduced tillage in organic farming, with care taken to ensure the full, deep soil profile is sampled, that N_20 emissions are measured, that the results are interpreted in the context of the climatic and agricultural conditions of the region, and that the viability of the systems are considered.

9.3 Concern: 'Higher yielding farming systems increase soil carbon levels'

It has been argued that the higher yields of non-organic farming must mean greater quantities of crop residues are being added to the soil[1000], so soil carbon build-up must be higher than with organic farming. This is sometimes also cited as a benefit of inorganic fertiliser use.[1001] Not only has this has become a somewhat popular view in the farming industry, but soil researchers and modellers also routinely assume that soil carbon levels are proportional to crop yields in their evaluations of the effects of agriculture.[1002]

As a generalisation, we believe this is totally incorrect. There is considerable evidence to show that a direct yield-soil carbon relationship is not a basic principle of agriculture. Both the history of agriculture[1003] and any comparison of European organic and non-organic farming, indicate that in practice crop yields are more often a *negative* indicator of soil carbon levels. Arable yields have been increasing for years, but the carbon level of cultivated soils is the lowest of all soil types (except deserts and semi-deserts). Modern high-yielding, intensive systems that use continuous cropping have much lower soil carbon levels than traditional mixed farming systems. The comparative evidence for organic farming in Europe also shows a negative correlation: non-organic farming has roughly 30% higher yields but only about 75% of the soil carbon levels of organic farming. (Note, an inverse relationship is not a basic principle, either).

An authoritative experimental example that disproves a positive relationship is the Rothamsted Broadbalk winter wheat trial, which started in 1843 and is the longest continuous arable trial. The trends in yields and soil carbon levels bear no relation to each other. Although the yields levels had increased greatly by the end, practically *no increase* in the soil carbon level occurred over the whole trial on the plots receiving inorganic fertiliser, while the manured plots produced large soil carbon increases for decades.[1004] Similarly, topsoil carbon levels fell continuously with the use of inorganic fertiliser and the use of dairy slurry in the long-term Askov trial in Denmark; and the soil carbon levels were no higher with the higher inorganic fertiliser application rate, "despite the significantly higher yields of the harvested crops."[1005]

There are also good examples from the comparative literature on organic farming. In the 18-year Swedish study by Kirchmann *et al*, 2007, the organic system had only half the yields of the non-organic system, but had 32% higher soil carbon levels (section 6.1). So, a focus on yield levels is not a suitable way of assessing the effects of different farming systems on soil carbon levels.

Despite this evidence, soil researchers commonly state that agricultural 'productivity' is one of the main determinants of soil carbon inputs in agriculture.[1006] For instance, in an extensive review, Lagreid (2002) concluded that increasing cropping intensity leading to increased yields, will eventually lead to increases in soil carbon.[1007] A 2004 European review on land management and soil carbon also states, "Most studies agree that mineral fertilization increases yield, consequently litter input, and consequently SOM."[1008] Clearly, a much closer examination of the evidence and consideration of the issues is needed.

A relationship between 'productivity' and soil carbon seems true of natural ecosystems, where greater growth means larger plants with larger roots, and so greater organic matter returns to the soil. However, 'yields' in agricultural systems are not at all equivalent to plant 'productivity' in natural systems. In agriculture, yield levels are the portion of the plant that is that harvested and *removed* from the farm, so yields are the compliment of the amount of plant residues added to the soil. Non-organic systems have actually achieved their higher yields partially by reducing the remaining biomass - the straw length, below-ground root system, grass leys – by using inorganic agrochemicals instead of organic inputs to the soil.[1009]

It is true that there are certain agricultural practices that, in certain conditions, increase yields in ways that *also* generate higher inputs of crop residues to the soil and so increase soil carbon levels.[1010] It appears that these specific cases have wrongly given rise to the view that higher yielding systems *in general* improve soil carbon levels, and to suggestions that it is advisable to use inorganic fertilisers. For instance, in unfertilised or degraded soil conditions where nitrogen is limited, fertilisation will increase overall plant growth and soil carbon levels.[1011] Similarly, in arid conditions, irrigation increases crop growth and can increase soil carbon levels.[1012] Importantly, it appears that much, possibly most, of the evidence that suggests that 'yields' or mineral fertilisation increase SOM are actually from such situations. For instance, an example cited by the European review quoted above is an Austrian study that found an average 2.1t/ha higher SOC level from optimal mineral fertiliser use *compared to unfertilised sites*, after 36 years.

There are a couple of major problems with this. Firstly, the evidence for soil carbon gains with the use of mineral fertiliser appears to have been greatly over-stated. For example, the 2.1tC/ha increase found in the Austrian study is very small, an increase of almost certainly less than 5% of the SOC level.[1013] There are also *many* studies that have shown that the use of inorganic fertiliser alone does *not* increase SOM levels (Leigh and Johnston, 1994, Jenkins *et al*, 1994, Raupp, 1991 and many others[1014]). In a review of long term farming trials around the world, the effect of mineral N fertiliser use on SOC levels was found to be minimal[1015] (contrary to the impression given in advice to the UK Government[1016]). European researchers have also noted that in improved grasslands, the relationship between soil carbon levels and the level of N fertiliser applied is actually negative, with the highest soil carbon increases occurring at low to moderate N fertiliser rates (presumably below the levels commonly used in Northwest European dairy farming), rather than at high rates, since the growth of root systems is greater in conditions of N stress.[1017]

Secondly, even in the specific situations cited, positive effects of fertiliser use are not actually arguments for the use of mineral fertiliser, 'high-yielding' systems, or 'intensive agriculture' (as understood in the conventional sense of greater use of agrochemicals or more industrial models of farming). The key factors are simply the use of some fertilisation (in general) and better soil water supply. Organic farming also greatly improve these factors (if required, irrigation can also be used) and, whatever its relative yields, is normally a far better option as it also improves many of the other aspects that promote soil carbon levels. Moreover, in the humid tropics, where the soils are predominantly acid, the use of inorganic ammoniated fertiliser has been found to be less effective in raising agricultural productivity than in temperate countries[1018], and inorganic fertilisers can even lead to yield declines in dry areas and drought seasons[1019].

We suggest that much of the confusion over this issue may be blamed on the use of unfertilised soils as a control, which is highly misleading, particularly in a UK and North European context. In the UK, and we believe in most western farming situations (and probably many other countries, such as China), practically all arable land and most improved grassland *is* fertilised, and the agricultural soils suffering from low soil carbon levels are often receiving high levels of fertiliser. So, it cannot be suggested that the problem of low soil carbon levels in these regions can somehow be addressed by fertilisation. Fertilisation in western agricultural systems is a non-negotiable given that it is a basic requirement for good agricultural productivity. (And even in natural ecosystems, soil is fertilised as the land is vegetated and supplying root exudates, detritus and excreta from grazing animals.) So, the real comparison that is needed to inform policy decisions is not the use of fertilisation *per* se, but comparisons of different fertilisation methods.[1020]

This review has shown that organic fertilisation, in contrast, *does* substantially raise soil carbon levels. Also, contrary to popular opinion, organic yields in many parts of the world are actually similar to non-organic farming levels (North America[1021]) and may on average be higher than inorganic fertiliser-based systems in developing countries, as organic fertilisation methods based on composting produce similar yields in average conditions in these countries but better yields in drought periods[1022].

A key point is that any narrow consideration of the effects of N fertiliser and 'intensive' agricultural practices on crop residue levels, risks over-looking the crucial wider 'knock-on' impacts on agricultural systems that start to occur once a reliance on inorganic inputs is introduced, including the simplification of rotations (continuous arable cropping instead of complex rotations with legumes and grass leys), undesirable side-effects on the extent of root systems etc., that we have tried to highlight in this report.

Each farming system affects the level of the non-yield biomass and the nature of the organic matter additions in very different ways. Generally, the more organic matter that is added, the more soil carbon levels rise.[1023] However, there is good evidence that soil carbon levels are not just - or sometimes at all - related to the amount of biomass produced. For example, in the long-term Rodale Institute trial in the US, the organic and non-organic systems had similar yields and supplied similar amounts of above-ground carbon input to the soil, but the organic systems produced significant increases in soil carbon, while there was little change in the non-organic system which relied on the incorporation of crop residues. Thus, in practice, soil carbon levels also strongly depends on other factors that determine how likely the carbon input will form stabilised soil carbon (see next point 4 for more details).

Discussions about increasing organic matter inputs to arable land have often focussed on crop residues, for the reason that they are often the only source of organic matter in intensive, continuously cropped systems based on inorganic fertiliser - what are normally considered intensive, 'high-yielding arable systems.' However, these systems are actually very ineffective at raising soil carbon levels as crop residues are the main type of organic matter that is *least* conducive to raising soil carbon levels. While small annual increases have been found in many trials of around ten years, additions of crop residues have often been found to have limited impact on soil carbon levels in long-term studies (and in some cases no effect at all) – see 7.5.[1024] Numerous studies over decades show that the incorporation of crop residues initially has 'a priming effect' on (promotes) the mineralisation of soil carbon.[1025] Cereal crop residues also tend to decrease soil aggregate stability[1026]: the carbohydrates in fresh crop residues are only able form soil aggregates strongly for a few weeks[1027] and cereals (such as wheat and maize) do not support high levels of fungal mycorrhizae which appear to be important for aggregating soils.[1028] This reduces the protection of humus. So, 'industrial' arable systems that rely on the incorporation of fresh crop residues cannot easily stabilise and build-up soil organic matter, compared to systems that use other organic materials.

Similarly, intensive, high-yielding livestock systems tend to produce animal waste in slurry form, rather than as solid manure. Slurry does not appear to have very positive effects on soil carbon (see 7.3).

In contrast to crop residues and slurry, the alternative organic matter types that are used in organic farming and many traditional farming systems - grass leys, farmyard manure, leguminous cover crops and compost - have been clearly shown to promote soil carbon accumulation and must therefore not be overlooked. Additionally, the size of root systems and the continuity of vegetation cover (and perhaps use of pesticides) are also factors that have been shown to influence the soil carbon level – see Chapter 7. Thus, how a farming system affects all these aspects is probably far more important for assessing the soil carbon storage impacts of farming systems than how much crop biomass or yield the system produces.

Unfortunately, the level of the harvested crop yield is being widely used by soil carbon modellers as the main indicator of the soil carbon level, with often little account taken of the farming system. Most estimates of past, current and future farmland soil carbon levels are calculated from models that use yield levels to estimate the soil carbon input level.[1029] For instance, researchers generally assume that the root biomass levels parallel above-ground plant biomass levels[1030], which they often assume depends on the crop yield. This neglects differences in the more important soil carbon inputs in agriculture: the root:shoot ratio, grass leys, manure, cover crops etc., and other factors that influence the stability of soil carbon.

In the UK greenhouse gas inventory, which excludes all other affects of agricultural practices on carbon stocks, there is even an assumption of an annual increase in the UK's cropland carbon stocks, "on the assumption that the annual average standing biomass of cereals has increased linearly with increase in yield between 1980 and 2000." [1031] This may not be the case.

Despite its inappropriateness for assessing farming systems, this approach is being used to inform the debate on the effects of farming practices on soil carbon levels, and even by some researchers to assess the comparative effects of organic and non-organic farming. For instance, a 2004 study to predict the effects of organic and non-organic farming on future soil carbon stocks, used the CENTURY soil model and based a large part of its assessment on a yield-soil carbon relationship, even though the model's standard crop growth parameters do not distinguish between organic and non-organic systems.[1032]

In a different way, this issue is also a major flaw of the 'ecological footprinting' methodology for assessing CO_2 emissions from farming (including organic versus non-organic farming). It also assumes the land carbon store impacts of farming depend on the crop yield. However, it calculates this by estimating the theoretical impacts of farming on the global forestry carbon store: it assumes that any farmed area means there is less land area available globally for newly planted forest to absorb CO_2, and the reduction is inversely determined by the crop yield level.[1033] In fact, it does not recognise the effects of farming on the soil carbon level at all, even though the global soil carbon store is much larger than the forestry carbon store. For European organic farming, given its lower yields, this approach is particularly misleading.

This situation is concerning as it is so very misleading. In our view, the issue needs to be corrected further assessments and recommendations to Government and industry are made of the potential for agricultural soil carbon storage and of the effects of different systems.[1034]

9.4 Concern: 'High organic matter additions have little effect on soil carbon levels'

Government officials have expressed scepticism of the potential for farming to sequester significant levels of carbon, citing the poor results of experiments where large quantities of organic matter were added to soils over a period but little was found to have converted into SOM.[1035] A view has also been expressed by European advisers that, as all organic matter applied to the soil has derived from plants, often with large carbon losses via an animal production stage, consequently, "no net positive effect of organic fertilization regarding SOM is expected," although best use should be made of agricultural residues nonetheless.[1036]

We are confident that this concern is wrong and that these views disregard the fact that very different amounts of soil carbon can be produced by organic matter additions and also that root systems and soil biology, rather than above-ground applications, may be much more important. The results of soil carbon sequestration attempts in trials that do not use organic farming practices are no indicator of the effects of organic farming (or indeed of agriculture generally). There is a large body of evidence that organic farming successfully produces higher soil carbon levels (28% higher in Northern European conditions), and this is achieved largely by introducing organic matter to the soil. It is not completely clear if organic farming always adds more organic matter than non-organic farming (though this seems to be true in many cases, such as with UK mixed farming systems using grass leys). However, the available research clearly indicates that organic farming tends to produce more soil carbon per unit of organic matter addition than non-organic systems, in some cases many times more. This cannot be over-looked.

For example, in a paper published in Nature[1037], an analysis of the first 15 years of the Rodale Institute trial showed that several tonnes of above-ground crop residue input each year in a typical non-organic arable system only produced a small (and statistically non-significant) increase in soil carbon (+147kgC/ha/yr), but the *same amount* of input produced significant levels of soil carbon sequestration in the organic systems (+440kgC/ha/yr in the organic arable system which had green manure crops, +800kgC/ha/yr in the organic dairy system where manure was also applied). This was confirmed again after 21 years of the trial, where the same level of above-ground carbon input (3tC/ha/yr) had produced an average soil carbon sequestration rate of 574kgC/ha/yr in the organic arable system, but only 293kgC/ha/yr in the non-organic system. And with just 12% more above-ground carbon input, the organic dairy system was sequestering an impressive 981kgC/ha/yr.[1038] So, the organic systems were sequestering *two and three times* as much soil carbon in relation to the above-ground carbon input, than the non-organic system.

An even greater difference was found in a ten-year trial in California (Kong *et al*, 2005[1039]), where the organic cropping system was, "disproportionately accumulating SOC" relative to its carbon input level. It received an estimated 70% more carbon input (above- and below-ground crop and cover crop biomass plus composted manure), but had a sequestration rate 14 times greater than the equivalent non-organic system where the carbon inputs consisted only of crop residues. This means that, per unit of biomass carbon input, it was sequestering *eight times* as much soil carbon than the non-organic system.[1040]

Many of the reasons for these differences have been identified and explained by the available scientific evidence. It is an established principle that, all other factors being equal (e.g. soil type and climate), soil carbon levels may increase in proportion to the amount of organic matter input to the soil.[1041] However, the evidence shows that this alone is too narrow an approach to take for raising agricultural soil carbon levels. The extent to which the soil carbon input will build up the soil carbon store also depends greatly on the *type* of organic matter. A recent review of the evidence on the effects of different organic matter types for the UK Government (Bhogal *et al*, 2007[1042]) showed that there is a very wide range of effectiveness, with the soil carbon conversion rate (the proportion of the soil carbon input converted to stable soil carbon) ranging from just 7% for cereal straw, to 23% for manure, to 50% for green waste compost (without N fertiliser use), in English conditions.[1043] There are also some indications that the form of livestock manure is important, with farmyard manure having much better effects than slurry – see 7.3.

This is because the type of organic material - its biochemical composition - determines other key factors that influence soil carbon sequestration: the level of resistant compounds in the material (lignin content[1044]), its C:N ratio[1045], and its ability to form stable aggregates, whereby the humus is then protected from degradation and can accumulate. Thus, some organic matter types are relatively ineffective at increasing soil carbon levels – especially, cereal straw, while other types are highly effective – such as, grass and compost.

The *below-ground* organic matter input - root systems, appears to be particularly important for soil carbon levels, as this provides substantial additional soil carbon input, has twice the lignin content of the above-ground parts of the plant, and is very effective at promoting soil aggregation (see Chapter 2 for details).[1046] So, farming systems that increase above-ground biomass input but neglect or inadvertently decrease the below-ground carbon input, may not achieve the results expected. The use of grass leys, deep-rooting species, green manure crops, and non-use of inorganic N fertiliser are all practices used by organic farming to increase the amount of roots in the soil. Research also indicates that the proportion of the time that the soil is covered by vegetation makes a large difference to soil carbon levels, so the use of winter cover crops in organic farming is also very valuable (e.g. see Rodale Institute trial below).

Arable crop residues are not an effective type: their incorporation into the soil tends to decrease soil aggregate stability and promote the mineralisation of soil carbon (see point 3). In contrast, as explained in Chapter 7, grass leys and manure (which both have higher levels of lignin than arable crops) and practices that increase root systems, increase the input of lignin and are much better at building the soil carbon store. Grass, clover, and green manure crops are also good as they support higher levels of fungal mycorrhizae than cereal crops, so they are more able to form stable aggregates and increase soil carbon levels.[1047] Moreover, well decomposed, composted materials produce long-term stabilisation of soil aggregates, as they contain humic substances that are stable binding agents of the soil particles (see 7.12). Green manure crops also promote aggregate stability and, even if the effects are short-term after they are ploughed-in[1048], they are better than[1049] and additional to cereal residues. The type of crops grown may also affect soil carbon storage as each species has differences in root growth, timing and level of root turnover/exudates, biochemical composition, and in the microbial community (so, more diverse rotations tend to include more suitable species, such as legumes, than continuous arable cropping).[1050]

In the Rodale Institute trial, research suggested that most of the difference in soil carbon levels between the organic and non-organic systems were probably due to the 70% plant cover of the organic systems (from the use of over-winter cover crops), compared to only 40% cover in the non-organic systems. This resulted in much higher fungal mychorrizal levels in the organic systems (see section 7.7).[1051] In the Californian trial, the key factor seemed to be the use of composted manure versus only crop residues.

The animal stage, however, cannot be presumed to be a negative factor. Indeed, in mixed organic farming systems - the normal system of organic farming in the UK and Northern Europe - the use of grazing ruminant livestock is a central and critical method for improving soil organic matter levels. Grazing promotes the growth of grass roots and livestock convert grass and straw – above-ground parts of plants – into manure/farmyard manure, all important components of good agricultural soil management (see Chapter 7). The economic role of livestock in raising soil carbon levels also cannot be overlooked, as the income from the livestock products enables the inclusion of a 1-4 year soil carbon-building grass/clover stage in the rotation to be economically viable (and also ensures that all land is producing food at all times). This is how mixed farming systems produce much higher soil organic matter levels in the cultivated stage of the rotation than non-organic farming systems using continuous cropping. (It should be noted that these arguments do not apply to white meat – pigs and poultry. These animals do not contribute to raising soil carbon levels and in fact simply increase the area of low-carbon arable land. This is a reason why the organic movement advises a much lower consumption of white meat.)

Thus, organic farming is much better at building up soil carbon levels as it, not only often increases organic matter inputs and provides a more favourable environment for the soil organisms that create the soil's aggregates but, instead of just relying on the incorporation of crop residues, it changes the balance of the soil carbon inputs to include much greater levels of the more effective types.

So, soil carbon sequestration is not just a question of the quantity of organic matter additions, but depends on the type of organic inputs produced (such as legumes and manure, rather than just crop residues and slurry), the level of below-ground biomass produced by the system (e.g. grass leys are important sources), and having favourable conditions for long-term soil carbon stabilisation (such as, continuity of vegetation cover). Organic farming addresses all of these factors.

9.5 Concern: 'Mineralisation rates may be higher under organic farming'

The concern has been expressed that the higher microbial activity of organic systems might mean more soil carbon is lost by mineralisation[1052] than in non-organic farming.[1053]

Based on the large body of comparative evidence presented in Chapter 6, showing that organic farming generally produces substantially higher soil carbon levels in cultivated soils than non-organic farming (with no study finding it produced a lower level[1054]), this concern is clearly unfounded. The scientific evidence on the biological processes behind soil carbon sequestration explains why higher soil microbial activity does not mean there is any disadvantage for soil carbon sequestration, and why it instead tends to promotes higher levels. This is because soil microbial activity is a function of the factors that produce the soil carbon store: the rate of soil carbon input (released from decomposing organic matter) and the stabilisation of soil carbon, factors that are both known to be enhanced in organic farming.

Soil microbial levels and activity are indeed generally higher in organic farming systems, as the evidence summarised below confirms. There is also a faster rate of soil organic matter decomposition and nutrient release in organic farming, as a result of this higher microbial activity (Marinari, 2007; Vazquez *et al* , 2003; Armstrong Brown *et al*, 2000).[1055] This is actually very important for the productivity of organic farming, as the system relies on the efficient decomposition of fresh organic matter in the soil (ploughed-in grass/clover leys or green manure crops) for releasing nitrogen and other nutrients for fertility, instead of inorganic fertilisers.[1056] However, it is also the case that a greater microbial biomass generally means a greater soil carbon level. Researchers have shown that there is a close positive association between soil microbial and soil carbon levels (Jenkinson & Ladd, 1981)[1057], and this holds true as regards the evidence for organic farming (see below). The microbial biomass also generally increases as a proportion of the total soil carbon in soils with increasing humus levels (and decreases in soils that are being exploited).[1058]

Organic farming therefore tends to increase the rates of *both* organic matter decomposition and soil organic matter (carbon) stabilisation at the same time.[1059] This apparent paradox is because microbial activity is the driver of both processes (actually, one of the several drivers of soil carbon stabilisation, others relate to the organic matter type and soil type). Conceptually, there are two main pools of soil carbon: the 'active' pool of decomposing fresh organic matter, and the stabilised carbon pool of humus associated with the soil's mineral particles.[1060] The rate of turnover of the carbon in the first pool is high and this pool is therefore involved in most of the microbial transformations of organic matter in the soil; the rate of cycling of carbon in the second pool is slow. Although microorganisms break down organic matter and release carbon, they also help stabilise a portion of the soil carbon input so that some carbon enters and stays in the second pool, instead of just passing through the first pool.

Microbes mediate this carbon stabilisation process by aggregating the soil, and generally soils with a higher microbial biomass stabilise more carbon[1061]. Polysaccharide gums produced by the microorganisms and networks of mycorrhizal fungal hyphae, bind the soil particles into aggregates which then encapsulate and protect humus from the decomposers (Elliott, 1986; Oades, 1988).[1062] This 'occluded' portion of the soil carbon is more stable than 'free' soil carbon, enabling carbon to accumulate.

However, the aggregates themselves also need to be stable if they are to protect their associated soil carbon and produce lasting increases in soil carbon. Aggregate stability is greatly influenced by the type of organic matter, a factor which organic farming addresses – see previous point. Additionally, it appears to be influenced by the soil fungal mycorrhizal levels, which organic farming promotes: root-derived carbon is especially important for building the soil carbon store[1063] and it has been suggested by researchers that mycorrhizal fungi largely control the stabilisation of root carbon in the soil.[1064]

Thus, a 'biologically active' soil is better predisposed to produce aggregate stability (Watts *et al*, 2001[1065]), and there is generally a correlation between the level of soil aggregation and the soil carbon level.[1066] This in turn means such a soil is better predisposed to produce soil carbon stabilisation and sequestration. Levels of vertical-burrowing earthworms (like the common earthworm) may also help by moving more carbon to the deeper soil layers, where carbon lasts longer. Soil organisms therefore play a positive role in soil carbon storage, and organic farming appears to boost many of the relevant factors.

In the evidence we have reviewed, the higher microbial level and/or activity of organic farming is associated with higher soil carbon levels in all but two cases, and never lower levels.[1067] Interestingly, the relationship seems to be linear, with frequently an approximately 10% increase in soil carbon content for each 20% increase in soil microbial biomass levels. For example, in a study of an experimental farm in Germany, although all plots were in the same crop rotation, the organically managed plots had 22% higher soil microbial levels and 11% higher soil carbon levels than the non-organic plots (Friedel et al, 2000). In a US farm survey, the five organic fields had a 44% higher soil microbial biomass level and a

22% higher soil carbon content, than the five non-organic fields (Liebig & Doran, 1999).[1068] A survey of organic and non-organic tomato fields in California found that the rhizosphere (root zone) soils[1069] of organic tomato plants had a greater microbial activity (though total bacterial and fungal abundances were similar) and the organic fields had 28% higher soil carbon levels, than the non-organic tomato plants and fields (Drinkwater *et al*, 1995[1070]). In a seven-year trial in the US, the organic system produced a 7.5% higher soil microbial biomass and 22% higher soil carbon level than the 'conventional' non-organic system (Fraser *et al*, 1988). In an Australian trial of vegetable production, the organically managed plots had a 46% higher microbial biomass carbon level and 24% higher soil organic carbon content than the conventionally farmed plots (Wells *et al*, 2000).[1071] The Swiss FiBL DOK trial found that the biodynamic plots had 35% higher microbial levels and 15% higher soil carbon levels after 21 years than the non-organic 'integrated' plots, even though they had the same crop rotations and same manure/slurry input level (unlike the biodynamic plots, the integrated plots received inorganic fertilisers and pesticides).

In the Swiss trial, the standard 'organic' (i.e. not the biodynamic) plots had the same soil carbon levels as the two non-organic systems after 21 years, despite having 17% and 44% higher microbial levels than each respectively, i.e. there was *no negative effect* from having a higher microbial level (though apparently no positive effect either in this case).[1072] Similarly, an Italian study found that an organically managed field had 70% higher soil microbial levels than an adjacent non-organically managed field, but the soil carbon levels were "not different" (Marinari *et al*, 2007).

Although soils with a higher microbial biomass generally stabilise more soil carbon, they also 'respire' more in the process[1073] (release more carbon as CO_2). Soil respiration includes both respiration by the living organisms in the bulk soil ('heterotrophic soil respiration'), and also the respiration by the plant roots and root 'rhizosphere' zone.[1074] The first reflects the activity of soil microorganisms. It is assumed to reflect the rate of decomposition of soil organic matter (soil carbon losses), but evidently this also reflects the higher level of soil carbon stabilisation (sequestration) occurring alongside. Plant root/rhizopshere respiration reflects the size of the plant roots and activity of the root zone. This may be higher in organic farming because of the much greater reliance on symbiotic relationships between the crop root and microorganisms (N-fixing bacteria in the root nodules of legumes and fungal mycorrhizae), and larger root systems. While this would mean additional losses of carbon from organic farming systems, these aspects are also a positive source of carbon inputs to the soil (root exudates etc.) and of soil carbon stabilisation. In fact, research shows that soil carbon levels are linearly related to soil average respiration rates.[1075]

The evidence indeed shows that soil respiration rates are higher in organic farming and that, in all cases reviewed, soil carbon levels are also higher. For example, in the Rodale Institute trial in the US, after ten years, despite similar levels of above-ground carbon input (and similar crop yields), the soil respiration rate was "significantly higher" in the organic systems: 138% more in the maize plots than the non-organic system.[1076] However, carbon sequestration was also much greater: the soil carbon levels ended 20% and 25% higher in the organic arable and dairy systems respectively than the non-organic system, after 21 years.[1077] In the US study of five farm pairs (Liebig & Doran, 1999), soil respiration was "consistently greater" on the organic farms: they had a 37% higher soil respiration rate (from field measurements taken within and between the crop rows), as well as a 22% higher soil carbon content and greater topsoil depth than the non-organic farms. The higher soil respiration rate was considered evidence of a "more active microbial population." Likewise, an 18-year trial in the Netherlands (Pulleman *et al,* 2003) found that the topsoil of the biodynamic field had both a 70% higher rate of CO_2 emission[1078] (measured via a 35-day soil incubation study) and a 60% higher soil carbon level than the non-organically managed field. Also, a six-year trial in Spain (Melero *et al*, 2006[1079]) found that the organically managed plots had a 27% higher soil respiration rate, but produced a 138% higher soil carbon level (and 66% higher yields).

(It should be noted that if field measurements are taken from fields which were being cropped at the time, and especially when taken within the crop rows, then it is presumably not clear whether higher soil CO_2 emissions are from higher heterotrophic soil respiration - i.e. represent soil organic matter decomposition - or from higher *plant root/rhizosphere* respiration, or both. In the case of the Melero *et al* study, the much greater productivity of the organic system implies that the organic crops had a much greater root biomass, suggesting that root respiration was probably the reason for the higher soil respiration rate in this case.)

Interestingly, while organic farming has higher soil microbial levels and apparently more biologically active soils than non-organic farming, it tends to have *lower* soil microbial respiration rates – the rate of CO_2 emission per unit of soil microbial biomass. In the trial by Melero *et al*, the organic plots also had a 117% higher soil microbial level than the non-organic plots. So, the fact that the soil respiration rate was only 27% higher and presumably has to cover the greater plant root respiration rate of the organic system, implies that the system had a lower (perhaps much lower) soil microbial respiration rate than the non-organic system.[1080] Similarly, an incubation study found that soil from an organic arable system had a 45% greater soil microbial biomass than a non-organic arable system over the monitoring period, but the microbial respiration rate was 25% lower than the equivalent non-organic systems (though such studies may not exactly reflect real soil conditions).[1081] Hopkins & Shiel also found that in grassland plots managed conventionally with inorganic fertiliser, the smaller microbial biomass respired at a greater rate than plots treated with manure.[1082]

One study, however, found the opposite, a higher soil microcial respiration rate: in a study by Fraser *et al*, 1988, the organic system had a 47% higher soil respiration rate than the 'conventional' continuous maize system in the top 7.5cm of the soil (246mgCO_2/kg soil vs. 167mg/kg over a day) but only an 18% higher soil microbial biomass in the same layer (though the numbers of bacteria and fungi organisms were about 50% higher).[1083] This was largely accounted for by the inclusion of an oat/clover crop in the organic rotation (which produced a higher microbial level and activity even on separate non-organically managed plots). Nevertheless, this 47% higher soil respiration rate not was at all indicative of a net soil carbon loss, as the organic system had a 50% *higher* soil carbon content in the top 7.5cm of the soil.

Organic farming has higher levels of soil microorganisms and microbial activity probably due to the combined effects of several factors, including a greater and more continuous supply of soil organic matter inputs, use of legumes and manure, non-use of pesticides and higher soil moisture levels – see Section 7.7. For instance, the use of legumes for soil fertility tends to increase soil microbial levels due to the greater below-ground supply of nutrients, compared to inorganic fertilisers applied on the soil surface.[1084]

The often lower microbial respiration rate may also indicate that organic farming produces more developed microbial populations. Microbial CO_2 emissions are meant to decrease as ecosystems mature and increase in species diversity[1085], as the more efficient competition for nutrients reduces losses, and perhaps longer, more complex food chains mean there is more cycling of carbon within the community before it is lost to the environment.[1086] Greater microbial diversity could arise from the larger and more stable carbon supply in organic systems (more constant plant presence from the leys and cover crops, allowing more a mature soil ecosystem to develop), the non-use of pesticides (which may affect some species) and the greater diversity of plants grown in organic farming rotations and grasslands[1087].

It is, finally, perhaps worth emphasising that it would anyway even in principle be extremely unlikely that organic farming could have the effect of reducing soil carbon levels because of a higher rate of organic matter mineralisation, as the system fundamentally relies on maintaining and promoting soil humus levels. While non-organic farming can function (in the short-term) without maintaining soil humus levels, as it uses inorganic fertilisers for productivity, humus levels and healthy soils are the main source of productivity in organic farming. So, any system that produced a higher overall rate of humus degradation than most non-organic systems, could not be a viable method of organic production. In our experience, biologically healthy ecosystems are usually characterised by higher species diversity and biological activity, and this quality helps to maintain ecological balance and, if anything, gradually increase the system's biological resources. Organic farming is therefore generally good at promoting both high microbial and high soil carbon levels, as these aspects are related and this is what the system is designed to do.

In conclusion, while the decomposition rate of fresh organic matter and soil carbon cycling in general may be higher, the higher soil biological activity of organic farming systems - plus the more favourable types of organic matter produced - means that organic farming systems are at the same time more disposed to form stable aggregates and build soil carbon levels, as proven by the body of comparative evidence.

9.6 Concern: 'Is organic farming producing soil carbon 'additionality' or just 'importing' extra carbon?'

One concern is whether the higher soil carbon levels on organic farms are a result of organic farmers using organic materials from non-organic farms, such as manure, thus transferring carbon from the non-organic to the organic sector and not necessarily producing 'new' soil carbon.[1088] If this was the case, there might be no real soil carbon benefit from organic farming at a national level. There was a similar reasoning in a 2007 review of soil carbon and organic matter for the UK Government.[1089] The authors concluded that the greater use of organic matter by any farmers – such as, manure, straw or biosolids - could not increase overall arable soil carbon levels because most of the available organic matter is already being applied, so this would just be moving the material between farms. A related concern is that any significant reliance on products from the non-organic sector - and any associated soil carbon gain - would not be possible in a situation of widespread organic farming, as these additional sources would then no longer be available.

This seems to be a particular concern in the US, as some researchers have concluded that high-yielding organic systems in the US are often importing nutrients from external sources.[1090] We presume this refers to the importation of manure from non-organic farms (as opposed to from other organic farms).

This is an important consideration which we attempt to evaluate in detail here. On balance, our conclusion is that this issue is unlikely to be a major factor, and it should not anyway undermine our +28%/+20% current estimate of the higher soil carbon level of organic farming since this is, in other respects, a conservative estimate of the full potential of organic farming.

The main reasons are as follows. Firstly, there is good evidence from the US that the soil carbon benefits of organic farming do not depend on 'carbon imports'. Secondly, in the UK, the use of external organic matter sources is fairly limited in the organic sector. Thirdly, other factors appear to explain much or most of the differences: organic systems usually produce considerable additional organic matter sources on the farm and also appear to provide much better soil carbon stabilisation conditions, than non-organic farming. Fourthly, organic farmers have a choice of strategies and even if some are now making use of available external organic matter sources, there is no reason to assume that the sector is inherently reliant on non-organic farming products. In other words, the issue of carbon 'additionality' is not just about the amount of organic matter imported by a system, but also about how the farming system affects the proportion of soil carbon inputs that is converted to stabilised soil carbon, and also to what extent the system is fundamentally reliant on any non-organic farming inputs to produce higher soil carbon levels.

Our review of the comparative soil carbon studies provides evidence that organic farming produces a soil carbon benefit *even when* there is no use of external organic matter sources. In the FiBL and Rodale Institute long-term trials, for example, the regular application of manure was designed to replicate the supply of FYM from the livestock housing of a mixed organic farming system (not an external manure supply to a crop-only farm). So, the 25% higher soil carbon levels for organic farming found by the Rodale Institute trial for a 'manure & legume'-based system represents the effects of self-sufficient organic farming without carbon 'imports'. This may also apply to some of the other trials included in this review.

Other evidence that carbon imports are not an issue in the US, comes from the finding that there is little difference in soil carbon levels between organic systems that use both manure and legumes - which may be relying on external manure, and 'legume-only' systems - which can be presumed to be self-sufficient in carbon. In the Rodale trial, the legume-based organic system produced a 20% higher soil carbon level than non-organic farming after 21 years, compared to the 25% higher level produced by the 'manure & legume'-based system (the difference between the two was not statistically significant). Similarly, in the survey of US trials by Marriott & Wander, there was *no* difference between the average of the three legume-based organic systems and the eight manure-based systems (four were using cattle manure and four poultry or pig manure).[1091] This survey found an average 14% higher soil carbon level after ten years of organic farming, which is comparable to the +20%/+25% results of the Rodale trial over 21 years.

For Northern Europe, the situation is somewhat less clear. The only study that addresses the issue is the Swedish trial, Kirchmann *et al*, 2007[1092], which provides some interesting insights. It found that an organic farming system that was importing a third of its manure[1093] and much of its straw produced a 32% higher soil carbon level than non-organic farming after 18 years. Using modelling and projecting forward, the researchers estimated that if these external inputs were eliminated and the organic system used a lower, self-sufficient level of manure and straw, then its eventual 'SOC equilibrium' level (the level once it has reached a steady state) would still be 25% higher than the non-organic farming system.[1094] This is because, although the exclusion of external inputs would reduce the soil carbon level of the organic system (it would not fully negate the benefit compared to non-organic farming, but would cut the difference by 57%), the organic and non-organic systems had not yet reached their ultimate soil carbon levels after 18 years and the levels would continue to diverge for some time. The combined effect of these opposing factors meant that self-sufficient organic farming would still produce a significant soil carbon benefit (+25%) and one that was only a fifth less than the observed benefit (25/32 x 100 = 78%). (It would still be higher in the organic system due to the growing of legumes every other year, use of cover crops, solid manure instead slurry, and higher weed levels, compared to the non-organic system).

Unfortunately, apart from the use of an external straw source in the organic system, which the authors admit was *not* representative of organic farming practice[1095], the study does not specify whether the systems used in the trial are typical of Swedish agriculture: i.e. with an organic system that is relying to this extent on external manure and a non-organic system that is using a diverse crop rotation with a grass/clover ley, which would have minimised the differences between the systems (these practices are certainly not representative of UK organic and non-organic farming). We would also question whether it is realistic to expect that organic farms in this situation would not adapt to a removal of external inputs by replacing these, at least partially, with alternative practices (e.g. by using a two-year instead of one-year ley, using available non-agricultural organic matter sources or composting). We also have doubts about the ability of current models to fully capture the positive effects of organic farming (see Section 4.4). So, while this result is reassuring, it is not clear how indicative this theoretical scenario and results are.

Nevertheless, this study illustrates the important point that the current data on the differences in soil carbon levels between organic and non-organic farming are likely to be only a partial representation of the soil carbon benefits of organic farming. The many aspects that are omitted from the current comparative studies (continued long-term divergence in soil carbon levels, differences in topsoil depth and subsoil carbon contents, and potential for adaptation), plus the probably unrepresentative use of similar diverse crop rotations for the organic and non-organic systems in many of the trials, could offset a large part (and perhaps far more than offset) the current contribution of some external organic matter inputs.

In the UK organic farming sector, there is probably a much lower reliance on external inputs than in the US. It is difficult to provide exact figures, but our information is that some 'imports' of carbon from the non-organic farming sector exist - in the form of manure, straw and animal feed, but they account for only a small proportion of all the manure/straw/feed used, and an even smaller proportion of all the soil carbon inputs used, by UK organic farmers.

Most organic UK farmers have their own supply of farmyard manure (FYM) and do not rely on non-organic manure, since most organic arable production is on mixed farms which means that they have livestock. Under Soil Association standards, organic producers also need to get permission from the Soil Association for the use of any non-organic manure and must then either stack the manure for several months or properly compost it before it can be applied to organic land[1096] (this is not required under the EU or general UK standards). Thus, it is generally only organic horticultural growers who use non-organic manure in the UK: horticultural crops need more regular applications of manure, but many organic horticultural operations are stockless without their own supply. We therefore estimate that out of around 4,600 UK organic producers, only around 200 horticultural growers are 'importing' non-organic manure. Because of the relatively small land areas of these holdings, the amount of non-organic manure used would thus be a maximum of 10% of the total manure applied by the organic sector and is actually likely to be substantially less than 10%, we believe.[1097] (Likewise, the fact that only a tiny percentage of all farmers, 1-5-2%, are 'exporting' FYM shows that the import of some non-organic manure by the organic sector cannot account for the low soil carbon levels of non-organic farmland.[1098])

Where there appears to be a greater level of imported carbon is with the straw used for the livestock bedding that produces the organic FYM. We estimate that as much as 40% of the straw used by the organic sector is from non-organic farms, in the UK. However, much of this is going to the specialist livestock farms in grassland regions that need straw for livestock bedding (due to the small size of the UK organic arable sector, there is currently not enough organic straw available for sale, so much is bought from the non-organic sector.)[1099] Some organic mixed farmers are also bringing in non-organic straw for their livestock bedding: organic straw is very valuable to organic mushroom producers, so where organic arable farmers have access to this market, many sell their straw and bring in non-organic straw.[1100] Their own straw generally comes back to the farm under the terms of 'mushroom compost agreements', whereby the mushroom producers return the compost to the farmer afterwards. This means these organic arable farmers are effectively doubling up their total straw input by using non-organic straw.[1101]

This seems unlikely to account for most of the observed differences in arable soil carbon levels, because livestock (rather than arable) farmers account for a large part of these straw imports and also because organic farmers are converting the straw - a form of organic matter with a relatively low capacity to produce stable carbon (see) - into a form that is about 40% more effective: FYM (see point 2 and 7.5).

As for animal feed, all organic cattle and sheep must be fed 100% organic feed, so organic cattle and sheep manure do not contain any carbon originating from the non-organic sector. A very small amount of organic pig and poultry feed is 'imported' - less than 10% of the total feed comes from the non-organic sector - but this is a temporary and restricted allowance that ends at the end of 2011.[1102]

There is therefore indeed some carbon transfer from the non-organic to the organic arable sector in the UK, though it is perhaps a smaller proportion of the total than is sometimes assumed. However, these carbon imports must be put in the context of all the carbon produced by organic farming. As explained in Chapter 7, as well as the carbon from the crop residues (often the only carbon source in specialised industrial non-organic cropping systems), organic farming produces additional sources of organic matter for its cultivated soils: grass leys, manure, green manure crops, more root exudates/biomass and more weeds. In many cases, though perhaps not all, this should amount to a higher level of on-farm soil carbon input production in organic than in non-organic farming.

Additionally, according to the available evidence, organic farming probably produces more (perhaps much more) soil carbon from all the organic matter that it produces, than the non-organic sector does from the organic matter it produces. This is because it produces more of its carbon in more effective organic forms: perhaps over 70% more root biomass than in non-organic farming; animal waste in the form of FYM rather than slurry; the conversion of straw to FYM or mushroom compost – perhaps a 40% increase in effectiveness; and use of composting by many organic horticultural and biodynamic farmers – perhaps a 5.7-fold increase in effectiveness (see Section 7.5). In addition, more manure is deposited directly on the pasture, so much less manure carbon is lost in storage. And, the conditions for carbon stabilisation appear to be better because of the better soil biological health of organically managed land. In the US Rodale Institute trial, for example, the ratio of sequestered soil carbon to the above-ground carbon input was *two and three times higher* in the two organic farming systems, than in the non-organic system.[1103]

For the same reasons, it is also probably not right to consider all carbon imports as a totally 'invalid' soil carbon benefit of organic farming. The use of non-organic farming inputs goes against strict organic farming principles. Nevertheless, from a soil carbon perspective, it is an important point that most of the carbon 'imported' from the non-organic farming sector is unlikely to have produced the same soil carbon increase in the non-organic sector. This is because organic systems 'add value' to these materials in carbon stabilisation terms, in the same way that organic farming increases the soil carbon conversion rate of the organic matter it produces. In other words, using imported non-organic straw to produce FYM should be a major benefit compared to the practices widely used in the non-organic sector where, on the one hand, large specialist arable farmers mostly plough-in their straw as they have no other use for it, while on the other hand, many livestock farmers have little bedding straw and so produce animal waste in slurry rather than FYM form. Additionally, the fact that under SA standards, non-organic manure has to be stacked or composted before being applied, should greatly raise its soil carbon effectiveness.

Therefore, given that non-organic farming manure and straw are currently available, any imports can perhaps be considered to be a soil carbon 'service' of the organic farming sector, as this produces more soil carbon from these products than if they were being applied on non-organic farmland. Importing manure also ensures that it is not otherwise treated as a waste product by the non-organic farming sector, which can cause pollution. With the current and continuing high level of specialisation in the non-organic farming sector, excess supplies of manure and straw will continue to be available for some time.

An additional consideration is: how would these organic farmers manage if these non-organic farming imports were not available? It is unreasonable to assume that they would simply continue as before without the inputs, especially if the imports were at a significant level. Organic farmers need to achieve a certain level of organic matter inputs and soil biological health to be commercially viable, but they normally have a choice of management strategies available. So, even if some organic farmers, such as in the US, are using large amounts of non-organic inputs just because they are currently available and this is a convenient option, this is not to say the US organic sector is fundamentally reliant on this source. In a theoretical situation of widespread organic farming, the organic sector would almost certainly turn to alternative strategies. In the US, there are two main organic farming approaches, 'manure & legume-based' and wholly 'legume-based', and importantly, as described above, there is little difference in soil carbon levels between the two. Therefore, if all supplies of non-organic manure were removed, US organic arable farmers would probably turn to more legume-based systems, and the soil carbon benefit of organic farming would remain similar to now.

In Northern Europe, there is currently no major alternative organic farming system for cultivated soils. Totally stockless arable systems - which have no livestock and are more reliant on leguminous green manure crops, are not generally considered economically viable in the UK and are rarely used. Anyway, in the UK, unlike in the US, stockless systems do not appear to provide the soil carbon benefit of mixed farming systems (see Shepherd *et al*, 2002, Section 6.5; indeed, this may be partly why they are not as economically viable). Nevertheless, there are various other options available for increasing soil organic matter and nutrient inputs: the wider use of cover crops (used by only a third of UK organic farmers, compared to almost all US organic farmers), composting and the use of food/green/paper waste are obvious examples. While more cover crops may not be an alternative for the horticultural farms that are currently importing manure, based on current practices/varieties (though, as with all aspects of organic farming, there is potential for development), a wider uptake of composting, or more use of cover crops plus composting, may be and would probably produce *higher* soil carbon levels than current practices.[1104]

With widespread organic farming, the current imbalance between the organic livestock and arable sectors would be largely resolved[1105] and there would be more organic straw available, which might address (or at least partially) the straw shortage. Alternative bedding materials, such as sand and wood shavings, are used by some organic farmers now and so these would be options to make up any remaining shortfalls.

Therefore, if the organic sector were to be completely independent of the non-organic farming sector, we should assume that it would adapt, and there is a fair chance that the alternatives will produce similar (and with the possibility of greater) soil carbon levels than current organic farming practices.

One final point: imports of organic matter from the non-organic farming sector should be distinguished from any imports of *non-agricultural* organic materials. There are large quantities of organic materials available that *should* be composted and returned to farmland - such as food waste, green waste or paper waste. Any such use by the organic faming sector is a valid benefit and should be greatly encouraged. Even if most of these are not currently organically produced, this is mainly because of the still small size of the organic sector. Food waste, especially, would be increasingly organic in origin as organic farming expands. The return of organic waste materials to the land to 'close the nutrient cycles' is a key principle of organic farming which would raise soil carbon levels and provide a sustainable source of crop nutrients.

Overall, it therefore seems likely that it is the extra organic matter and better carbon stabilisation conditions produced by organic management that accounts for most or all of the higher soil carbon levels of organic farming, than the fact that there is some imported carbon from the non-organic sector. And, given that in other respects, the current observed differences in soil carbon levels between organic and non-organic farming are a conservative indication of the full effects of organic farming, and that there is anyway potential for farmers to adapt, this issue should not undermine our +28%/+20% estimate of the average higher soil carbon level of organic farming, which we suggest is a reasonable working estimate of the soil carbon benefit of organic farming, based on the evidence reviewed.

Nevertheless, to improve understanding of this area, we suggest that future soil carbon studies of organic and non-organic farming should attempt to identify the contribution of any carbon imported from the non-organic farming sector to the total soil carbon input of the organic farms (based on actual measurements of both), and also, where possible, identify the relative carbon conversion rates (percentage of the soil carbon input which forms stabilised, lasting soil carbon) for organic and non-organic farming.

9.7 Concern: 'Is there is a 'carbon trade-off' between yields and soil carbon levels?'

The opposite concern to point 2 (that high-yielding systems produce higher soil carbon levels) has also been expressed: maybe higher soil carbon levels come *at the expense* of a higher yield because of a 'carbon trade-off'.[1106] This is based on the concept that there is only a certain level of plant carbon production possible per unit area (depending on the level of sunlight and rate of photosynthesis), so any greater carbon input to the soil could only come about because less carbon has been committed to produce yields and more to the growth of the rest of the plant. This concern appears to be supported by the fact that, in Europe, organic farming produces a 30% or so higher soil carbon level but has 30% or so lower yields than non-organic farming.

There are certainly a few ways in which it could be argued that a carbon 'trade-off' must be contributing to the higher soil carbon levels of organic farming. For instance, the higher root biomass to crop yield ratio in organic farming suggests that there is some trade-off occurring between soil carbon inputs and yields. Organic crop roots also support greater fungal mycorrhizal populations which could be reducing the energy expended by the plants on the crop yield.[1107] And, for some crops, the non-use of herbicides and greater weed competition in organic systems accounts for much of the yield difference. However, on close analysis, it does not appear that this is necessarily the case. Many of these factors also play an important positive role in the productivity of organic systems (see below) and total carbon production is boosted by other aspects of the system. So this apparent carbon-trade off may not actually exist overall, as shown by the 'win-win' results of some organic farming systems. Overall, there appear to be other more significant reasons for the higher soil carbon levels of organic farming than a 'carbon trade-off'.

A summary of the disadvantages of current industrial farming systems shows that the low carbon levels of non-organically managed cultivated soils are not due to basic biological constraints in the amount of carbon that can be produced. From our review, there are four main ways by which industrial systems fail to produce higher soil carbon levels (the relative contributions of which are not known):

1. Though they have increased crop yields, industrial farming systems do not maximise the amount of plant carbon produced per hectare, so they are reducing the level of soil carbon input possible.
2. Industrial farming systems do not make good use of the organic matter they produce, as the manure produced is not being applied to the arable and horticultural land area.
3. Industrial farming systems produce their organic matter in forms that have relatively poor soil carbon conversion capacities, reducing the amount of soil carbon produced per unit plant carbon.
4. Industrial farming systems have little vegetation cover (much bare soils) and low soil microbial levels, which reduces soil aggregation and the capacity for soil carbon accumulation.

Most of these aspects were discussed in detail in Chapters 5. As regards the first point, industrial farming systems clearly operate at levels of plant carbon production per hectare that are far below the maximum possible (compare a field of wheat supporting just one short plant species and for just part of the year, to a mature woodland, for example). Even within agriculture, there is much room for increasing total carbon production levels without reducing yields. For instance, while the move to large farms means many farms in the West have become much more economically competitive (as they have economies of scale and produce large enough harvests to supply the commodity markets), large farms can often produce lower yields per hectare than small farms.[1108] Much of the high productivity of industrial systems actually has nothing to do with diverting the farmland's productive potential into more yield: to a large extent the natural soil ecology that would normally fuel crop yields *via* soil organic matter production is by-passed when synthetic inorganic fertilisers are used (which instead directly fuel crop yields).

Organic farming tries to address these deficiencies in non-organic farming systems by harnessing natural processes to produce a more positive overall outcome. Some 'win-win' examples show that the different results of organic farming cannot be put down to a carbon trade-off. The clearest case is the agricultural systems in North America, where organic arable yields are almost the same as non-organic systems *and* their soil carbon levels are much higher. For example, in the long-term Rodale trial, the yields of the organic and non-organic systems were similar (6.4-6.6t/ha for maize and 2.2-2.5t/ha for soya), but the organic systems produced much higher soil carbon levels (20% and 25% higher levels after 21 years; see section 6.2). In a survey of US farming trials, the yields of organic systems compared to non-organic were similar: wheat 3% less (16 sets of data); maize 6% less (69 sets of data); and soya 6% less (55 sets of data).[1109] In other words, there is little carbon trade-off in North America. In addition, there is little yield difference in the field horticulture sector[1110] where there is some evidence that organic farming produces particularly high soil carbon levels compared to non-organic farming (58%, 138% and 325% higher levels were found by a UK and two Spanish studies, respectively[1111]). In the developing world, moreover, organic farming substantially increases yields by about 80%[1112], partly because the higher soil organic matter levels reduce the adverse impacts of drought conditions. These cases show that higher soil carbon levels do not inherently depend on a yield carbon trade-off. There is certainly not always, however, a win-win outcome: in Europe, organic cereal and potato yields are 30-40% lower than in non-organic farming.[1113]

This effectiveness of organic farming appears to be the result of a combination of factors: organic farming apparently increases soil carbon levels by changing not just (i) the proportions of the yield/non-yield carbon supply ratio, but also (ii) the total amount of carbon produced by the farmed area (including exudates) (iii) and the proportion of the carbon supply that is converted to stable soil carbon.

As explained in Chapter 7, in organic farming, unlike much non- organic farming, the soil carbon input of cultivated soils is *not* restricted to the carbon fixed by the crop plants: other organic matter sources are provided and these probably account for most of the higher soil carbon levels. Grass leys and manure are supplied by the livestock stage of the system. Additional plants are grown in the otherwise-unproductive periods between the cropping seasons (i.e. green manure crops, such as over-winter cover crops), thus using more of the available land and sunlight and reducing the area of bare soil. Instead of all weeds being eradicated by herbicides, organic weed control methods usually leave a low level of weeds that provides a small additional soil carbon supply. Some farmers also bring in organic matter from non-agricultural sources, such as green waste, food waste and paper waste.

Organic farming also appears to significantly improve the biological conditions for the conversion of plant carbon to soil humus[1114], as much more of the soil carbon input is in organic matter forms that are particularly effective at producing stable soil carbon and enhancing soil aggregation: i.e. with the grass leys, use of grazing and straw bedding to produce solid manure, greater root to shoot ratio, composting, avoiding agrochemicals, and incorporating the organic matter deep into the soil. Also, soil microbial levels are higher. Thus, more of the non-yield carbon produced is converted to humus than in non-organic systems that rely heavily on crop residues (cultivated soils) or liquid slurry (grasslands).

As for yield levels, while organic farming does not use the agrochemicals which produce high yields in non-organic farming, the system promotes yield levels in many alternative ways. Importantly, the higher soil organic matter levels, and the factors that produce this, are themselves beneficial for agricultural productivity. For instance, high SOM levels provide important soil structural benefits for crop production: one researcher suggests that a well-structured soil provides a 5-10% crop yield benefit.[1115] This is because good soil structure (aggregation) increases the soil nutrient and water supply[1116] and improves the soil's physical conditions for root growth.[1117] Humus also holds readily plant-available P and K, and research shows it is especially important for the supply of P.[1118] Ploughed-in grass/clover leys have been found to provide a unique crop yield benefit, which may be because they provide nutrients at times and at positions in the soil profile that are hard to achieve with inorganic fertilisers.[1119] Green manure crops improve the soil's N supply, and deep-rooting green manure plants 'mine' (supply) P and K from the subsoil[1120]. Yield benefits would probably be particularly significant in arid regions and areas with degraded soils.[1121]

Crop growth is also often limited by the supply of other soil nutrients or water (rather than just sunlight or N,P,K). By increasing soil organic matter levels and bringing the soil back to life, organic farming improves the soil's trace mineral supply[1122], something that is not usually achieved with inorganic fertilisers. As well from the soil structural improvements, this is by the addition of trace minerals in the organic matter applications[1123], the release of nutrients during the microbial decomposition of organic matter[1124], and from the enhanced nutrient uptake from the networks of fungal mycorrhizal hyphae[1125]. The high soil humus levels, deeper roots and fungal mycorrhizal networks[1126] of organic systems also improve the water supply for plants, boosting growth in times of water shortage. As a result, organic farming often produces higher yields than non-organic systems in times of drought.[1127] Humus, for example, can hold the equivalent of 80–90% of its weight in moisture.[1128] Though clearly this is not a representative example, under favourable soil conditions, plants with mycorrhizae have been shown to produce up to four or five times as much growth as similar plants without mycorrhizae[1129]. The greater diversity of crops grown in organic systems (diverse crop rotations and multiple plant species in the grassland[1130]) also reduces the competition for nutrients and should promote overall production as each species has its own ecological niche (such as root depth in the soil). The non-use of inorganic N fertiliser also reduces the levels of fungal diseases which affect cereal yields.[1131] All these and other aspects of organic farming, such as crop rotation[1132], promote the productivity of the system and compensate (to different extents, depending on the region) for the non-use of agrochemicals.

These results are the product of organic farming's different approach to non-organic farming, using practices that produce *synergies* between the yield and environmental aims, which then avoids (or reduces) the trade-offs that otherwise occur in agricultural systems. Organic farming harnesses soil organic carbon cycling as its source of fertility: it *uses* regular and high levels of organic matter inputs, high microbial levels and good soil aggregation for productivity. Thus, in organic farming, the promotion of soil carbon levels also generally means the promotion of soil fertility and yield levels.

Importantly, organic farming is not operating at the limits of its productivity. Organic farming has received just a small fraction of the investment and development that agrochemical-based farming systems have and there are many interesting areas available for development. Specifically, there is good potential for further developing organic farming in ways that would increase both yield and soil carbon levels, either by further increasing the organic matter input levels or with additional synergistic practices. Organic matter and nutrient inputs could, for example, be maximised by much wider use of green manure crops, by using composted green/food/paper waste (the large supply from national recycling schemes should be put to such use) and by making progress in the use of biosolids or 'night soil' (untreated human waste)[1133].

Several specific practices also have the potential to increase the overall crop biomass production and yields of organic farming at the same time: greater use of deeper-rooting plants[1134], inter-cropping (which can double biomass production and increase total crop yields by 60% in tropical conditions[1135]), growing mixtures of crop varieties which produces small yield gains[1136], and agro-forestry. In the UK, for example, undersowing forage maize crops with legumes or intercropping maize with kale for silage, would greatly increase the vegetation cover of maize fields; this would improve the weed control and perhaps overall yields for farmers[1137]. These approaches are based on the proven concept that a diversity of plants produces more overall biomass[1138], including crop yield, as the plants occupy different ecological niches. (Note, such combined yield gains are not identified in conventional yield measurements which only account for the yields of a single crop per unit area). These solutions should at the same time increase the biomass and root exudate soil carbon supply, microbial and fungal mycorrhizal levels and the depth of soil carbon distribution, i.e. increase soil carbon inputs, soil aggregation and so soil carbon accumulation.

Another way in which the yields of organic farming and crop biomass production might be increased at the same time is through investment in crop breeding. Organic farming productivity in the UK is currently curtailed by the fact that the sector has to rely on non-organic varieties. Modern cereal varieties have been specifically bred to respond to inorganic fertilisers, rather than to the soil humus and mycorrhizal nutrient supply that is the basis of organic systems. However, this breeding has reduced the size of the crop root systems which has had the undesirable side-effect of reduced the nutrient uptake efficiency of modern cereals.[1139] A UK organic crop breeding programme would therefore be very beneficial.

There are also many ways in which organic farming yields and soil carbon levels can be increased separately. For instance, yields can be increased by addressing underlying soil trace mineral deficiencies (field treatment of UK organic farms has often produced very positive and long-lasting effects on productivity). Likewise, to increase organic farming soil carbon levels (in ways other than by increasing organic matter inputs), wider use of composting, conversion of remaining slurry-based livestock systems to straw-based systems, and the wider adoption of biodynamic methods would all be very beneficial.

So, technically, there appears to be no significant or inherent trade-off between soil carbon levels and yield levels in organic farming or agriculture generally, and the current differences in yield and soil carbon levels between organic and non-organic farming result from differences in a more complex set of factors, than just a different distribution of carbon between the systems. In principle, the approach of organic farming offers a means of increasing soil carbon levels while avoiding a significant trade-off in crop yields.

Admittedly, however, with the current farming systems in Europe, there is a yield reduction with organic farming, i.e. there is currently effectively a 'trade-off' *in practice* in Europe. There may be a concern that these lower yields could mean that an increase in organic farming would lead to an expansion of arable land abroad, and thus soil carbon losses. However, this is unlikely to be the case. Firstly, there is significant potential to increase production in temperate regions: in Central and Eastern Europe, Caucasus and Central Asia, agricultural production is now only 60-80% of 1990 levels.[1140] The European food supply can also be easily improved by reducing the large amount of food wastage. There is also great potential to increase the supply by changing the meat/vegetable balance of western diets (such a re-balancing would occur anyway with widespread organic farming, by a reduced use of cereals for producing pigs and poultry[1141]). The Soil Association has also taken action to ensure that the UK organic food market does not contribute to the global expansion of farmland into natural areas, by adopting a new standard that prohibits the use of ingredients from areas that were in primary habitat from 2007.[1142]

At a global level, this issue might anyway not be a problem as the differences in yields may even out between countries. For instance, while organic yields are similar to non-organic farming in North America (a major global food supplier), organic crop and livestock yields are around 80% higher than current yields in developing countries (where yield increases are most needed), as found by a review of 133 studies in developing countries.[1143] Moreover, organic farming yields are similar or higher than the yields that are achieved by using inorganic fertiliser in these countries, as organic farming methods (using composting, agro-forestry and leguminous crops) produce similar yields in average conditions but higher yields in dry conditions[1144] (and without having to continuously pay for increasingly expensive agrochemicals).

In fact, the SOM-based approach of organic farming is particularly important for developing countries in drought-prone regions: as well as substantially increasing yields, the much greater drought resistance of organic farming is an important food security benefit that cannot be matched by inorganic fertiliser-based systems. This is also an important point as regards the viability of soil carbon sequestration, as there are concerns that the cost of implementing sequestration measures would be particularly great in the developing world because of the large number of small-holder farmers.[1145] As organic farming is greatly advantageous for the farmers, the soil carbon benefits could be reaped as a side-product at no extra cost.

Moreover, as explained, there are many ways in which organic farming yields can be raised using the organic principles for further development, some of which can also further improve soil carbon levels. It should be borne in mind that the potential availability of nitrogen from biological fixation and livestock manure is two to three times greater than the current global production of inorganic nitrogen fertiliser.[1146]

Also, it should be pointed out that the current uncontrolled expansion of agriculture into the tropical rainforests and savannahs of South America and South-East Asia - and the associated release of enormous amounts of carbon - is nothing to do with low-yielding farming systems (there is plenty of under-used farmland in the northern hemisphere[1147]). It is being driven by the intensification of livestock production, global agricultural markets and the growth of the food processing industry.

For instance, there are three reasons for the growing demand for soya, which is the main driver of the destruction of the Brazilian Cerrado and a contributor to Amazon rainforest clearance. One is the rise of high-yielding pig and poultry factory farming systems, which rely heavily on soya. These systems produce large amounts of cheap meat, which has fuelled a large rise in white meat consumption[1148] and driven up the global demand for grain. Factory farming systems have been expanding in recent decades throughout Southeast Asia, Central and South America. Another cause is the rise of high-yielding intensive grain-based cattle rearing systems. These systems rely heavily on grain feed from warm countries (in particular, soya), in place of using grass, and also have the disadvantage of reducing beef production levels and increasing beef imports. The third reason is the food processing industry: 30-40% of the economic value of soya is for food[1149], to supply derivatives such as soya oil and lecithin for use in processed foods[1150]. The food processing industry is also the main driver of the rapid deforestation in SE Asia, because of the large demand for palm oil.[1151] See section 4.2 for more details of these issues. Also, since 2007, global demand for cropland has been greatly exacerbated by the politically driven expansion of the biofuels industry. Overall, a return to grass-based livestock systems, lower meat consumption, more localised food systems and much less processed foods - as advocated by the organic movement - would greatly reduce grain, beef and palm oil imports and help stop the destruction of these massive tropical carbon stores.

Finally, there is also no certainty at all that current non-organic farming yields can be sustained in the future. The yields of non-organic systems depend on the routine use of nitrogen, phosphate and potassium (N,P,K) fertiliser.[1152] But inorganic fertilisers are facing increasingly serious price and supply problems. The manufacture of synthetic N fertiliser is energy-intensive and its price tracks energy prices: N fertiliser prices have doubled in the last few years[1153] and are expected to continue rising in the long-term as global oil and gas supplies tighten. P and K fertiliser have even greater supply problems, as global reserves are finite and rapidly being exhausted.[1154] Prices have already risen four-fold[1155] and many farmers are now not applying P and K this year (2009).[1156] As prices have risen, fertiliser use in the UK has been declining and use is now at the lowest level for 35 years.[1157] If this situation continues, non-organic yields could well fall in future.[1158] So, the current comparative level of organic farming yields may be less important than the future prospects for organic and non-organic productivity, and the opportunity to put agriculture on a development path that will at the same time substantially increase soil carbon levels.

9.8 Concern: 'Soil carbon sequestration only occurs until a new equilibrium is reached'

Some of the scepticism over soil carbon sequestration relates to the view that it is only a transitional effect of a change in management and occurs only until the soil's carbon content has reached a new equilibrium level. In particular, critics point out that the rates of carbon sequestration tend to diminish about twenty years after a switch to improved practices. We believe this attitude is very wrong and suggest that there may be some other concerns over the 'SOC equilibrium' approach.

It is an established principle of soil carbon theory that all soils under a given system of management have'equilibrium' carbon content.[1159] After a positive management change, carbon gains occur until a new equilibrium level is reached and this change follows a certain pattern: the rate of change may be initially slow, then the annual soil carbon gains increase and remain at their highest for several years, before declining again progressively with time.[1160] In this way the development of the soil carbon sink can be likened to the development of the biomass carbon sink in a newly planted forest, which increases quickly as the trees grow in the early years but the increase slows as the forest approaches maturity.[1161]

It is therefore widely accepted that soils take a long time to fully reach a new equilibrium level after a management change (100 years or more in temperate regions[1162]), but *the majority* of the carbon build-up takes place within a few decades. UK researchers say that typically half of the soil carbon accumulation over 100 years occurs within the first 20 years.[1163] For convenience, the IPCC's soil carbon accounting guidelines, which are based on this SOC equilibrium approach, assume that *all* of the soil carbon change after a management change occurs within a standard 20 year period (other timeframes can be used, if supported by evidence).[1164]

This front-loaded pattern has, however, been widely perceived as a problem for policy purposes and as a barrier to accounting, on the grounds that any annual sequestration rate identified in studies (such following the adoption of organic farming) must be temporary and will reduce over time. Soil carbon sequestration has often tended to be dismissed as a GHG mitigation option on these grounds. And Cranfield University, for example, have stated that they are excluding soil carbon differences from their LCA assessment of the comparative GHG emissions of organic and non-organic farming for the UK Government as, "soil carbon operates at a steady state for any system. It is higher for organic but not endlessly increasing."[1165] The accounting problem arises because, while the IPCC accounts for all GHG emissions, LCA and carbon footprinting calculations generally only account for the on-going annual emissions produced by the management regime, not time-limited emissions or gains that are considered to result from a 'management change'.

We believe this attitude is very wrong. This front-loaded pattern of change is afterall a real *strength* for policy-makers, not a drawback. It is major carbon stock changes in the next 20 years that are going to be critical for the planet if we are to avoid reaching dangerous atmospheric CO_2 levels (emissions probably need to peak by 2015 or 2016 and then rapidly fall 80% by 2050[1166]). Activities that increase soil carbon stocks are therefore powerful weapons in the race against time on climate change. Moreover, carbon sequestration still continues afterwards, albeit at declining rates, for up or over a hundred years. In addition, because the accumulated carbon is normally in the organic form of humus, there is the lasting benefit of the improvement in soil structure and quality. This will improve climate adaptation by reducing the impacts of flooding, droughts, water shortages and desertification (see section 10.3), thereby also improving global food and water security. This is an important permanent benefit of higher soil carbon levels. So, it is very important that the soil carbon effects of farming systems are considered, not ignored.

There are other concerns with the 'SOC equilibrium' approach. We accept this concept is well grounded (such as from the results of long-term controlled experiments). The IPCC's default'20 years to equilibrium' approach also appears to be a very practical methodology, and may be an acceptable start for capturing agricultural soil carbon effects in national GHG inventories, including those of organic farming. Nevertheless, we have several reservations over the adequacy of relying on this approach for GHG accounting and other policy purposes. Below are some initial considerations of the drawbacks.

The assumption that soil normally operates at a steady state is inconsistent with some of the 'real life' information indicating that many EU farmland soils may *not* be in a steady state (Section 4.2 and Chapter 5). Although the overall evidence on this subject is unclear and many questions remain, it is a fact that some survey and modelling evidence suggests that some European cultivated soils and UK grasslands may be losing (politically) significant amounts of topsoil carbon each year, that temperate grasslands have the potential to be building significant amounts of soil carbon, and that many agricultural practices have been identified that may be affecting overall soil carbon levels (topsoils and subsoils). This view also appears to conflict with the 'real life' evidence from natural ecosystems and some authoritative experimental and modelling evidence that soil carbon *can* continuously build up over long periods in some situations, at least if there are major changes in the regime or continual large amounts of organic matter input.

Additionally, most current understanding about the potential for soil carbon sequestration in agriculture is derived from research with non-organic farming systems, and we would strongly caution against applying conclusions from current non-organic farming systems to agriculture generally (and particularly when assessing the potential of organic farming!). As yet, there is insufficient scientific evidence to generalise about the long-term soil carbon sequestration potential of organic farming, though we note that soil carbon has been found to continuously increase for over 20 years in *some* organic farming situations.

We therefore question whether the current accounting approach is fully capturing the soil carbon trends of non-organic farming, if it is adequately representing the comparative effects of organic farming, and if it can capture the full potential for soil carbon sequestration (ie. with improved management). The specific problems seem to be that the '20 years to SOC equilibrium' approach: does not account for changes in soil depth; it may not be capturing more on-going effects from the continual development of farming systems; and it does not allow for the possibility that some systems may be able to produce long-term changes. These issues are considered below. (Note, we are not questioning the validity of the concept in principle, just the suitability of relying on this concept for policy purposes.)

Natural ecosystems, for example, offer some scenarios for how the '20 years to equilibrium' approach may be too limited to show the full potential for carbon sequestration. Cultivated soils are normally highly degraded compared to soil under native vegetation and this difference is surely some indication of what could be potentially achieved with positive management. Natural forests and grasslands gradually built up soil over very long time periods (centuries), which is how the soil carbon store originally accumulated on the planet. The natural rate of soil formation is considered to be slow (averaging about 1 ton of soil/ha/year[1167]). But it is variable and the naturally slow rate by just the weathering of the parent rock material is greatly accelerated by the influence of vegetation and its acids (chemical weathering)[1168], and micro-organisms also play a primary role[1169]. Therefore, it seems not unreasonable to ask if farm management regimes that specifically promote the soil's natural processes could not re-build soil at rates that might be significant in terms of carbon sequestation and over long timescales.

One way in which the potential for capturing soil build-up is limited under the 'SOC equilibrium' approach is because it only captures changes in SOC content levels, not soil depth. However, the soil carbon store can decrease or increase *whether or not* the SOC content is changing, if the soil depth is changing (as long as this is not wholly due to a change in soil density). It is therefore important to know if any farming systems are changing the soil depth. There are already good indications that soil depth is decreasing on some non-organic farmland because of erosion.[1170] There is also some evidence - from six studies - that organic farming produces higher topsoil depths.[1171] A soil depth increase would seem most likely to occur in healthy soils that have high levels of living organisms, regular grass periods, deep-rooting plants, and the regular addition of manures or composts, ie. the conditions found in organic farming.

As well as this exclusion of soil depth from the SOC equilibrium approach, there are other reasons why carbon losses or gains resulting from soil depth change are not being captured. The basic IPCC methodology - which is based on the SOC equilibrium approach - only accounts for soil carbon content changes *in the top 30cm* of soils (ie. ignoring soil depth). It also only accounts for gains or losses that are associated with *changes* in management. So if any changes in soil depth are on-going in nature (due to the on-going effects of the management regime), they would not be accounted even if soil depth was included (though this would then remove the barrier to inclusion in the LCA and carbon footprinting calculations). Additionally, there is a lack of data on soil depth as most studies of soil carbon levels do not measure the soil depth. This should be addressed and if evidence emerges that changes in soil depth are or could be a significant factor in soil carbon storage or the timeframe for soil carbon sequestration, then soil depth should be included in future soil carbon estimates.

There is also the question as to whether the 'SOC equilibrium' accounting approach sufficiently captures the dynamic nature of farming systems. In practice, this accounting approach requires that the management of each area of land is categorised, and only temporary carbon gains or losses associated with the transition between a limited set of specified management regimes are captured (such as the adoption of mixed farming, or the use of animal manure). However, the IPCC recognises that actually, "soil C stocks typically do not exist in an absolute equilibrium state … given that many of the driving variables affecting the stocks are dynamic;" it instead suggests the term "near equilibrium".[1172]

This point could be particularly important in agricultural systems. The continual development of farming could well be causing an on-going trend of soil carbon losses (or gains) through many changes that would not be identified by the current 'SOC equilibrium' approach (such as changes in the root biomass of the varieties being used). The evidence of topsoil carbon losses in at least some agricultural soils that have been not been converted from grassland in recent decades (Section 4.2) and our analysis of the large number of past and current developments in agricultural practice that could be affecting soil carbon levels (Chapter 5), suggests that there are indeed probably several negative and overlapping management influences occurring at any one time. Moreover, what may appear to researchers as a state of 'near equilibrium' (a very low rate of losses that appears insignificant in terms of the total soil carbon stock) may nevertheless constitute an on-going trend of carbon losses that is significant in terms of GHG emissions (for example, average annual losses of only 0.33% of the starting SOC level are significant in policy terms, being roughly equivalent to 200kgC/ha/yr or 1 million t C/yr for the UK's arable area[1173]).

In recent decades, western farming systems have been steadily moving away from a focus on soil organic matter maintenance, towards the on-going development of low-residue/high-yielding crop practices and varieties. Thus, many of the management factors that may be contributing to soil carbon losses could be considered to be individual strands of a general 'system change', to which a more long-term or on-going timeframe than the standard 20-year period might apply. Likewise, organic farming is not one specific set of practices, but an approach which comprises current practices and the gradual development and introduction of other practices that are in line with its underlying principle of 'production through organic matter inputs and promoting soil life'. The current focus on specific management regimes and their associated 'SOC equilibrium' levels, may therefore be overlooking the general direction of development of agricultural systems and the possibility of more long-term soil carbon changes (positive or negative).

There is also a question over what timescale applies to any identified year-on-year SOC level increase under organic farming, and whether any management regime can produce a long-term policy-significant increase in SOC levels. Currently, any long-term soil carbon gains or losses are assumed to be only the 'tail-end' legacy of an earlier management change and not significant in policy terms. However, it should first be noted that significant soil carbon changes can occur for much longer than the 20-year default period, given that (i) while the standard accounting approach assumes that *all* of the soil carbon change occurs within 20-years, in practice only half of the total change over 100 years occurs within the first 20 years (typically) and the rest thereafter, and (ii) even tiny SOC increases are significant in policy terms (such as, increases of only 0.3%/yr - see above), so changes might remain significant for a long time.

Secondly, long-term SOC increases are presumably particularly likely if the final equilibrium level is high. For instance, if the starting levels are low and the amount and quality of organic matter input is high. For example, in the Rothamsted Hoosfield barley trial, which has been running since 1852, the application of manure at 35t/ha/year (an unrealistically high level) resulted in *significant* soil carbon increases occurring continuously for *over 150 years*, although the rate of increase slowed over this time. The soil carbon level tripled from 30tC/ha to 90tC/ha[1174], ie. it changed from a low to a high level for an arable soil.

Grasslands provide another example. Here the direct evidence (of stable or falling topsoil carbon levels in the UK) appears to conflict with theory. Based on soil measurements and modelling, researchers believe that permanent grasslands in temperate regions are steadily accumulating soil carbon year-on-year under current management conditions[1175] (by 450-800kgC/ha/year[1176]), ie. they are major carbon 'sinks' (with the exception of drained peatlands). Grasslands may therefore be an important case of an agricultural system where – if maintained in the right condition – the soil can sequester carbon on an on-going basis, whether by increases in soil depth or in carbon content.

Our review of the comparative studies indicates that cultivated soils in Northern Europe currently have about 28% higher SOC levels after roughly around 15 years of organic farming than under non-organic farming, on average. However, it is perhaps important to stress that we do not yet know the typical equilibrium level or the typical length of time for SOC increases under organic farming. However, the average SOC equilibrium level of organic farming is likely to be greater than 28% higher than non-organic, given that most organically managed soils have probably not yet reached their equilibrium level and that there may be soil carbon losses occurring with non-organic farming in some regions.

The small amount of long-term evidence points to the occurrence of long-term soil carbon increases with organic farming (up to and over 20 years) in some cases. Eight of the twelve long-term monitoring studies of organic farming that we identified found that the soil carbon level increased over the study period.[1177] One of these, the Swedish 'K-trial' found increases occurred with organic farming over the whole 33-year period of the trial, including large increases in the thirteen-year period 19 to 32 years after the start (1976 to 1989). Over this period, the organic treatment produced a 20% increase in topsoil carbon (0-10cm depth) and a 50% increase in subsoil carbon (50-60cm).[1178] The Rodale Institute found substantial soil carbon increases occurred steadily over 27 years in its trial of two organic systems (see section 6.2). There is also some evidence for long-term gains with organic systems that use compost. Compost has a high humus content, so a particularly high SOC equilibrium level and longer-than 20 years of sequestration may be especially likely with compost. Soil carbon levels stayed steady with the use of composting in the Swiss FiBL DOK trial, but soil carbon increases occurred continuously over the 33 and 18 year study periods of the Swedish 'K-trial'[1179] and the German IBR Darmstadt trials of biodynamic farming (which involved organic farming with composting and biodynamic treatments).[1180]

There is also the interesting example of a UK organic farmer who has been applying small amounts of good quality compost to his fields for over 20 years.[1181] Soil tests have shown continuous increases in SOC content from a initial level of 2.9-3.5% to 4.0-4.1% now (a 25% or so increase, or an average increase of over 1% of the starting SOC level each year). This has occurred despite intensive arable cropping, including continuous cropping on some land. In his acre of glasshouse, however, he has been applying a much larger amount of compost and the SOC levels have risen from 2.3-2.9% to an impressive 10.4-10.9% (a roughly four-fold increase, or 20% increase per year). The farmer suggests that the maximum (ie. equilibrium) SOC level for his soils may be 11.5-12%, as this is the level of the compost he is applying. If this is so, this implies that his fields may continue sequestering carbon for much longer than 20 years. This still does not take account of any possible additional long-term increases by increases in soil depth.

In conclusion, the ability of the 'SOC equilibrium' approach and standard 20-year timeframe for capturing the soil carbon effects and potential of farming should be kept under review, particularly with regard to changes in soil depth, the ability to capture on-going trends in the development of farming systems, and the length of time for policy-significant levels of carbon sequestration. Meanwhile, the concept should not be used as a barrier to accounting for the soil carbon impacts of organic and non-organic farming.

9.9 Concern: 'Agricultural soil carbon stores are insecure'

So far, there has been little engagement with the subject of soil carbon by the organisations and initiatives that are actively promoting emission reduction activities. This is despite the fact that there is explicit allowance within the Kyoto Protocol for industrial ('Annex B') countries to partly achieve their reduction commitments with forestry or agricultural management.[1182] Agricultural soil carbon activities are omitted from the Clean Development Mechanism (CDM) of the Protocol, which gives carbon credits to western companies that invest in low-carbon development in developing countries. Likewise, the 'gold standard' of the World Wildlife Fund excludes agricultural soil carbon sequestration from eligibility for carbon credits.[1183] One reason for these exclusions is that soil carbon sinks are considered to be insecure.

The concern is that any higher soil carbon level, such as produced by organic farming, has no guarantee of permanence. For instance, a 2004 European report on land management practices and soil carbon levels stated, "There remain a lot of uncertainties with respect to C sequestration … Long-term SOM gains may be lost very rapidly when management practices that increased SOC content are abandoned again." [1184]

In this sense, all biological forms of carbon sequestration are insecure compared to reducing the use of fossil fuels. Nevertheless, we believe that this concern is unfounded or at least greatly exaggerated. This outlook ignores evidence that soil carbon sequestration is actually reasonably secure and probably more secure than forestry (which is accepted in these schemes), and that the methods used by organic farming may be particularly secure. It also ignores the important point that soil carbon seuquestration is a powerful tool for achieving large-scale reductions in GHG emissions over a relatively short-time-scale.

Firstly, it is important to point out that the permenancy of accumulated humus in stable circumstances is more than adequate for policy purposes. The average lifetime of humus in the soil is 100s to 1000s of years[1185], and in the subsoils (where organic farming also seems to increase levels), it can be several millennia[1186]. Moreover, losses are continually replaced by new humus, so overall levels do not change in stable management conditions. Presumably this would apply to the carbon built up by organic farming.

The concern about what would happen if the management system is abandoned is different. In such cases, the humus is indeed much less secure. Nevertheless, it does not disappear immediately. Although soil carbon is normally considered to be lost more rapidly than it accumulates[1187], it actually takes at least a decade for just half the higher carbon level to disappear, and decades for all to disappear. For instance, it took 30 years for the soil carbon level of ploughed-up permanent grass to reach that of continuously cropped arable soil, with half lost in the first ten years.[1188] This already indicates that, in the worst situation, the security of soil carbon sequestration is far greater than a forest that can always be burnt down, and the carbon lost immediately. However, this is the most negative evidence on this that we know of and the security of the higher soil carbon level of organic farming is likely to be much better..

The half-life (length of time for half to decompose) of the accumulated soil carbon from ryegrass residues (ploughed-in grass leys) has been reported to be about 25 years.[1189] Then, the effects of farmyard manure are very long-lasting: in a UK trial on clay soil, almost half of the extra soil carbon that had accumulated from 20 years of FYM application still remained 130 years after the applications had stopped.[1190] On a sandy loam soil, however, the half-life of accumulated soil carbon has been found to be only 20 years (the rate was the same for FYM, compost and biosolids).[1191] This is still, though, a reasonably long time in current policy terms. Additionally, there are indications that organic farming also builds carbon in the deeper layers of the soil[1192] which are more protected from mineralisation than the topsoil carbon and should be longer-lasting in changed circumstances.

This contrasts with the carbon built up under reduced tillage (currently the main option put forward for raising soil carbon levels with non-organic farming). This produces soil carbon of a different, instable form and not stable humus associated with the soil mineral particles. Disturbance of the soil by ploughing can cause most of the accumulated carbon to be released instantly (see Section 9.2).

So, overall, the soil carbon benefits of organic farming should be relatively secure in policy terms, compared to forestry schemes and the use of reduced tillage.

This concern with security may partly have arisen from experiences with forestry carbon sequestration schemes in developing countries. Afforestation offers the attraction of large annual biomass gains over several decades. However, there is the possibility of insufficient care of the trees after their initial planting and concerns that there may always be an incentive to cut down the trees, particularly as they mature, which would release all the carbon again. Growing awareness of these drawbacks has to some extent undermined the credibility of carbon sequestration schemes in general.

However, agricultural soil carbon sequestration has a very major advantage over forest plantations in that the carbon sequestration effectively starts as soon as the positive management starts and half of the total potential sequestration occurs within the first 20 years.[1193] This is in complete contrast to forestry, where the gains take many years to achieve as a carbon 'investment' is required to establish the trees.[1194] In fact, it has been estimated that, with global forest plantations, it would be over 20 years before the initial carbon emissions are offset and global net carbon sequestration starts.[1195] So, unlike new forests, agricultural soil carbon sequestration really can "buy time" in initiating major emission reduction in the short-term and help avoid dangerous climate change. This also means that *even if* a positive agricultural system is abandoned, with the lack of establishment inputs, soil carbon sequestration does not pose the risk of a negative sequestration result if it is abandoned early on, that afforestation schemes can.

As well as the opportunity of immediate gains with soil carbon sequestration, the situation should also be also more positive in agriculture than forestry because of farmers' constant, close management of their land. There may be some inherent insecurity with a soil carbon increases achieved under non-organic farming, as most carbon sequestration practices would be additional to or replacing activities that the farmer would choose for his commercial objectives. So, non-organic farmers may need to be continually encouraged (or required) to implement the practices, making soil carbon gains susceptible to a change of priorities by farmers or government. However, the soil carbon gains of organic farming are relatively secure as higher soil carbon levels are an inherent product of organic farming methods.

Also, farmers normally convert to organic farming with the intention of remaining organic. Entry into organic farming is not something that is undertaken lightly by farmers, with the option to easily pull out like from other agri-environmental schemes. It generally requires a significant financial and personal commitment to make the transition into organic management and marketing. Even if a few organic farmers out of the total revert in any one year (such as if the farmer retires and the farm is sold to a non-organic farmer), this does not seriously affect the national soil carbon store, which would increase as long as the overall area of organic farming expands. If there really are concerns about the potential for a more wholesale scale of reversion, there is plenty of scope for policy measures to prevent this. For instance, to expand the market, investment in food public procurement policies and official promotion of all benefitscan be implemented, let alone options of financial or legal support. Indeed, these are the sorts of measures that should be looked at to take the expansion of organic farming forward in the first place.

It also has to be said that this consideration of the rate of soil carbon losses that would occur if a positive land management is abandoned is focussing on the absolute worst-case scenario and cannot be the main perspective for policy decisions. Surely the issue is whether efforts should be made to increase the total area of farmland that is managed for higher soil carbon levels (indefinitely).

Concerns about 'security' have not been a barrier to the official recognition of other organic farming benefits that are just as 'non-permanent', such as biodiversity (in fact policy gains in almost every policy areas are inherently 'insecure'). It is accepted that organic farming generally maintains a higher level of wildlife, so, if more farmers farm organically, this increases the level of farmland wildlife. Moreover, given the climate adaptation, other environmental, animal welfare, nutritional[1196] and rural employment benefits of organic farming, higher soil carbon is just *one of several* major policy reasons for investing in the long-term expansion of organic farming. If, as much evidence indicates, organic farming is indeed a more suitable agricultural system for meeting policy objectives, then there would be every reason to continue to ensure that agriculture remains this way. In other words, investment in organic farming is embedded in a much wider and deeper range of societal and policy interests than perhaps, say, forest planting schemes.

Finally, concerns over the 'insecurity' of any gains in soil carbon seem rather over-stated at this point in time, considering: the urgency of the need to reduce GHG emissions, the large potential of soil carbon sequestration compared to the global GHG emissions, the fact that soil carbon sequestation can deliver immediate year-on-year gains and 'buy time', and the climate adaptation and food security 'by-product' benefits of soil carbon sequestration that do not exist with most other GHG emission reduction options.

In conclusion, the soil carbon benefits of organic farming are actually fairly secure, and there is significant potential for landowners and policy-makers to take positive and timely action on climate change here.

Overall, this analysis of the various concerns that are currently holding-back policymakers from promoting agricultural soil carbon storage, underlines the point that conclusions about the potential of soil carbon sequestration should not be drawn simply from research and experience with non-organic farming. Organic farming is a different agro-ecosystem and different evidence and concepts apply. The conditions and potential for carbon sequestration are different and overall favourable with organic farming.

10. Policy approaches for promoting soil carbon levels

10.1 Introduction

This review of the available scientific evidence has confirmed that organic farming generally produces significantly higher soil carbon levels than non-organic farming. This benefit is a by-product of the system. There also appears to be significant potential for organic farming practices to be further developed to increase soil carbon levels, such as through more use of composting. In non-organic farming, in contrast, the potential for improving soil carbon levels currently appears to be limited.

Therefore, given the large contribution of the past soil carbon losses to climate change, the continuing losses of soil carbon, the huge potential for carbon sequestration and its role in climate adaptation, the soil carbon benefit of organic farming is very valuable and be promoted. This issue should be addressed by agricultural and climate policies in four main ways:

1) The fact that agricultural soil carbon impacts are excluded from climate policy assessments of agriculture and carbon accounting schemes must be corrected.
2) There should be a strategy to maximise the soil carbon levels of agriculture based on a stategy to expand and develop organic farming, with a parallel approach to improve non-organic farming soil carbon levels.
3) Work to define a sustainable diet (as is being championed by the Council of Food Policy Advisors and the Sustainable Development Commission) should take account of the importance of grass-fed livestock in conserving existing soil carbon stocks in permanent grasslands and in sequestering carbon in cultivated land via temporary grass leys on mixed farms.
4) The major carbon source 'hot-spots' should be directly addressed.[1197] For the UK, this means drastically reducing imports of beef, soya and palm oil, reversing peatland drainage and returning the fenlands to mixed farming.

10.2 National GHG inventories and agricultural GHG emission assessments

Agricultural soil carbon losses should be accounted for and controlled like all CO_2 emissions. This would also help draw attention to the scale of the current losses (from grassland conversion, tropical habitat clearance and erosion) and the potential for rebuilding soil carbon stocks and reversing some of the past emissions, which is not possible with the emissions from fossil fuels. Agricultural soil carbon impacts should therefore be included in all national GHG inventories and emission reduction targets. This should be done in a way that captures the different soil carbon impacts of organic farming.

In principle, soil carbon stores should already be reported in national GHG inventories. According to the IPCC reporting guidelines, there should be annual assessments of the changes in agricultural soil carbon stocks in relation to management changes occurring in the country (not just 'land use' changes). In principle, this should - to a large extent - capture the effects of conversion to organic farming. For instance, the guidelines specifically account for the soil carbon losses/gains resulting from changes in the proportion of arable farms using temporary grass leys and livestock manure. But the guidelines are not being implemented in the UK and only a couple of EU countries are reporting this (such as, Portugal).[1198]

The IPCC guidelines are a basic, albeit reasonably comprehensive, method of capturing the soil carbon impacts of agricultural management.[1199] According to the guidelines, countries should be categorising all agricultural soils according to the level of organic matter input, and any change in the management of farmland that moves land from one input level to another (such as from continuous arable to rotational arable/ley systems, or from arable/ley systems to arable/ley plus manure use) is assumed to produce a soil carbon gain or loss. The total carbon gain/loss is the difference between the soil carbon equilibrium level of the first management regime and the equilibrium level of the new regime, and the change from one level to the other is assumed to occur linearly over a 20 year period, which produces annual soil carbon sequestration/loss figures. For convenience, the guidelines provide default carbon equilibrium levels ('soil carbon stock change factors') for four organic matter input levels (and the associated management practices) for cropland and grassland (or national data can be used, if there is sufficient evidence).[1200]

National GHG inventories should therefore be reporting on agricultural soil carbon changes, including capturing much of the soil carbon benefit of organic farming, given that most organic farmland was converted within the last twenty years (the default IPCC period for accounting for soil carbon changes). Unfortunately, the only soil carbon changes that are being reported in the UK's GHG inventory at the moment, are the impacts of changes in 'land use' each year (eg. conversion of land from, or to, cropland or grassland) and the carbon losses from drained lowland organic soils (fenlands).[1201] The other impacts of farm management changes on soil carbon stocks are not being reported. It is important that this is reddressed in future. Accounting for the higher soil carbon benefit of organic farming (and other practices where there is evidence of increases) would help offset greenhouse gas emissions and politically incentivise the much wider adoption of good soil management.

Secondly, the exclusion of soil carbon impacts from assessments of the Global Warming Potential (GWP) of farming systems must be addressed, such as the Life Cycle Analyses analysis of organic and non-organic farming sectors by Cranfield University for the Government[1202], the 'carbon footprint' calculations for labelling food products (being developed in the UK by the Carbon Trust/BSI[1203] and Tesco, and similar initiatives in France and Germany[1204]) and the 'ecological footprinting' methodology. These schemes are meant to provide guidance on the climate impacts of organic and non-organically produced foods to policymakers and consumers. So, they need to be sufficiently reliable and capture the major differences between the farming systems. Soil carbon is certainly such an issue.

Unfortunately, the IPCC soil carbon methodology does not easily lend itself for use in these calculations as GWP assessments of food products normally only capture on-going emissions that apply to the whole sector. They generally don't capture constant qualities, such as the higher soil carbon levels of organic farming, or any emissions/gains that are considered to be temporary because they are only associated with the initial adoption of the system, such as the soil carbon sequestration after conversion to organic farming. Another glaring gap in the current LCA and food labelling methodology is the omission of the major overseas 'land use change' impacts (natural habitat destruction) of different farming systems. Again, the IPCC guidelines do not help directly, as they do not relate emissions caused in other countries to the importing country (and have not so far been categorising 'land use change' emissions as agricultural). Clearly, some way must be found to include the full soil carbon impacts of agriculture, otherwise these assessments are grossly mis-representing the climate impacts of organic and non-organic farming.

The methodology used by the CALM farm carbon footprint accounting scheme[1205] assumes that some farming practices can produce annual changes in soil carbon levels, based on the IPCC 'land use change' approach. It accounts for the soil carbon impacts of year-to-year changes in the area of grass and woodland on the farm. This would capture the higher grassland area of organic farming, but not the higher soil carbon levels of organic arable land compared to non-organic arable land.

One way to use the IPCC soil carbon methodology (which is calculated on an area basis) in the LCA and food carbon footprinting calculations (which are calculated on a 'per tonne' basis), would be to use figures for the sequestration rate for conversion to organic farming and to consider the portion of land that has been or is being converted to organic farming (out of the total area of organic farmland). The rate could be derived either from the percentage differences in the soil carbon levels of organic and non-organic farming found by this review (eg. by using the per ha sequestration rate we have estimated for UK organic farming), or by using the soil carbon stock change figures for the adoption of relevant practices cited in the IPCC guidelines (use of rotational arable/ley systems, manure use). For example, if two-thirds of the UK's organic famland was converted in the last 20 years while a third already existed 20 years ago, the annual sequestration rate for conversion to organic farming could be reduced by a third, and then applied to all organic farming. This would not be totally satisfactory (for instance, it would not give recognition to the benefit of long established organic farmland in storing more carbon, the rate of conversion may not be constant), but it would be a logical and reasonable approach.

Additionally, the soil carbon sequestered by overseas organic feed production should be included in all

LCA and footprinting assessments of the GWP of organic meat, milk and eggs. This could, perhaps, be based on the calculations we have carried out (Section 8.3), which are based on annual soil carbon sequestration data (though ideally these would be refined and extended to red meat). Inclusion of the overseas land use change impacts of imported animal feed and the knock-on effects of dairy specialisation on beef imports should be easier to include, as these are annual on-going emissions.

10.3 Agricultural policy initiatives

Agricultural policy approaches should be also developed to incentivise farmers to maintain higher soil carbon levels. A number of issues would need to be considered.

One consideration is whether any gains in soil carbon should be recognised separately or whether only an 'overall GWP' approach should be taken, with any soil carbon gains offset against the GHG emissions of farming (nitrous oxide, methane, and CO_2 from energy use). With the latter approach, it would be impossible for many UK farmers to achieve a net saving of carbon, at least for the time-being. If the official figure of 13.8 million tonnes of CO_2eq[1206] by UK farming is divided by the 11.5 million ha of cropped and managed grassland[1207], UK farmers would on average have to sequester over 1t C/ha on all their managed land each year to be carbon neutral (assuming there are no on-going losses which to add to this). This is far higher than it has been estimated could be achieved by non-organic farming, and also higher than our estimate of what conversion to organic farming could reliably achieve in the UK.

More significantly, if each farm was required to balance its own emissions or to achieve a certain precentage reduction, then the ability of farmers to achieve this would diverge sharply across the industry. The actual amounts that can be sequestered on any one farm are highly variable and depend on the farm type and starting level of soil carbon. Most importantly from a policy perspective, the amount that would need to be sequestered would depend on whether the farm has livestock or not (given that livestock produce the highest GHG emissions). Farms with livestock, and therefore mixed farms and most organic farms, would be in a much more difficult position. This means that with an overall GWP farm-by-farm approach, all-arable farmers could actually be disincentivised from adopting organic farming or other mixed farming practices, even though the move to specialisation in the industry has been one of the key causes of the loss of soil organic matter in the UK (from the loss of temporary grassland and availability of manure). Additionally, to properly recognise the climate impacts of different systems, an 'overall GWP' approach would have to be 'life cycle' and include *indirect* emissions and indirect soil carbon impacts (such as from overseas animal feed production and land use impacts). Care would also have to be taken to ensure that farmers did not simply reduce their emissions by reducing their production levels (such as by converting farmland to woodland), which would simply export food production and emissions abroad.

An overall GWP approach in some form probably has merits. However, higher soil carbon might then become just one of many issues and possibilities in the pursuit of balancing the GHG accounts, and the complexity of such a scheme appears likely to reduce the chances of implementation.

Nevertheless, a specific and separate promotion of soil carbon levels is well justified given that soil carbon has considerable additional importance over the other GHG sources. Soil carbon levels are not just a driver of climate change and have the potential to reverse emissions, but they also play a role in climate adaptation and the achievement of other major policy objectives. According to a new report from the FAO, *"Many agricultural mitigation options, particularly those that involve soil carbon sequestration, also benefit adaptation, food security and development. These options involve increasing the levels of soil organic matter. This would translate into better plant nutrient content, increased water retention capacity and better structure, eventually leading to higher yields and greater resilience.." [1208]*

The other policy benefits are:

- Climate adaptation and water – soil humus levels determine the soil's water-holding capacity[1209] and drainage rates. Low soil carbon levels are therefore likely to exacerbate the impacts of climate change, by increasing the risk and severity of droughts, water shortages and surface-water flooding. Higher humus levels should converesly improve all these factors: they should reduce the need for irrigation, help food production to be maintained during droughts, and increase water infiltration rates, reducing the risk of flooding[1210]. For instance, a UK study has found that organic farmers use 26% less irrigation water per tonne of potatoes (partly also due to more efficient irrigation practices).[1211] The Rodale Institute's long-term trial in the US found that in drought years, organic maize crops yielded 33% more than non-organic maize, and organic soya yielded 78% more than non-organic soya.[1212] During torrential rains in 1999, measurements from the same trial found that water capture in the organically managed plots was double that of the non-organic plots.[1213]

- Maintaining yields & food security – as well as producing higher yields during droughts (above), (i) raising soil organic matter levels would protect the large area of vulnerable agricultural land in semi-arid areas from desertification and so help maintain the world's food supply.[1214] And, (ii) the application of non-agricultural organic matter to farmland (green/food/paper waste, sewage sludge) will 'close the nutrient cycle' by returning key nutrients to the soil.[1215] This is especially urgent for phosphate (P) and potash (K) as globally mined supplies are running out. Agricultural yields will start to fall if measures are not put in place in the near future to replenish soil P and K levels by recycling.[1216] Other soil nutrient deficiencies would also be addressed.
- Energy & cost saving - good soil humus levels help reduce diesel fuel use in farming, by improving the 'workability' of the soil that determines the ease of ploughing, a main fuel-using operation in farming and an increasing cost in food production. Good soil humus levels also reduce the need for inorganic fertiliser, reducing the use of fossil fuels to manufacture fertiliser and saving farmers money.
- Human health - soil humus and microbial populations play a central role in human nutrition as they supply the trace minerals needed in the diet, by releasing and storing the minerals in the soil.[1217] The large body of comparative studies of organic and non-organic foods shows organic foods have higher average levels of trace minerals[1218], generally ascribed to the use of organic matter for soil fertility.
- Biodiversity - soil earthworms and microbes are part of the wild food chain that supports above-ground biodiversity.[1219] A high soil carbon level is therefore likely to be associated with more farmland wildlife, which is itself another carbon store.
- Contamination – humus stabilises toxic compounds in the soil[1220], and diverse soil microbial populations with complex metabolic pathways can break down pollutants and control pathogens.[1221]

If soil carbon levels are to be specifically promoted, one approach would be to introduce a financial, or other, incentive for farmers, where the level of the incentive is proportional to the level of the soil carbon benefit. Again, there are aspects that need to be considered. If the incentive only rewards *increases* in soil carbon levels, it would not reward farmers who have already increased their soil carbon to a good level and are now stably maintaining their levels. The 'benefit' would therefore be better represented by the difference between the current soil carbon level and the natural or target level for that soil type (such as under the native vegetation), with a greater incentive for closer levels. Topsoil depth and the subsoil carbon content would have to be part of the calculation. However, values for the current and target soil carbon stock level for each farm's soils would need to be gathered or developed, which would be difficult and highly time-consuming to prepare.[1222]

Also, incentives could not, in practice, be based on monitoring the *actual* soil carbon levels and progress towards to the target level at each farm. Soil carbon levels vary greatly from field to field and even within fields, and soil carbon levels also fluctuate year-to-year depending on the stage of crop rotation and weather. Trends are only evidence by constant monitoring over many years. So monitoring a whole farm's soil carbon stock would in principle require continual, deep and multiple soil sampling of all fields.

An alternative and more practical approach would be an 'activity-based' incentive scheme, that recognises that certain farming practices or systems produce higher soil carbon levels and that rewards farmers for the use of these, irrespective of how much the levels are actually increased at each individual site. This would recognise that all that matters is that the average levels of soil carbon are increased as much as posible across the industry. For example, incentives could be geared to reward the most effective organic matter types on a sliding scale starting with, say, leguminous green manure crops, then fresh ruminant manure, then composted FYM, then grass leys, and then true compost (from suitable mix of materials). It would need to be considered whether types/practices that may simply maintain current levels should be included, such as probably straw and crop residues. Care would need to be taken to exclude practices that increase other GHG emissions and have no overall GHG benefit. (For example, as well as the uncertainty over whether there really is an overall soil carbon benefit from minimum-tillage in the UK, it seems to increase nitrous oxide emissions which would may negate any soil carbon benefit.[1223])

Maintenance and increases in soil carbon should be encouraged on all farms, and an activity-based system is a good approach. As yet, the total amount of carbon that is likely to be sequestered with current non-organic farming systems appears to be either small or uncertain. The adoption of minimum tillage, until now the the most popular option for non-organic farming, is already widely used and seems to have marginal benefit in the UK – see Section 9.2. Most all-arable farmers do not have access to manure and are probably unlikely to consider reverting to mixed farming systems with grass leys, unless the incentives are very high or this is part of a much broader, wholesale system change that has other attractions. The wide use of cover crops and composting should in principle be feasible and should be promoted. Neverthless, all such options require non-organic farmers to adopt additional or different practices to their normal activities, and as yet the extent of the soil carbon gains that would be achieved in a commercial non-organic farming context are unknown. The achievement of soil carbon gain would therefore require on-going policy intervention and may be costly in terms of implementation, management and monitoring and there would be concerns about the longer-term permanence of the practices.

There is, however, very good potential for taking forward this issue on a large-scale through the much wider uptake of organic farming methods. Organic farming can be adopted by all farmers in all conditions and there is now solid evidence for the achievement of substantial soil carbon increases. Organic farming would also produce soil carbon benefits abroad (via imported organic feed and reduced use of grain feed). Additionally, there is considerable potential for further developing organic farming soil carbon and yield levels. Given the need to act quickly on emissions and to prepare for climate adaptation, organic farming must be an excellent tool for addressing soil carbon, and especially as organic farming delivers a range of other important policy benefits as well.

It is therefore proposed that the main approach to agricultural soil carbon sequestration should be to give much greater policy support for the wider adoption and development of organic farming. Information about the soil carbon benefit of organic farming should be promoted to the industry, environmental agencies and the public. Conversion support should be targetted at current specialist arable and horticultural farms, where soil carbon levels are usually particularly low, and the cultivated organic soil types (eg. fenlands) which are losing large amounts of soil carbon. The farm stewardship schemes could be extended to include a soil carbon component, with the payments for organic crop production increased to recognise the soil carbon benefit, and a carbon stewardship component included in the environmental stewardship schemes for non-organic farmers, based on the use of effective organic matter types. Other policy approaches to increasing organic farming should also be pursued, such as greater use of public procurement schemes, development of the organic food market and much more R&D investment.

Another interesting approach that could be developed by both the industry and policymakers is to harness the market to promote soil carbon, by enabling agricultural soil carbon sequestration/maintenance to be traded on the carbon trading markets. For the reasons discussed above, this would have to be 'activity-based' (not based on actual soil measurements). The 2006 UK Climate Change Programme included a policy commitment to, "examine the scope and feasibility of a market based mechanism to facilitate trading of greenhouse gas reductions from agriculture," which included carbon storage in soils.[1224] Organic farmers could, for example, receive fixed annual payments for soil carbon sequestration for the first twenty years after conversion and then for keeping their soil carbon intact thereafter, in the same way as is happening now with forestry. 'Avoided deforestation' is rewarded with Certified Emission Reductions (CERs) that can be traded on the carbon markets, thereby giving a value to standing forest. The voluntary carbon credit market already trades such offsets.[1225]

11. Conclusions and recommendations

"The trend for greater organic C on farms managed with organic production practices deserves attention from policy makers in light of current discussions regarding agriculture's role in mitigating the greenhouse effect through sequestration of C." Liebig & Doran, 1999, US study of organic and non-organic farms.[1226]

Soil carbon is probably the most important aspect of agriculture for the climate. Almost 90% of agriculture's GHG mitigation potential resides in improving soil carbon levels and, unlike other greenhouse gas sources, soil carbon levels play a direct role in climate adaptation. Yet, the soil carbon impacts of agriculture are being ignored by current GHG accounting systems. The large on-going soil carbon losses from the conversion of grasslands to arable land in the UK are not being included in agriculture's GHG emissions (this would raise the current figures by 12%), the basic IPCC soil carbon guidelines for agricultural management are not being implemented, the carbon losses from the destruction of tropical habitats for imported food and feed products are not being accounted for, and most Life Cycle Assessments of agriculture have failed to consider soil carbon impacts at all. This means that the GHG emissions of agriculture have been greatly under-estimated, the emissions of organic farming greatly over-estimated, and the real potential of soil carbon sequestration for reducing GHG emissions has not been clear.

The review of the comparative soil carbon studies of organic and non-organic farming in this report, covering 39 studies and over 100 individual comparisons, shows that organic farming produces substantially higher soil carbon levels than non-organic farming on cultivated land. The level of increase varies, such as, according to length of time under organic management. However, increases with organic farming have been shown across different regions and climatic conditions, and for different types of organic farming system. A higher soil carbon level is an inherent product of organic farming because the system is based on using organic matter to provide soil fertility, instead of using inorganic fertilisers.

On the basis of the studies reviewed, organic farming produces an average of around 28% higher soil carbon levels than non-organic farming in northern Europe after around 15 years of organic management, and around 20% more for all countries studied (in Europe, North America and Australasia after around 12 years. (The reliability of these figures depends on how representative the studies reviewed are of organic farming and of agricultural conditions globally). For the UK, this would mean an extra about 64 million t carbon being stored in arable soils. Conservatively assuming that this increase would be produced only over a twenty year period, this represents a soil carbon sequestration rate of approximately 560kgC/ha/year for each hectare of cultivated land converted to organic farming in the UK, for the next twenty years at least, and lower amounts thereafter.

On this basis, we have estimated that the widespread adoption of organic farming in the UK would offset about 23% of UK agriculture's GHG emissions. At a global level, the effects of agricultural soil carbon sequestration are even greater (because of the more favourable ratio of the area of cultivated land to GHG emissions). Assuming a higher possible sequestration level of 1tC/ha/year with best practices, we provisionally suggest that and if agriculture was globally converted to organic practices, this could offset around 11% of all global GHG emissions, each year for at least the next twenty years.

Sectoral analyses suggest that the soil carbon benefit of organic farming offsets 44-72% of the GHG emissions of organic arable crops and 29-39% of the GHG emissions of organic white meat at least, for twenty years (and lower amounts thereafter). This means that widespread conversion to organic famring would drastically reduce the GHG emissions of these sectors for at least twenty years.

Soil carbon sequestration by organic farming also provides the lasting benefit of improving soil structure and quality, because the accumulated carbon is in the organic form of humus which improves soil aggregation. This will improve climate adaptation by reducing the impacts of flooding, droughts, water shortages and desertification, and it would protect the large area of vulnerable agricultural land in semi-arid areas from desertification, thereby improving global food and water security.

These estimates of the soil carbon effects of organic farming are conservative as they are based on studies of the topsoil carbon levels of cultivated soils only, which is all that most studies have measured. They do not include the increase in agricultural soil carbon storage that would also results from the almost certainly greater percentage of permenant grassland with widespread organic farming, or the large carbon savings from the likely greatly reduced tropical habitat destruction, or the significant potential for further developing organic farming practices to further increase its capacity to build soil carbon.

There are also indications that organic farming may increase soil carbon storage by increasing topsoil depth and subsoil carbon contents, and also grassland soil carbon levels, and these are the areas where scientific data is most needed to complete the picture of the soil carbon impacts of organic farming. If organic farming increases soil carbon storage over a deeper soil profile – as five or six sets of comparative data indicate, this is of great importance for long-term soil carbon sequestration given that the lower soil layers contain a large portion of the total soil carbon stock and that the stability of soil carbon increases greatly with depth. Future comparative soil carbon studies should therefore sample the soils to at least 50cm (or the full soil depth, if less). If organic farming also increases grassland soil carbon levels, this would be very significant given the large area and higher soil carbon levels of grassland.

The review of the scientific evidence on the factors and biological processes of soil carbon accumulation shows that soil carbon levels are determined by a number of biological factors, not just the level of organic matter inputs. Agriculture affects these factors. Organic farming increases soil carbon levels by: producing additional sources of organic matter, creating organic matter in forms that are more effective at producing soil carbon, integrating crop and livestock systems, and by increasing the proportion of vegetation cover which promotes the soil's micro-organisms that stabilise soil carbon. These benefits result from the fact that organic farming is based on inputs of fresh organic matter to the soil and its decomposition by soil microbial activity. This releases nutrients for crop production (replacing the use of inorganic fertilisers) and, at the same time, this process also produces humus (stable soil carbon). Together with other aspects that promote the living organisms in the soil and soil aggregation, this approach raises the soil's carbon level.

It is also clear that grass-fed livestock have a critical role to play in minimising carbon emissions from farming, and this must be set against the issue of methane emissions from cattle and sheep. Grasslands for grazing livestock, whether permanent pasture or temporary grass on mixed farms (which account for most UK organic cultivated land), are important soil carbon stores. Advocates of a shift from red meat to grain-fed white meat to address the methane issue could find this has the effect of exchanging methane emissions for carbon emissions from the soil and the destruction of tropical habitats (to produce soya feed), as well as having far reaching impacts on our countryside, wildlife and animal welfare.

It is concluded that soil carbon sequestration – achieved through the widespread adoption of organic farming - would substantially reduce greenhouse gas (GHG) emissions and improve the 'carbon balance' of UK agriculture and the world for the next twenty years, at least. It would also improve the resilience of agriculture and assist adaptation to climate change.

On the basis of these important climate benefits, we therefore make four main policy recommendations and a number of other more specific and additional recommendations:

Main Policy Recommendations

1. Soil carbon impacts should be fully accounted for and considered in climate policy and agricultural GHG accounting systems, in line with IPCC recommendations and including overseas impacts.
2. National and global strategies for large-scale soil carbon sequestration should be adopted based on a major expansion and development of organic farming, with a parallel approach to improve non-organic farming.
3. Work to define a sustainable diet (as is being championed by the Council of Food Policy Advisors and the Sustainable Development Commission) should take account of soil carbon impacts including the

importance of grass-fed livestock in conserving existing soil carbon stocks in permanent grasslands and in raising the soil carbon level of cultivated land via temporary grass leys on mixed farms.

4. The major national and global carbon source 'hot-spots' should be also directly addressed. For the UK, this means drastically reducing imports of beef, soya and palm oil, reversing peatland drainage, and returning the cultivated fenlands (lowland peaty soils) to rotational arable/grass ley farming.

Other more specific and additional recommendations:

For Government and the food and farming industry:

1. Far greater political and industry attention should be paid to the protection of the soil's carbon store and to the potential for re-building soil carbon levels.
2. The UK and other countries should implement the IPCC guidelines to account for the soil carbon impacts of changes in farm management in the national GHG inventories as soon as possible.
3. Impacts on the soil carbon store should be included in all LCA or footprinting calculations of the climate impacts of farming systems, including the soil carbon impacts of animal feed production and 'land use change' impacts.
4. There should be official public recognition of the soil carbon benefit of organic farming by the Government and IPCC, and a strategy should be developed for the large-scale expansion and development of organic food and farming, including technical support and market development.
5. Organic farming conversion support should be targetted at the specialist arable and horticultural farms. The farm stewardship schemes could be extended to include a soil carbon component, with the payments for organic crop production increased and a sliding scale of payments made available for non-organic farmers for the use of effective organic matter types (such as, cattle manure).
6. Trade policy and rules should in future be developed on along radically different lines to ensure that they become important tools in the promotion of sustainable and ethical sourcing, instead of facilitating the exploitation of natural resources.
7. Agricultural soil carbon sequestration should be included in the Clean Development Mechanism (CDM) of the Kyoto Protocol and in the 'gold standard' of the World Wildlife Fund, and support should be given to organic farmers to engage in the voluntary carbon trading/offset markets.
8. Conclusions about the potential for increasing soil carbon storage that are derived from research and experience with non-organic farming systems should not normally be applied to organic farming; such conclusions should instead derive from the specific research on organic farming soil carbon storage.
9. Further progress should be made to improve the supply and use of national organic matter resources from the food and waste industry back to farmland (ie. food waste, paper/card waste, and human excreta), including by reviewing the benefits of using organic waste for soil treatment versus energy, and ensuring that all new planning developments have a separation of domestic and industrial waste.
10. The organic sector and carbon footprinting organisations should encourage organic and non-organic farmers using their schemes to annually monitor their soil carbon levels, to provide comparative and long-term soil carbon data, with a view to improving the accounting of agricultural soil cabon storage and the comparative effects of organic farming.
11. The EU organic standards on peat use should be tightened to be the same as the SA standards (for horticulture, only allowed for horticultural propogation) and more investment should be directed at finding a suitable alternative to peat-based compost.
12. The organic sector should progress the issues of using composted human 'night soil' or biosolids (treated human sewage, which is allowed in non-organic farming) on organic farmland, to close the nutrient cycle; this could be done by removing the prohibition on human excreta in the EU organic standards and by allowing national decisions based on common EU criteria on treatment and safety.
13. Organic farmers should try to take further steps to increase their soil carbon levels, for example by wider use of composting, green manures, deep-rooting plants, complex species mixtures in the grass ley, inter-cropping, varietal mixtures, producing and using manure instead of slurry, using food industry and municipal organic matter waste, biodynamic methods, and by keeping organic (high carbon) soil types under grass rather than in regular cultivation.

14. Organic farmers should consider ways to increase their farms' non-crop woody biomass carbon stores (in ways that do not reduce food production), such as by increasing the extent of hedgerows and trees and better farm woodland management (including coppicing, agroforestry).

For the research community (and research funding bodies):

15. Much more research should be undertaken into the comparative long-term soil carbon levels of UK organic farming, including large-scale surveys of farms, including horticultural land and grassland.
16. Comparative soil carbon studies should capture more information, including sampling the whole topsoil profile, topsoil depth, soil bulk density, the levels of above- and below-ground carbon inputs, the levels of carbon in 'imported' organic matter, and soil microbial and invertebrate biomass levels.
17. Publications on comparative soil carbon studies should attempt to provide more detailed analysis of the comparative soil carbon storage of organic farming, including details of the proportion of organic matter input that is converted to stable soil carbon, and report differences in tC/ha.
18. Research should continue into the biological mechanisms of soil carbon sequestration (addressing all aspects discussed in this report), the relationship to agricultural management, and the comparative impacts on these soil processes of organic farming.
19. Work should continue into monitoring and quantifying the changes in soil carbon content across the country, including (i) sampling the whole topsoil and deeper layers (at least to 50cm) and changes in soil depth and bulk density, and (ii) collect information on the management practices at each site, including whether the farm management is organic or non-organic, and changes in ploughing depth.
20. Comparative research should be undertaken to quantify differences in the levels and stability of the soil carbon inputs in organic and non-organic farming (including levels of above- and below-ground biomass, root exudates, and manure/slurry use; for arable crops, horticultural crops and grassland).
21. Work should continue to develop more reliable soil dynamic models, modelling approaches and data, to ensure that all agricultural factors other than arable crop residues are well represented, and to include subsoil and biological components that address the differences found in organic systems.
22. More research into the contribution of root systems and fungal mycorrhizae to the accumulation of soil carbon and the significance for agricultural management.
23. The impact of avermectins, and other common livestock veterinary drugs found in manure and slurry, on overall grassland soil carbon storage should be fully and conclusively investigated.
24. The comparative carbon stock levels of the higher soil and terrestrial wildlife supported by organic farming should be assessed and quantified.
25. The design and reporting of comparative soil carbon research should be improved to facilitate policy use: (i) soil carbon changes under rotational arable/grass should be reported separately from continuous arable land, and permanent grassland; (ii) where possible, methodologies should be sensitive enough to identify likely and politically significant soil carbon differences as statistically significant (eg. a 10% difference); (iii) given the difficulties in achieving this in practice, care should be taken that a lack of statistical significance of the differences is not unintentionally communicated as a lack of existence of a difference, and the observed differences should always be clearly reported; and (iv) terminology should be clarified, with all grazed grassland included as 'agricultural land'.
26. Funding should be provided for the organic R&D community and organic sector organisations to develop and promote ways for organic farmers to significantly increase their soil and biomass carbon store, whilst also promoting their food production levels (such as by developing the additional practices mentioned at the end of section 9.7).

END

ANNEX I Evidence for on-going trends in agricultural soil carbon levels

- This Annex present further details on the evidence for on-going trends. Although arable soils already have the lowest soil carbon levels of all major land types in Europe, they are considered to be one of the two main sources of the soil carbon losses, while forests soils[1227] and most grassland soils are believed to be gaining carbon (although the situation appears different in the UK, with grassland being either stable or a source of topsoil losses). Peatlands that have been drained are also losing large amounts of soil carbon.[1228] The evidence is, however, confusing and conflicting.

The 25-year NSI survey of *all* the topsoils (not just agricultural soils) of England and Wales (0-15cm, 1978/83 - 1994/2003) found that carbon losses were occurring at 92% of the sites, in all land types, and with an average loss for all topsoils of 0.6% of the existing carbon level each year. Extrapolating to the whole UK and to 30cm, it was conservatively estimated that 13 million t of C were being lost from the UK's soils each year (Bellamy *et al*, 2005[1229]). However, concerns with the methodology used for measuring the high carbon peaty soils[1230] and with the bulk density calculation[1231] mean these findings are unreliable (Smith *et al*, 2007[1232]).

This UK NSI survey found that the amount of carbon being lost is proportional to the level of carbon in the topsoil. So, 'unmanaged' grasslands (rough grazing, upland grasslands and moorlands) and bogs, which have the highest carbon levels of all soils, were showing the greatest gC/kg and total topsoil carbon losses. Permanent managed grassland which has lower average SOC contents were losing less carbon overall, and cultivated soils which have even lower average SOC contents were losing even less carbon overall.[1233] However, it was not a consistent situation of losses everywhere. Most land use types and soils with starting SOC contents above 3% (3gC/kg soil) were overall losing carbon, but soils with SOC contents below 3% were gaining soil carbons.[1234]

There is also variability within the managed farmland soils. For the arable soils, although there was an overall loss of carbon, soils with an initial SOC content of under 2% were actually gaining carbon, as a whole. The carbon content of soils that were originally in arable cropping and maintained in arable cropping were largely unchanged or increased slightly.[1235] So, it was only those cultivated soils with a SOC content of over 2% that were losing carbon, and the decline was greatest for those with the highest SOC contents (soils with over 10% SOC content).[1236] The carbon losses from cultivated land was largest from soils which had been ploughed out of permanent grassland and peaty soils in tillage (the English fenlands), while levels increased slightly for sandy soils and medium silts ("possibly reflecting regular livestock manure inputs to root crops on these soils").[1237]

While the existence of on-going losses from arable soils matches the trend for cultivated soils throughout Europe, the observation that grasslands were losing carbon suggests that the UK's grasslands may be in a much worse state than in the rest of Europe, which is concerning.[1238]

The UK's National Soil Inventory (NSI) survey did not report on the results for farmland separately at the time of the publication of their findings in 2005. Given the concerns raised by Smith *et al*, the National Soil Resources Institute (NSRI) has since provided the Soil Association with figures for the rate of carbon loss for agricultural land for mineral soils alone (soils with less than 15% SOC content, ie. excluding the organic soil types).[1239] This data is in gC/kg of soil/yr for the top 15cm over the 25-year period of the NSI survey, 1978-2003, for England and Wales.[1240] See Box for full data. This data should be reasonably reliable as it excludes the organic soil types and is not affected by the bulk density calculation[1241].

The mean rate of loss from the mineral soils in the survey was 0.33gC/kg soil/yr from the arable/grass ley soils and 0.40gC/kg/yr for permanent managed grassland, with considerable variation between sites, especially the arable sites.[1242] These work out at annual losses of 1% and 0.8% respectively of the original soil carbon content of the arable and permanent grassland sites at the start of the survey.

Results of the NSI survey of agricultural soils in England and Wales

The NSRI provided the results from the National Soil Inventory survey of England and Wales for the rate of carbon loss for the farmland mineral soils alone, ie. soils with less than 15% SOC content.[1243] The data is for the top 15cm, for all of the sites that were re-sampled. The initial sampling was in 1978-83, and the re-sampling was carried out in 1994/95 for arable soils and 1995/96 for permanent grassland. It should be noted that these are *average figures* and, for the arable/grass ley sites, the figures are heavily influenced by a relatively small number of sites that had very high soil carbon losses. At most arable/ley sites, the soil carbon losses were much smaller and many of the lowest carbon arable and grassland sites gained small amounts of carbon.

Notes:

- 'Median' is the value at the middle of the set of data, ie. value at the point in the range of samples where half the data has a higher value and half has a lower value.
- Permanent grassland data – we presume this data is just for managed permanent grassland and excludes rough grazing, as the letter group was included in the 'non-agricultural land' category in Bellamy *et al*, 2005.

% of the farmland soil carbon store lost each year[1244]

	Mean loss rate (gC/kg soil /yr)	(95% confidence) (gC/kg soil /yr)	Median loss rate (gC/kg soil /yr)	1980 level (*all* soils) (gC/kg soil)
Arable/grass ley : (813 mineral soil sites)	**- 0.33g/kg**	(-0.25 to –0.42)	- 0.07g/kg	**34g/kg**
Permanent grassland: (639 mineral soil sites)	**- 0.40g/kg**	(-0.31 to –0.49)	- 0.23g/kg	**50g/kg**

The far column shows the average starting soil C levels in 1980, at the start of the survey.[1245] As this was for all soil types, the average starting level for the mineral soils only would have been lower. Therefore, comparing these levels, we can conclude that the average annual losses from the mineral soil sites was:

- **Arable/grass ley: over 1% of the average starting soil carbon content, per year**
- **Permanent grassland: over 0.8% of the average starting soil carbon content, per year**

This is consistent with earlier reported findings of the survey that arable/ley soils and permanent grasslands, for all soil types in England and Wales, are each losing 1.1% of their 1980 carbon content each year. The average SOC content for arable/ley soils fell from 3.4% in 1980 to 2.8% in 1995 and for permanent grass from 5% to 4.2%, falls of 17% and 16% respectively of the original value in 15 years.[1246]

The NSRI emphasise that the mean rates are largely determined by the very high losses at a small proportion of the sites, so the median loss rates are more likely to be representative of the typical change in UK farmland topsoils. If most of the losses from arable land are from the cultivation of grassland and fenland, these findings are then consistent with the UK GHG Inventory: an annual fall of over 1% in the UK's arable soil carbon store implies an annual loss of over 2.3milliontC/yr[1247], which is close to the inventory estimate of 1.9milliontC/yr net being released each year from the ploughing-up of grass and cultivation of fenland.[1248] The inventory does not, however, include any losses from permanent grassland.

The NSRI explain that the results of the subset of sites that were resampled (shown here) cannot be directly compared with the results from all of the sites, which were reported in Bellamy *et al*, 2005. Only 40% of the initially sampled sites were re-sampled. To get nationally-representative distribution for all of the sites, they made estimates for the remaining 60% of the original sites that were not resampled, which would have given a somewhat different distribution and average loss rates for the sites reported here.

We are grateful to the National Soil Resources Institute for providing this information, August 2008.

What are the uncertainties?
There remains considerable uncertainty over the rates of soil carbon loss from UK farmland and its contribution to climate change. These uncertainties are:

- the trend and scale of the changes at the majority of sites and for long-established arable land (ie. once land that was converted from grasslands and fenlands are excluded)
- the bulk density calculation means that any data presented in terms of total soil carbon stocks (eg. tC/ha/yr or total tC) is somewhat unreliable but the degree of inaccuracy is unknown[1249]
- as the soil was only sampled to 15cm in both the NSI survey and Countryside Survey, the trends for the deeper soil layers and for topsoil and overall soil depths remain unknown
- the differences between continuous arable land and rotational arable/grass land in mixed systems
- uncertainty over how much of the losses from the soil carbon store are entering the atmosphere each year, and how much is entering other carbon sinks such as the water system.

Although the finding of soil carbon losses from arable land is supported by the other UK survey, the Countryside Survey (see main text), this is not the case for other land types, such as grasslands, where there is a discrepancy between the findings of widespread losses by the NSI survey and the findings of little change by the Countryside Survey.

In addition to the surveys, there have been four attempts to model soil carbon levels across Europe. These used models that simulate climate-vegetation-land dynamics and data on the relationship between climate, crop yields and soil carbon levels. Two of these studies concluded that Europe's arable soils are losing carbon, one concluded that arable soils are in the range of slightly gaining or slightly losing carbon over the long-term, and one concluded arable soils are gaining carbon. See BOX for a summary of the studies. The results lend some support to the findings of the surveys that arable topsoils in Europe are losing carbon.

The two modelling studies, Janssens *et al*, 2005[1250], and Zaehle *et al*, 2007, had similar findings to each other (bearing in mind that they considered different areas) and the national surveys, so they are probably the best current estimates. This suggests that Europe's arable soils are currently losing around 30 million tC/yr (EU25, Norway and Switzerland).[1251] As the arable area is 126.5 million ha with a 1990s soil C stock of 11 billion t[1252], this gives an average of loss of 237kgC/ha/yr, almost 0.3% of the total soil C per year.

However, there are important limitations with the estimates from modelling studies. Inevitably, they are only as good as the data and assumptions used. All of the modelling studies are mainly based on the concept that the soil carbon input to farmland is proportional to the crop yields, and there is unfortunately little consideration of the effects of agricultural management.

The possible cause of any widespread losses from all land types, as found by the NSI survey, is also unclear. Drainage of peatlands and afforestation would explain the soil carbon losses in certain areas, but not the falls at 92% of the UK survey sites. Climate change (rising temperatures, rising CO_2 levels, increasing drought and altered weather patterns) is a mechanism that would apply country-wide. (This might, for instance, help explain the increase in the losses with rising soil moisture for cultivated soils.[1253]) Temperatures in Europe have risen in recent decades, in fact more than climate change modelling predictions.[1254] However, the consensus among UK researchers is now tending to the view that climate change is not having a significant negative effect (at least not yet), as this is not suggested by the data from, for example, the UK's longest soil carbon monitoring study, or by modelling studies. The long-term continuous arable trials at Rothamsted appear to show a possible effect of climate change on the plots' soil carbon levels and there has been a clear local temperature rise since the early 1980s[1255], but this is ruled out by the researchers.[1256]

Modelling studies on the current soil carbon status of Europe's farmland

There have been four recent attempts to model soil carbon levels across Europe. Here is a summary of the results and some of the strengths and weakness of each study, based on the published papers.

1. Janssens *et al*, 2005[1257]

Description: an update of Janssens *et al*, 2003[1258] which used the CESAR model, but taking lower figures from the range of estimates produced than the mean, to try to match the national soil surveys' results.

- Results: "arable soils are predicted to be losing C in all European countries", in total **losing 46 million t of C each year** (+/-30 million tC) for the 34 countries of geographical Europe (excluding European Russia). Grasslands are predicted to be gaining a total of 40 million tC/yr (+/-26 m).[1259]
- Strengths: the estimate is based on the observed data *and* modelling, unlike the other studies.
- Weaknesses: exclusion of the positive effects of manure applications; the 'legacy' effects of prior conversion of grassland to arable land (important in the UK); the significant management changes that occurred in Central and East European countries; and of the positive effects of rising CO_2 levels.

2. Zaehle *et al*, 2007[1260]

Description: long-term modelling of future changes in European soil carbon levels, 1990-2100. It used an advanced version of the Lund-Potsdam-Jena land-vegetation model (LPJ-DGVM) and four climate models.

- Results: arable soils are predicted to be **losing 19.3 million t C each year** (+/-9 million tC) and grasslands losing 14.5 million tC/yr (+/-13.2m), in the 1990s, for the EU15, Norway & Switzerland.
- Strengths: accounts for extreme climate events which reduce plant growth (eg. heat-waves); and it found similar EU25 arable results to Janssens *et al*, 2005, which took account of the soil surveys.
- Weaknesses: excludes changes in management that could affect plant growth; and soil C losses to watercourses. Also, probably used earlier, over-optimistic estimates of the 'CO_2 fertilisation' effect.

3. Smith *et al*, 2005[1261]

Description: long-term modelling of future changes in European soil carbon levels, 1990-2080. It used the Rothamsted soil C model, Lund-Potsdam-Jena land-vegetation (LPJ) model, and four climate models.

- Results: over the long-term, arable and grassland soil C levels are **either slowly increasing (if climate change is promoting plant growth) or slowly falling (if not)**. In the most optimistic scenarios, in which estimates of higher plant growth from rising CO_2 are "the maximum possible", the estimated long-term gains are 11-78kgC/ha/yr for croplands and 36-69kgC/ha/yr for grasslands (EU25, Norway & Switzerland; mineral soils, 0-30cm). The paper does not state current rates or provide the lower estimates (ie. if climate change does not increase plant growth, but technological development continues), but the information suggests that the estimated maximum losses are roughly of a similar magnitude to the maximum gains (giving around +/-10 million tC/yr for all arable soils).
- Strengths: separately calculates the impacts of climate change on soil carbon, and on plant growth.
- Weaknesses: exclusion of the effects of agricultural practices on soil carbon other than by yield levels; and exclusion of organic soil types, some of which are believed to be losing large amounts of carbon. The upper estimates probably use earlier, over-optimistic estimates of the 'CO_2 fertilisation' effect.

4. Gervois *et al*, 2008[1262]

Description: retrospective modelling of soil carbon, 1901–2000, accounting for changes in manure use, inorganic fertiliser, ploughing depth and maize irrigation. Used ORCHIDEE-STICS vegetation-crop model.

- Results: European croplands are **gaining 160 kgC/ha/year** (+/-150kgC) due to a slow 'rebound' after the move from manure to N fertiliser, but are decreasing in some areas (eg. southern England).
- Strengths: takes account of the negative effect on soil carbon inputs of the higher 'harvest index' of modern cereal varieties; and uses lower, more realistic assumptions of the 'CO_2 fertilisation' effect.
- Weaknesses: assumed pre-1950 fertilisation depended solely on manure use, while actually N-fixing plants and rotational grass/arable systems were the main basis of European farming and supplied large amounts of root biomass. Also, no account of the smaller root biomass of modern varieties.

The observed carbon falls in the UK's and Europe's arable soils (in some surveys) are also an order of magnitude greater than the very small losses that are predicted by modelling the effects of climate change. Smith *et al*, 2007[1263], estimate that in response to climate change, soil carbon levels would be falling by at most 0.08% of the total SOC each year (-67kgC/ha/yr) on European croplands and half this rate on grasslands, if just the increase in soil carbon mineralisation[1264] from the rise in temperatures is accounted for. Using a more complex soil model and allowing also for higher plant growth (from rising temperatures and the so-called 'CO_2 fertilisation effect'), Smith *et al* predict that the effect from climate change is more likely to be only -0.02% and +0.02% of total SOC/year for arable and grassland, respectively.

In considering to what extent agricultural management might be responsible, it is important to note that the reported findings of the surveys do not give the full picture. There are some additional indications that agricultural practices are an important factor in the current soil carbon trends.

One interesting aspect is the apparent correlation between the magnitude of the soil carbon losses and the intensity of agricultural management, in the UK NSI survey. The results of the survey, as presented in the journal *Nature,* show that *for the same level of original soil carbon*, the average rate of carbon loss is *far higher* under arable and rotational grassland than under permanent managed grassland. This in turn has a far higher average rate of loss for the same level of original soil carbon, than rough grazing and non-agricultural land. For example, for the 100-200g C/kg soil category, the average rate of loss was only c.1.2gC/kg soil in the 'non-agricultural' land category, but c.3.2g/kg under permanent grassland, and c.5g/kg under arable/rotational grassland. The correlation is not statistically significant, given the slight overlapping of the error bars (and therefore further research is needed to confirm an association).[1265] Nevertheless, this is consistent with other evidence which points to the impact of agricultural practices. The most likely cause of elevated topsoil carbon losses on farmland compared to other land types, would surely be the effect of agricultural practices.

The researchers did not point out this correlation but highlighted the fact that the soil carbon losses were smallest from arable land, as the SOC levels are now very low in this category, and that the overall soil carbon losses are mostly coming from grassland, which have relatively high levels of carbon. This supports a link with agricultural management, as such a situation would be the natural end-result of a significantly higher rate of degradation on arable land. However, this might be mainly due to large-scale losses occurring from some categories of arable land (eg. land that was previously ploughed out of grassland), and may not necessarily reflect widespread losses.

ANNEX II Calculations of the area of feed production per t of grain-fed livestock with organic farming (see Chapter 8)

a) WHEAT, BARLEY & OAT FEED AREA CALCULATION
We assumed that 52% of total manufactured feed used by each sector, including feed used by the poultry integrators, is currently wheat and barley of UK/EU origin, but we did not adjust for a specific inclusion rate for each sector. This was increased by a factor of 1.794 to ensure that the total UK/EU wheat, barley and oats feed used in the UK was accounted for.

For adjust for organic production, we assumed that organic dairy cows would on average consume only 70% of the grain of non-organic animals (grass is a larger constituent of their diet), and that organic poultry for meat consume an additional 45% more grain and organic laying hens consume 6% more grain[1266], per tonne of output (they consume more per t being free-range and slower-growing). We also used current UK organic farming yields of 5.4t/ha for wheat and 4.7t/ha for barley, to produce a notional organic 'cereal' yield.[1267] This therefore takes account of the lower yield of organic farming, which then produces a larger arable area for carbon sequestration per tonnes of livestock product.

	UK livestock production, t/yr, 2006[1268]	**Manufactured feed used in UK, t**[1269]	**Total cereal feed of UK/EU origin used currently, t** (column 3 x 0.52 x 1.794[1270])	**Total cereal feed needed of UK/EU origin if livestock are organic, t** (col 4: poultry - meat: x 1.45; eggs x 1.06; milk: x 0.7)	**Organic arable area to produce the feed, ha** (column 5 x 0.197 ha/t[1271])	**Cereal area area, ha, per t UK organic livestock** (column 6 / 2)
Pigs	670,000	1,561,000	1,456,226	1,456,226	286,877	0.428
Poultrymeat	1,500,000	4,358,000	4,065,491	5,894,962	1,161,308	0.774
Eggs (unit = 20,000)	443,000	1,125,000	1,049,490	1,112,459	219,154	0.495
Milk (unit = 1m^3)	13,720,000	2,804,000	2,615,796	1,831,057	360,718	0.026
(Total)		(9,848,000)	(9,187,003)	(10,294,704)		

b) UK/EU MAIZE GLUTEN FEED AREA CALCULATION
We assumed that 31% of maize gluten feed[1272] used in the UK is of EU origin and that 1t of maize gluten requires 1.2t of maize to produce[1273]. We assumed that EU production of organic maize would involve a carbon sequestration rate of 560kg/ha/yr.

	UK livestock production, t/yr, 2006[1274]	**Maize gluten feed used in UK, by sector, t**[1275]	**Maize gluten feed of UK/EU origin, t**[1276] (column 3 x 0.31)	**Maize gluten feed needed if livestock organic, t** (column 4: milk: x 0.7)	**Maize area to produce the feed, ha** (x 0.253 ha/t[1277])	**UK/EU maize area, ha, per t UK organic livestock** (column 5 / 2)
Pigs	670,000	46,830	14,517	14,517	3,673	0.0055
Poultrymeat	1,500,000	-	-	-	-	-
Eggs (unit = 20,000)	443,000	-	-	-	-	-
Milk (unit = 1m^3)	13,720,000	420,600	130,386	91,270	23,091	0.0017
(Total)		(467,430)	(144,903)		(26,764)	

The area figures for wheat, barley and oats area were then added to those for maize gluten, to give total UK/EU cereal area per t of organic livestock and then the total extra GHGs from the UK/EU soil C losses:

Cereal area per t UK organic livestock, ha/t	UK/EU maize area, ha, per t UK non-organic livestock	Total arable area per t of UK organic livestock, ha/t
0.428	0.0055	**0.434**
0.774	-	**0.774**
0.495	-	**0.495**
0.026	0.0017	**0.028**

c) IMPORTED SOYA FEED AREA CALCULATION

The overseas (non-EU) area of feed production with widespread organic farming was calculated, by adding the results of the following calculations for soya and maize gluten. We have only taken account of manufactured feed and feed used by the poultry integrators, not feed used for home-mixing.

We assumed that 100% of soya feed and 69% of maize gluten feed[1278] used in the UK is imported from outside Europe and that 1t of maize gluten requires 1.2t of maize to produce[1279], and that this would be the same with widespread organic farming. Also that, the yields of organic feed production would be 6% less per hectare than non-organic production (ie. using the yields of organic arable farming in the US[1280]: organic soya - 2.7t/ha and organic maize - 8.4t/ha[1281]). We also assumed - as explained above - that organic dairy cows would on average consume only 70% of the grain of non-organic animals, and that organic poultry for meat consume an additional 45% more grain and organic laying hens consume 6% more grain[1282], per tonne of output.

	UK livestock production, t/yr, 2006[1283]	**Soya feed used in UK, by sector, t**[1284]	**Soya feed needed if livestock are organic, t** (column 3: poultrymeat: x 1.45; eggs x 1.06; dairy: x 0.7)	**Overseas organic farming area to produce the soya, ha** (column 4 x 0.42 ha/t[1285])	**Overseas organic soya area per t UK organic livestock, ha** (column 5 / column 2)
Pigs	670,000	241,955	241,955	101,621	0.1517
Poultrymeat	1,500,000	692,922	1,004,737	421,999	0.2813
Eggs	443,000	95,625	101,363	42,572	0.0961
Milk (unit = $1m^3$)	13,720,000	95,532	66,872	28,086	0.0020
(Total)		(1,126,034)	(1,414,927)	(594,278)	

d) IMPORTED MAIZE GLUTEN FEED AREA CALCULATION

	UK livestock production, t/yr, 2006[1286]	**Maize gluten feed used in UK, by sector, t**[1287]	**Maize gluten feed of non-EU origin if livestock are organic, t** (column 3 x 0.69. Plus milk: x 0.7)	**Overseas organic area to produce the maize, ha** (x 0.142 ha/t[1288])	**Overseas organic maize area, ha, per t UK organic livestock** (column 5 / 2)
Pigs	670,000	46,830	32,313	4,588	0.0068
Poultrymeat	1,500,000	-	-	-	-
Eggs	443,000	-	-	-	-
Milk (unit = $1m^3$)	13,720,000	420,600	203,150	28,847	0.0021
(Total)		(467,430)	(238,694)	(33,904)	

The area figures for for maize gluten were then added to those for soya, to give the total imported feed crop area per t of organic livestock:

Overseas organic soya area per t UK organic livestock, ha	Overseas organic maize area, ha, per t UK organic livestock	Total overseas arable area per t of UK organic livestock, ha/t
0.1517	0.0068	**0.159**
0.2813	-	**0.281**
0.0961	-	**0.096**
0.0020	0.0021	**0.004**

(Note: these calculations are simply to show the proportion of carbon offset made by the higher soil carbon of organic farming, not to suggest that this level and area of production would occur. Widespread organic farming would result in a large decrease in white meat production, due to the organic requirement for outdoor systems.)

Units:

1 Mg = 1 megagram = 1 x 10^6 = 1 million gram = 1 tonne (metric)
1 Gg = 1 gigagram = 1 x 10^9 = 1 billion grams = 1000 tonnes
1 Tg = 1 teragram = 1 x 10^{12} =1 million milion grams = 1 million t
1 Pg = 1 petagram = 1 x 10^{15} = 1 million billion grams = 1 billion t

1 Gigatonne = 1 x 10^9 = 1 billion t

[1] "Food Security and Agricultural Mitigation in Developing Countries: Options for Capturing Synergies"; UN Food and Agriculture Organisation; Rome; November 2009. Also, press relrease: Promoting climate-smart agriculture - Report explores mutual benefits, trade-offs in tackling hunger and climate ch ange, 5 November 2009.

[2] Intergovernmental Panel on Climate Change (IPCC) Working Group III (WGIII) (2007): 'Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change' B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds). http://www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4-wg3-spm.pdf

[3] Smith P., Martino D., Cai Z., Gwary D., Janzen H.H., Kumar P., McCarl B., Ogle S., O'Mara F., Rice C., Scholes R.J., Sirotenko O., Howden M., McAllister T., Pan G., Romanenkov V., Schneider U., Towprayoon S., Wattenbach M. and Smith J.U. Greenhouse fas mitigation in agriculture. *Philosophical Transactions of the Royal Society of London Series B Biological Sciences* (2008) 363, 789-813. Published on-line 6 September 2007.

[4] http://www.decc.gov.uk/en/content/cms/publications/lc_trans_plan/lc_trans_plan.aspx

[5] See section 10.2 for examples and references.

[6] Low organic matter levels restrict crop yields in drought periods and in developing country regions, for example. See section 9.7 for examples and references.

[7] eg. The UK's Stern Review (www.sternreview.org.uk) warned that unless action is taken within the next 10-20 years, the environmental damage caused by climate change later in the century could cost between 5 and 20% of global GDP every year.

[8] Pete Smith, Daniel Martino, Zucong Cai, Daniel Gwary, Henry Janzen, Pushpam Kumar, Bruce McCarl, Stephen Ogle, Frank O'Mara, Charles Rice, Bob Scholes, Oleg Sirotenko, Mark Howden, Tim McAllister, Genxing Pan, Vladimir Romanenkov, Uwe Schneider, Sirintornthep Towprayoon, Martin Wattenbach and Jo Smith; Greenhouse gas mitigation in agriculture**,** *Phil. Trans. R. Soc. B* 2008 **363**, 789-813.

[9] Due to the relatively high tonnes of soil carbon per ha, "Even small increases in SOM will have a large sequestration effect … especially in the northern and western Atlantic European countries," Baritz *et al*, 2004, Task group 5 Land Use Practices and SOM.

[10] Williams, A., E. Audsley, & D. Sandars, 2006. "Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities." Main Report. Defra Research Project IS0205. Cranfield University and Defra.

[11] For example, the scheme being developed in the UK by the BSI/Defra and Tesco. PAS-2050 (2008) BSI Standards Solutions, Defra and the Carbon Trust. PAS 2050 – assessing the life cycle greenhouse gas emissions of goods and services. http://www.bsi-global.com/en/Standards-and-Publications/How-we-can-help-you/Professional-Standards-Service/PAS-2050/

[12] King *et al*, 2004 and Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561.

[13] See section 9.2.

[14] Eg. Review Of Existing Information On The Interrelations Between Soil And Climate Change, Final Report, 16 December 2008, CLIMSOIL report for the European Commission. http://ec.europa.eu/environment/soil/pdf/climsoil_report_dec_2008.pdf

[15] 15 September 2009, speech by EU Agriculture Commissioner, Mariann Fischer Boel, reported on www.euractiv.com/en/cap/commission-farmers-need-help-cut-carbon/article-185476

[16] Defra press release, SOS-Saving Our Soils, 24 September 2009. http://www.defra.gov.uk/news/2009/090924b.htm

[17] Page 23, CLIMSOIL report for the European Commission, 16 December 2008.

[18] As opposed to inorganic carbon. Soil inorganic carbon is not considered in this review as it is not normally considered by agricultural soil carbon researchers on the grounds that there is limited data on this carbon pool and management typically has a larger impact on soil organic carbon stocks; available information on inorganic carbon levels shows inconsistent and small effects of management, such as irrigation and soil acidifying practices. IPCC, AFOLU volume, 2006.

[19] As the soil organic carbon store is twice the atmospheric carbon level, a 1% increase in the soil organic carbon store equates to 2% of atmospheric C levels. If soil carbon sequestration removes carbon as it is being emitted from other sources, before the sinks have been able to take it up, then presumably the full 2% reduction could occur. This would be far greater than the effect of emissions of carbon, such as by soil carbon losses, because currently the year-on-year atmospheric CO2 increase is only about 40-50% of the amount of C emitted. For instance, in the 1990s, a total of about 7.8 billion tC were emitted each year by man's activities, but the annual atmospheric increase was only 3.2billion tC/yr, ie. 41% of the extra emissions (see Houghton *et al*, 2003, and subsequent revised estimates on-line), as 59% of the additional emissions were being absorbed by the response of natural systems, such as the ocean. So, for example, for each 1% fall in global soil organic carbon levels that is released as CO2, if 40% of this remains after 'sinks' absorb 60%, this would cause an atmospheric increase of 40% x 2% = 0.8%.

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[20] Total area of UK agricultural land is 18,702,000ha (Agriculture in the United Kingdom 2008, Defra). Total land area of the UK is 24,432,994ha (CEH *et al*, 2008). So, 18,702,000/24,432,994 = 76.5%

[21] Page 5, "Soil Organic Matter: Its Importance in Sustainable Agriculture and Carbon Dioxide Fluxes," Edward Johnston, Paul R. Poulton, and Kevin Coleman, 2009, Chapter 1, Vol 101, Advances in Agronomy, *in press*.

[22] There can be 2-4 tonnes of earthworms per hectare of agricultural soils. Lavelle P, Spain AV. 2001. Soil Ecology. Dordrecht: Kluwer Academic Publishers. Cited in Pimental, 2006.

[23] Composition of organic matter as defined by Lampkin (1992) and Hodges (1991). Cited in Sheperd *et al*, 2002.

[24] Shepherd, M.A., R. Harrison & J. Webb, Managing soil organic matter - implications for soil structure on organic farms, Soil Use and Management (2002) 18, 284-292. Stable humus materials are: humic acids, fulvic acids and humin; Troeh, R. Frederick & Louis Milton Thompson, "Soils and Fertility," 2005. Published by Wiley-Blackwell.

[25] Stevenson, 1994. Cited in Marriott & Wander, 2006.

[26] 1. "Assessment of anecic behavior in selected earthworm species: Effects on wheat seed burial, seedling establishment, wheat growth and litter incorporation", Nico Eisenhauer, Sven Marhan and Stefan Scheu, Applied Soil Ecology, Volume 38, Issue 1, January 2008, Pages 79-82. 2. Boersma & Kooistra, 1994; Jongmans *et al*, 2001. Both of latter cited by Pulleman *et al, 2003.*

[27] Shepherd *et al*, 2002.

[28] Humus covers a range of substances that are advanced products of decomposition and products resynthesized by microorganisms (protein-like substances, organic acids, tannins, lignins, waxes, fats, carbohydrates, gums) and high molecular weight substances (humic acids, fulvic acids and 'humus'). Shepherd *et al*, 2002.

[29] Lignin is one of the most slowly decomposing components of dead vegetation, contributing a major fraction of the material that becomes humus as it decomposes; Wikipedia. Few soil microorganisms are able to completely mineralise lignin, which requires strong oxidation agents; Rasse *et al*, 2002.

[30] Unpublished paper on soil carbon and organic farming, provided to the Soil Association by Dr Julia Cooper, Newcastle University, 9 October 2007.

[31] Soil respond linearly to increasing rates of residue or carbon additions, in both short- and long-term experiments. 1. Studies cited in Kong *et al*, 2005. 2) The 'Market Garden experiment' summarised in "Soil Organic Matter: Its Importance in Sustainable Agriculture and Carbon Dioxide Fluxes," Edward Johnston, Paul R. Poulton, and Kevin Coleman, 2009, Chapter 1, Vol 101, Advances in Agronomy, *in press*.

[32] It also generally assumed that each management regime has an 'equilibrium' SOC content, so even if organic matter additions are increased, eventually the soil carbon levels will stabilise at a higher level and that higher level of organic matter addition will be needed just to maintain the new level.

[33] The amounts of carbon retained in the soil are low for arable crop residues, higher for leguminous plants and even higher for digested or already decomposed organic matter, such as manure or compost – see Chapter 7. For arable crop residues the conversion rate varies from 2-20% according to Kong, Angela Y. Y., Johan Six, Dennis C. Bryant, R. Ford Denison and Chris van Kessel , "The Relationship between Carbon Input, Aggregation, and Soil Organic Carbon Stabilization in Sustainable Cropping Systems" Published in Soil Sci Soc Am J 69:1078-1085 (2005) Published online 2 June 2005.

[34] For more information on soil aggregation, see section 9.5.

[35] 1. The mucigels released by rhizosphere (rootzone) microflora contribute to aggregate stability; Haynes *et al*, 1991. Cited by Shepherd *et al*, 2002. 2. Root systems increases the soil microbial biomass which produces polymers that act as binding agents; Jastrow *et al*, 1998; Tisdall & Oades, 1979. Cited by Rasse *et al*, 2005. 3. Tisdall & Oades, 1982; cited by Wells *et al*, 2000.

[36] Eg. Haynes & Naidu, 1998. Cited in Shepherd *et al*, 2002.

[37] Humic substances provide long-term stabilisation of soil aggregates, as they are relatively stable binding agents. Haynes *et al*, 1991. Cited in Shepherd *et al*, 2002.

[38] Earthworms promote soil aggregation: Swaby, 1950; Scullion & Malik, 2000; and Scullion *et al*, 2002. All cited by Pulleman *et al*, 2003.

[39] Elliott, 1986; Oades, 1988. Cited in: Puget P. & L.E.Drinkwater, Short-term dynamics of root-and shoot-derived carbon from a leguminous green manure, Soil Sci. Soc. Am J.. 65:771-779 (2001).

[40] Several studies have now shown that soil aggregation strongly influences soil carbon sequestration, and carbon cycling. Chaney & Swift, 1984; cited in Shepherd *et al*, 2002. Also, Tisdall & Oades, 1982; Jastrow, 1996; Six *et al*, 1998; Gale *et al*, 2000; Puget *et al*, 2000; Denef *et al*, 2004; all cited in Kong *et al*, 2005.

[41] The less clay, the greater the rate of mineralisation of carbon in the soil and the lower the level of humus, so clay soils have a greater capacity to stabilise carbon than sandy soils. Shepherd *et al*, 2002; Bhogal *et al*, 2007, Defra Project SP0561.

[42] Reproduced with the kind permission of Dr Paul Hepperly, Rodale Institute, Pennsylvania.

[43] For additional information on the contribution of roots to the soil carbon store, see section 7.6. All information in this paragraph from: Rasse, D.P., Rumpel, C. & Dignac, M.F. 2005. Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. Plant and Soil, 269, 341-356.

[44] 1. Rasse *et al*, 2005. 2. Sisti *et al*, 2004; cited page 28, "The Role of Organic Agriculture in Mitigating Climate Change,"J. Kotschi & K. Müller-Sämann, IFOAM, May 2004. 3. A dominant role of root C in soils has also been suggested by: Boone,1994; Milchunas et al, 1985; Norby and Cotrufo,1998; all cited in Rasse *et al*, 2005. 4. A simulation study suggested maize root systems contribute 1.8 times more carbon to soils than the above-ground biomass: Molina et al, 2001; cited in Rasse *et al*, 2005. 5. Gale *et al*, 2000; cited in Puget & Drinkwater, 2001. 6. German study of the annual weed *Amaranthus retroflexus L.* found a positive effect of roots on soil carbon levels but a negative effect of the leaves and stems; "Mechanisms of soil carbon storage in experimental grasslands," S. Steinbeiss, V. M. Temperton, and G. Gleixner, Biogeosciences Discussions, 4, 3829–3862, 2007.

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[45] According to this source, the root biomass is generally about 22% of the above-ground biomass for arable crops (ie. 18% of total crop biomass), per unit area (for US conventional cropping systems). Eg. wheat: 0.23 x above-ground biomass, maize: 0.22, tomato: 0.30 (aboveground biomass excludes tomato yield); Table 2, Kong *et al*, 2005, first four values adapted from S.Williams based on extensive dataset. The ratio is probably generally higher for organic farming – see section 7.6.

[46] This suggestion of 'as or almost as much' is based on studies to date, but there is still "great uncertainty" over the size of the contribution of this source of carbon. The root exudates contain water-soluble carbon-containing compounds that form a nutrient source for soil microorganisms, though a portion of this instead bonds to the soil's mineral particles, while the root hair debris and sloughed cells contain water-insoluble carbon-containing material. Rasse *et al*, 2005.

[47] An average 2.4-fold greater residence time for root carbon in the soil compared to shoot carbon, for an average 7.5 months, based on *in situ* studies. Rasse *et al*, 2005.

[48] Table 2, Rasse *et al*, 2005. Roots also have other resistant compounds like suberin.

[49] Rasse *et al*, 2005. There may also be a greater priming effect of shoot carbon on the mineralisation of existing SOC, than root carbon, but more research is needed on this. Note, combining all the factors mentioned suggests roots contribute as much soil carbon as 'shoots' in arable systems (if the carbon level per kg of roots and shoots is similar): 0.2 (biomass C) x 2 (continuous release C) x 2.4 (persistence) = 96% of shoot contribution to soil carbon. This estimate may be conservative, as most soil carbon studies do not sample the subsoil and even long-term soil sampling studies are of limited duration, compared to the potential age of humus in the soil. Also, the figures would be different in organic farming, which tends to have a larger root: shoot ratio and might also have higher root exudate levels.

[50] "Use of the Carbon:Nitrogen Ratio," SOIL, AGRON 305, www.agronomy.ksu.edu

[51] See Chapter 7.

[52] Drinkwater, L.E., Wagoner, P., Sarrantonio, M., 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature 396, 262–264.

[53] The C:N ratio of SOM is relatively constant and typically about 10:1, ranging between 9:1 and 14:1. Page 5 and 25, Johnston *et al*, 2009, *in press.*

[54] Troeh, Frederick R., & Louis Milton Thompsen,"Soil and Soil Fertility," 2005. Published by Wiley-Blackwell. See Chapter 7 for more information on C:N ratios.

[55] Page 54, CLIMSOIL report for the European Commission,16 December 2008. http://ec.europa.eu/environment/soil/pdf/climsoil_report_dec_2008.pdf Three-quarters of the UK's soil carbon store is in Scotland's peat uplands, "Indicators of Sustainable Development in the UK", DETR, 1997.

[56] New Scientist article 9.11.94, page 6

[57] Page 54, CLIMSOIL report for the European Commission,16 December 2008. Note, an earlier DETR document, said soils in England, Wales and Scotland contain some 21.78 billion tonnes of carbon, of which 16.4 btC is in Scottish peat uplands - Indicators of Sustainable Development in the UK, DETR, 1997.

[58] Page 17, table 1-21, Inventory and Projections of UK Emissions by Sources and Removals by Sinks due to Land Use, Land Use Change and Forestry, Annual Report, July 2008. Centre for Ecology & Hydrology, University of Aberdeen, Forest Research Alice Holt, National Soil Resources Institute, Centre for Terrestrial Carbon Dynamics (Universities of Sheffield, Edinburgh, York & University College London), Agri-Food & Biosciences Institute, Queen's University Belfast. Note, 'grassland' includes all types as well as heaths and wetlands (although the standard IPCC land use categories distinguish between grassland and wetland). The total UK soil carbon store to 1m depth is 5.144 billiont of C, according to this source.

[59] The figure of 63% was derived by using the % of C in the 0-30cm out of the total 0-1m depth cropland C stock for each UK country (page 18, table 1-22, CEH *et al*, 2008) and weighting these by the size of the carbon stock in each UK country (page 17, CEH *et al,* 2008). Applying this to the total 738million tC in UK cropland, gives a carbon stock of 465milliontC for the 0-30cm layer of cultivated land. Note, a higher figure of 562milliontC for the top30cm was given in this older paper: P. Smith, R. Milne, D.S. Powlson, J.U. Smith, P. Falloon, K. Coleman, Revised estimates of the carbon mitigation potential of UK agricultural land, Soil Use and Management, Vol. 16, No. 4, ages 293-295, 2000; published on-line 19 January 2006.

[60] Page 18, table 1-22, CEH *et al*, 2008. The following figures are for 'mineral' soil types only.
http://www.edinburgh.ceh.ac.uk/ukcarbon/docs/2008/Defra_Report_2008.pdf
Cropland:

- in England is assumed to contain 77tC/ha in the top 30cm and 43tC/ha in 30cm-1m (= total of 120tC/ha over 1m);
- in Wales, the respective amounts are 75tC/ha and 47tC/ha (= total 122tC/ha over 1m depth);
- in Scotland, the respective amounts are 121tC/ha and 33tC/ha (= total 164tC/ha over 1m depth).

Grassland:

- in England is assumed to contain 96tC/ha in the top 30cm and 50tC/ha in 30cm-1m (= total of 146tC/ha over 1m);
- in Wales, the respective amounts are 110tC/ha and 54tC/ha (= total 164tC/ha over 1m depth);
- in Scotland, the respective amounts are 188tC/ha and 58tC/ha (= total 246tC/ha over 1m depth).

[61] CLIMSOIL report for the European Commission,16 December 2008.

[62] Page 15, CLIMSOIL report for the European Commission,16 December 2008.

[63] Defra, "Critical levels of soil organic matter, 1997.

[64] Usually less than 5%. Page 5, "Soil Organic Matter: Its Importance in Sustainable Agriculture and Carbon Dioxide Fluxes," Edward Johnston, Paul R. Poulton, and Kevin Coleman, 2009, Chapter 1, Vol 101, Advances in Agronomy, *in press*.

[65] 1. Page 5, "Soil Organic Matter: Its Importance in Sustainable Agriculture and Carbon Dioxide Fluxes," Edward Johnston, Paul R. Poulton, and Kevin Coleman, 2009, Chapter 1, Vol 101, Advances in Agronomy, *in press*. The SOC level of the non-organic

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arable soils in the studies reviewed in this paper was only 1-2%: see section 6.2. 2. The average topsoil SOC content of cultivated land in England and Wales was 2.8% in 1995 (Webb *et al*, 2001). 3. The average soil carbon content of Scottish arable soils is around 3.6% (Scottish Soils database. Jan Dick, Pete Smith, Ron Smith, Allan Lilly, Andrew Moxey, Jim Booth, Colin Campbell, Drew Coulter, "Calculating farm scale greenhouse gas emissions," June 2008). 4. Author's note: arable land in mixed farming systems has higher levels than continuously cropped land, and organic soil types have higher levels than mineral soils.

[66] Ignoring for the moment the 'new' soil carbon topics of biochar and phytoliths, which may be more inorganic in chemistry and need further consideration. For instance, they may be also good for increasing soil carbon levels, but do they equally enhance the other important soil functions that rely on soil humus/soil structure, such as soil water-holding capacity and infiltration?

[67] For instance, Table 12, page 35, of this review for the UK Government shows that the amount of soil carbon that can be sequestered per unit of soil carbon input ranges from 7% for cereal straw, to 23% for farm manures, to 43% for green waste compost. Bhogal, A., Chambers, B.J., Whitmore, A.P. &. Powlson, D.S. (2007). *The effects of reduced tillage practices and organic material additions on the carbon content of arable soils.* Scientific Report for Defra Project SP0561.

[68] Rainer Baritz, Stefaan De Neve, Gabriela Barancikova, Arne Gronlund, Jens Leifeld, Klaus Katzensteiner, Heinz-Josef Koch, Christian Palliere, Joan Romanya, Joost Schaminee; Reports of the Technical Working Groups Established under the Thematic Strategy for Soil Protection. Volume III – Organic mater and Biodiversity, Task group 5 Land use Practices and SOM. EUR 21319 EN/3, 872 pp. Page 443, http://ec.europa.eu/environment/soil/pdf/vol3.pdf

[69] In the UK, certain forms of mineral fertiliser, such as certain forms of potash, can be applied in some specific "exceptional" circumstances, if the standard organic fertilisation methods are inadequate for the crop nutrition or soil condition. P.33, Annex 1A, Compendium of Organic Standards, Defra. In some other regions/countries such as New South Wales, Australia, where there are naturally low P levels and this is a critical production issue, there may be more widespread use of rock phosphate in the organic farming sector, while the non-organic farming sector will use P sources such as di-ammonium phopshate and superphosphate; Derrick & Dumaresq, 1999.

[70] "Because of the heavy reliance on natural soil fertility and disease suppression, soil organic carbon and soil organic matter quality is a crucial component in organic farming, more than in any other farming system." Baritz *et al*, 2004, Reports of the Technical Working Groups Established under the Thematic Strategy for Soil Protection, task group 5 Land use Practices and SOM.

[71] There is now a large, and growing, body of scientific evidence confirming that organic farming methods do indeed increase food nutrient levels. This includes several scientific reviews that have found that organic food has higher average mineral levels. 1. Worthington V. Nutritional quality of organic versus conventional fruits, vegetables, and grains, Journal of Complimentary Medicine 2001; 7 No. 2: 161–173. This found that found that organic crops had significantly higher levels of all 21 nutrients analysed compared to non-organic produce, including statistically significant higher levels of iron (21% more), magnesium (29% more) and phosphorus (14% more). 2. Soil Association (2001) Organic Farming, food quality and human health: a review of the evidence. 3. FSA, 2009. Contrary to the long-standing political position of the UK Food Standards Agency that organic food has no health benefits, their own review found that in almost all cases studied organic foods had higher beneficial nutrients, and this includes the majority of the studies where the difference was statistically significant (note, the FSA put this information in Appendix12 and dismissed it as 'not important' in the main text of the report, and their publicity of the report did not communicate this information). 4. Review compiled for the national French food agency AFSSA, by Denis Lairon of the University of Aix-Marseille, concluded that organic crops contain more dry matter (are more nutrient dense) and more minerals – such as iron and magnesium, published in 2009 in the journal Agronomy for Sustainable Development.

[72] Gardner, J.C. & Clancy, S.A. (1996). "Impact of farming practices on soil quality in North Dakota." Chapter 20, Methodfor Assessing Soil Quality, SSSA Special Publication No 49, pp 337-343.

[73] FAO. www.fao.org/organicag

[74] USDA. 1980. Report and Recommendations on Organic Farming. Washington, DC: U.S. Department of Agriculture.

[75] Freibauer, A., M.D.A. Rounsevell, P. Smith, and A. Verhagen (2004): Carbon sequestration in European agricultural soils. *Geoderma*, 122:1-23, and Virtual Journal of Geobiology 3(8), Part 3C. http://www.bgc-jena.mpg.de/~afreib/

[76] ECCP (European Climate Change Programme), 2003. Working group sinks related to agricultural soils. Final report, 76pp. Cited in Baritz *et al*, 2004, Task group 5 Land Use Practices and SOM, http://ec.europa.eu/environment/soil/pdf/vol3.pdf.

[77] Ana Frelih-Larsen, Anna Leipprand, Sandra Naumann (Ecologic) and Olivier Beucher (Baastal), 2008, " Background Paper for Stakeholder Consultation Workshop Climate Change Mitigation in Agriculture – Policy Options for the Future June 2008." See PICCMAT project website: http://www.climatechangeintelligence.baastel.be/piccmat/files/PICCMAT_policy_paper_June08.pdf

[78] Bente Foereid and Henning Høgh-Jensen, "Carbon sequestration potential of organic agriculture in northern Europe – a modelling approach", Nutrient Cycling in Agroecosystems 68: 13–24, 2004.

[79] For 1850- 2005. Figure derived as follows. Soils accounted for 28.2% of the net loss of carbon due to 'land use changes and forestry' over 1850-1990 (35bnt out of the total of 124bn tC); Houghton, R. A. 1999, The annual net flux of carbon to the atmosphere from changes in land use 1850–1990, Tellus 51B, 298–313. For 1850-2005, the total net loss of carbon due to 'land use changes & forestry' is estimated to be 156 billion tC; http://cdiac.ornl.gov/trends/landuse/houghton/houghton.html. Assuming that soils account for the same proportion of C losses due to 'land use changes & forestry' over 1850-2005 as they did over 1850-1990, then 28.2% of 156bn tC = 44 bn tC losses from soil, 1850-2005.

[80] From 1850-2000, total global carbon emission from fossil fuel use was 283 PgC (ie. 283 billion t C); Marland, G., T.A. Boden, and R.J. Andres. 2006. Global, Regional, and National CO2 Emissions; in Trends: A Compendium of Data on Global Change; Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A. From 1850-2000, 'changes in land use & forestry' are estimated to have released 149 billion tC; Houghton, R.A. (2003), Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000, Tellus Series B-Chemical and Physical Meteorology, 55, 378–390. Thus, the total C emissions for 1850-2000 are 283 (fossil fuels) +

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149 (net 'land use change & forestry' emissions) = 432bn tC. Assuming the different categories of biosphere carbon losses account for the same proportion of all the carbon emissions from 'land use & forestry' over 1850-2000 as over 1850-1990, then soils accounted for 28.2% and vegetation biomass losses due to wood harvesting (for timber & fuelwood) accounted for 16% (section 3.2, Houghton, 1999) of 149bntC = 42 bntC and 23.8bntC over 1850-2000, respectively. Thus, fossil fuels accounted for 283/432 x 100 = 65.5%, soil carbon losses for 42/432 x 100 = 9.7%, timber & fuelwood harvesting for 23.8/432 x 100 = 5.5% and . vegetation losses by clearance for agriculture for the remaining 19.3%.

[81] Section 4.1, Houghton, 1999. Note, previous estimates of the % of soil carbon lost on cultivation were 50%, but observations of a 50% reduction generally only apply to the upper 20-30cm of the soil. Thus, soil carbon losses on cultivation [for the whole soil profile/1m depth] have been revised to 25-30% (Davidson & Ackerman, 1993).

[82] Table 1, Houghton, 1999. The assumed soil carbon losses for conversion to croplands range from 0 to 51tC/ha (mostly 10-50tC) for 1m soil depth, eg. a loss of 47tC/ha for the cultivation of grasslands in Europe and North America, a loss of 33tC/ha for the conversion of temperate deciduous forest, and a loss of 24tC/ha for the conversion of tropical forest in Latin America.

[83] Hepperly, Paul Ph.D. & Tim J. LaSalle, Ph.D.,Regenerative Organic Farming: A Solution to Global Warming," The Rodale Institute. Author's note: if this just refers to the topsoil, then the total soil carbon loss would be less than this indicates.

[84] For instance, a large proportion of today's central European forests were brought into cultivation between the fifteenth and seventeenth centuries. Baritz *et al*, 2004, Task group 5 Land use Practices and SOM.

[85] For 1850-2000, 5bntC are estimated to have been lost from Europe soils; Houghton, R.A. (2003) Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000. Tellus Series B-Chemical and Physical Meteorology, 55, 378–390. We have not checked if this includes the drainage of peatlands which has been a major source of soil carbon losses in some countries including the UK. 5/149 x x100 = 3.356% of the total.

[86] Houghton, 1999.

[87] Section 3.1, Houghton, 1999. Also, carbon losses from shifting cultivation and wood harvesting in Africa, were not included.

[88] Many aspects of 'improved' grassland management are also likely to reduce soil carbon levels, including peatland drainage, the cultivation and re-seeding of the grass every five years or so, that commercial grass varieties may have different depths of root systems, the low species diversity of improved grasslands (no/few deep-rooting plants), the wide use of inorganic fertilisers (which can cause root systems to bemore shallow) and, for rough grazing land, the occurrence of over-grazing. Also, there are many reasons why cultivated soils have lower soil carbon levels than naturally vegetated land (ie. it not just due to the cultivation), including the higher proportion of time the soil is bare in arable systems, that the plants are annuals rather than permanent (smaller root systems), the use of inorganic fertilisers which tends to make root systems more shallow, etc.

[89] Section 2.2.1 of Houghton, 1999, says that the effects of peat drainage in the former Soviet Union were not considered. Peatland drainage is also not mentioned with respect to other world regions, but it is a very large on-going source of soil carbon losses in the UK (drainage for conversion to improved grassland) and SE Asia (conversion to palm oil plantations).

[90] Houghton, 2003.

[91] If current typical soil carbon rates for cultivated land were used and assumed to apply to all cropland whenever it was converted, then even if cropland in earlier decades actually had higher soil carbon levels at the time of conversion and more recent management practices have caused further reductions, this would not necessarily change the total amount estimated to have been lost, only the distribution of the losses over time, ie. some of the losses could be more recent than would have been accounted for. However, if cropland that was already converted in 1850 has since lost carbon, such as European cropland, then these losses have not been accounted for and would suggest the figure is an under-estimate. On the other hand, if the figures used for the soil carbon stocks for cropland are those for continuously cropped land, then the estimate would be over-estimating the levels for the proportion of cropland that is still in mixed farming systems (ie. receiving manure and in rotational grass ley/cropping systems). Additionally, the land area data for Europe and North America is obtained from the FAO, but FAO definitions of cropland include not just cultivated cropland but grass grown for silage (as well as temporary pasture and temporary fallow; email from R.Houghton, 15.5.2009) and this could have higher soil carbon levels than is being assumed.

[92] Assuming a loss of 33t/ha of soil carbon over 1m depth for the conversion of temperate deciduous forest (Table 1, Houghton, 1999), then 320 million ha x 33 = 10.56 billion tC lost before 1850. 44 bn + 10.6 bn = 54.6billion tC in total.

[93] Lal, R., Soil Carbon Sequestration Impacts on Global Climate Change and Food Security, *Science*: Vol. 304. no. 5677, pp. 1623 – 1627, 11 June 2004.

[94] King J.A., R.I. Bradley, R. Harrison & A.D. Carter, 2004, "Carbon sequestration and saving potential associated with changes to the management of agricultural soils in England", Soil Use and Management 20 pp. 394–402.

[95] Email communication, Peter Melchett, Policy Director and organic farmer, Soil Association, 9 August 2008.

[96] In modern agrochemcal-based systems, "the use of external nutrient inputs more less successfully buffers against negative effects of SOM loss." Baritz *et al*, report of Task group 5 Land use Practices and SOM, 2004.

[97] Notes by Dr Adrian Williams, Cranfield University, "Soil C in the LCA work", received 20 February 2006.

[98] MAFF, 1970, "Modern farming and the soil." Ministry of Agriculture, Fisheries and Food.

[99] After 1846, following the repeal of the Corn Laws (high import barriers) and the introduction of the policy of free trade in agricultural produce [except during the two world wars], UK agricultural prices fell and productivity declined and the UK changed from being almost self-sufficient in food to only 40% self-sufficient by 1914 as British farmers couldn't compete with cheap imports, such as from North America; productivity continued to decline in the 20s and 30s; after joining the EU in 1973, with the re-establishment of trade barriers and the introduction of subsidies to support agriculture, UK productivity has risen again; speaking notes, speech by Lord Haskins, The Foundation for Science and Technology Meeting on Food Security at The Royal Society, Carlton House Terrace, 15 October 2008. For instance, in many areas, productivity was limited by rising soil acidification and few farmers could afford to apply lime (until grant aid for lime use was introduced in the mid-30s); also, prior to WWII very,

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very little grain was grown on the Cotswolds or other limestone areas, because these naturally had such low levels of phospate that economic yields were not normally possible; email communication, Richard Young, 31 July 2009.

[100] "Final Report on Working Group on Sinks Related to Agricultural Soils, Second ECCP Progress Report – Can we meet our Kyoto targets?," by the working group on the carbon store of agricultural soils, European Climate Change Programme, 2003.

[101] "Consultation on the proposed EU Soil Framework Directive and initial Regulatory Impact Assessment," July 2007. Soil Association conversion to pounds using the exchange rate of 6 August 2009.

[102] "Climate change – can soil make a difference?," report of the conference, "Soil and Climate Change", Brussels, 12 June 2008. http://ec.europa.eu/environment/soil/conf_en.htm

[103] Officially, agricultural CO2 emissions are 1.8million tC and account for 13.2% of UK agriculture's 'end-user' GHG emissions of 13.8milliontC. Adding the Land Use Change carbon losses (1.9milliontC) would take the total CO2 emissions to 3.7milliontC, which would be 3.7/(13.8+1.9) = 23.6% of the total. GHG data from: National statistics – 2008 UK provisional figures. Annex B- Emissions of all greenhouse gases, carbon dioxide, methane and nitrous oxide by source and end-user. http://www.decc.gov.uk/en/content/cms/statistics/climate_change/climate_change.aspx Note, this still does not account for the CO2 and N20 emissions from the manufacture of inorganic N fertiliser, or the fact that the UK's soil N20 emissions may be under-estimated, so total UK agricultural GHG emissions are really still higher and with a different proportion accounted for by CO2.

[104] Tables 1-31, 1-1, 1-2 and 1-7, Inventory and Projections of UK Emissions by Sources and Removals by Sinks due to Land Use, Land Use Change and Forestry, Annual Report, July 2008. Centre for Ecology & Hydrology , University of Aberdeen, Forest Research Alice Holt, National Soil Resources Institute, Centre for Terrestrial Carbon Dynamics (Universities of Sheffield, Edinburgh, York & University College London), Agri-Food & Biosciences Institute, Queen's University Belfast. http://www.edinburgh.ceh.ac.uk/ukcarbon/docs/2008/Defra_Report_2008.pdf

[105] Calculation: In 2006, land converted to cropland was emitting 14,312,000tCO2; it is assumed that 99% of this was previously grassland (according to the proportion indicated in Table 1-2), ie. an emission of 14,168,880tCO2 due to 'within agricultural' changes. Land converted to grassland, however, was sequestering 8,720,000tCO2; assuming that 94% of this land was previously cropland (based on the proportions indicated in Table 1-2), this means an annual sequestration of 8,196,800tCO2. This gives a net emission of 14,168,880 – 8,196,800 = 5,972,080tCO2, from 'within agricultural' land use change (ploughing-up of grassland). x12/44 = 1.63milliontC. Source: Tables 1-1, 1-2 and 1-31, CEH *et al*, July 2008.

[106] 88% of grassland to arable conversion in the 1990s was in England and Scotland. Table 1-17 to 1-20, page 16, CEH *et al*, 2008. http://www.edinburgh.ceh.ac.uk/ukcarbon/docs/2008/Defra_Report_2008.pdf

[107] Tables 1.7 and 1-31, CEH *et al*, July 2008.

[108] National statistics – 2008 UK provisional figures. Annex B- Emissions of all greenhouse gases, carbon dioxide, methane and nitrous oxide by source and end-user. http://www.decc.gov.uk/en/content/cms/statistics/climate_change/climate_change.aspx Converted from CO2 to C by using conversion factor of x 12/44.

[109] Janssens IA, Freibauer A, Schlamadinger B, Ceulemans R, Ciais P, Dolman AJ, Heimann M, Nabuurs G-J, Smith P, Valentini R, Schulze E-D. 2005. The carbon budget of terrestrial ecosystems at country-scale—a European case study. Biogeosciences 2:15–26.. http://www.biogeosciences.net/2/15/2005/bg-2-15-2005.pdf

[110] Zaehle, S., Bondeau, A., Carter, T., Cramer, W., Erhard, M., Prentice, I.C., Reginster, I., Rounsevell, M.D.A., Sitch, S., Smith, B., Smith, P.C., Sykes, M. (2007): Projected changes in terrestrial carbon storage in Europe under climate and land-use change, 1990-2100. Ecosystems 10(3) 380-401.

[111] Smith, J.U., Smith, P., Wattenbach, M., Zaehle, S., Hiederer, R., Jones, R.J.A., Montanarella, L., Rounsevell, M.D.A., Reginster, I. , Ewert, F., (2005). Projected changes in mineral soil carbon of European croplands and grasslands, 1990-2080. Global Change Biology, 11(12), 2141-2152. [Smith et al, 2005a, or Jo Smith et al, 2005]

[112] Zaehle *et al* estimated that arable soil C losses are 19.3 million tC/yr for the EU15, Norway and Switzerland. Janssens *et al* estimated that arable soil C losses are 46 million tC/yr for the 34 countries of geographical Europe (exc. European Russia). We have therefore assumed a level of 'around 30 million tC/ha/yr' for the EU25, Norway & Switzerland arable area.

[113] Countryside Survey (data owned by NERC – Centre for Ecology & Hydrology). See: UK results from 2007; England results from 2007; Scotland results from 2007; Wales results from 2007; http://www.countrysidesurvey.org.uk/ Arable/horticultural soils were only habitat for which this survey found a long-term soil carbon fall, 1978-2003. For grasslands: in Scotland, for example, improved grassland went from 58.8gC/kg soil in 1978 to 58.4g/kg in 1998 to 59.0g/kg in 2007; while acid grassland went from 238.6g/kg to 265.8g/kg to 226.2g/kg respectively (a significant fall from 1998 to 2007, but no significant change 1978-2007).

[114] NSI: initial sampling 1978-83, re-sampling 1995/96 for managed grassland and 2003 for rough grazing; Countryside Survey: sampling in 1978, 1998 and 2007.

[115] The findings of this survey have been reported differently in different reports, due to the use of different datasets and consideration of different soil depths. The figures we have cited are those advised by the researchers of the survey (email communication, Dr Steven Sleutel, 1 October 2008). 480kgC/ha/yr for 0-30cm: "Regional simulation of long-term organic carbon stock changes in cropland soils using the DNDC model: 1. Large-scale model validation against a spatially explicit data set," S. Sleutel, S. De Neve, D. Beheydt, C. Li & G. Hofman, Soil Use and Management, December 2006, 22, 342–351. 900kgC/ha/yr for 0-1m: "Carbon stock changes and carbon sequestration potential of Flemish cropland soils," by Steven Sleutel, Stefaan De Neve, Georges Hofman, Pascal Boeckx, Daan Beheydt, Oswald Van Cleemput, Inge Mestdagh, Peter Lootens, Lucien Carlier, Nancy Van Camp, Hans Verbeeck, Inge Vande Walle, Roeland Samson, Noël Lust And Raoul Lemeur, Global Change Biology (2003) 9, 1193–1203.

[116] Reported in,"Land-use Change and Forestry in Austria: A Scientific Assessment of Austria's Carbon Balance in Light of Article 3 of the Kyoto Protocol, INTERIM REPORT IIASA IR-98-028/May," by M. Jonas, B. Mayr, S. Schidler, M. Sotoudeh, H. M. Knoflacher. Original reference (in German): Dersch, G., and K. Böhm, 1997a: Beiträge des Bodenschutzes zum Schutz der Atmosphäre und

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des Weltklimas. In: *Bodenschutz in Österreich. Bodenzustand - Entwicklungstendenzen -Schutzmaßnahmen* [Blum, W.E.H., E. Klaghofer, A. Köchl, and P. Ruckenbauer (scientific management); Köchl, A. (project coordination)]. Federal Office and Research Center for Agriculture (BFL), Vienna, Austria, pp. 411–432.

[117] Countryside Survey (data owned by NERC – Centre for Ecology & Hydrology). See: UK results from 2007; England results from 2007; Scotland results from 2007; Wales results from 2007; http://www.countrysidesurvey.org.uk/ Note, arable/horticultural soils were only habitat for which this survey found a long-term soil carbon fall, 1978-2003.

[118] Bellamy P.H., P.J. Loveland, R.I.Bradley, R.M. Lark & G.J.D. Kirk, "Carbon losses from all soils across England and Wales 1978-2003", Nature, Vol 437, 245-248, 8 September 2005. Notes on methodology: the top 15cm of soil of almost 6000 sites spaced 5km apart across England and Wales were sampled between 1978 and 1983, and about 40% of the sites (2179) were re-sampled in three phases between 1994 and 2003. The arable and rotational grass sites were re-sampled in 1994-95 (853 of the original 2,578 sites), the managed permanent grassland sites re-sampled in 1995-1996 (771 of 1,579), and the other sites in 2003. The loss/gain values for the sites that were not re-sampled were obtained by applying a loss rate factor that had been derived from the re-sampled sites in relation to the original SOC content. For more details see Annex I.

[119] The mean soil carbon loss for mineral soils only was - 0.33gC/kg of soil (95% confidence: -0.25 to –0.42); higher loss rates were found for higher-carbon soils. See Annex 1 for data.

[120] In a report for Defra in 2003, arable soils in England fell into two broad groups (i) fine loamy and clayey soils with more than 18% clay (which accounted for about 75% of surveyed arable sites), of which about 50% had less than 2.3% SOC content in the top 15cm in1995, and (ii) coarse loamy and sandy soils with less than 18% clay (which accounted for about 25% of surveyed arable sites), of which just below 40% had less than 1.3% SOC content in the top 15cm in 1995. "Initial assessment of the projected trends of soil organic arbon in English arable soils," by ADAS, Defra project SP 0533.

[121] Section 2, Johnston *et al*, 2009, *in press.*

[122] Figure 3, Bellamy *et al*, 2005.

[123] Results for England and Wales, 1980 to 1995. J. Webb, P. J. Loveland, B. J. Chambers, R. Mitchell and T. Garwood, "The impact of modern farming practices on soil fertility and quality in England and Wales," Journal of Agricultural Science, Cambridge (2001), **137**, 127–138.

[124] Results for England and Wales, 1980 to 1995. J. Webb, P. J. Loveland, B. J. Chambers, R. Mitchell and T. Garwood, "The impact of modern farming practices on soil fertility and quality in England and Wales," Journal of Agricultural Science, Cambridge (2001), **137**, 127–138.

[125] Barancikova *et al*, "History and present state of organic carbon monitoring on agricultural land of Slovakia," presentation. See also: Barancíková G, 2002, Monitoring of content and quality of soil organic matter, in: Kobza (ed.): Soil Monitoring of Slovak Republic, Present state and development of monitored soil properties, The results of Partial Monitoring System – Soil as a part of Environment Monitoring of Slovak Republic for period 1997-2001, Bratislava, 54-73; cited in Baritz *et al*, 2004.

[126] Tove Heidmann, Bent T. Christensen and Svend E. Olesen, "Changes in soil C and N content in different cropping systems and soil types," in "Greenhouse Gas Inventories for Agriculture in the Nordic Countries," Proceedings from an international workshop, Helsingør, Denmark 24-25 January 2002.

[127] Barancikova *et al*, "History and present state of organic carbon monitoring on agricultural land of Slovakia," presentation. See also: Barancíková G, 2002, Monitoring of content and quality of soil organic matter, in: Kobza (ed.): Soil Monitoring of Slovak Republic, Present state and development of monitored soil properties, The results of Partial Monitoring System – Soil as a part of Environment Monitoring of Slovak Republic for period 1997-2001, Bratislava, 54-73; cited in Baritz *et al*, 2004.

[128] Cited on page 59, CLIMSOIL report for the European Commission, December 2008. http://ec.europa.eu/environment/soil/pdf/climsoil_report_dec_2008.pdf

[129] UK methane emissions per dairy cattle per year are: 105kg from enteric fermentation plus 25.8kg from manure (based on average cattle weight 577kg). Assuming a stocking level of 2 dairy cattle per ha, this means dairy cattle release: 2 x (105 + 25.8) x 21 (conversion factor for methane to C02) x 12/44 (conversion to carbon equivalent) = 1,498kgCeq/ha/yr of methane. So, grassland would give an offset of 670/1498 x 100 = 45% offset. Beef cattle emissions are 39% of those of dairy cattle, per animal. Reference for methane emission data for cattle from page 374, Annexes of the UK Greenhouse Gas Inventory, 2007: http://www.airquality.co.uk/reports/cat07/0905131425_ukghgi-90-07_Annexes_Issue2_UNFCCC_Final.pdf

[130] "Scientists at the University of Durham have estimated that for England alone this could increase net greenhouse pollution by up to 400,000 kilotonnes [400 million tC] per annum. By contrast, if all of the peatlands were restored to good condition, they could become a modestly significant sink for up to 40,000 kilotonnes of carbon per annum." Statement by Lord Cameron, House of Lords session 2007-2008. Proceedings, page 81. This is figure is very large, and given that most of the peat is in Scotland, it implies extremely large carbon losses for the whole UK (several times the UK's official GHG emissions of 178milliontC/yr). We have not been able to confirm the figure directly with the university.

[131] Inventory and Projections of UK Emissions by Sources and Removals by Sinks due to Land Use, Land Use Change and Forestry, Annual Report, July 2008. CEH *et al.* http://www.edinburgh.ceh.ac.uk/ukcarbon/docs/2008/Defra_Report_2008.pdf

[132] Section 2.1, "Peatlands in National Inventory Submissions 2009 – An analysis of 10 European countries," Alexandra Barthelmes, John Couwenberg & Hans Joosten, Greifswald University, Wetlands International, Ede, 2009. Produced for the UN-FCCC meetings in Bonn, August 2009. http://www.wetlands.org/WatchRead/tabid/56/ctl/ArticleView/mid/1570/articleId/2360/Default.aspx

[133] The mean temperature across England and Wales increased by about 0.5°C and there were also changes in rainfall distribution; Hulme *et al*, 2002, cited in Bellamy *et al*, 2005. It is now believed that the warming effects of climate change have been enhanced by up to 25% in Europe since the 1970s - especially in Northern and Eastern Europe - due to a reduction in haze from the fall in air pollution; study by Dr Vautard *et al* in Nature Geoscience, 18 January 2009.

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[134] Smith *et al*, 2007 estimate that in response to climate change, soil carbon levels would be falling by at most 0.08% of the total SOC each year (-67kgC/ha/yr) on European croplands and half this rate on grasslands, if just the increase in soil carbon mineralisation from the rise in temperatures is accounted for. Using a more complex soil model and allowing also for higher plant growth (from rising temperatures and the so-called 'CO2 fertilisation effect'), Smith *et al* predict that the effect from climate change is more likely to be only -0.02% and +0.02% of total SOC/year for arable and grassland, respectively. Fig 1. Pete Smith, Stephen J. Chapman, W. Andy Scott, Helaina I. J. Black , Martin Wattenbach, Ronnie Milne , Colin D. Campbell, Allan Lilly, Nick Ostle, Peter E . Levy , David G. Lumsdon, Peter Millard, Willie Towers, Sönke Zaehle, and Jo U. Smith. Global Change Biology (2007) 13, 2605–2609.

[135] Ivan A. Janssens, Annette Freibauer, Philippe Ciais, Pete Smith, Gert-Jan Nabuurs, Gerd Folberth, Bernhard Schlamadinger, Ronald W. A. Hutjes, Reinhart Ceulemans, E.-Detlef Schulze, Riccardo Valentini, A. Johannes Dolman. "Europe's Terrestrial Biosphere Absorbs 7 to 12% of European Anthropogenic CO2 Emissions", Published on-line in Science,Vol 300, 6 June 2003, www.sciencemag.org

[136] Presentation, "UK losses of soil carbon – due to climate change?," Pat Bellamy, Natural Resources Department, Cranfield University, at the conference, "Soil and Climate Change", Brussels, 12 June 2008. http://ec.europa.eu/environment/soil/conf_en.htm

[137] Houghton, Carbon Flux from Land-Use Change 1850 – 2005, http://cdiac.ornl.gov/trends/landuse/houghton/houghton.html; and Houghton *et al*, 2003.

[138] In 2004, global anthropogenic GHG emissions were estimated to be 49billion tCO2-equivalent [or 13.4 billion tC-eq]; page 103, IPCC (WGIII), 2007. http://www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4-wg3-chapter1.pdf. However, the estimate of carbon emissions from 'land use change and forest management' has now been revised down from 2.2billion tC/yr (Houghton, 2003) to 1.5billion tC (http://cdiac.ornl.gov/trends/landuse/houghton/houghton.html). Assuming this means that the estimate of total global GHG emissions are then also 0.7billion tC lower, or around 12.7 billion tC-eq, this means that the carbon emissions from tropical deforestation are 1.5/12.7 x 100 = 11.8% of total global anthropogenic GHG emissions.

[139] The degradation and burning of Indonesia's peatlands releases 1.8billion tCO2/yr, Hooijer et al (2006): 29. As the effects of drainage extend far into the neighbouring forest regions, this figure is an underestimate. See "How the palm oil industry is Cooking the Climate," Greenpeace report, 2007, http://www.greenpeace.org/raw/content/international/press/reports/cooking-the-climate-full.pdf In Indonesia, IIED estimate the percentage share of land-use on deforested land to be oil palm (32%), rubber (30%), rice (19%) and cassava (19%); Grieg-Gran, M., "The cost of avoiding deforestation, Report prepared for the Stern Review of the Economics of Climate Change," International Institute for Environment and Development, 2006. Cited page 109, "Slaughtering the Amazon," Greenpeace report, 2009, http://www.greenpeace.org/international/press/reports/slaughtering-the-amazon. Conversion to carbon: 1.8 billion tCO2 x 12/44 = 491 million tC/yr. Carbon losses for palm oil are 0.32 x 491 = 157 million tC/year, at least.

[140] Based on the Brazilian Government's 'preferred figure' of 100tC/ha for deforestation, Greenpeace have estimated that the Amazon cattle industry is the source of 570million t CO2/year due to Amazon deforestation. However, the cattle industry supplies both the beef and leather markets, eg. only 73% of the value of the export trade of Brazil's cattle industry is for beef (the rest is for leather). As only 20% of Brazil's beef is exported, this means beef exports cannot account for more than 0.2 x 570 million = 114 million tC02/yr, or 114 x 12/44 = 31 million tC/yr (part of is due to leather). However, other sources (eg. Saatchi *et al*, 2007) suggest that the average level of above- and below-ground forest biomass is actually 150tC/ha, ie. 50% higher. Source for all previous information: "Slaughtering the Amazon," Greenpeace report, June 2009, updated July 2009. Based on all this, we estimate that Brazil's beef exports account for carbon losses of the order of 20-35 million tC/yr from Amazon deforestation.

[141] Based on data from Cranfield University (see 2007 reference at end of this note), the total current UK GHG emissions from UK beef production are 4.17tC_{eq}/t beef x UK beef production of 869,000t/yr (for 2006) = 3.6milliontC/yr. So, say, a ten percent GHG reduction would produce a carbon saving of 360,000tC/yr, compared to the estimated 20-35 million tC released each year from deforestation of the Amazon as a result of beef production for exports (see below). It is currently fairly commonly believed in the UK that more intensive, grain-based cattle systems reduce methane emissions and thus reduce overall GHG emissions, since it is argued that fewer cattle are needed to produce the same quantity of milk or beef, which means less methane emissions per unit of milk. While this may possibly be true for intensive versus less intensive/extensive non-organic dairy production, this may not be the case if the combined effects on both dairy and beef production are considered. Moreover, this is anyway not the case for non-organic versus *organic* dairy production, even though organic farming is overall less intensive than current non-organic production systems. The detailed Life Cycle Assessment of organic and non-organic farmng by Cranfield University for the UK Government found that total GHG emissions per unit of milk were *the same* for UK organic dairy and non-organic dairy production (though other emissions were higher, organic dairy production has a 28% lower energy use); draft figures received by email from Cranfield University, August 2007, intermediate results from the project,"Developing and delivering environmental Life-Cycle Assessment (LCA) of agricultural systems", Defra project (IS0222), an updated version of the earlier LCA study Williams *et al*, 2006. This LCA assessment anyway over-estimated the GHG emissions of organic farming: for example, all the soil carbon benefits of organic farming were omitted.

[142] 1. Chadd S.A., Davies W.P. & Koivisto J.M., 2002. 'Practical production of protein for food animals', Protein sources for the animal feed industry, Expert Consultation and Workshop, FAO Animal Production and Health. 2. Bajjalieh N., 2002, 'Proteins from oilseeds', In**:** Protein Sources for the Animal Feed Industry. Expert consultation and workshop. Bangkok, 29 April - 3 May 2002; (Proceedings); FAO Animal Production and Health Proceedings, no. 1*; FAO Expert Consultation and Workshop on Protein Sources for the Animal Feed Industry*, Bangkok, 29 Apr - 3 May 2002 / FAO. Animal Production and Health Div. , 2004, p.141-159. 3. The two preceeding sources suggest that the soya meal (for animal feed) represents a large majority, 72%, of the value of the soya bean. The following suggested that feed use represents a lower level of around 60% of the value of soya, with soya oil for food representing the remaining 40%: oral communication, Tony Bell, BOCM Pauls, 25.9.2007.

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[143] "An assessment of greenhouse gas emissions from the UK food system and the scope for reduction by 2050 - How low can we go?," b**y** Eric Audsley, Matthew Brander, Julia Chatterton, Donal Murphy-Bokern, Catriona Webster, Adrian Williams; a report for WWK UK and the Food Climate Research Network, 2009.

[144] "Brazil: places we protect – The Cerrado," The Nature Conservancy in Brazil; http://www.nature.org/wherewework/southamerica/brazil/work/art5082.html Brazil is the second largest exporter of soya in the world, accounting for 36% of global trade in soya; "Slaughtering the Amazon," Greenpeace report, 2009, http://www.greenpeace.org/international/press/reports/slaughtering-the-amazon.

[145] "Cerrado, The Brazilian Savannah," World Wildlife Fund. http://www.panda.org/what_we_do/where_we_work/cerrado/

[146] "Brazil's carbon challenge: Brazil's carbon footprint comes mainly from land uses, not energy." 2009, article by Tim Hirsch, Worldwatch Institute. http://www.worldwatch.org/node/6162

[147] "Brazil's carbon challenge: Brazil's carbon footprint comes mainly from land uses, not energy." 2009, article by Tim Hirsch, Worldwatch Institute. http://www.worldwatch.org/node/6162

[148] "Amazon," Greenpeace. http://www.greenpeace.org/international/campaigns/forests/amazon)

[149] The Amazon is estimated to store 80-120 billion t of carbon, and is the world's most important forest carbon store. "Slaughtering the Amazon," Greenpeace report, June 2009, updated July 2009, http://www.greenpeace.org/international/press/reports/slaughtering-the-amazon.

[150] Successive reports by the World Bank, the Brazilian government and research institutes, and analysis by Greenpeace consistently conclude that cattle ranching occupies about 80% of all deforested land in the Amazon region. Page 14, "Slaughtering the Amazon," Greenpeace report, June 2009, updated July 2009.

[151] "Slaughtering the Amazon," Greenpeace report, June 2009, updated July 2009. In the last couple of years, however, Brazil's beef export trade has not increased and has reduced due to challenging trade and economic conditions; "Brazilian beef price and exports plunge," 24 July 2009, http://thescotsman.scotsman.com/dan-buglass/Brazilian-beef-price-and-exports.5490025.jp

[152] "Slaughtering the Amazon," Greenpeace report, June 2009, updated July 2009.

[153] Based on the Brazilian Government's 'preferred figure' of 100tC/ha for deforestration, Greenpeace have estimated that the Amazon cattle industry is the source of 570million t CO2/year due to Amazon deforestation. As only 20% of Brazil's beef is exported, this means beef exports cannot account for more than 0.2 x 570 million = 114 million tC02/yr, or 114 x 12/44 = 31 million tC/yr. It should be less than this, as only 73% of the value of the export trade of Brazil's cattle industry is for beef, the rest is for leather. However, other sources (eg. Saatchi *et al*, 2007) suggest that the average level of above- and below-ground forest biomass is actually around 150tC/ha, ie. 50% higher. Source for all previous information: "Slaughtering the Amazon," Greenpeace report, June 2009, updated July 2009. Based on all this, we estimate that Brazil's beef exports account for carbon losses of the order of 20-35 million tC/yr from Amazon deforestation.

[154] "Slaughtering the Amazon," Greenpeace report, June 2009, updated July 2009.

[155] Pages 10 & 11, report by EBLEX (English beef and lamb executive),"In the Balance? - The future of the English beef industry,"2009. http://www.eblex.org.uk

[156] Imports are likely to carry on increasing until at least 2013: the UK dairy cow herd fell a further 2.7 per cent in 2009, with the loss of 175,000 dairy cross beef cattle born between April 2008 and March 2009. "NBA warns of beef supply shortfall," 12 August 2009, http://www.farmersguardian.com/news/business/nba-warns-of-beef-supply-shortfall/27158.article

[157] "Between 1990 and 2007 … The dairy herd fell by 38%, while the suckler herd has remained fairly stable. The comparatively faster rate of decline in the dairy herd is due partly to improving milk productivity (and the effect of the production limit imposed by the EU milk quota system), as well as a protracted period of poor returns to milk producers and the pressures of environmental regulations." The origins of the beef imports are complicated by the fact that the UK started importing beef at a significant level following the beef shortfall arising from the introduction of the decade-long ban on 'over thirty months' cattle entering the food chain (1996-2005), after the BSE outbreak. However, though the ban ended in 2005, the development in the dairy sector in the meantime mean that the UK supply of beef is no longer sufficient. The increased competition from cheap imports and consequent low prices and lack of profitability for the English beef suckler cow herd means production from this alternative source has not increased to compensate for the reduced dairy herd and is also slowly declining. Page 7 etc, "In the Balance? - The future of the English beef industry," EBLEX, May 2009, http://www.eblex.org.uk Recent reports from beef producers in Scotland currently sound more positive, eg. "Brazilian beef price and exports plunge," 24 July 2009, http://thescotsman.scotsman.com/dan-buglass/Brazilian-beef-price-and-exports.5490025.jp However, EBLEX warns that, "While cattle prices have increased since 1990 in current terms, in real terms prices have fallen;" page 4, "In the balance? - The future of the English beef industry,""

[158] Page 4, Report by EBLEX,"In the Balance? - The future of the English beef industry," May 2009.

[159] After which they are culled and replaced. Page 6, report by EBLEX (English beef and lamb executive),"In the Balance? - The future of the English beef industry," May 2009. http://www.eblex.org.uk

[160] According to this, along with the USA, the UK was one of the top two importers of processed beef from Brazil, importing 51,000t in 2008 (25% of Brazil's total processed beef exports. Italy, Netherlands, Germany and Belgium imported another 17% between them.) Table 3, page 30, "Slaughtering the Amazon," Greenpeace report, 2009. Original source: Secretaria de Comércio Exterior (SECEX), 2009.

[161] Page 31, "Slaughtering the Amazon," Greenpeace report, 2009.

[162] The EU imposed a restriction on imports of beef from Brazil in January 2008; for the first half of 2009, the UK imported 1,100t vs. 4,500t in the same period the previous year; "Brazilian beef price and exports plunge," 24 July 2009, www.theScotsman.scotsman.com Shipments of total beef from Brazil to the EU were 47,000t for the first five months of 2009, of which processed beef was 33,000t; this total import volume is 28% less than over the same five months in 2008; "Brazilian beef exports continue to decline," 17 July 2009, Food Alert, Irish Food Board, http://www.bordbia.ie/Pages/Default.aspx

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[163] In 2008, the EU imported over 80,000t of processed beef from Brazil. Pages 30 and 31, "Slaughtering the Amazon," Greenpeace report, 2009. Original source: Eurostat External Trade Data, downloaded 16 April 2009

[164] 1. A three-year moratorium on Amazon deforestation was adopted by major Brazilian soya traders in 2006 2. Various other actions are described in this article, in response to the Greenpeace report: "Brazilian beef giant announces moratorium on rainforest beef," Rhett A. Butler, August 13, 2009, http://news.mongabay.com/2009/0813-bertin_moratorium.html

[165] Brazil's National Climate Change Plan, published on 1 December 2008 and presented at the UN climate conference in Poland, set detailed targets to reduce the annual deforestation rate in the Amazon by a total of 70 percent between 2006 and 2017. "Brazil's carbon challenge: Brazil's carbon footprint comes mainly from land uses, not energy." 2009, article by Tim Hirsch, Worldwatch Institute. http://www.worldwatch.org/node/6162

[166] In the last few years, Brazil has struggled to maintain its export levels; "Brazilian beef exports continue to decline," 17 July 2009, Food Alert, Irish Food Board, http://www.bordbia.ie/Pages/Default.aspx See also references below on action by and against the beef industry to protect the Amazon.

[167] "Slaughtering the Amazon," Greenpeace report, June 2009, updated July 2009. In the last few years, Brazil has struggled to maintain its export levels; "Brazilian beef exports continue to decline," 17 July 2009, Food Alert, Irish Food Board, http://www.bordbia.ie/Pages/Default.aspx

[168] Over 90% of current Amazon deforestation is illegal (2006/07 data). "Slaughtering the Amazon," Greenpeace report, June 2009, updated July 2009. http://www.greenpeace.org/international/press/reports/slaughtering-the-amazon

[169] 1. "Brazil's carbon challenge: Brazil's carbon footprint comes mainly from land uses, not energy," article by Tim Hirsch, 2009, Worldwatch Institute. http://www.worldwatch.org/node/6162 2. An internal document from one of the leading players in Brazil's beef industry says Brazil has an area almost the size of the EU 'available for cultivation' in areas that are not already 'occupied' or 'forestry reserves.' 3. 'Brazil also has around 100 million hectares of unexplored or underused agricultural frontiers, without its use meaning deforestation, especially of the Amazon. They are degraded pastures or savannah areas;' Rocha (2008). Source of the last two references: "Slaughtering the Amazon," Greenpeace report, June 2009, updated July 2009. 4. Less than 3% of the Cerrado is under legal protection; WWF, http://www.panda.org/what_we_do/where_we_work/cerrado/

[170] 1. "If while reducing further clearcutting of the Amazon you actually increase the occupation of the Cerrado, we might or might not have a net reduction in land-use change emissions in Brazil," quote from Roberto Smeraldi, director of Friends of the Earth Amazon programme"; cited in "Brazil's carbon challenge: Brazil's carbon footprint comes mainly from land uses, not energy," article by Tim Hirsch, 2009, Worldwatch Institute. http://www.worldwatch.org/node/6162

[171] There is significant potential to increase beef production in temperate regions on existing farmland. In Central and Eastern Europe, Caucasus and Central Asia, agricultural production is now only 60-80% of 1990 levels; Greenpeace, 2008, "Cool Farming: Climate impacts of agriculture and mitigation potential." Also, much grassland has been converted to arable land in the UK and rest of Europe (to fuel the increase in grain-fed meat & dairy systems), and could be reconverted back to permanent or rotational grassland. An initial assessment of the impacts of widespread organic farming in England and Wales by Reading University estimated (using one scenario, based on the production records of 176 organic farms), that there would be a 68% increase in beef production (cancelling imports, which are currently equivalent to 31% of UK production levels), a 55% increase in lamb production (making the UK self-sufficient in lamb, as UK currently imports an additional 43% on top of domestic production) and a large decrease in white meat (pig and poultry) production; "England and Wales under organic agriculture: how much food could be produced?", by Philip Jones with Richard Crane , Centre for Agricultural Strategy, Policy and Development, University of Reading. See Press release, 24 June 2009, http://www.rdg.ac.uk/about/newsandevents/releases/PR21951.asp. [Author's note, an increase in grass-fed beef production in the northern hemisphere does not imply an increase globally, as the increase would replace imported beef and the excess should be exported to replace the unsustainable and grain-based beef production in other countries.]

[172] 1. A 2007 UNEP report recognises that oil palm plantations are now the leading cause of rainforest detruction in Malaysia and Indonesia; Nellemann, C., Miles, L., Kaltenborn, B., Ahlenius, H. (2007), "The last stand of the orangutan - State of emergency: Illegal logging, fire and palm oil in Indonesia's national parks, rapid response assessment"; United Nations Environment Program (UNEP); available at: http://www.unep-wcmc.org/resources/PDFs/LastStand/orangutanreport_1to11.pdf. 2. The Indonesian Palm Oil Research Institute (IOPRI) estimates that two-thirds of currently productive palm oil plantations involved deforestation. Both this and pre vious reference cited page 12, "How the palm oil industry is Cooking the Climate," Greenpeace report, November 2007. http://www.greenpeace.org/raw/content/international/press/reports/cooking-the-climate-full.pdf 3. A slightly earlier publication says that palm oil was the secondary driver of deforestation in Indonesia: Wetlands International estimate that concessions granted for oil palm and timber were key drivers of deforestation in Indonesia, particularly on peatland: 58% (10.34 million ha) for timber and 42% (7.48 million ha) for oil palm; Hooijer et al (2006), Table 4, Concessions on peatland in Indonesia. 4. IIED estimate the percentage share of land-use on deforested land to be oil palm (32%), rubber (30%), rice (19%) and Cassava (19%); source: Grieg-Gran, M., "The cost of avoiding deforestation, Report prepared for the Stern Review of the Economics of Climate Change," International Institute for Environment and Development, October 2006. Both this and previous reference cited in "Slaughtering the Amazon," Greenpeace report, 2009. http://www.greenpeace.org/international/press/reports/slaughtering-the-amazon.

[173] 1. "How Unilever palm oil suppliers are burning up Borneo," Greenpeace report, April 2008. 2. Malysia and Indonesia are the source of 85% of the globally traded palm oil; www.americanpalmoil.com

[174] In Indonesia, IIED estimate the percentage share of land-use on deforested land to be oil palm (32%), rubber (30%), rice (19%) and cassava (19%); Grieg-Gran, M., "The cost of avoiding deforestation, Report prepared for the Stern Review of the Economics of Climate Change," International Institute for Environment and Development, 2006. Cited page 109, "Slaughtering the Amazon," Greenpeace report, 2009. http://www.greenpeace.org/international/press/reports/slaughtering-the-amazon.

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[175] 1. The degradation and burning of Indonesia's peatlands releases 1.8billion tCO2/yr, Hooijer et al (2006): 29. As the effects of drainage extend far into the neighbouring forest regions, this figure is an underestimate. See: "How the palm oil industry is Cooking the Climate," Greenpeace report, 2007. http://www.greenpeace.org/raw/content/international/press/reports/cooking-the-climate-full.pdf 1.8 billion tCO2 x 44/12 = 491 million tC/yr. For palm oil alone, 0.32 x 491 = 157 million tC/yr. 2. Greenpeace estimate that the degradation of Indonesia's peatlands for palm oil production accounts for annual emissions of at least 476million tCO2 [x12/44 = 130million tC]; page 25, http://www.greenpeace.org/raw/content/international/press/reports/hidden-carbon-liability-of-palm-oil.pdf. The figure for all palm oil will be larger, as it includes non-peatland deforestion and palm oil from other countries.

[176] Boswell *et al*, 2007. Page 117, CLIMSOIL report for the Eueopean Comission, 16 December 2008.

[177] FAO (2006): 56. Cited in "How the palm oil industry is Cooking the Climate," Greenpeace report, November 2007.

[178] Already in 2007, most of the lowland rainforest on Sumatra and Kalimantan (the main Indonesian part of Borneo) and 10million of the 22.5million ha of peatland in Indonesia had been destroyed, mainly due to palm oil plantations. A further 20million ha of palm oil plantation is planned in Indonesia. "How the palm oil industry is Cooking the Climate," Greenpeace.

[179] Riau Province's peatlands store 14.6 bn tC in 4 million ha [=3650tC/ha]. "How the palm oil industry is Cooking the Climate," Greenpeace report, 2007.

[180] www.americanpalmoil.com

[181] 1. *'In Indonesia it is estimated that producing 1 tonne of palm oil on peatland will cause emissions of between 15 and 70 tonnes of CO2 over the life cycle of 25 years as a result of forest conversion, peat decomposition and emission from fires associated with land clearance.'* Rieley, J O *et al* (2008), 'Life-cycle analysis of land use change on tropical peatlands,' Ecosystems 2008 (in press); data quoted by CARBOPEAT project www.geog.le.ac.uk/carbopeat/press/pr2.html February 2008; cited in Greenpeace report, page 28, http://www.greenpeace.org/raw/content/international/press/reports/hidden-carbon-liability-of-palm-oil.pdf 2. Earlier, Wetlands International estimated that each tonne of palm oil produced on peatland results in a release of 10-30tCO2 per t of palm oil from peat decomposition, cited in "How the palm oil industry is Cooking the Climate," Greenpeace report, November 2007. 2.

[182] 80% of palm fruit oil is used for producing food. www.americanpalmoil.com

[183] www.americanpalmoil.com

[184] page 28, http://www.greenpeace.org/raw/content/international/press/reports/hidden-carbon-liability-of-palm-oil.pdf

[185] Europe is an importer of palm oil for food and biofuel. "How the palm oil industry is Cooking the Climate," Greenpeace report, November 2007.

[186] "How the palm oil industry is Cooking the Climate," Greenpeace report, November 2007.

[187] "How the palm oil industry is Cooking the Climate," Greenpeace report, November 2007.

[188] W. Knorr, I. C. Prentice, J. I. House & E. A. Holland, Long-term sensitivity of soil carbon turnover to warming, *Nature* **433**, 298-301. http://www.nature.com/nature/journal/v433/n7023/full/nature03226.html

[189] Smith, J.U., Smith, P., Wattenbach, M., Zaehle, S., Hiederer, R., Jones, R.J.A., Montanarella, L., Rounsevell, M.D.A., Reginster, I. , Ewert, F., (2005). Projected changes in mineral soil carbon of European croplands and grasslands, 1990-2080. Global Change Biology, 11(12), 2141-2152.

[190] Using the Lund–Potsdam–Jena model, this predicts that, in response to climate change, SOC levels are likely to only slightly fall by around a 0.02%/yr of the starting SOC content on cropland and slightly increase by 0.02%/yr on grassland, using a model of several soil C pools and accounting for higher plant growth. "Climate change cannot be entirely responsible for soil carbon loss observed in England and Wales, 1978-2003," Pete Smith, Stephen J. Chapman, W. Andy Scott, Helaina I. J. Black , Martin Wattenbach, Ronnie Milne , Colin D. Campbell, Allan Lilly, Nick Ostle, Peter E . Levy , David G. Lumsdon, Peter Millard, Willie Towers, Sönke Zaehle, and Jo U. Smith. Global Change Biology (2007) 13, 2605–2609. Rapid Communication in Global Change Biology in 2007.

[191] W. Knorr, I. C. Prentice, J. I. House & E. A. Holland, Long-term sensitivity of soil carbon turnover to warming, *Nature* **433**, 298-301 http://www.nature.com/nature/journal/v433/n7023/full/nature03226.html

[192] Stephen P. Long, Elizabeth A. Ainsworth, Andrew D. B. Leakey, Josef Nö̈sberger, Donald R. Ort , "Food for Thought: Lower-Than-Expected Crop Yield Stimulation with Rising CO2 Concentrations." Science, 30 June 2006, Vol 312 www.sciencemag.org

[193] Caspersen *et al*, 2000; cited by Houghton, R.A. (2003) Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000. Tellus Series B-Chemical and Physical Meteorology, 55, 378-390.

[194] Oren *et al*, 2001; Schlesinger & Lichter, 2001; cited by Houghton, 2003.

[195] Page 52, Johnston *et al*, 2009, *in press.*

[196] Centre for Terrestrial Carbon Dynamics (CTCD) http://www.ctcd.group.shef.ac.uk/science/soil/soil.html#soil1

[197] See section 9.5 on the effects of organic farming on soil respiration rates.

[198] C3 and C4 refer to two of the three types of carbon fixation processes used by plants for photosynthesis. C3 plants are the most common. The C4 process is more evolved and enables photosynthesis to be more efficient, with less water loss and a more efficient carbon delivery system. C4 plants occur mainly in the tropics, as they are better adapted to conditions of drought, high temperatures, and N or CO2 limitation. C4 plants only account for 1% of all plant species, but 5% of the Earth's plant biomass, and 30% of all terrestrial carbon fixation. "C3 carbon fixation", "C4 carbon fixation", Wikipedia.

[199] Stephen P. Long, Elizabeth A. Ainsworth, Andrew D. B. Leakey, Josef Nö̈sberger, Donald R. Ort , "Food for Thought: Lower-Than-Expected Crop Yield Stimulation with Rising CO2 Concentrations." Science, 30 June 2006, Vol 312 www.sciencemag.org

[200] Long *et al*, 2006.

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[201] Stephen P. Long, Elizabeth A. Ainsworth, Carl J. Bernacchi, Chalres P. Chen, Orla C. Dermondy, Evan H. DeLucia, Patrick B. Morgan, Randall L. Nelson, Donald R. Ort, and Shawna L. Naidu, "Response of crop photosynthesis to CO2, ozone and temperature," Departments of Plant Biology and of Crop Science, University of Illinois, USA. Presentation by Professor Stephen Long, "Food Crops in a changing climate," 26-27 April 2005; scientific discussion meeting by the Royal Society.

[202] Centre for Terrestrial Carbon Dynamics (CTCD) http://www.ctcd.group.shef.ac.uk/science/soil/soil.html#soil1

[203] Email communication, Pete Smith, 31 May 2008, Professor of Soil & Global Change, Institute of Biological and Environmental Sciences, University of Aberdeen.

[204] We were told that studies show that peaty soils do *not* have a higher temperature sensitivity to decomposition - email communication, Pete Smith, email communication, 31 May 2008, Professor of Soil & Global Change, Institute of Biological and Environmental Sciences, University of Aberdeen. On the other hand, Bellamy *et al*, 2005, quote a study showing that "more-organic soils … appear to be more sensitive to temperature changes."

[205] 1. 40-60% of the total soil carbon over 1m depth occurs below 25cm: Arrouays D.; Pelissier P., "Modeling carbon storage profiles in temperate forest humic loamy soils of France," Soil science, 1994, vol. 157, n°3, pp. 185-192. Cited in Sleutel *et al*, 2003. 2. For UK cultivated soils, based on official data, about 37% of the total soil carbon over 1m depth occurs below 30cm; see box, "Size of the UK and EU soil orgnaic carbon stores, Chapter 2 of this report.

[206] Mineralisation is the conversion of nutrients in organic form (ie. stored in SOM) into inorganic forms - unpublished paper on soil carbon and organic farming, provided to the Soil Association by Dr Julia Cooper, Newcastle University, 9 October 2007. SOM 'oxidation' is when soil carbon is converted to atmospheric CO2.

[207] Jean-François Soussana, INRA Clermont, France. Workshop on soil at International conference "Organic agriculture and climate change," Enita Clermont, France, 17-18 April 2008.

[208] Shepherd, M.A., R. Harrison & J. Webb, Managing soil organic matter - implications for soil structure on organic farms, Soil Use and Management (2002) 18, 284-292.

[209] The common earthworm *Lumbricus terrestris* can burrow to a depth of 150 - 240 cm. "Earthworms in agricultural production sytems," http://www.assuredcrops.co.uk/sources/4000134/4001069/4032643/Earthworms.pdf?id=4032643

[210] eg. the roots of cereals can grow six feet long in deep soil. Oral communication, Pete Douglas, Soil Association, Producer Services department, 1 September 2008.

[211] See Chapter 2

[212] Swiss FiBL DOK trial of farming systems. Fließbach *et al*, 1999. Cited in: Fließbach, A., H.R. Oberholzer, L. Gunst & P. Mäder, 2007, "Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming," Agriculture Ecosystems & Environment 118:273-284.

[213] Section 5, Baritz *et al*, 2004, Task group 5 on Land Use Practices and SOM, http://ec.europa.eu/environment/soil/pdf/vol3.pdf.

[214] Section 5, Baritz *et al*, 2004, Task group 5 on Land Use Practices and SOM, http://ec.europa.eu/environment/soil/pdf/vol3.pdf.

[215] Van Meirvenne M Pannier J Hofman G & Louwagie G 1996. Regional characterisation of the long-term change in soil organic carbon under intensive agriculture. Soil Use and Management 12, 86-94.

[216] In the Belgian study (province of West Flanders, c.1952-c.1992, 939 arable sites), there was a topsoil carbon increase of about 25% or 9.3tC/ha over 40 years, made up of a 17% increase in SOC content (1.07% to 1.27% SOC) and a 44% increase in ploughing depth (22.4cm +/-4cm to 32.2cm +/- 5cm). The plough-layer depth was observed visually, and taken to be the topsoil layer. The soil carbon increase was accounted for by the increase in slurry application, due to an 8-fold increase in pig numbers.

[217] Oral communication Ian Bradley (retired), Principal Research Scientist, National Soil Resources Institute (NSRI), Cranfield University, 9 March 2006. Also see, Evans, R., "Soils at risk of accelerated erosion in England and Wales,"1990, *Soil Use and Management* 6: 125-131. http://www3.interscience.wiley.com/journal/119377524/abstract?CRETRY=1&SRETRY=0

[218] Mentioned in, "The State of Soils in England & Wales*,"* page 6, Environment Agency, 2004. Original reference: "Soil protection in the UK," Soil Survey and Land Research Centre, 2000, Cranfield University, 5pp.

[219] Calculation: 2.2 million t of soil x assumed 2.4% average carbon content = 52,800t of carbon. The figure of 2.4% is derived from the 1980 SOC content for arable/ley soils in England and Wales of 3.4% (Webb *et al*, 2001), and the annual rate of SOC loss for mineral arable/ley soils in England and Wales from the NSI survey of 0.33gC/kg soil (provided by NSRI, August 2008). So, 34 – (0.33 x 29) = 24.4gC/kg in the year 2009, ie. 2.4%.

[220] Oral communication Ian Bradley (retired), Principal Research Scientist, NSRI, 7 March 2007.

[221] Lal *et al*, 1998. Cited in Baritz *et al*, 2004, Task group 5 Land Use Practices and SOM.

[222] Lal, 2003. Cited in Baritz *et al*, 2004, Task group 5 Land Use Practices and SOM.

[223] M.Frankignoulle *et al.*, Science **282**, 434 (1998).

[224] For instance, soils in Mediterranean areas often have low or very low SOM content, many less than 0.5% organic carbon; these soils are naturally close to the threshold of degradation and desertification and small increases in organic matter in these types of soils can prevent the risk of erosion. Baritz *et al*, report of Task group 5 Land use Practices and SOM, 2004.

[225] Dregne, H.E. and Chou, N.T. 1994. Global desertification dimensions and costs. In H.E. Dregne (ed.). Degradation and restoration of arid lands. Lubbock, USA; Texas Technical University.

[226] Five comparative studies have looked at soil depth and all found that the topsoil was deeper on the organic farms: Armstrong *et al*, 2000; Liebig & Doran, 1999; Gerhardt,1997; Reganold *et al*, 1993; and Reganold *et al*, 1987. See section 6.6.

[227] This was suggested as a cause of the large soil carbon losses reported by the survey for organic soil types, by Smith *et al*, 2007. We are suggesting that this might also be a factor in the mineral soil results.

[228] Section 3.14. www.scotland.gov.uk/cru/kd01/lightgreen/rccs-00.asp

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[229] "Paper for information - Paper 8 – Livestock production subsidy schemes and cross-compliance provisions," Agricultural Use And Management Of Common Land Stakeholder Working Group, December 2002. http://www.defra.gov.uk/WILDLIFE-COUNTRYSIDE/issues/common/manage/pdf/swg2paper8.pdf

[230] Dr Ronny Milne, CEH in Edinburgh, who collects the land use change data for the national inventory, has confirmed that there are issues with the terminology. Oral communication, Dr Ronny Milne, 2 February 2006.

[231] For instance, the UK NSI survey (Bellamy *et al*, 2005), and Houghton, 2003.

[232] Eg. see Houghton, 2003.

[233] For instance, all of these modelling studies are mainly based on the concept that the soil carbon input to the soil is proportional to the crop yields: Janssens *et al*, 2005; Zaehle *et al*, 2007; Smith *et al*, 2005; and Gervois *et al*, 2008. See Annex I.

[234] Zaehle, S., Bondeau, A., Carter, T., Cramer, W., Erhard, M., Prentice, I.C., Reginster, I., Rounsevell, M.D.A., Sitch, S., Smith, B., Smith, P.C., Sykes, M. (2007): Projected changes in terrestrial carbon storage in Europe under climate and land-use change, 1990-2100. Ecosystems 10(3) 380-401.

[235] US organic arable yields compared to non-organic: maize – 6% less (69 sets of data); soya – 6% less (55 sets of data). Survey of results of replicated farming trials from seven state universities and two independent research facilities, for different parts of the US, including rain-fed and irrigated regions, Bill Liedhardt, University of California.

[236] Also, 70 – 85 % of the peatland area in the Netherlands, Germany and Poland is in agricultural use. Around 16% of the European peatland area is used in agriculture (cropland & grassland), including the vast majority of peats in continental Western Europe (Byrne *et al.*, 2004) (Annex 8). All cited page 76, CLIMSOIL report for the European Commission,16 December 2008.

[237] King *et al.*,2005; cited in CLIMSOIL report for the European Commission,16 December 2008.

[238] Johnston *et al*, 2009, *in press.*

[239] J. Webb, P. J. Loveland, B. J. Chambers, R. Mitchell and T. Garwood, "The impact of modern farming practices on soil fertility and quality in England and Wales," Journal of Agricultural Science, Cambridge (2001), **137**, 127–138.

[240] As well as the reduced use of FYM, for parts of the Silt Region, the decrease in SOC stocks "may also be attributed to" the continued effects of a change from mainly mixed farming in the past to more specialised cropping systems now. S. Sleutel, S. De Neve & G. Hofman, "Estimates of carbon stock changes in Belgian cropland." Soil Use and Management (2003) 19, 166-171.

[241] Tove Heidmann, Bent T. Christensen and Svend E. Olesen, "Changes in soil C and N content in different cropping systems and soil types," in "Greenhouse Gas Inventories for Agriculture in the Nordic Countries," Proceedings from an international workshop, Helsingør, Denmark 24-25 January 2002.

[242] Pete Smith, Stephen J. Chapman, W. Andy Scott, Helaina I. J. Black , Martin Wattenbach, Ronnie Milne , Colin D. Campbell, Allan Lilly, Nick Ostle, Peter E . Levy , David G. Lumsdon, Peter Millard, Willie Towers, Sönke Zaehle, and Jo U. Smith. "Climate change cannot be entirely responsible for soil carbon loss observed in England and Wales, 1978-2003," Global Change Biology (2007) 13, 2605–2609.

[243] Email communication, Rob George, Soil Association, 21 January 2009. Only 1.5-2% of farmers surveyed were 'exporting' manure in 2008, page 69, The British Survey of Fertiliser Practice, 2008.

[244] Pages 34, 42 and 45, The British Survey of Fertiliser Practice, 2008. https://statistics.defra.gov.uk/esg/bsfp/2008.pdf The authors note that the survey was established to provide data on inorganic fertiliser use and it may not be totally representative in its manure data.

[245] Pages 43, The British Survey of Fertiliser Practice, 2008. https://statistics.defra.gov.uk/esg/bsfp/2008.pdf

[246] Email communication, Jon Grimes, Soil Association Certification,18 December 2008.

[247] 1.5milliont is 1990s data, Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561. An estimate for 2008 is 1.5 milliont, The British Survey of Fertiliser Practice, 2008.

[248] Page 68, The British Survey of Fertiliser Practice, 2008. https://statistics.defra.gov.uk/esg/bsfp/2008.pdf Figures have been slightly increased to account for the 3% of all 'organic manures' that are biosolids, and which are not animal manures.

[249] Oral communication, Christopher Atkinson, Standards Manager and Northern Development Manager, Soil Association, 22 July 2009.

[250] Water UK, 2006; cited by Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561.

[251] Section 2.1, Baritz *et al*, 2004, Task group 5 Land use and SOM, http://ec.europa.eu/environment/soil/pdf/vol3.pdf.

[252] Burton CH, Turner C (eds) (2003) Manure Management Treatment Strategies for Sustainable Agriculture. Silsoe Research Institute, Silsoe, UK. Cited in: Smith *et al*, 2007.

[253] Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561.

[254] Page 68, The British Survey of Fertiliser Practice, 2008. https://statistics.defra.gov.uk/esg/bsfp/2008.pdf Figures have been slightly increased to account for the 3% of all 'organic manures' that are biosolids, and which are not animal manures.

[255] Figures cited exclude manure deposited on pasture and 'daily spread' figures. Breakdown of all manure produced in the UK dairy sector: 45.5% deposited on pasture; 30.6% slurry system; 9.8% solid manure system; 14.1% daily spread. Breakdown of all manure produced in the UK beef sector: 50.5% deposited on pasture; 6% slurry system; 20.7% solid manure system; 23% daily spread. Page 377 of the Annexes to the UK Greenhouse Gas Inventory 2007, http://www.airquality.co.uk/reports/cat07/0905131425_ukghgi-90-07_Annexes_Issue2_UNFCCC_Final.pdf

[256] The finding of 480kgC/ha/yr for 0-30cm was the figure advised by the researchers of the survey (email communication, Dr Steven Sleutel, 1 October 2008): "Regional simulation of long-term organic carbon stock changes in cropland soils using the DNDC model: 1. Large-scale model validation against a spatially explicit data set," S. Sleutel, S. De Neve, D. Beheydt, C. Li & G. Hofman, Soil Use and Management, December 2006, 22, 342–351.

[257] The British Survey of Fertiliser Practice, 2008, Defra. https://statistics.defra.gov.uk/esg/bsfp/2008.pdf

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[258] Mean application rates for 2004-08;% of areas is data for 2008. The British Survey of Fertiliser Practice, 2008, Defra. https://statistics.defra.gov.uk/esg/bsfp/2008.pdf

[259] Pete Smith, Stephen J. Chapman, W. Andy Scott, Helaina I. J. Black , Martin Wattenbach, Ronnie Milne , Colin D. Campbell, Allan Lilly, Nick Ostle, Peter E . Levy , David G. Lumsdon, Peter Millard, Willie Towers, Sönke Zaehle, and Jo U. Smith. "Climate change cannot be entirely responsible for soil carbon loss observed in England and Wales, 1978-2003," Global Change Biology (2007) 13, 2605–2609.

[260] "Initial assessment of the projected trends of soil organic arbon in English arable soils," by ADAS, Defra project SP 0533.

[261] Eg. spelt grows 6ft tall.

[262] Dr Christine Watson, Scottish Agricultural College, Soil Association conference, Edinburgh, 9 January 2004.

[263] Ewert F, Rounsevell MDA, Reginster I, Metzger M, Leemans R (2005) Future scenarios of European agricultural land use. I: estimating changes in crop productivity. Agriculture, Ecosystems and Environment, 107, 101–116. Cited by Smith *et al*, 2007.

[264] Smith *et al*, 2007.

[265] Chloupek *et al*, 2006, Applied Genetics 2: 779-786; cited in "What will limit crop yields in the future?" presentation by Professor Carlo Leifert, Soil Association conference, November 2008, http://92.52.112.178/Web/SA/saweb.nsf/leifert_workshop5.pps

[266] For example, there has been a reduction in the level of broad-leaved weeds over winter due to pre-harvest applications of Round-up. Email contribution, Peter Melchett, Policy Director and organic farmer, Soil Association, 6 October 2009.

[267] Email contribution, Peter Melchett, Policy Director and organic farmer, Soil Association, 6 October 2009.

[268] "Straw," Biomass energy centre, www.biomassenergycentre.org.uk.

[269] Straw yields are about 3.5t/ha for wheat and 2.75t/ha for barley. About 40% of the 7 million t of wheat straw are chopped and returned to the soil, about 30% are used on-farm, and about 30% are sold. Most of the 2.75 million t of barley straw are used as bedding and feed. "Straw," Biomass energy centre, www.biomassenergycentre.org.uk.

[270] 1. According to this 2007 report for Defra, straw incorporation adds an estimated 50kgSOC/ha to a 30cm deep soil for up to 20 years; Table7, Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561. Assuming an average wheat straw yield of 3.5t/ha (see reference above), this suggests an addition of 175kgC/ha/yr for up to 20 years, or up to 3.5tC/ha in total over 20 years. This means an increase in soil carbon levels by up to 6% in 20 years (eg. 3.5tC increase on 60tC/ha soil is 5.8%), assuming no other management changes. 2. According to this 2003 report for Defra, straw and stubble incorporation added an estimated 164kgC/ha/yr for the first five years and 940kgC/ha in total over 20 years for the top 30cm of soil; "Initial assessment of the projected trends of soil organic arbon in English arable soils," by ADAS, Defra project SP 0533. This would increase soil carbon levels by about 2% in 20 years (eg. 1t increase on 60tC/ha soil is +1.7%), assuming no other management changes.

[271] Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561.

[272] 1. Webb et al, 2001; 2. Janssens et al, 2003, www.sciencemag.org; 3. Pete Smith et al, 2007.

[273] In the 'ley-arable' experiment by Rothamsted (1948-2002), conversion of a long-term permanent grass field to continuous arable cropping reduced the soil carbon level to that of a long-term arable site in about 30 years, from 64tC/ha to 41tC/ha. Figure 6, page 20, Johnston *et al*, 2009, *in press.*

[274] According to the IPCC land use categories, 'permanent grassland' means all grassland (managed and unmanaged) over 20 years. Tables 1-1 and 1-2 (page 2), Inventory and Projections of UK Emissions by Sources and Removals by Sinks due to Land Use, Land Use Change and Forestry, Annual Report, July 2008. Centre for Ecology & Hydrology, University of Aberdeen, Forest Research Alice Holt, National Soil Resources Institute, Centre for Terrestrial Carbon Dynamics (Universities of Sheffield, Edinburgh, York & University College London), Agri-Food & Biosciences Institute, Queen's University Belfast. Author's note: Defra normally uses different land use definitions which means that different figures for grassland are reported elsewhere, which is a source of confusion. For instance, elsewhere, Defra often uses 'grassland' just to refer to *managed* grassland; and it classifies grassland according to whether it is under or over 5 years old, rather than the 20 year cut-off used by the IPCC.

[275] Table 1-17 to 1-20, page 16, CEH *et al*, 2008. In addition, smaller amounts of grassland were converted to forests and urban land. http://www.edinburgh.ceh.ac.uk/ukcarbon/docs/2008/Defra_Report_2008.pdf

[276] These figures are not the *average* difference in soil carbon stocks between grassland and cropland in the UK (which is slightly more, see Table 1-22) but reflect the average difference in soil carbon stocks between the grassland which is *currently being converted* to cropland in the UK, weighted to take into account the actual balance of soil types that are being converted. Tables 1-23 to 1-26, page 20, CEH *et al*, 2008. http://www.edinburgh.ceh.ac.uk/ukcarbon/docs/2008/Defra_Report_2008.pdf Note, the units shown in these tables should be tC/ha, not kg/m^2 (email communication from Dr R.Milne to R.Young, 12 October 2009).

[277] Freibauer *et al*, 2004, in press when cited by Baritz *et al*, 2004. http://www.bgc-jena.mpg.de/~afreib/

[278] Soil Association estimate based on the official figures in the UK's GHG inventory for emissions/gains from the LULUCF sector. In 2006, land converted to cultivated land was emitting 14,312,000tCO2; we have assumed that 99% of this was previously grassland (according to the proportion indicated in Table 1-2), ie. an on-going emission of 14,168,880tCO2 from the earlier ploughing-up of permanent pasture. Land converted to grassland, however, was sequestering 8,720,000tCO2; assuming that 94% of this was conversion from cropland (based on the proportions indicated in Table 1-2), this means a sequestration of 8,196,800tCO2 from 'arable to grass' conversion. Thus, this gives a net emission of 14,168,880 – 8,196,800 = 5,972,080tCO2 in 2006, from 'within agricultural' land use change. X12/44 = 1.63milliontC as the net emission resulting from earlier & on-going ploughing-up of grassland. We have ignored the soil C loss figures in the inventory for 'Grassland remaining grassland' as these are small and mostly due to peat extraction for ornamental horticulture. Data from page 35, Table 1-31, Inventory and Projections of UK Emissions by Sources and Removals by Sinks due to Land Use, Land Use Change and Forestry, Annual Report, July 2008. CEH *et al.* http://www.edinburgh.ceh.ac.uk/ukcarbon/docs/2008/Defra_Report_2008.pdf

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[279] 1.6/13.8 million x 100 = 11.6milliontC/yr. UK agriculture's GHG emissions are 13.8 million tC/yr, from: National statistics – 2008 UK provisional figures. Annex B- Emissions of all greenhouse gases, carbon dioxide, methane and nitrous oxide by source and end-user. http://www.decc.gov.uk/en/content/cms/statistics/climate_change/climate_change.aspx Converted from CO2 to C by using conversion factor of x 12/44.

[280] Under the new 2006 IPCC guidelines, however, soil carbon changes have been integrated into the emissions for the 'Agriculture & Forestry' sector, so this may become more transparent in future.

[281] For all emission scenarios, "Annual area of land use change 2007-2020 assumed to be same as annual rate of change for 1990-2006." See text, tables 4-2 to 4-5 and Figure 4.4 (page 59), CEH *et al*, 2008.

[282] Holger Kirchmann, Lars Bergström, Thomas Kätterer, Lennart Mattsson and Sven Gesslein, "Comparison of Long-Term Organic and Conventional Crop–Livestock Systems on a Previously Nutrient-Depleted Soil in Sweden," Published in Agron J 99:960-972 (2007). Published online 5 June 2007.

[283] The IPCC Tier 1 soil carbon methodology calculates the size of the soil carbon losses on the change from permanent unmanaged grassland according to the type of following management regime, including whether it becomes 'improved' grassland, rotational grass/ley arable land, or continously cropped arable land, and if manure is regularly applied etc. Volume 4, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, IPCC, 2007.

[284] Eg. Balesdent *et al*, 2000. Cited Sheperd *et al*, 2002. See section 9.1

[285] Email communication, Peter Melchett, Policy Director and organic farmer, Soil Association, 26 November 2008.

[286] Shallow tillage methods became fairly widespread in the English arable land in the 1970s, but the 1993 ban on straw burning necessitated a return to the plough to bury the straw and stubble, but since then reduced tillage systems have become more widespread again. "Initial assessment of the projected trends of soil organic arbon in English arable soils," by ADAS, Defra project SP 0533.

[287] 1. According to the authors of this recent review of the scientific evidence on min-till for the UK Government, their current best estimate is that adoption of min-till practices would temporarily raise soil carbon levels by around 160kgC/ha/yr for 3 or 4 years in English and Welsh conditions, the level tending to fall back each time the land is ploughed; Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561. This implies a total temporary SOC increase of 480-640kgC/ha, or an increase of just around 1% of the total arable soil carbon level during those 3-4 years (eg. 0.64tC increase on 60tC/ha soil = +1.1%). If, on average, the arable land subject to min-till is roughly half-way to this level at any one time, this suggests that the actual effect of the adoption of min-till is an increase in the soil carbon store on this land of just 0.5% of the total, or so. 2. An earlier literature survey deduced that a change from ploughing to reduced tillage may be expected to increase soil carbon levels by about 40kgC/ha/yr over all soil types; King *et al*, 2003; cited in "Initial assessment of the projected trends of soil organic arbon in English arable soils," by ADAS, Defra project SP 0533. 2. According to this 2003 report to Defra, the adoption of reduced tillage in England in the 1970s would have marginally increased soil carbon levels for five years, but the re-adoption of ploughing after the 1993 ban on straw-burning would have reversed the increase; but then the more recent return to reduced tillage practices since the 1990s would have increased levels again by an estimated 40kgC/ha/yr (from King *et al*, 2003) for five years; "Initial assessment of the projected trends of soil organic arbon in English arable soils," by ADAS, Defra project SP 0533. This suggests an increase in soil carbon levels of under 1% (eg. 40kgC x 5 years = 0.2t/ha. 0.2t increase on 60tha soil = 0.3% increase).

[288] Chan *et al*, 2002; Clapp *et al*, 2000; Doran, 1980; Franzluebbers *et al*, 1994; Sainju *et al*, 2002. Cited in Rasse *et al*, 2005.

[289] Angers *et al*, 1995; Angers *et al*, 1997; Balesdent *et al*, 2000; Deen and Kataki, 2003. Cited in Rasse *et al*, 2005.

[290] Nieder & Richter 2000. C and N accumulation in arable soils of West Germany and its influence on the environment – Developments 1970 to 1998. J. Plant Nutrition Soil Sci. 163, 65-72 http://cat.inist.fr/?aModele=afficheN&cpsidt=1460407 Cited in Baritz *et al*, 2004, Task group 5 Land Use Practices and SOM.

[291] Van Meirvenne M Pannier J Hofman G & Louwagie G 1996. Regional characterisation of the long-term change in soil organic carbon under intensive agriculture. Soil Use and Management 12, 86-94. See section 9.1 of this report for more details.

[292] In this Danish arable soil survey, there was an overall increase in soil carbon levels. The increase was nearly all occurring in the 25-50cm depth of the sandy soils (below the standard sampling depth). The SOC gains were occurring in the coarse sandy soils, which were receiving more cattle manure and had more grass and catch crops in the rotation than the loamy soils, which were losing carbon. This management difference also implies that the coarse sandy soils were being ploughed more than the loamy soils, to incorporate the manure, grass and cover crops. Thus, a possible explanation for the finding that an increase occurred in the deeper soil layer, as opposed to the top soil layer or at all, is that perhaps the deep incorporation of organic matter by ploughing or an increase in the depth of ploughing had resulted in more soil carbon entering the deeper soil layers, increasing the total soil carbon store. An alternative explanation is that the grass and cover crops were depositing carbon deeply in the sandy soils. Tove Heidmann, Bent T. Christensen and Svend E. Olesen, "Changes in soil C and N content in different cropping systems and soil types," in "Greenhouse Gas Inventories for Agriculture in the Nordic Countries," Proceedings from an international workshop, Helsingør, Denmark 24-25 January 2002.

[293] Agriculture in the UK, 2007, Defra, 2008.

[294] "Critical appraisal of state and pressures and controls on the sustainable use of soils in Wales." CEH Project CO1920. Centre for Ecology and Hydrology, 2002, Environment Agency/National Assembly for Wales Contract 11406.

[295] "The State of Scotland's Farmed Environment," 2005. http://www.macaulay.ac.uk/LINK/

[296] "Paper for information - Paper 8 – Livestock production subsidy schemes and cross-compliance provisions," Agricultural Use And Management Of Common Land Stakeholder Working Group, December 2002. http://www.defra.gov.uk/WILDLIFE-COUNTRYSIDE/issues/common/manage/pdf/swg2paper8.pdf. The uplands are classed as 'Less Favoured Areas' (LFAs). For the sheep sector, as well as the Sheep Annual Premium Scheme payments available to all UK sheep farmers, there were extra

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headage payments for hill farmers, the Hill Livestock Compensatory Allowance (HLCA). The payments for sheep were highest in the 'Severely Disadvantaged Areas' of the LFAs.

[297] Email communication, Martin Peck, organic livestock farmer, Wales, and member of the SA Agriculture Standards Committee, 17 February 2009.

[298] The sheep quota system was introduced in 1993 and was based on the number of sheep farmers had been claiming subsidy on in 1991. The likelihood of quota introduction was being discussed well before 1991, inadvertently allowing time for farmers to build up their breeding ewe numbers in advance. Email communication, Martin Peck, organic livestock farmer, Wales, and member of the SA Agriculture Standards Committee, 17 February 2009.

[299] Agriculture in the United Kingdom, Defra

[300] This is an EU wide scheme with different versions in each country, including each devolved regions of the UK. Scotland and Wales have opted for 'historic' payments based on the average subsidy the farmer received between 2000 and 2002. England and Northern Ireland are using a mix of historic payments and area payments. In England, there will be an eight-year transition from historic payments to 'regional average' payments, over which time the regional average component progressively increases. England has been subdivided into three agricultural regions with differing payment rates: moorland within the upland Severely Disadvantaged Areas; the rest of the upland SDA; and all land outside the upland SDA. "Agriculture – Single Farm Payment Scheme," Christopher Barclay, 28 December 2005, House of Commons Standard Note. http://www.w4mp.org/html/library/standardnotes/snsc-03680.pdf

[301] Agriculture in the United Kingdom 2006, and 2007, Defra.

[302] EEA, 2003. Cited in Baritz *et al*, 2004, Task group 5 Land Use Practices and SOM.

[303] Cormack, W. & Metcalfe, P., "Energy Use in Organic Farming Systems" MAFF, 2000. Defra research project OF0182.

[304] Cormack, W. & Metcalfe, P., "Energy Use in Organic Farming Systems" MAFF, 2000. Defra research project OF0182.

[305] Defra, "Agriculture in the United Kingdom, 2006", table 6.1, Defra, 2007.

[306] Defra, "Agriculture in the United Kingdom, 2005," Defra, 2006

[307] "Initial assessment of the projected trends of soil organic arbon in English arable soils," by ADAS, Defra project SP 0533.

[308] "Warm-weather crops: forage maize." http://www.ecn.ac.uk

[309] "Soil erosion control in maize," Institute of Grassland and Environmental Research, Report for MAFF (Defra) SP404, Project end date 5 May 2001.

[310] "Warm-weather crops: forage maize." http://www.ecn.ac.uk

[311] "Warm-weather crops: forage maize." http://www.ecn.ac.uk

[312] "Soil erosion control in maize," Institute of Grassland and Environmental Research, Report for MAFF (Defra) SP404, Project end date 5 May 2001.

[313] "Soil erosion control in maize," Institute of Grassland and Environmental Research, Report for MAFF (Defra) SP404, Project end date 5 May 2001.

[314] "Soil erosion control in maize," Institute of Grassland and Environmental Research, Report for MAFF (Defra) SP404, Project end date 5 May 2001.

[315] A 30-year maize experiment found that the restitution of maize stalks vs. removal for silage had no impact on SOC contents (Reicosky et al., 2002). Clapp et al. (2000) observed that 13 years of maize 'shoot' restitution in a non-fertilized conventionally tilled system slightly decreased the contribution of maize to soil organic carbon (SOC) stocks from 9.1 tC/ ha for roots alone to 8.7 tC/ha for roots plus shoots. Cited in Rasse *et al*, 2005.

[316] Poulton PR (1996) The Park Grass experiment 1856–1995. NATO ASI Series I. In: Evaluation of Soil Organic Matter Models Using Existing Long-Term Datasets, Vol. 38 (eds Powlson DS, Smith P, Smith JU), pp. 377–384. Springer-Verlag, Heidelberg. Cited in: Smith *et al*, 2007.

[317] For example, there has been a reduction in broad-leaved weeds in non-organic cereal stubbles over winter due to increased herbicide use, in particular pre-harvest applications of Round-up. Email communication, Peter Melchett, Policy Director and organic farmer, Soil Association, 6 October 2009.

[318] "A companion to archaeology," by John L. Bintliff. Published by Blackwell Publishing, 2004 ISBN 0631213023

[319] 6,036,000 (permanent managed grass) + 4,359,000 (rough grazing) + 1,238,000 (common rough grazing) = 11,633,000ha. 2008 data, Table 3.1, Agriculture in the UK, 2008.

[320] A mixture of modern varieties, made up of a selection of grass species that are more palatable to livestock and productive than the self-sown mix of indigenous grasses on permanent pasture. Martin Peck, organic livestock farmer and member of the Soil Association Agriculture Standards Committee, oral communication, 18 February 2009.

[321] Email communication, Martin Peck, organic livestock farmer, Wales, and member of the Soil Aassociation Agriculture Standards Committee, 16 February 2009.

[322] Page 91, Chapter 10, "Assessment of carbon fluxes in ploughed upland grasslands: a plot-scale experiment to detect the effect of cultivation on soil organic carbon (WP 2.6)", Inventory and Projections of UK Emissions by Sources and Removals by Sinks due to Land Use, Land Use Change and Forestry, Annual Report, July 2008. CEH *et al.*

[323] Bellamy *et al*, 2005. 'Large' losses particularly refers to the total amounts of carbon lost from the UK's grasslands, not necessarily to the tonnes lost per ha. Other explanations are methodological flaws, ie., the fact that only a shallow soil layer (0-15cm) was measured, and neither soil depth nor bulk density were measured so changes in these parameters (such as due to compaction of deeper cultivation) could have given the impression of a soil carbon loss, even if there was no change.

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[324] Page 91, Chapter 10, "Assessment of carbon fluxes in ploughed upland grasslands: a plot-scale experiment to detect the effect of cultivation on soil organic carbon (WP 2.6)", Inventory and Projections of UK Emissions by Sources and Removals by Sinks due to Land Use, Land Use Change and Forestry, Annual Report, July 2008. CEH *et al.*

[325] Page 91, Chapter 10, "Assessment of carbon fluxes in ploughed upland grasslands: a plot-scale experiment to detect the effect of cultivation on soil organic carbon (WP 2.6)", Inventory and Projections of UK Emissions by Sources and Removals by Sinks due to Land Use, Land Use Change and Forestry, Annual Report, July 2008. CEH *et al.*

[326] For instance, under the IPCC soil carbon accounting guidelines, improvement is assumed to increase the soil carbon store. Volume 4, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, IPCC, 2007.

[327] Gill et al., 1999; Gleixner et al., 2005; cited in Steinbeiss *et al*, 2007.

[328] Full details given in section 7.14

[329] High levels of rainfall create anaerobic conditions in the soil which, especially at low temperatures, results in very low decomposition rates and the slow formation of peats. Johnston *et al*, 2009, *in press.*

[330] New Scientist article 9.11.94, page 6.

[331] "Scientists at the University of Durham have estimated that for England alone this could increase net greenhouse pollution by up to 400,000 kilotonnes [400 million tC] per annum. By contrast, if all of the peatlands were restored to good condition, they could become a modestly significant sink for up to 40,000 kilotonnes of carbon per annum." Statement by Lord Cameron, House of Lords session 2007-2008. Proceedings, page 81. This is figure is very large, and given that most of the peat is in Scotland, it implies extremely large carbon losses for the whole UK (several times the UK's official GHG emissions of 178milliontC/yr). We have not been able to confirm the figure directly with the university.

[332] Email communication, Martin Peck, organic livestock farmer, Wales, and member of the SA Agriculture Standards Committee, 16 February 2009.

[333] Inventory and Projections of UK Emissions by Sources and Removals by Sinks due to Land Use, Land Use Change and Forestry, Annual Report, July 2008. CEH *et al.* http://www.edinburgh.ceh.ac.uk/ukcarbon/docs/2008/Defra_Report_2008.pdf

[334] See pages 11, 23 and 35, CEH *et al*, 2008. The fenlands include the East Anglian Fen and Skirtland and limited areas in the rest of England. Carbon losses from the fenlands are included in the figure of emissions for 'cropland remaining cropland' (968,000tCO2 x 12/44 = 264,000tC). But this figure also allows for an assumed level of carbon *sequestration* by an assumed increase in the standing crop biomass associated with higher-yielding breeds (which we consider questionable). Table 1-7, Inventory and Projections of UK Emissions by Sources and Removals by Sinks due to Land Use, Land Use Change and Forestry, Annual Report, July 2008. Centre for Ecology & Hydrology *et al.*

[335] The fenlands include the East Anglian Fen and Skirtland and limited areas in the rest of England. 445Gg = 445billion g = 445,000tC/yr. Table 1-7, Inventory and Projections of UK Emissions by Sources and Removals by Sinks due to Land Use, Land Use Change and Forestry, Annual Report, July 2008. Centre for Ecology & Hydrology *et al.*

[336] Burton and Hodgson,1987. Cited page 76, CLIMSOIL report for the European Comission, 16 December 2008.

[337] Most of the EU falls into the wet temperate climate zone, except Spain, and parts of Greece and the south-eastern European countries.

[338] Table 5.6 (cultivated organic soils) and Table 6.3 (drained grassland organic soils), Volume 4, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, IPCC, 2007. The factor for cultivated organic soils (cold temperate) was raised from 1tC/ha/yr under the GPG-LULUCF 2003 guidelines to 5tC/ha/yr in the 2006 IPCC Guidelines.

[339] "Carbon labelling and Tesco," 29 April 2008, Tesco.

[340] Oral communication, Ben Raskin, Horticultural Development Manager, Soil Association, 11 August 2008. According to Tesco, peat is used for growing some tomatoes, but this may refer to imported tomatoes.

[341] PAS-2050 (2008) BSI Standards Solutions, Defra and the Carbon Trust. PAS 2050 – assessing the life cycle greenhouse gas emissions of goods and services. http://www.bsi-global.com/en/Standards-and-Publications/How-we-can-help-you/Professional-Standards-Service/PAS-2050/

[342] "Carbon labelling and Tesco," 29 April 2008, Tesco.

[343] Note, this number actually refers to the number of separate sites studied; only one study is counted where the same sites were studied by different researchers and more than one publication exists (eg. there have been several publications of the Rodale Institute FST trial). A higher SOC level is stated or shown by the results in at least 29 of the studies. A higher SOC is implied by the results of two other studies: in the Robertson *et al* study, the SOC levels do not seem to be stated but a higher level appears clearly implicit given that the organic system gained SOC year-on-year (80kgC/ha/yr) while the non-organic system did not gain any soil carbon over the 9 years of the trial; and by the finding that the organic farms were building soil carbon while the non-organic farms were losing soil C in the survey by Hülsbergen & Küstermann, 2008.

[344] Explanatory note regarding 'statistical significance' of individual study results: we have included statistically significant and statistically non-significant higher SOC results as this is a review of all the available published evidence for policy purposes. The objective is (i) to see if organic farming is associated with a common, consistent effect across the whole body of evidence and (ii) to establish the scale and nature of the differences. Because the overall trend is very consistent (and includes many statistically significant results, ie. those where the difference is 'scientically' identified as an impact of organic farming, rather than due to chance variation, for stance), we can conclude that in general organic farming produces higher SOC levels. For assessing the consistency and size of the average difference, it is a necessity to look at all the findings, not just statistically significant results. This is because it is difficult for scientific studies in this area to achieve statistically significant results, so there would be much less evidence available if we restricted ourselves to those studies which found significant effects. Also, for estimating the average differences as modest differences might be common and would be very politically important to know of, we would not wish to count these as findings of no difference or omit them, as this would give a skewed picture of the actual differences associated

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with organic farming. All results need to be included and considered for the average difference found be as representative as possible. The difficulty in achieving statistically significant results in indi vidual studies comes from the fact that there is often much variability in the results and the sample sizes may be too small for modest differences to be identified as statistically significant.

[345] Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561.

[346] This is the percentage difference in the soil organic carbon (SOC) contents (usually topsoil only); it does not include differences in soil depth (which is almost never reported), so it is not the total percentage difference in the soil carbon storage level. Where the figure is not directly provided in the ensuing text of this chapter, the differences were calculated as follows. In the couple of cases where we did not know the starting SOC levels, we have assumed the same starting soil carbon levels for the organic and non-organic systems (which would make these inaccurate). In the couple of cases where there were results for 'organic' and 'biodynamic' farming, we have only used the standard 'organic' results, to avoid confusion and as composting/biodynamic methods are not widely used in organic arable systems. For the FiBL DOK trial, after 21 years, the organic system had a SOC content of 1.330% versus the 'integrated non-organic' system (the system that was considered typical of the region) of 1.334%, hence 0% difference; the biodynamic system had a SOC content of 1.494%, a 12% difference. For the Rodale trial, after 21 years, the soil C contents of the organic dairy and arable systems were 2.5% and 2.4% respectively, 25% and 20% more than the 2% of the non-organic system. We have used these results as they are the ones available in scientific papers, but they are an underestimate as the researchers say the differences have increased since then. For the University of California trial, we compared the 560kgC/ha/yr increase on the organic system, which gave a 33% SOC level increase, to the average of the two equivalent non-organic systems (15kgC/ha/yr), suggesting a SOC level increase of only 0.9% in these latter system, giving a final soil C difference of 32% (assuming the same starting levels).

[347] Holger Kirchmann, Lars Bergström, Thomas Kätterer, Lennart Mattsson and Sven Gesslein, "Comparison of Long-Term Organic and Conventional Crop–Livestock Systems on a Previously Nutrient-Depleted Soil in Sweden," Published in Agron J 99:960-972 (2007). Published online 5 June 2007.

[348] Fließbach, A., H.R. Oberholzer, L. Gunst & P. Mäder, 2007, "Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming," Agriculture Ecosystems & Environment 118:273-284.

[349] Mäder, P., A. Fließbach, A. Dubois, L. Gunst, P.Fried & U. Niggli, 2002, "Soil fertility and biodiversity in organic farming," Science 296:1694-1697.

[350] Raupp, J. & M. Oltmanns. 2006, "Soil properties, crop yield and quality with farmyard manure with and without biodynamic preparations and with inorganic fertilizers", p. 135-155, *In* J. Raupp, et al., eds. Long-term Field Experiments in Organic Farming.

[351] Raupp, J (2001). Manure fertilization for soil organic matter maintenance and its effects upon crops and the environment, evaluated in a long-term trial. In: Rees *et al*., *Sustainable Management of Soil Organic Matter*. CABI Publishing, New.York. See also: Raupp, J. (1995): The long-term trial in Darmstadt: Mineral fertilizer, composted manure and composted manure plus all biodynamic preparations; in Raupp, J., p.28-36. Darmstadt, Institute for Biodynamic Research. Ist Meeting Concerted Action: Fertilization Systems in Organic Farming.

[352] Sebastiana Melero, Juan Carlos Ruiz Porras, Juan Francisco Herencia, Engracia Madejon, "Chemical and biochemical properties in a silty loam soil under conventional and organic management," 2006, Soil & Tillage Research 90 (2006) 162–170.

[353] Hepperly, P.R., D. Douds, Jr. & R. Seidel, 2006, "The Rodale Institute Farming Systems Trial 1981 to 2005: long-term analysis of organic and conventional maize and soybean cropping systems", p. 15-31. Chapter in: J. Raupp, et al., eds. Long-term Field Experiments in Organic Farming. International Society of Organic Agriculture Research (ISOFAR), Bonn, Germany.

[354] Pimentel, D; Hepperly, P; Hanson, J; Douds, D; Seidel, R. (2005) "Environmental, Energetic, and Economic Comparisons of Organic and Conventional Farming Systems" *BioScience* 55: 573–582). Note, the FST trial has also been reported on in earlier publications: Petersen *et al*, 1999 (first 15 years) and Wander *et al*, 1994 (first ten years).

[355] As two of the nine trials are included separately in this table (Rodale and University of California trials, three comparisons), we have only counted eight of the eleven comparisons in this survey in our calculation of the overall average difference for all studies.

[356] "Total and Labile Soil Organic Matter in Organic and Conventional Farming Systems," Emily E. Marriott and Michelle M. Wander, Published in Soil Sci Soc Am J 70:950-959 (2006). Published online 19 April 2006. Note, one of the nine trials surveyed in this study was the Rodale Institute FST trial, which had its own listing in the table, so onl y 8 comparisons for this study have been used to calculate the average figure.

[357] Kong, Angela Y. Y., Johan Six, Dennis C. Bryant, R. Ford Denison and Chris van Kessel , "The Relationship between Carbon Input, Aggregation, and Soil Organic Carbon Stabilization in Sustainable Cropping Systems" Published in Soil Sci Soc Am J 69:1078-1085 (2005) Published online 2 June 2005.

[358] Robertson G.P., E.A Paul & R.R. Harwood, 2000, "Greenhouse Gases in Intensive Agriculture: Contributions of Individual Gases to the Radiative Forcing of the Atmosphere," Science, Vol 289, pages 1922-1925, 15 September 2000. www.sciencemag.org

[359] Raupp, J. (1995b). Soil Parameters of the K-Trial. In: Main effects of various organic and mineral fertilization on soil organic matter turnover and plant growth. Proceedings of the Concerted Action AIR 3-CT 94 "Fertilization Systems in Organic Farming". Publication of the Institute for Bio-dynamic Research Dermstadt, 5: 22-27. See also: the results from the soil surveys published in: Pettersson & v.Wistinghausen, 1977; Pettersson, Brinton & v.Wistinghausen, 1979; and Pettersson, Reents & v.Wistinghausen, 1992. Details available on-line: http://www.jdb.se/sbfi/publ/k-trial.pdf

[360] Granstedt, A. & L. Kjellenberg, Organic and biodynamic cultivation - a possible way of increasing humus capital, improving soil fertility and providing a significant carbon sink in Nordic conditions, paper presented at the 16th IFOAM Organic World Congress, Modena, Italy, June 16-20, 2008. http://orgprints.org/12625/1/Granstedt_12625_ed.doc

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[361] Clark, M.S., Horwath, W.R., Shennan, C. & Scow, K.M. (1998). Changes in soil chemical properties resulting from organic and low-input farming practices. *Agronomy Journal* **90**, 662-671.

[362] It is reported that this study found that organic farming produced an increase in topsoil and subsoil carbon levels; cited in Stolze *et al*, 2000. Diez, T., Bihler, E. and M. Krauss (1991). Auswirkungen abgestufter Intensitäten im Pflanzenbau auf Lebensgemeinschaften des Ackers, Bodenfruchtbarkeit und Ertrag. IV. Auswirkungen abgestufter Pflanzenbauintensitäten auf Bodenkennwerte und Nährstoffbilanz. Landwirtschaftl. Jahrbuch 68 (3): 354-361.

[363] Fraser D.G., Doran J.W., Sahs W.W. and Lesoing G.W. 1988. Soil microbial populations and activities under conventional and organic management. J. Environ. Qual. 17: 585–590.

[364] S. Marinari, K. Liburdi, G. Masciandaro, B. Ceccanti, S. Grego, "Humification-mineralization pyrolytic indices and carbon fractions of soil under organic and conventional management in central Italy," Soil & Tillage Research 92 (2007) 10–17.

[365] P. Gosling & M. Shepherd, "Long-term changes in soil fertility in organic arable farming systems in England, with particular reference to phosphorus and potassium," Agriculture, Ecosystems and Environment 105 (2005) 425–432.

[366] M. Pulleman, A. Jongmans, J. Marinissen & J. Bouma, "Effects of organic versus conventional arable farming on soil structure and organic matter dynamics in a marine loam in the Netherlands," Soil Use and Management (2003) 19, 157-165. See also: Droogers P & Bouma J 1996. Biodynamic vs conventional farming effects on soil structure expressed by simulated potential productivity. Soil Science Society of America Journal 60, 1552-1558.

[367] Armstrong Brown, S.M., H.F. Cook & H.C. Lee, 2000, "Topsoil characteristics from a paired farm survey of organic versus conventional farming in southern England." Biological Agriculture & Horticulture 18:37-54.

[368] Pulleman, M.M., J. Bouma, E.A. van Essen and E.W. Meijles, Soil Organic Matter Content as a Function of Different Land Use History, *Soil Science Society of America Journal* 64:689-693 (2000). http://soil.scijournals.org/cgi/reprint/64/2/689.pdf

[369] Oberholzer, H.R., Nowack, K., & Mäder, P., Soil microbiological aspects in winter cereal fields of organic and integrated farms, Proceedings of 13th IFOAM Scientific Conference, 2000.

[370] A field trial in the Swabian Mountains of Germany, on plots that had been farmed organically and non-organically since 1972; no significant differences were found. Cited in Gosling & Shepherd, 2005. Friedel, J.K., 2000. The effect of farming system on labile fractions of organic matter in calcari-epileptic regosols. J. Plant. Nutr. Soil Sci. 163, 41–45.

[371] Wells, A.T., K.Y. Chan, and P.S. Cornish. 2000. Comparison of conventional and alternative vegetable farming systems on the properties of a yellow earth in New South Wales. Agric. Ecosyst. Environ. 80:47–60.

[372] Liebig, M. A.; Doran, J. W. 1999: Impact of organic production practices on soil quality indicators. Journal of Environmental Quality 28: 1601-1609. http://jeq.scijournals.org/cgi/content/abstract/28/5/1601

[373] Derrick, J.W., Dumaresq, D.C., 1999. Soil chemical properties under organic and conventional management in southern New South Wales. Austr. J. Soil Res. 37, 1047–1055.

[374] Gerhardt RA 1997. A comparative analysis of the effects of organic and conventional farming systems on soil structure Biological Agriculture and Horticulture 14, 139-157.

[375] Gardner, J.C. & Clancy, S.A. (1996). "Impact of farming practices on soil quality in North Dakota." Chapter 20, Method for Assessing Soil Quality, SSSA Special Publication No 49, pp 337-343.

[376] Drinkwater, L.E., D.K. Letourneau, F. Workneh, A.H.C. van Bruggen & C. Shennan. 1995, "Fundamental differences between conventional and organic tomato agroecosystems in California," Ecological Applications 5:1098-1112.

[377] Note, one of the three pairs of farms was also the subject of the study Murata & Goh, 1997, so we have not reported that as a separate study (although the reported data slightly varies from that in this study, the sampling seems to have been within a year or so of this study and it also found an overall 3% difference). Nguyen, M.L., Haynes, R.J., Goh, K.M., 1995. Nutrient budgets and status in three pairs of conventional and alternative mixed cropping farms in Canterbury New Zealand. Agric. Ecosyst. Environ. 52, 149–162.

[378] John P. Reganold, Alan S. Palmer, James C. Lockhart, A. Neil Macgregor, Soil Quality and Financial Performance of Biodynamic and Conventional Farms in New Zealand, SCIENCE, 16 April 1993, Volume 260, pp. 344-349. http://www.sameti.org/ORGANICFARMING/15%20Soil%20Quality%20-%20John%20P.%20Reganold.pdf

[379] Muller D.J., Huyck L.M. & Reganold J.P. 1992. Temporal variation in aggregate stability on conventional and alternative farms. J. Am. Soil Sci. Soc. 56: 1620–1624. The soil carbon levels of the same two farms have also been measured and reported on in earlier publications: 1) Reganold, J.P., L.F. Elliott, and Y.L. Unger. 1987, "Long-term effects of organic and conventional farming on soil erosion," Nature 330:370-372 2) Reganold, J.P. 1988. Comparison of soil properties as influenced by organic and conventional farming systems. American Journal of Alternative Agriculture 3: 144-155. 3) Pierson F.B & Mulla D.J, An Improved Method for Measuring Aggregate Stability of a Weakly Aggregated Loessial Soil, Soil Sci Soc Am J 53:1825-1831 (1989).

[380] Capriel, P. (1991). Vergleichende Bodenuntersuchungen von konventionell und alternativ bewirtschafteten Betriebsschlägen - 2. Mitteilungen. IV. Humuschemische Untersuchungen. *Landwirtschaftl. Jahrbuch* 68 (4): 427-430.

[381] Garcia, C., Alvarez, C.E., Carracedo, A. & Iglesias, E. (1989). Soil fertility and mineral nutrition of a biodynamic avocado plantation in Tenerife. *Biological Agriculture and Horticulture* **6**, 1-10. http://digital.csic.es/bitstream/10261/6185/1/BHA.pdf

[382] A four-year plot trial of vegetable production; the biodynamic plots had significantly higher soil carbon levels than the organic plots, which had significantly higher levels than the non-organic plots. Abele, U. 1987. Produktqualität und Düngung—mineralisch, organisch, biologisch-dynamisch. (Product quality and fertilization: Minerl, organic, biodynamic.) Schriftenreihe des Bundesministers für Ernährung, Landwirtschaft und Forsten, Reihe A, Heft 345, Landwirtschaftsverlag, Münster-Hiltrup, Germany.

[383] This translates Abele, 1987, into English: Koepf, H.H. 1993. Research in Biodynamic Agriculture: Methods and Results. Bio-Dynamic Farming and Gardening Association, Inc., Kimberton, Pennsylvania.

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[384] Forman T 1981. An introductory study of the bio-dynamic method of agriculture. Diploma Thesis, University of Sydney, New South Wales. For details of the study see: Reganold, John, P., Soil Quality & Profitability of Biodynamic & Conventional Farming Systems, Organic Farming & Biodynamic Agriculture Training resource book.

[385] Petersen, S. O., Debosz, K., Schønning, P., Christensen, B. T. and S. Elmholt (1997). Phospholipid fatty acid profiles and C availability in wet-stable macro-aggregates from conventionally and organically farmed soils. *Geoderma* 78: 181-196. Cited by: Stolze *et al*, 2000.

[386] Pomares *et al* (1994). Actas del primer congreso de la Sociedad Española de Agricultura Ecologica; Toledo. Cited by: Stolze et al, 2000.

[387] Labrador *et al* (1994). Actas del primer congreso de la Sociedad Española de Agricultura Ecologica; Toledo. Cited by: Stolze et al, 2000.

[388] A study in Washingon state, US. Goldstein, W.A. & Young, D.L. (1987). An agronomic and economic comparison of a conventional and a low input cropping system in the Palouse. *American Journal of Alternative Agriculture*, 2:2, 51-56. Cited in: Shepherd *et al*, 2003.

[389] Study of a pair organic and non-organic fields, 1986-92, Germany; reported as having found that organic farming produced a more pronounced increase in topsoil and subsoil carbon than non-organic farming (cited in Stolze *et al*, 2000), but the difference in the final soil carbon level between organic and non-organic farming is unclear. Welp, G. (1993). Bodenmikrobiologische und humuschemische Untersuchungen auf ökologisch und konventionell bewirtschafteten Flächen. In: MURL (ed): *Abschlußbericht Forschungs- und Entwicklungsvorhaben "Alternativer Landbau Boschheide Hof" 1979-1992.* Forschung und Beratung, No. 49, 56-66.

[390] We have not checked these studies which are not written in English: it is possible that they found differences but this was not reported as they were not statistically significant; it is perhaps also possible that differences were not identified as the methods of measuring soil carbon were less sensitive at that time. 1. Amman, J. (1989). Vergleichende Untersuchungen von Humuskriterien bei konventionell und alternativ wirtschaftenden Betrieben. *Bayer. Landw. Jahrbuch*: 1012-1016. 2. König, W., Sunkel, R., Necker, U., Wolff-Straub, R., Ingrisch, S., Wasner, U. and E. Glück (1989). Alternativer und konventioneller Landbau - Vergleichsuntersuchungen von Ackerflächen auf Lößstandorten im Rheinland. *Schriftenreihe der LÖLF* 11.

[391] This UK study compared soil carbon levels on converted and unconverted fields of organic farms, and also excluded the effect of mixing farming, a key practice of UK organic farming. See details in section 6.3. Shepherd M.A., Harrison R., Webbs J., 2002: Managing soil organic matter – implications for soil structure on organic farms. Soil Use and Management no. 18, 284-292.

[392] Cited in Stolze *et al*, 2000. The researchers report a positive result for organic farming but half the farms had not even converted and two had converted only a year before (all of the farms are reported on together). See summary in section 6.3. Løes, A.K., Øgaard, A.F., 1997. Changes in the nutrient content of agricultural soil on conversion to organic farming in relation to farm-level nutrient balances and soil contents of clay and organic matter. Acta Agric. Scand. Sec. B. Soil Plant Sci. 47, 201–214.

[393] Mentioned in Kirchmann et al, 2007 as a study where higher levels were found with organic management. However, this US study did not compare organic and non-organic farming systems but was a two-year experiment comparing the effects of organic amendments and inorganic fertiliser on plots of both previously organically managed farms and previously conventionally managed farms. There was an average 62% increase in soil carbon after two years on the sites receiving organic amendments (for the previously organic and non-organic sites together; the results for the previously organic and non-organic sites are not reported separately). Anyway, the crops were not the same in the first year of the trial, with melons being grown on the previously non-organic sites and maize on the previously organic sites. Bulluck, L.R., III, M. Brosius, G.E. Evanylo, and J.B. Ristaino. 2002. Organic and synthetic fertility amendments influence soil microbial, physical and chemical properties on organic and conventional farms. Appl. Soil Ecol. 19:147–160.

[394] This was a 449-day soil incubation study of carbon and microbial loss rate, not a study of the level or fate of carbon in the soil on farmland, and the starting SOC data is not given (nor the average over the monitoring period, although the researchers say the level "did not differ significantly" among the farming systems). Kirchmann *et al*, 2007 said this study showed that organically managed soils lost more SOC, which is not true according to this paper. The two organic systems lost more than one non-organic systems (loss per kg of soil, not in relation to starting level which is not given), less than one non-organic system, and similar to another non-organic system; the differences were not statistically significant. Breland, T.A., and R. Eltun. 1999. Soil microbial biomass and mineralization of carbon and nitrogen in ecological, integrated and conventional forage and arable cropping systems. Biol. Fertil. Soils 30:193–201.

[395] This found no significant differences in organic C after 2 yr of organic orchard management in central California. We have excluded this as meaningful differences would not be expected after such a short time. Werner, M.R. 1997. Soil quality characteristics during conversion to organic orchard management. Applied Soil Ecology 5:151-167. Cited by Clark *et al*, 1998.

[396] Note, we have rejected as invalid two studies that appeared in some of these reviews (Shepherd *et al*, 2003; Løes & Øgaard, 1997) and we have presented two studies as having found positive differences that one of these reviews suggested had not found differences, (Gosling & Shepherd, 2005; Friedel at al, 2000), as they had found higher levels of 10% and 11%.

[397] "An Assessment of the Environmental Impacts of Organic Farming," by Mark Shepherd, Bruce Pearce, Bill Cormack, Lois Philipps, Steve Cuttle, Anne Bhogal, Peter Costigan & Roger Unwin, 2003. A review for Defra-funded project OF0405. Published as Annex 3 of the Organic Action Plan. http://www.defra.gov.uk/farm/organic/policy/research/pdf/env-impacts2.pdf

[398] M.A. Shepherd, R. Harrison & J. Webb, "Managing soil organic matter - implications for soil structure on organic farms," Soil Use and Management (2002) 18, 284-292.

[399] "The Environmental Impacts of Organic Farming in Europe," by Matthias Stolze, Annette Piorr, Anna Häring, and Stephan Dabbert, 2000, (Organic Farming in Europe: Economics and Policy; 6) ISBN 3-933403-05-7

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[400] Reganold, John, P., Soil Quality & Profitability of Biodynamic & Conventional Farming Systems, Organic Farming & Biodynamic Agriculture Training resource book.

[401] The three arable studies that were reported to be in semi-arid regions or regions with frequent dry periods are, in the order given in the text: Gardner & Clancy, 1996 (North Dakota); Derrick & Dumaresq, 1999 (dryland, Australia); Mulla *et al*, 1992 (dryland Palouse region, Washington state). The 8-year vegetable/arable trial by Clark et al, 1998, took place in Caligornia's semi-arid Sacramento Valley. The horticulture trial by Melero *et al*, 2006 was in semi-arid conditions in southwest Spain. The North Dakota site studied by Gardner & Clancy is in the Great Plains, "originally described as the great American desert" where there are frequent dry periods and farmers have traditionally used fallow seasons. It is possible that some of the other studies were also in semi-arid or drought-prone regions, such as: Liebig & Doran, 1999 (Nebraska & North Dakota, US); Fraser *et al*, 1988 (east Nebraska, US); Kong *et al*, 2005 (California) and Marinari *et al*, 2007 (Lazio province, central Italy).

[402] Baritz *et al*, report of Task group 5 Land use Practices and SOM, 2004, http://ec.europa.eu/environment/soil/pdf/vol3.pdf.

[403] Bruinsma, 2003. Cited by Kirchmann *et al*, 2007.

[404] Dregne, H.E. and Chou, N.T. 1994. Global desertification dimensions and costs. In H.E. Dregne (ed.). Degradation and restoration of arid lands. Lubbock, USA; Texas Technical University.

[405] Organic farming produced a 10.2% soil carbon increase over the eight years over 0-30cm depth but all the increase occurred in the top 15cm where it produced a 23% increase (page 667, Clark *et al*, 1998). See next section 2 for details of the study.

[406] Pulleman *et al*, 2000, found 14% higher SOC levels on organic grassland (3 comparisons), but the non-organic fields had been longer under grass than the organic fields so this is conservative. Shepherd *et al*, 2002, found 16% higher levels (6 comparisons; but its 'non-organic' samples were mostly unconverted fields on the organic farms rather than 'mainstream' non-organic grassland farms, so this could be conservative). The average of these is a 15% difference. Armstrong *et al*, 2000, found 11% lower SOC levels but just over double the topsoil depth, on organic permanent pasture. In this case, we have assumed that the much greater depth more than makes up for the lower SOC level and any lower bulk density, and would support the 15% level found by the other studies, as a minimum. (Topsoil depth was not measured in the first two studies, so those results could be conservative.) Details of these three studies are summarised later in this section.

[407] 40-60% of the total soil carbon in the 1m profile occurs below 25cm. Arrouays D.; Pelissier P., "Modeling carbon storage profiles in temperate forest humic loamy soils of France," Soil science, 1994, vol. 157, n°3, pp. 185-192. Cited in Sleutel *et al*, 2003.

[408] At least five studies found that organic farming increases soil carbon in the deeper layers, though two found no difference in the 15-30cm layer. In Switzerland, the FiBL DOK trial found a significant higher soil carbon content for the biodynamic compared to the non-organic 'integrated' system down to 60cm. In Pennsylvania, the Rodale Institute trial found organic farming had higher soil carbon levels than non-organic farming down to 30cm. In the UK, Armstrong et al, 2000, found that organic permanent grasslands had double the topsoil depth of non-organic grasslands (no difference on cultivated land). Increases in both topsoil and subsoil carbon content with organic farming are also reported for Diez *et al*, 1991; Raupp, 1995b; Welp, 1993; and Løes & Øgaard, 1997 (as we have not checked the last two, confirmation is needed of the level of change, and if the study really represents organic farming); cited in Stolze *et al*, 2000. The two that found no difference in the 15-30cm layer (they did not sample more deeply than this), were two US studies: Clark *et al*, 1998, and Fraser *et al*, 1988.

[409] Bhogal *et al*, 2009, Scientific Report for Defra Project SP0561.

[410] These four European studies are: Melero *et al*, 2006; IBR Darmstadt trial; Swedish K-trial; and Diez *et al*, 1991.

[411] Rodale FTS trial; the University of California trial; the Michegan University trial; and Clark*et al*, 1998. (As far as we know, the trial by Fraser *et al*, 1988 did not monitor the changes, it only measured the differences in the last two years. Additionally, the study by Marriott & Wander, 2006, did not report on the changes over time, only on the comparative results at one point in time.)

[412] Fließbach *et al*, 2007.

[413] Holger Kirchmann, Lars Bergström, Thomas Kätterer, Lennart Mattsson and Sven Gesslein, "Comparison of Long-Term Organic and Conventional Crop–Livestock Systems on a Previously Nutrient-Depleted Soil in Sweden," Published in Agron J 99:960-972 (2007). Published online 5 June 2007.

[414] The crop carbon inputs were estimated from the measured crop yields using standard values from literature - presumably from non-organic systems, not by directly measuring the residues produced by each system. Ie. this may not be accurate.

[415] "The amount of solid manure applied to the organic system … was… 50% greater than the animal density that could be supported from yield levels." Page 961, Kirchmann *et al*, 2007.

[416] The authors say this practice, "does not represent realistic management of an organic system. In reality, the straw from at least one cereal crop per rotation needs to be removed and used as animal bedding." P. 966, Kirchmann *et al*, 2007.

[417] Note, this doesn't seem to make sense: the non-organic system is reported as using slurry, not solid manure which would be produced if the farm was really using straw for bedding.

[418] The final long-term SOC 'equilibrium' values would be 15gC/kg vs. 12gC/kg. Table 3 , Kirchmann *et al*, 2007.

[419] Until 1940, the farm was mixed, with dairy cattle and arable cropping. "In 1942, sheep were introduced and more land was converted into perennial grassland such that by 1978 most of the land was perennial grassland." Kirchmann *et al*, 2007.

[420] Averages of the three soil layers are Soil Association figures. Other data from Figures 10-11, page 16: http://www.jdb.se/sbfi/publ/k-trial.pdf The results from the soil surveys were published in: Pettersson & v.Wistinghausen, 1977; Pettersson, Brinton & v.Wistinghausen, 1979; and Pettersson, Reents & v.Wistinghausen, 1992.

[421] Granstedt, A. & L. Kjellenberg, Organic and biodynamic cultivation - a possible way of increasing humus capital, improving soil fertility and providing a significant carbon sink in Nordic conditions, paper presented at the 16th IFOAM Organic World Congress, Modena, Italy, June 16-20, 2008. http://orgprints.org/12625/1/Granstedt_12625_ed.doc Author's note: this calculation may not

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fully take account of any differences in topsoil depth, which does not seem to have been measured, so the researchers may have underestimated the comparative soil carbon levels of the organic systems if they had also produced greater topsoil depths.

[422] Soil Association figures: 146/135 x 100 = 8.1%, 160/135 x 100 = 18.5%.

[423] See 'Results and discussion', Granstedt *et al*, 2008. http://orgprints.org/12625/1/Granstedt_12625_ed.doc

[424] Granstedt *et al*, 2008. http://orgprints.org/12625/1/Granstedt_12625_ed.doc

[425] Treatment details available on: http://www.biodynamic-research.net/ras/s/ltteng/lvda1eng/treatments/

[426] After ten years, SOC levels were: non-organic 0.79%, organic 0.92%, and biodynamic 1.02%. Raupp J 1995a. The long-term trial in Darmstadt: mineral fertilizer composted manure and composted manure plus all biodynamic preparations. In: Proceedings of the Concerted Action AIR3-CT94-1940, Fertilization Systems in Organic Farming, ed J Raupp, Institute of Biodynamic Research Dermstadt pp 28-36.

[427] The medium N fertilisation corresponded to normal farming practice. The soil was a sandy luvisol. Raupp, J (2001). Manure fertilization for soil organic matter maintenance and its effects upon crops and the environment, evaluated in a long-term trail. In: Rees *et al*., *Sustainable Management of Soil Organic Matter*. CABI Publishing, New.York.

[428] Note, this treatment replicates the effects of a typical mixed organic farming system, with livestock supplying the manure for application on the arable land (ie. this is not organic matter 'imported' from another farm).

[429] According to the researchers, this system is "typical of Swiss agriculture", as "most Swiss farms are dairy farms that recycle their own cattle manure ... on arable land." Fließbach *et al*, 2007.

[430] The levels reported for 1998 are: organic 1.330%, integrated 1.334%, 'non-organic' 1.300%, and biodynamic 1.491%. Table 4, Fließbach *et al*, 2007 (note, we believe the units should be gC/kg soil, the same as in Figure 2, not mg/kg).

[431] See Figure 2, Fließbach *et al*, 2007. Current soil carbon theory is that, after a management change, the soil carbon level gradually changes to the SOC 'equilibrium level' associated with the new regime, over a period of 20 or so years; see section 9.8. The were differences in the observed starting SOC levels in this trial. (Note, the inorganic fertiliser-only treated plots were actually not fertilised at all in the first rotation, and only 'converted' to the inorganic fertiliser-only treatments from the start of the second rotation; however, this does not seem to have affected the final results.)

[432] For the 28 years to 2005, the average change in soil carbon levels per ha/year have been calculated as: -207kgC/ha/yr for the inorganic fertiliser-only plots, -123kgC/ha/yr for the organic plots, -84kgC/ha/yr for the integrated plots, while the biodynamic plots gained +42kgC/ha/year. Mäder, P., Fliessbach, A., Dubois, D., Gunst, L., Jossi, W., Widmer, F., Oberson, A., Frossard, E., Oehl, F., Wiemken, A., Gattinger, A., Niggli, U. (2006): The DOK experiment (Switzerland). In the book: Long-term field experiments in organic farming. Raupp, J., Pekrun, C., Oltmanns, M., Köpke, U. (eds.). pp 198. Koester, Bonn. Cited in,"Low Greenhouse Gas Agriculture: Mitigation And Adaptation Potential Of Sustainable Farming Systems," FAO, May 2008.

[433] Fließbach, A., H.R. Oberholzer, L. Gunst & P. Mäder, 2007, "Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming," Agriculture Ecosystems & Environment 118:273-284.

[434] Fließbach *et al*, 1999 (in German). Cited page 281, Fließbach *et al*, 2007.

[435] Fließbach *et al*, 2007.

[436] Fließbach *et al*, 2007.

[437] From 1957 to 1973, the land was in a diverse crop rotation with a three year grass/clover ley and receiving manure, so SOM levels should then have been high. In the years before the trial, 1973 – 1976, the land was cropped without manure. Then it was put into grass/clover for a year, in 1977.

[438] Fließbach *et al*, 2007.

[439] For instance, even if the ploughing depth was not greater than previously, organically managed soils tend to have higher levels of vertical burrowing earthworms and other organisms which could help distribute the soil carbon more deeply.

[440] Niggli, Urs, "Organic agriculture –a option for mitigation and adaptation," powerpoint presentation for FAO press conference, 2009.

[441] Sebastiana Melero, Juan Carlos Ruiz Porras, Juan Francisco Herencia, Engracia Madejon, "Chemical and biochemical properties in a silty loam soil under conventional and organic management," 2006, Soil & Tillage Research 90 (2006) 162–170.

[442] Over 40 million ha are in this system in North America (USDA, 2003). Fertilizer and pesticide applications in this system followed Pennsylvania State University Cooperative Extension recommendations for maize and soya. Hepperly, P.R., D. Douds, Jr. & R. Seidel, 2006, "The Rodale Institute Farming Systems Trial 1981 to 2005: long-term analysis of organic and conventional maize and soybean cropping systems", p. 15-31. Chapter in: J. Raupp, et al., eds. Long-term Field Experiments in Organic Farming. International Society of Organic Agriculture Research (ISOFAR), Bonn, Germany.

[443] With arable crops grown to supply animal feed and the livestock supplying manure to apply on the arable crops.

[444] The organic rotations included legumes (other than soya) and small grain crops (wheat and cereal rye), as well as soya and maize. Pimentel, D; Hepperly, P; Hanson, J; Douds, D; Seidel, R. (2005) "Environmental, Energetic, and Economic Comparisons of Organic and Conventional Farming Systems" *BioScience* 55: 573–582).

[445] Pimentel *et al*, 2005. Note, the differences between the organic and the non-organic systems were statistically significant, but not the differences between the two organic systems.

[446] Pimentel *et al*, 2005. Hepperly *et al*, 2006.

[447] Pimentel *et al*, 2005. Table 2, Hepperly *et al*, 2006. Note, different figures have been cited for this. Figures of 1,218kg, 857kg, and 217kg are the mean rate of three recent years (2002, 2004, 2006), not the average over the trial.

[448] Hepperly, Paul Reed Ph.D, The Impact of Agriculture and Food Systems on Greenhouse Gas, Energy Use, Economics and the Environment The Rodale Institute.

[449] Email communication, Dr Paul Hepperly, Research Director, Fulbright Scholar, Rodale Institute, US; 28 February 2009.

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[450] Hepperly *et al*, 2008.

[451] Paul Hepperly, Jeff Moyer, David Pimental, David Douds Jr., Kristine Nichols & Rita Seidel, "Carbon Sequestration in Organic Maize/Soybean Cropping Systems," paper for the 16th IFOAM Organic World Congress, Modena, Italy, June 16-20, 2008. Archived at http://orgprints.org/view/projects/conference.html

[452] These maize yields exclude the first five years of the trial when the systems were still establishing. Hepperly *et al*, 2006.

[453] Hepperly *et al*, 2008.

[454] Hepperly *et al*, 2008.

[455] Over the first 15 years, the level of above-ground carbon input was very similar in all systems, with 44tC/ha applied on the organic dairy system (25 from crop residues + 19 from manure), 39tC/ha for the arable system, and 43tC/ha for the non-organic system. Note, the units are cited as $x10^{-3}$ kgC but we assume they should be $x10^{3}$ kgC. Drinkwater, L.E., Wagoner, P., Sarrantonio, M., 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature 396, 262–264.

[456] Over 21 years, the annual above-ground carbon input was about 3.35tC/ha in the 'manure' system and about 3tC/ha in the 'legume' and non-organic systems. Hepperly *et al*, 2006. (Note, figures of 10tC/ha and 9tC/ha are cited in Pimentel *et al*, 2005, but they do not correspond to the figures in Drinkwater *et al*, 1998 (39-44tC/ha over 15 years), so are probably wrong.)

[457] Drinkwater, L.E., Wagoner, P., Sarrantonio, M., 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature 396, 262–264. Soil Association calculation: we calculate that the other plants in the rotation of the organic arable system had an average soil carbon retention rate of almost seven times that of maize: the 48% proportion of the soil carbon input that was maize produced 12% of the SOC increase and the 52% proportion that was other plants produced 88%. Adjusting for the different input rates: if other plants made up the same 48% proportion, they would have produced only 81.2% of the SOC increase (ie. 88/52 x 48 = 81.2%). Comparing the SOC increases: an 81.2% SOC increase for other plants compared to the 12% SOC increase for maize, gives a **6.8-fold** higher SOC retention rate for other plants compared to maize (81.2/12 = 6.8 times). However, the 'other plants' included some 'small grain' cereals (wheat and cereal rye), as well as legumes (alfalfa and soya), so the difference does not just represent the different effect of legumes vs. cereals.

[458] Hepperly *et al*, 2008.

[459] Kong, Angela Y. Y., Johan Six, Dennis C. Bryant, R. Ford Denison and Chris van Kessel , "The Relationship between Carbon Input, Aggregation, and Soil Organic Carbon Stabilization in Sustainable Cropping Systems" Published in Soil Sci Soc Am J 69:1078-1085 (2005) Published online 2 June 2005. Note, the tC/ha figures were derived from the measurements of SOC% in 1995 and 2003, and measurements of soil bulk density in 2003; it was assumed that there had been no drastic change in bulk density between 1993 and 2003.

[460] See Table 3, which shows that the organic system converted 0.56tC/ha/yr (OMT, column 4), or 5.6tC/ha over ten years. This is 6.25% of its estimated cumulative C input of 89.6tC (OMT, column 5). This conversion rate is eight times that of the CMT (conventional maize-tomato) system (0.4/51.8 x 100 = 0.77% conversion rate). We used the CMT system for comparison as this would be a more conventional non-organic rotation than the LMT system (non-organic maize-tomato system with legumes), and also because the LMT system had a small SOC *loss*, so a comparison with this would have given an infinitely higher carbon conversion rate for the organic system. Note, the researchers did not allow for a higher root biomass with the organic system, and did not include the continuous root carbon supply in their calculation, so they have underestimated the total soil carbon inputs and especially for the organic system (hence our use of the term 'biomass' to indicate that this only includes the soil carbon input from the crop residues, green manure biomass and compost); nevertheless, these findings are illustrative of the difference in soil carbon effects between organic and non-organic systems from a more conventional perspective of the comparative effects of farming systems in relation to their (above-ground) productivity levels.

[461] "Total and Labile Soil Organic Matter in Organic and Conventional Farming Systems," Emily E. Marriott and Michelle M. Wander, Published in Soil Sci Soc Am J 70:950-959 (2006). Published online 19 April 2006**.**

[462] Robertson G.P., E.A Paul & R.R. Harwood, 2000, "Greenhouse Gases in Intensive Agriculture: Contributions of Individual Gases to the Radiative Forcing of the Atmosphere," Science, Vol 289, pages 1922-1925, 15 September 2000. www.sciencemag.org

[463] Cited as 8g of C/m^2/year. Conversion: $8g/m^2 = 0.008kg/m^2 = 80kg/ha$.

[464] Reduced tillage systems concentrate the crop residues on the surface, whereas tillage distributes the residues over the plough-depth, so soil carbon level comparisons between these systems must meaure the whole soil profile, at least to the bottom of the ploughed layer (0-25cm), if they are to be reliable. See 9.2 for more details on these systems.

[465] Clark, M.S., Horwath, W.R., Shennan, C. & Scow, K.M. (1998). Changes in soil chemical properties resulting from organic and low-input farming practices. *Agronomy Journal* **90**, 662-671.

[466] The researchers report that after 8 years, the soil total C was 23% higher in the organic systems than the Conv-2 system used as a baseline. However, this is calculated only for the top 15cm and is calculated compared to the Conv-2 system at the start of the trial, not for 1996. We have preferred to use the results for the whole 0-30cm and using the 1996 results for both the organic and non-organic systems, to exclude any weather-related effects, for instance. We believe this gives a better comparison of the difference in soil carbon storage between the systems, even though the results are then less positive for organic farming.

[467] Fraser D.G., Doran J.W., Sahs W.W. and Lesoing G.W. 1988. Soil microbial populations and activities under conventional and organic management. J. Environ. Qual. 17: 585–590.

[468] P. Gosling & M. Shepherd, "Long-term changes in soil fertility in organic arable farming systems in England, with particular reference to phosphorus and potassium," Agriculture, Ecosystems and Environment 105 (2005) 425–432.

[469] Soil Association conversion. Figures are cited in terms of SOM levels: 41.4g/kg and 37.6g/kg for the organic fields, and 35.8g/kg for non-organic. Using x 0.575, gives SOC levels of 23.8g/kg, 21.6g/kg, and 20.6g/kg, respectively.

[470] Email communication, Dr Francid Rayns, HDRA, 9 November 2009.

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[471] The objective of the study is described as being to, "determine what was the result of typical conventional systems converting to typical organic systems of management," which certainly appears very suitable, but on reflection the study apears to have been designed to focus on one-one farm conversion effects, to the neglect of the broader effects of converting the non-organic farming sector and differences in the general balance of systems between the sectors. This a subtle but perhaps important different.

[472] Soil Association conversion of SOM to SOC, using factor x 0.581, as stated in text (1/1.72). For the arable farms, SOM levels are cited as: 4.08% on the organic versus 3.04% SOM on the non-organic farms. For the horticultural farms, the SOM levels are cited as 4.10% versus 2.60% on the non-organic farms.

[473] If this increase is wholly accounted for by a decrease in bulk density, from the soil being healthier and less compacted, then this would not mean an increase in soil carbon due to this greater depth.

[474] We assume the pasture was managed grass, not rough grazing but it is not stated.

[475] M. Pulleman, A. Jongmans, J. Marinissen & J. Bouma, "Effects of organic versus conventional arable farming on soil structure and organic matter dynamics in a marine loam in the Netherlands," Soil Use and Management (2003) 19, 157-165. The same fields are also reported on in Droogers & Bouma, 1996.

[476] The results are cited as 24g/kg SOM for the organic field and 15g/kg SOM for the non-organic field. Dividing by the conversion factor cited in the text, 1.72, gives %SOC values of 1.4% and 0.87% respectively.

[477] These soil carbon results are converted from the SOM results in the paper, by reading off the bar chart where figures were not given in the text and using the 2:1 conversion ratio for SOM to soil organic carbon stated in the paper. Of the 45 results, we have excluded twelve, comprising all organic arable fields that had been organic for less than three years, all grassland fields that had been in grass less than a year, and a non-organic arable field that had been in organic grass the year before.

[478] This average range cited is the average of the minimum years of all the organic farms, and the average of the maximum years of all the organic farms (exact ages were not given for each farm, only ranges).

[479] Note, Gosling & Shepherd, 2005, referred to this as an example of a comparative study where the researchers did not find any difference between organic and non-organic farming. This is not totally correct as they found a modest (and significant in real terms) difference, although the results were not statistically significant (inevitable because of the small sample size).

[480] Note, while modest compared to the findings of other studies, the significance of 'modest' differences should never be underestimated. A 10% higher SOC level in the UK's arable soils would mean an extra 30 million t of C being stored, so modest differences are still politically important (0.1 x 60t x 5 million ha = 30 million).

[481] S. Marinari, K. Liburdi, G. Masciandaro, B. Ceccanti, S. Grego, "Humification-mineralization pyrolytic indices and carbon fractions of soil under organic and conventional management in central Italy," Soil & Tillage Research 92 (2007) 10–17.

[482] The fact that the difference was not statistically significant, and that this result goes against the general trend in the comparative studies of higher levels for organic farming, means that this is not necessarily indicative of a lack of a positive effect of organic farming and could be due to any of (or a combination of) the following: loss of accumulated soil carbon during the fallow period, a lower initial soil carbon level on the organic field, natural variation, inaccuracies in the sampling methods, or lack of a positive effect of the organic management.

[483] Marinari *et al*, 2007.

[484] Rasse *et al*, 2005.

[485] Garcia, C., Alvarez, C.E., Carracedo, A. & Iglesias, E. (1989). Soil fertility and mineral nutrition of a biodynamic avocado plantation in Tenerife. *Biological Agriculture and Horticulture* **6**, 1-10. http://digital.csic.es/bitstream/10261/6185/1/BHA.pdf

[486] Average SOM results of three samplings were 9.87% for the organic plantations vs. 2.32% for the non-organic plantations. 9.87/2.32 x 100 = 425%, or 325% greater. Conversion from SOM to SOC by Soil Association, using factor x 0.575.

[487] Liebig, M. A.; Doran, J. W. 1999: Impact of organic production practices on soil quality indicators. Journal of Environmental Quality 28: 1601-1609. http://jeq.scijournals.org/cgi/content/abstract/28/5/1601

[488] This assumes that the slightly lower soil bulk densities found on the organic farms for the top 7.6cm apply to the whole 30.5cm layer. The differences in topsoil depth, compared to the non-organic farms, were: +43%, +9%, +9%. The soil bulk densities in the top 7.6cm as a % of the non-organic farms were: 96.9%, 95.7%, 96.6%. Table 5, Liebig & Doran, 1999.

[489] Cited page 51, "Good Growing – why organic farming works", by Leslie A.Duram, 2005.

[490] Cited by Shepherd *et al*, 2002.

[491] Gardner, J.C. & Clancy, S.A. (1996). "Impact of farming practices on soil quality in North Dakota." Chapter 20, Methodfor Assessing Soil Quality, SSSA Special Publication No 49, pp 337-343.

[492] SOM levels were an average of, organic: 57.8t/ha, and non-organic: 51.5t/ha.

[493] The topsoil depths of the non-organic farms totalled 28.3cm, the topsoil depths of the organic farms totalled 31.7cm, ie. average difference of +12%. Table 20-1, page 341, Gardner & Clancy, 1996.

[494] Table 3, Drinkwater, 1995. The researchers excluded the three non-organically managed fields with Vertisols (a soil type with a high clay content) from these results, so that "confounding soil type variation was removed." According to Fig. 2, there were no organic fields on Vertisols, so this exclusion made the soil types similar for the organic and non-organic samples.

[495] The organic farm has been managed organically since the mid-1960s and uses a diverse 20-year crop rotation.

[496] Reganold *et al*, 1988. Cited in Mulla *et al*, 1992, p. 1623.

[497] Reganold *et al*, 1988. Cited in Sheperd *et al*, 2002, and "Effects of Alternative and Conventional Farming Systems on Agricultural Sustainability," www.agnet.org/library

[498] Wells, A.T., K.Y. Chan, and P.S. Cornish. 2000. Comparison of conventional and alternative vegetable farming systems on the properties of a yellow earth in New South Wales. Agric. Ecosyst. Environ. 80:47–60.

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[499] Page 76-68, Reganold, John, P., Soil Quality & Profitability of Biodynamic & Conventional Farming Systems, Organic Farming & Biodynamic Agriculture Training resource book. http://www.sameti.org/ORGANICFARMING/15%20Soil%20Quality%20-%20John%20P.%20Reganold.pdf

[500] Only the data for the top 7.5cm are reported.

[501] Soil Association figure. The average soil carbon levels of each system were calculated by weighing the average pasture soil carbon values for the organic and non-organic systems by 0.48 and 0.3 respectively, and the average values for the cropping phases by 0.52 and 0.7 respectively, giving average soil carbon levels of 3.374% for the organic system and 3.26% for the non-organic system, for 0-7.5cm. For 0-15cm, it was assumed that both systems had the average value of the non-organic system of 3.26% for 0-7.5cm for the 7.5-15cm layer, and that the 7.5-15cm layer contributed as much soil as the 0-7.5cm layer, giving an overall average of around 3.17% for the organic system and 3.26% for the non-organic system. So, overall difference = around 3.317/3.26 x 100 = 1.75%.

[502] Reganold JP 1995. Soil quality and farm profitability studies of biodynamic and conventional farming. In: Soil Management in Sustainable Agriculture, eds H F Cook & H C Lee, Wye College Press Wye, pp 1-11.

[503] Shepherd M.A., Harrison R., Webbs J., 2002: Managing soil organic matter – implications for soil structure on organic farms. Soil Use and Management no. 18, 284-292.

[504] In the published papers of this study, the survey methodology and results are presented after a literature review of previous comparative studies of organic farming soil carbon levels, with no mention of the very different approach taken by this study.

[505] There were a total of 29 comparisons but only 33 farms were sampled, so most of the non-organic samples came from largely organic farms. According to one of the researchers who took the samples, his "recollection is that most of the conventional fields were on partially converted farms." Email communication, Dr Paul Gosling, Warwick HRI, University of Warwick, 9 March 2009.

[506] Samples of already converting farms are often biased and unrepresentative of the non-organic farming sector generally and perhaps particularly in the UK, for two reasons: (i) especially in the first phase of expansion of organic farming in a country, farmers who were already largely farming organically or extensively or inclined to this approach are usually the first group of farmers to convert, and (ii) in the absence of financial and other support, farms which convert are likely to already be using mixed farming systems, as the changes required are small compared to the more important structural and knowledge/skills changes required of all-arable systems. These are important aspects that require attention by policymakers in the design of their policies to assist organic farming conversion, but they are not inherent characteristics of organic farming itself and such issues should be excluded as far as possible from comparisons of the effects of organic and non-organic farming. These features of the existing organic sector may be be less prominant in countries where organic farming is less reliant on mixed farming systems (eg. USA, Mediterranean regions) and where the economics of organic farming are more obviously attractive to more business-minded non-organic farmers (eg. in regions where there is little yield penalty with conversion, etc.)

[507] And where this was not explicitly stated in the published paper, this could be reasonably inferred, such as from the introduction to the study and from the clear and typical management differences between the organic and non-organic systems.

[508] According to one of the researchers, "The conventional fields on organic farms might be expected to have lower soil C as the farmers would concentrate manure and other organic inputs on the organic land. They may also be using reduced chemical inputs in some cases if their ideology was more organic, I can certainly remember one such case. On the other hand some of the more business minded converts to organic were farming intensively in both systems. I don't think you can assume that the farms were bias one way or another [in their management of the 'non-organic' fields]." Email communication, Dr Paul Gosling, Warwick HRI, University of Warwick, 10 March 2009. Author's note: for the purposes of the comparative assessment in this report, it is clearly important to know that the sample of 'non-organic' fields *can* be assumed to be managed using normal non-organic farming practices (the normal choice, range and balance of practices found in commercial situations), which is not possible in this case.

[509] Email communication, Dr Paul Gosling, Warwick HRI, University of Warwick, 10 March 2009.

[510] This monitored the effects of organic conversion on soil carbon levels, and found that organic farming increased the SOC level from a low starting point. Løes, A. K. and A. F. Øgaard (1997), "Changes in the nutrient content of agricultural soil on conversion to organic farming, in relation to farm level nutrient balances and soil contents of clay and organic matter." *Acta Agric. Scand., Sect. B, Soil and Plant Sci.* 47:pp. 201-214.

[511] B. R. Taylor, D. Younie, S.Matheson , M. Coutts, C.Mayer, C. A. Watson and D R. L. Walker, "Output and sustainability of organic ley/arable crop rotations at two sites in northern Scotland," Journal of Agricultural Science (2006), 144, 435–447.

[512] Scottish Soils database. Jan Dick, Pete Smith, Ron Smith, Allan Lilly, Andrew Moxey, Jim Booth, Colin Campbell, Drew Coulter, "Calculating farm scale greenhouse gas emissions," June 2008.

[513] "Changes to soil quality indicators following conversion to organic vegetable production," (OF 0401). "Conversion to organic field vegetable production," (OF 0126T and OF 0191) and "Organic field vegetable production - baseline monitoring of systems with different fertility building strategies," (OF 0332).

[514] Email communication, Dr Francis Rayns, HDRA, 9 November 2009.

[515] Mark Measures, Director of the Institute of Organic Training and Advice (www.organicadvice.org.uk), monitoring of ten organic farms, oral communication, 20 March 2007; Iain Tolhurst, 2008, oral communication, 12 March 2008.

[516] Email communication, 7 January 2009. Peter Segger, organic farmer, Wales, and chair of soil carbon workshop at Soil Association conference, 18 November 2008. Field SOM levels have risen from 5-6% to 7-7.2%, while the glasshouse level has risen from 4-5% to 18-19%. The farmer conducts large numbers of SOM tests and monitors the volume of compost. Soil types are varied: medium loams; silty loams; average clay content is 18-23%.

[517] Cited in: "Low greenhouse gas agriculture: mitigation and adaptation potential of sustainable farming systems," FAO May 2008. Reference: Küstermann, B., Kainz, M., Hülsbergen, K.-J. (2008): Modeling carbon cycles and estimation of greenhouse gas emissions from organic and conventional farming systems. *Renewable Agriculture and Food Systems* **23**, 38-52.

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[518] The results have been reported very differently in two other reports: 1) the 18 organic farms were sequestering 54kgC/ha/yr more than the 10 non-organic farms, in "Contribution of Organic Agriculture to Mitigate and Adapt to Climate Change," presentation by Andreas Fließbach, FiBL, available on CD of proceedings, International conference "Organic agriculture and climate change," Enita Clermont, France, 17-18 April 2008); and, 2) the organic farms were sequestering 110-396kgC/ha/yr while the fields managed with integrated pest management were losing 249tC/h/yr and 55tC/ha/yr; "Organic farming and climate change," UNCTAD/WTO report, 2007 (original reference: Küstermann, B., Wenske, K. and Hülsbergen, K.-J. (2007): Modellierung betrieblicher C- und N-Flüsse als Grundlage einer Emissionsinventur [Modelling carbon and nitrogen fluxes for a farm based emissions inventory]. Paper presented at Zwischen Tradition und Globalisierung - 9. Wissenschaftstagung Ökologischer Landbau, Universität Hohenheim, Stuttgart, Deutschland, 20-23.03.2007. Archived: http://orgprints.org/9654/

[519] Küstermann, B., Kainz, M., Hülsbergen, K.-J. (2008): Modeling carbon cycles and estimation of greenhouse gas emissions from organic and conventional farming systems. *Renewable Agriculture and Food Systems* **23**, 38-52.

[520] Holger Kirchmann, Lars Bergström, Thomas Kätterer, Lennart Mattsson and Sven Gesslein, "Comparison of Long-Term Organic and Conventional Crop–Livestock Systems on a Previously Nutrient-Depleted Soil in Sweden," Published in Agron J 99:960-972 (2007). Published online 5 June 2007.

[521] 15gC/kg soil vs. 12gC/kg soil. 15/12 X 100 = 125%. Table 3, Kirchmann *e al*, 2007**.**

[522] They estimated that if straw was not imported for the bedding and instead some of the straw produced on the farm was removed (enogh for the amount of bedding needed to support the amount of animals that the organic yields could support), then the equilibrium SOC level of the organic system would fall by 17% (from 18gC/kg to 15gC/kg).

[523] Bente Foereid and Henning Høgh-Jensen, "Carbon sequestration potential of organic agriculture in northern Europe – a modelling approach", Nutrient Cycling in Agroecosystems 68: 13–24, 2004.

[524] Table 3. Soil Association conversion: 1gC/m^2 = 10kgC/ha. So, -351gC/m^2 over 100 years = -3.51gC/m^2/yr = 35kgC/ha/yr.

[525] Dr Foereid has told us, "Yes, biomass production is assumed to depend linearly on yield. This is probably wrong (for several reasons), but we have no other proxy to estimate biomass production from," email communication, 1 September 2008.

[526] Cited in Stolze et al, 2000. Note, we have not checked these studies ourselves.

[527] Pages 15 & 76, CLIMSOIL report for the European Commission, December 2008.

[528] Bhogal *et al*, 2009, Scientific Report for Defra Project SP0561.

[529] Ana Frelih-Larsen, Anna Leipprand, Sandra Naumann (Ecologic) and Olivier Beucher (Baastal), " Background Paper for Stakeholder Consultation Workshop: Climate Change Mitigation in Agriculture – Policy Options for the Future," June 2008. See PICCMAT project website: http://www.climatechangeintelligence.baastel.be/piccmat/files/PICCMAT_policy_paper_June08.pdf

[530] Compendium of Organic Standards, September 2006, Defra, Annex 1 A (Principles of Organic Production at Farm Level), para 2.1, "The fertility and the biological activity of the soil must be maintained or increased, in the first instance, by: (a) cultivation of legumes, green manures or deep-rooting plants in an appropriate multi-annual rotation programme; (b) incorporation of livestock manure from organic livestock production in accordance with the provisions and within the restrictions of paragraph 7.1 of part B of this Annex [limits on per ha N application]; (c) incorporation of other organic material, composted or not, from holdings producing according to the rules of these Standards." http://www.defra.gov.uk/farm/organic/standards/pdf/compendium.pdf

[531] 1. Little, T., "Research review: monitoring and management of energy and emissions in agriculture," Institute of Organic Training & Advice, funded by Defra. 2. Hodges, R.D. (1991), "Soil organic matter: its central position in organic farming." In: Wilson, W.S. (ed.). "Advances in Soil Organic Matter Research: The Impact on Agriculture and the Environment." Royal Society of Chemistry, Cambridge. pp 355 – 364.

[532] In Mediterranean areas, organic holdings are often without animals.

[533] Grazing can lead to higher soil carbon levels as a result of a greater return of carbon to the soil: Vandasselaar & Lantinga, 1995; Schnabel *et al*, 2001. Grass cutting results in a higher allocation of carbon to the roots of grass; Crawford *et al*, 1997. All cited in Baritz *et al*, 2004, Task group 5 Land use Practices and SOM, http://ec.europa.eu/environment/soil/pdf/vol3.pdf.

[534] Section 3.1.2, "Effect of short-term leys", Johnston, Edward; Paul R. Poulton; & Kevin Coleman; 2009, Chapter 1, "Soil Organic Matter: Its Importance in Sustainable Agriculture and Carbon Dioxide Fluxes," Vol 101, Advances in Agronomy, *in press*. In the Rothamsted trial, grass-clover grazed by sheep and grass with N fertiliser were trialled and had the same results.

[535] Figure 6-3, Jenkinson, 1965. Cited in Troeh, R. Frederick & Louis Milton Thompson, "Soils and Fertility," 2005.

[536] Introducing legumes into grazing lands can promote soil carbon storage through enhanced productivity from the associated N inputs. Soussana *et al*, 2004; cited in CLIMSOIL report for the European Commission,16 December 2008.

[537] Johnston *et al*, 1994; de Neergaard, 2000; Høgh-Jensen and Schjoerring, 2001. Cited in: Bente Foereid and Henning Høgh-Jensen, "Carbon sequestration potential of organic agriculture in northern Europe – a modelling approach", Nutrient Cycling in Agroecosystems 68: 13–24, 2004.

[538] Section 6.2.1.2, Volume 4, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, IPCC, 2007.

[539] Rasse, D.P., Rumpel,C. & Dignac, M.F. 2005. Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. Plant and Soil, 269, 341-356.

[540] 1. Page 86, CLIMSOIL report for the European Commission,16 December 2008. 2. This German study found that grasslands increase the soil carbon content in the top 20cm but *reduce* the level in the 20-30cm layer, and suggested that this is because grasslands have more shallow roots than arable plants: "Mechanisms of soil carbon storage in experimental grasslands," S. Steinbeiss, V. M. Temperton, and G. Gleixner, Biogeosciences Discussions, 4, 3829–3862, 2007. Author's note: there may be significant differences between natural grassland, rough grazing, inorganically-fertilised, and organically managed grasslands.

[541] Bull *et al*, 2000; Nierop *et al*, 2003; cited in Rasse *et al*, 2005.

[542] Table 2, Rasse *et al*, 2005.

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[543] 1. Reid & Goss, 1981, found that maize, wheat and tomato decreased aggregate stability, while lucerne and ryegrass increased it; cited in Puget & Drinkwater, 2001. 2. Haynes & Beare (1997) found that wheat and barley were less effective at producing aggregate stability than Italian ryegrass, praire grass, lupins and white clover. The latter two (both legumes) produced "unexpectedly high aggregate stability" "relative to their rather small root mass and length" with white clover producing a similar degree of aggregate stability to Italian ryegrass. It was suggested that the roots of legumes may support a different microbial population to non-legumes (perhaps linked to the N-fixing nature of the plants), and the length of fungal hyphae associated with aggregates for lupins was four times greater than that of wheat. The reason proposed for the higher aggregate stability of grass was the larger root mass of grass than wheat and barley, supplying more carbon in the root zone [exudate, root hair turnover, cell sloughing], supporting a greater microbial biomass, and so producing more of the soil-binding carbohydrates; Haynes, R.J., and M.H. Beare, 1997, Influence of six crop species on aggregate stability and some labile organic matter fractions. Soil Biol. Biochem. 29:1647 – 1653; cited in Puget & Drinkwater, 2001.

[544] 1. Haynes & Beare proposed that the reason for their finding of a higher aggregate stability of grass than wheat and barley was the larger root mass of grass, supplying more carbon in the root zone, supporting a greater microbial biomass, and so producing more of the soil-binding carbohydrates; Haynes, R.J., and M.H. Beare, 1997. 2. "… observations that aggregate stability is greatest under grass because of continued production of these components [SOM components that stabilise soil aggregates], and decreases under arable cultivation," Shepherd *et al*, 2002. 3. Reid & Goss, 1981; cited in Puget & Drinkwater, 2001.

[545] 1. The greater aggregate stability of perennial ryegrass compared to arable crops is attributed to (as well as to the production of polysaccharides in the root zone) the increased fungal population associated with these species: Tisdall & Oades, 1979 (study of ryegrass); and Haynes & Beare, 1991 (study of wheat, barley, ryegrass, praire grass, white clover and lupins); both cited in Puget & Drinkwater, 2001. 3. Adam & Tisdall, 1984, suggested that the fine roots of ryegrass and associated fungal hyphae hold soil particles into water-stable aggregates; cited by Wells *et al*, 2000. 2.Dr Christine Watson, Scottish Agricultural College, oral communication, Soil Association conference, Edinburgh, 9 January 2004.

[546] Rasse *et al*, 2005.

[547] Clover leys are known to particularly help maintain soil organic matter. Lampkin, 1986; Arden-Clarke & Hodges, 1987; cited in Armstrong Brown *et al*, 2000.

[548] "Organic farming methods," http://www.defra.gov.uk/farm/organic/systems/method.htm. The manure application limit results from the N application limits in the standards (to limit N leaching): the EU organic standards have an upper limit for N application via manure of 170kgN/ha/yr over the whole farm (including manure deposited by grazing livestock). Additionally, under UK organic standards, there is a limit of 250kgN/ha/yr for any one area of land. Some information on actual application rates comes from a survey of four mixed arable organic farms in England, the FYM application rates over the previous five years were as follows (it is not specified whether this is per year or over the five years): two applied no FYM, one applied 15-20t/ha on the grass ley, and one applied 10t/ha on the ley and 25t/ha on the potato fields; P. Gosling & M. Shepherd, "Long-term changes in soil fertility in organic arable farming systems in England, with particular reference to phosphorus and potassium," Agriculture, Ecosystems and Environment 105 (2005) 425–432.

[549] 1. "Several long-term studies have reported that SOC contents remained unchanged or were decreased by the addition of shoot residues to cropped soils as compared to the root contribution alone (Campbell et al., 1991; Clapp et al., 2000; Reicosky et al., 2002; Soon, 1998);" cited in Rasse *et al*, 2005. 2. German study of the annual weed *Amaranthus retroflexus L.* found a positive effect of roots on soil carbon levels but a negative effect of the leaves and stems; "Mechanisms of soil carbon storage in experimental grasslands," S. Steinbeiss, V. M. Temperton, and G. Gleixner, Biogeosciences Discussions, 4, 3829–3862, 2007.

[550] For example: 1. Table 3, Bhogal *et al*, 2007, Report for Defra Project SP0561. This review of English studies shows that the application of cattle FYM increased SOC levels in all 7 long-term studies. 2. A 12-year experiment in Belgium using FYM at 10t/ha/yr, Hofman & Van Ruymbeke, 1980; cited in Sleutel *et al*, 2003. 3. US Rodale trial, see sections 6.2 and 9.4

[551] Bente Foereid and Henning Høgh-Jensen, "Carbon sequestration potential of organic agriculture in northern Europe – a modelling approach", Nutrient Cycling in Agroecosystems 68: 13–24, 2004.

[552] Table 2, Rasse *et al*, 2005.

[553] FYM is assumed to contain 49% 'decomposable' organic matter, 49% resistant organic matter, and 2% humified organic matter. Section 5.5, Johnston, Edward; Paul R. Poulton; and Kevin Coleman; 2009, Chapter 1, "Soil Organic Matter: Its Importance in Sustainable Agriculture and Carbon Dioxide Fluxes," Vol 101, Advances in Agronomy, *in press*.

[554] Williams & Cooke, 1961; cited in Shepherd M.A., Harrison R., Webbs J., 2002: Managing soil organic matter – implications for soil structure on organic farms. Soil Use and Management no. 18, 284-292.

[555] Ansorge, 1966; Meiklejohn, 1968; Waksman, 1952. Cited in Fraser *et al*, 1988.

[556] Berry & Karlen, 1993; and Estevez *et al*, 1996. Both cited in Pulleman *et al*, 2003.

[557] Murillo, 1996. Cited by Pulleman *et al*, 2003.

[558] Section 5.2.1 and table 3, Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561. This shows that on a dryweight basis, FYM increases SOC levels by 60kgC/ha/yr (+/-20kg) per tonne of manure dry solids in UK conditions. Assuming an average dry matter level of 25%, this means that the increase is about 15kgC/ha/yr per t of FYM freshweight.

[559] Table 3, Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561. Average of results of 15 trials from 8 long-term studies in England. Author's note: this includes some broiler litter and slurry results, but the average for the six cattle FYM results is also 23%. Also, the application rate for the Broadbalk and Hoosfield trials were actually 35t/ha/yr *freshweight*, not dryweight as indicated. However, the researchers have assured us that the calculation of the SOC conversion rates remain correct; email communication from Andy Whitmore, 20 May 2009.

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[560] Four of the six studies of cattle FYM were on soils with a relatively low clay content (6-12%), so the level might be higher on clay soils and generally. Also, the study which found the second lowest 'carbon retention rate' of the six cattle FYM studies (Hoosfield) was not comparable to the others, as it was a very long-term trial; normally SOC gains are much lower after the first twenty years or so, so this trial will have under-estimated the benefit of FYM in this study in comparison to the others. Also, the conversion rates may be different for organic FYM and compost.

[561] Yamulki, Sirwan; Effect of straw addition on nitrous oxide and methane emissions from stored farmyard manures; Agriculture, Ecosystems and Environment 112 (2006) 140–145. Most of the carbon lost from manure/FYM during storage is released as CO2, with a small amount lost as methane. Over 4 months, C content of organic FYM fell from 185 to 77.3kgC/t.

[562] This is based on (i) carbon loss rate of 58% for organic FYM storage over four months, and (ii) average 'carbon conversion rate' of 23% for non-organic FYM. Thus, the overall amount of carbon present in the initial fresh FYM that ends up, after storage, as soil carbon is: 42% x 23% = 10%.

[563] Hoosfield spring barley long-term trial (1852+), on a silty clay loam, Rothamsted, Johnston *et al*, 2009, *in press*.

[564] Section 3, Johnston *et al*, 2009, *in press.*

[565] 25-year Market Garden experiment (1942-1967), sandy loam soil (12% clay), Woburn; Johnston *et al*, 2009, *in press.*

[566] It is generally assumed that half of the soil carbon gains that would occur in the 100 years after a positive management occur in the first 20 years, but it is considered that soil carbon losses occur more quickly. Bhogal *et al*, 2007.

[567] The IPCC guidelines on this are presumably based mainly on evidence of the effects of farmyard manure. The guidelines do not, however, clearly distinguish between the use of farmyard manure and liquid slurry. Ch. 5, Volume 4, IPCC, 2007. http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html

[568] Table 1, Yamulki, 2006. This is a study by IGER using manure from South-west England. Before storage, the organic manure contained 163kg of C/t , compared to 132kgC/t for non-organic manure, a difference of 23%, while organic FYM had 185kgC/t compared to 153kgC/t for non-organic manure, a difference of 21%. After four months of storage, organic FYM (manure mixed with straw), contained only 5.2% more C than non-organic FYM (77.3 vs 73.5kgC/t), though it had 18% more C than non-organic manure without straw (77.3 vs. 65.6kgC/t). Author's note: 18% may be the relevant figure in many cases as organic farmers are more likely to convert their manure to FYM than organic farmers. No reason is given in the study for the higher C content of organic manure, but it may be a product of the higher grass (more roughage) and lower grain diet of non-organic cattle.

[569] Butler *et al* (2008) 'Fatty acid and fat-soluble antioxidant concentrations in milk from high and low input conventional and organic systems: seasonal variation', *Journal of the Science of Food and Agriculture J Sci Food Agric* 88:1431–1441. Also, quote by Gillian Butler, livestock production manager at Nafferton Ecological Farming Group, who led the research, in "Cows that eat outdoors produce healthier milk,"Independent, 28 May 2008. In the study, grazing provided 84% of the food for dairy cattle on organic farms in summer, compared to 37% for non-organic dairy cattle.

[570] Yamulki, 2006. Author's note: this higher C content of directly deposited manure may be beneficial for soil C levels, although on the other hand there may also be benefits for soil C levels from converting urine and manure to FYM with straw (in the same way as there seems to be from converting slurry to FYM) and benefits from the storage in terms of the composition of the manure.

[571] The arable-ley system comprised a five year rotation of three years of grazed grass plus two years of cropping. The additional 18% increase cited here is compared to the *starting* SOC level. Section 3.1.2, Johnston *et al*, 2009, *in press.*

[572] Section 5.2.1, page 19, Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561.

[573] Oral communication, Pete Douglas, Soil Association Producer Services department, 3 September 2008.

[574] Breakdown of all manure produced in the UK beef sector: 50.5% deposited on pasture; 6% slurry system; 20.7% solid manure system; 23% daily spread. Page 377 of the Annexes to the UK Greenhouse Gas Inventory 2007, http://www.airquality.co.uk/reports/cat07/0905131425_ukghgi-90-07_Annexes_Issue2_UNFCCC_Final.pdf

[575] 12-25% clay content soils. Johnston *et al*, 2009, *in press.*

[576] At Askov, a mixture of FYM (10t/ha/yr freshweight) and slurry (4t/ha/yr) was applied until 1972, then just 25t/ha/yr of dairy slurry (freshweight) was applied (x0.5 and x1.5 rates were trialled also). The soil carbon level (0-20cm) was falling only slightly from 1920 until 1972 (x1 rate), after which the rate of decline appears to have increased. The soil clay content was 12% clay. Figure 18.1, Christensen, B.T. & Johnston, A.E. (1997) Soil organic matter and soil quality – lessons learned from long-term experiments at Askov and Rothamsted. In: *Soil Quality for Crop Production and Ecosystem Health.* Developments in Soil Science 25, 349-430.

[577] Tove Heidmann, Bent T. Christensen and Svend E. Olesen, "Changes in soil C and N content in different cropping systems and soil types," in "Greenhouse Gas Inventories for Agriculture in the Nordic Countries," Proceedings from an international workshop, Helsingør, Denmark 24-25 January 2002. Note, not all the +900kgC/ha/yr can be assumed to be due to manure, as the cause could be partially that such land was also subject to more of other beneficial practices, such as the use of grass leys.

[578] Bente Foereid and Henning Høgh-Jensen, "Carbon sequestration potential of organic agriculture in northern Europe – a modelling approach", Nutrient Cycling in Agroecosystems 68: 13–24, 2004.

[579] Figures for cattle FYM/slurry, page 73, The British Survey of Fertiliser Practice, 2008, Defra.

[580] Salomonsen, 2000. Cited in: Bente Foereid & Henning Høgh-Jensen, 2004.

[581] C:N ratio reported for the FYM applied in the 'Market Garden experiment,' Woburn, UK, Johnston *et al*, 2009, *in press.*

[582] Standard C:N ratio for FYM, according to Danish sources: Salomonsen, 2000. Cited in: Bente Foereid & Henning Høgh-Jensen, 2004. Author's note: there was also an increase in the level of catle slurry

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[583] UK cattle manure typically has a C:N ratio of c.20:1; "Recycling of Agricultural, Municipal and Industrial Residues in Agriculture," RAMIRAN 2002, Proceedings of the 10th International Conference of the RAMIRAN Network, May 2002. The C:N ratio of organic manure can be somewhat higher than non-organic manure, due to a higher C content, eg. 16.3:1 vs. 14.5:1 in one UK case (but for FYM, once straw was added, it was 19:1 for both organic and non-organic); "Greenhouse gas emission from organic and conventional farming systems and options for mitigation," Sirwan Yamulki, IGER Innovations 2004. For FYM, the C:N ratio varies greatly, depending on the bedding material added and length of storage; "Tools for managing manure nutrients," www.organic.aber.ac.uk For example, the addition of straw (which has a very high carbon content) increases the C:N ratio, and storage means a loss of both C and N; "Greenhouse gas emission from organic and conventional farming systems and options for mitigation," Sirwan Yamulki, IGER Innovations 2004.

[584] Diek Mansvelt, Jan & M.J. van de Lubbe, "Checklist for sustainable landscape management," final report of the EU Concerted Action AIR3-CT93-1210: the Landscape and Nature Production Capacity of Organic/Sustainable Types of Agriculture, published by Elsevier, 1999.

[585] Johnston *et al*, 2009, *in press.*

[586] Reijs, Joan W.; Sonneveld, Marthijn P. W.; Sørensen, Peter; Schils Rend L. M.; Groot Jeroen C. J.; Lantinga Egbert A.; The effects of different diets on utilization of ntrogen fro cattle slurry applied to grassland on a sandy soil in The Netherlands," Agriculture, ecosystems & environment, vol. 118, 65-79.

[587] "Poultry manure is less likely to contribute to soil OC since it is rapidly mineralised (Robinson and Sharp, 1995)"; Wells *et al*, 2000. Robinson, J.S., Sharpley, A.N., 1995. Release of Nitrogen & Phosphorus from Poultry Litter. J. Environ. Qual. 24, 62–67.

[588] Eg. this Australian study of organic and non-organic farming, Wells *et al*, 2000. About 65% of P was applied in the form of poultry manure in a survey of 29 commercial vegetable farms in New South Wales in the 1990s.

[589] Optimisation of nitrogen mineralisation from winter cover crops and utilisation by subsequent crops. Runs 01 August 1995 - 30 June 1999. Henry Doubleday Research Association. http://orgprints.org/7936/

[590] Section 2.4.3, Baritz *et al*, 2004, http://ec.europa.eu/environment/soil/pdf/vol3.pdf.

[591] An ideal green manure is a balance of 'fixers' and 'lifters'. Examples of green manure 'N fixer' (leguminous) crops are: crimson clover, vetches and black meddick (trefoil). Examples of green manure 'lifter' crops are cereal rye and fodder rape. Other plants used in the UK as green manure crops in organic farming include: phacelia, mustard, and stubble turnips.

[592] "Green Manures," Stockfree Organic, Vegan-Organic Information Sheet #8 www.networkforclimateaction.org.uk

[593] Compared to only 13% for straw and 50% for FYM in the trial, 'Organic manuring experiment', Woburn, 12% clay content soil. Section 3.1.3, 'Effect of different types of organic inputs,' Johnston *et al*, 2009, *in press.* Original reference: Mattingly, 1974. Note, there is no mention of the continuous carbon supply from the roots of the growing green manure crops (root exudates etc.), so we presume that this 35% carbon retention rate is based only on the biomass carbon supply. However, the root supply would add further carbon and might be a main source of the retained carbon – see Chapter 2.

[594] Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561.

[595] Such as if the clay contents of the soils are lower than average.

[596] Barthès *et al*, 2004; Freibauer *et al*, 2004. Cited in Smith *et al,* 2007.

[597] "Use of the Carbon:Nitrogen Ratio," SOIL, AGRON 305, www.agronomy.ksu.edu

[598] Most fresh plant material contains around 40% carbon, but varying amounts of N, hence varying C:N ratios."Use of the Carbon:Nitrogen Ratio," SOIL, AGRON 305, www.agronomy.ksu.edu

[599] Page 216, Troeh, Frederick R., & Louis Milton Thompsen,"Soil and Soil Fertility," 2005. Published by Wiley-Blackwell.

[600] eg. C:N ratio of 13:1 for lucerne (alfalfa): "Use of the Carbon:Nitrogen Ratio," SOIL, AGRON 305, www.agronomy.ksu.edu eg. C:N ratio of 15:1 for legumes: Composting 101, Carbon and Nitrogen, www.ucce.ucdavis.edu

[601] For example: red clover has a C:N ratio of 27:1 and brown mustard 32:1. Mazzoncini *et al*, Effects of green manure crops on soil nitrogen availability and crop productivity in a Mediterranean organic farming. The green manure crop had a C:N ratio of 19:1; A.Granstadt, "The mobilization and immobilization of soil nitrogen after green manure crops at three different locations in Sweden," in Soil Management in Sustainable Agriculture. Proceedings, Third International Conference on Sustinable Agriculture, Wye College, UK, 1993.

[602] Drinkwater, L.E., Wagoner, P., Sarrantonio, M., 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature 396, 262–264.

[603] The C:N ratio of SOM is relatively constant and typically about 10:1, ranging between 9:1 and 14:1. Page 5 and 25, Johnston *et al*, 2009, *in press.*

[604] Troeh, Frederick R., & Louis Milton Thompsen,"Soil and Soil Fertility," 2005. Published by Wiley-Blackwell.

[605] See: 1. Troeh, Frederick R., & Louis Milton Thompsen,"Soil and Soil Fertility," 2005. Published by Wiley-Blackwell. 2. Basic Biological Factors of Soil Carbon and Nitrogen, presentation by Kristina A. Goings, National Soil Survey Center, NRCS, USDA, Lincoln, Nebraska, USA.

[606] Study of the effects of lupins and white clover vs. grass, barley and wheat on aggregate stability, Haynes & Beare, 1997; cited in Puget & Drinkwater, 2001. Also, in its long-term farming trial, the Rodale Institute found that the use of cover crops in organic farming promoted higher fungal mycorrhizal levels, which was proposed as a reason for the higher soil carbon levels of organic farming in the trial – see point 7.

[607] Eg. "During winter, soil is often left bare after harvest. Where applicable, sowing of green manure/catch crops should become a routine operation, since many positive indirect effects result from it, including increased SOM." Baritz *et al*, 2004.

[608] 1. This study found that maize ('corn') root carbon was much less likely to associate with soil aggregates than vetch (a leguminous plant used as a green manure/cover crop) root carbon. Puget P. & L.E. Drinkwater, Short-term dynamics of root-and

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shoot-derived carbon from a leguminous green manure, Soil Sci. Soc. Am J.. 65:771-779 (2001). 2. Reid & Goss, 1981, found that maize, wheat and tomato decreased aggregate stability, while lucerne and ryegrass increased it; cited in Puget & Drinkwater, 2001. 3. This study found that legumes (lupins and white clover) produced "unexpectedly high aggregate stability" and more than wheat and barley, it was suggested that the roots of legumes may support a different microbial population, and the length of fungal hyphae associated with aggregates for lupins was four times greater than that of wheat; Haynes, R.J., and M.H. Beare, 1997, Influence of six crop species on aggregate stability and some labile organic matter fractions. Soil Biol. Biochem. 29:1647 – 1653; cited in Puget & Drinkwater, 2001.

[609] Bolton et al, 1985; Fraser *et al*, 1988.

[610] Shepherd *et al*, 2002.

[611] Haynes & Naidu, 1998; cited in Shepherd *et al*, 2002.

[612] Oral communication, Phil Stocker, Director of Farmer and Grower Relations, 29 January 2009.

[613] Hepperly *et al*, 2008.

[614] Eg. Baritz *et al*, 2004, Task group 5 Land Use Practices and SOM, http://ec.europa.eu/environment/soil/pdf/vol3.pdf.

[615] Oral communication, Pete Douglas, Soil Association Producer Services department, 1 September 2008.

[616] "Lodging of cereal crops," http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/crop1271

[617] In 2006, the average organic farming yields of all English regions for were 5.1t/ha for wheat and 4.7t/ha for barley (note, this probably under-estimates the national average organic farming wheat yield as this figure is not weighted by production levels in each region; if the NE and NW regions are excluded, the average is 5.4t/ha which may be more representative); page 31, "England and Wales under organic agriculture – How much food could be produced", University of Reading, 2009. This compares to the average national UK yields in 2006 of 8t/ha for wheat and 5.9t/ha for barley; Agriculture in the UK 2008, Defra.

[618] "Quantities of straw grown in the UK," Biomass energy centre, www.biomassenergycentre.org.uk.

[619] There was an increase with straw application in all but three of 14 cases from five studies in England, and an average SOC gain of around 50kgC/ha/yr per tonne of straw (freshweight). Table 7, Bhogal *et al*, 2007, report for Defra Project SP0561.

[620] For example: 1. A 17-year UK trial (1985-2001) comparing straw incorporation versus burning found straw incorporation produced no increase in soil carbon at one site (Rothamsted) and at another site, where the soil carbon levels were lower (Woburn, soil with 12% clay content), though straw incorporation produced a roughly 15% SOC increase, only about 10% of the added carbon from the straw was retained in the soil. 2. In an earlier trial, also at Woburn, straw use produced a 33% higher SOC level after six years than the use of N fertiliser alone (0.92%C vs. 0.69%C), but yet the carbon retention rate of the straw was very low, at only 13% ('Organic Manuring Experiment' using 7.5t of straw/ha/yr, dry matter) (note, this trial apparently produced the highest carbon retention rate of all of the UK trials on cereal straw application - see Table 7 of the Defra review, Bhogal *et al*, 2007). Reference: sections 3.1.3 and 3.1.4, Johnston *et al*, 2009, *in press*.

[621] Unlike the positive view of FYM in terms of soil benefits, it was a common perception by farmers that there was little benefit from ploughing-in straw (ploughing-in was promoted by all-arable farmers who had little other option for disposing of their straw); email communication, Richard Young, organic farmer, 1 June 2009. Similarly, there is a general view by organic farmers that there is more benefit for the soil from manure production and application (ie. grazing) than grass incorporation (ie. cutting); oral communication, Phil Stocker, Director of Farmer and Grower Relations, Soil Association, 11 February 2009.

[622] Tables 7 & 12, Bhogal *et al*, 2007. Note, the straw application rate for site no. 4 (Woburn, six-year trial) in Table 7 was actually 7.5t/ha/yr *dry matter* (Johnston *et al*, 2009), not freshweight as indicated. However, the researchers have assured us that the calculation of the SOC conversion rates remain correct; email communication from Andy Whitmore, 20 May 2009.

[623] We question whether the soil carbon retention rate from straw could be higher under organic farming, given that higher N (or N mineralisation) levels are commonly reported for organically managed soils, than for soils managed with inorganic fertilisers. If this is simply because of the higher SOM level, then this would presumably not help as some of this existing SOM would have to be mineralised to release the N. However, there could possibly be a benefit if there is also a greater availability of already mineralised N, such as due to the higher nutrient-retention quality of better aggregation and more microbial nutrient turnover. This is not a subject that we have studied as part of this review, however. Some studies that have found higher N (or N mineralisation) levels are: 1. Kirchmann *et al*, 2007. 2. Marriott & Wander, 2006. 3. Melero *et al*, 2006. 4. Pulleman *et al*, 2003. 5. Derrick & Dumaresq, 1999. 6. Reganold *et al*, 1993. 7. Fraser *et al*, 1988. The only data that we have on the SOC retention rate for organic cereal straw is the Rodale trial, where there was an almost seven times lower SOC retention rate for organic maize than for other plants in the rotation of the organic arable system (see section 6.2); though this appears to support the non-organic farming findings of a very low soil carbon retention rate of cereal straw, the 'other plants' in the rotation included wheat and cereal rye as well as legumes, so definitive conclusions cannot be drawn.

[624] Reference for wheat, barley, oats and rye straw: Diek Mansvelt *et al*, 1999. Reference for maize straw: "Use of the Carbon:Nitrogen Ratio," SOIL, AGRON 305, www.agronomy.ksu.edu

[625] "Use of the Carbon:Nitrogen Ratio," SOIL, AGRON 305, www.agronomy.ksu.edu

[626] In each generation of decomposing microbes, much of the decomposable carbon is used up as the energy source and lost as CO2, leaving only a small proportion as new SOM and microbial biomass [say, 25% of the decomposable carbon]. When the C:N ratio is above about 30:1, then there is excess carbon which has to be decomposed by a second generation of microbes utilizing nutrients from the decomposition of the first generation of microbes [or from the decomposition of existing humus], which means that much of the carbon that was left after the first generation is then lost by respiration by the second generation, leaving very little carbon finally remaining as new humus and microbial biomass [eg. only 25% of 25% of the decomposable carbon]. Troeh, Frederick R., & Louis Milton Thompsen,"Soil and Soil Fertility," 2005. Published by Wiley-Blackwell. Plant materials with high C:N ratios have insufficient N levels to allow rapid, efficient decomposition and need to take N from the soil; Basic Biological

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Factors of Soil Carbon and Nitrogen, presentation by Kristina A. Goings, National Soil Survey Center, NRCS, USDA, Lincoln, Nebraska, USA.

[627] Note, in principle, in non-organic systems, extra N fertiliser could be applied at the right time to assist the decomposition process and increase the carbon retention rate. But this is presumably not happening at the moment, and more fertiliser use would also increase GHG emissions (from manufacture, fuel for spreading, soil N20 emissions etc.), offsetting the benefit of more soil carbon. As regards soil N20 emissions: in the UK about 0.6% of the N in N fertiliser applied on arable crops is released as N20 (2.4% for potatoes and brassicas); "Scottish Agriculture and Global Change - Nitrous Oxide Emissionjs from Fertiliser use," by the Universities of Edinburgh and Aberdeen, published January 2005 by the Scottish Executive. N20 is a greenhouse gas with a warming effect 310 times as great as C02.

[628] "Straw," Biomass energy centre, www.biomassenergycentre.org.uk. About 40% of the 7 million t of wheat straw are chopped and returned to the soil, about 30% are used on-farm, and about 30% are sold. Most of the 2.75 million t of barley straw are used as bedding and feed.

[629] Kong, Angela Y. Y., Johan Six, Dennis C. Bryant, R. Ford Denison and Chris van Kessel , "The Relationship between Carbon Input, Aggregation, and Soil Organic Carbon Stabilization in Sustainable Cropping Systems" Published in Soil Sci Soc Am J 69:1078-1085 (2005) Published online 2 June 2005.

[630] Rasse, D.P., Rumpel, C. & Dignac, M.F. 2005. Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. Plant and Soil, 269, 341-356.

[631] G. P. Lafond, M. Stumborg, R. Lemke, W. E. May, C. B. Holzapfel and C. A. Campbell, Quantifying Straw Removal through Baling and Measuring the Long-Term Impact on Soil Quality and Wheat Production, Agron J 101:529-537 (2009).

[632] S. W. Duiker, R. Lal, *Soil Tillage Res.* **52**, 73 (1999).

[633] Email communication, Rob George, Soil Association, 21 January 2009.

[634] Oral communication, Phil Stocker, Director of Farmer and Grower Relations, Soil Association, 11 February 2009.

[635] Diek Mansvelt, Jan & M.J. van de Lubbe, "Checklist for sustainable landscape management," final report of the EU Concerted Action AIR3-CT93-1210: the Landscape and Nature Production Capacity of Organic/Sustainable Types of Agriculture, published by Elsevier, 1999.

[636] This is based on (i) carbon loss rates of 58% and 20% for organic FYM storage over four months and organic composting respectively, and (ii) 'carbon conversion rates' of 23% for non-organic FYM and 50% for composting in the absence of inorganic N fertiliser (see points 2 and 11). Thus, the amount of carbon in FYM before storage that ends up as soil carbon is: 42% x 23% = 10% (ie. 38% more than then the 7% SOC conversion rate for UK straw). And, the amount of carbon in the material used for composting that ends up as soil carbon is: 80% x 50% = 40% (ie. 5.7 times as much as the 7% carbon conversion rate for UK straw). The rates may be different for organic FYM and compost, so this is a preliminary estimate.

[637] This assumes that the higher 'carbon conversion rate' of FYM/compost applies to the carbon in FYM or compost that originates from straw and is not just the effect of the non-straw carbon sources in the FYM/compost. This seems to be supported by the indications of a lower soil carbon effect of slurry, as well as straw. As FYM is the alternative to the separate production & application of both straw and slurry, given the lower C conversion rates of both straw and also, we assume, slurry, this means that the production of FYM is raising the carbon conversion rates of at least one source, but presumably all.

[638] Note, the relative contributions of the manure/compost versus the green manure crops and non-use of agrochemicals are unknown in these trials. See section 6.2 for details.

[639] Mineralisation is the conversion of nutrients in the organic form (i.e. stored in SOM) into inorganic forms - unpublished paper on soil carbon and organic farming, provided to the Soil Association by Dr Julia Cooper, Newcastle University, 9 October 2007. SOM 'oxidation' is when soil carbon is converted to atmospheric CO2.

[640] See section 6.6.

[641] 1. Rasse *et al*, 2005. 2. Sisti *et al*, 2004; cited page 28, "The Role of Organic Agriculture in Mitigating Climate Change,"J. Kotschi & K. Müller-Sämann, IFOAM, May 2004. 3. A dominant role of root C in soils has also been suggested by: Boone,1994; Milchunas et al, 1985; Norby and Cotrufo,1998; all cited in Rasse *et al*, 2005. 4. A simulation study suggested maize root systems contribute 1.8 times more carbon to soils than the above-ground biomass: Molina et al, 2001; cited in Rasse *et al*, 2005. 5. Gale *et al*, 2000; cited in Puget & Drinkwater, 2001. 6. German study of the annual weed *Amaranthus retroflexus L.* found a positive effect of roots on soil carbon levels but a negative effect of the leaves and stems; "Mechanisms of soil carbon storage in experimental grasslands," S. Steinbeiss, V. M. Temperton, and G. Gleixner, Biogeosciences Discussions, 4, 3829–3862, 2007.

[642] The exudates are water-soluble and provide a nutrient source for soil microorganisms, so are often mineralised within a few hours (resulting in elevated soil carbon levels around root systems). However, a portion of the exudates also quickly bonds to the soil's mineral particles which then restricts their degradation. Rasse *et al*, 2005.

[643] It is considered that this continuous root carbon supply may provide as much carbon to the soil as root residues, but there is still "great uncertainty" over this. Rasse *et al*, 2005.

[644] Based on studies with complete datasets, root-derived carbon is estimated to have a 2.4-fold residence time in the soil than plant 'shoot' derived carbon; many mechanisms for this have been identified. Rasse, D.P., Rumpel, C. & Dignac, M.F. 2005. Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. Plant and Soil, 269, 341-356.

[645] Puget P. & L.E. Drinkwater, Short-term dynamics of root-and shoot-derived carbon from a leguminous green manure, Soil Sci. Soc. Am J.. 65:771-779 (2001).

[646] Note, this is only the biomass carbon, and it excludes the continuously released carbon in root exudates/root hair turnover so root carbon is not just 20% of the total amount of carbon produced by the vetch.

[647] Note, as well as the root biomass, about four weeks worth of the root carbon supply from the exudates/root hairs of the vetch were included in the study: the carbon supply from the vetch was monitored by labelling the vetch with a carbon isotope four

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weeks before the incorporation of the vetch. But the vetch had been planted seven months before the first measurements were taken, so the total root exudate/root hair carbon supply to the soil over the life of the vetch would have been much more.

[648] Puget & Drinkwater, 2001.

[649] Rasse *et al*, 2005.

[650] Jean-François Soussana, INRA Clermont, France. Workshop on soil at International conference "Organic agriculture and climate change," Enita Clermont, France, 17-18 April 2008.

[651] Rasse *et al*, 2005.

[652] 1. Rasse *et al*, 2005. 2. Sisti *et al*, 2004; cited page 28, "The Role of Organic Agriculture in Mitigating Climate Change,"J. Kotschi & K. Müller-Sämann, IFOAM, May 2004. 3. A dominant role of root C in soils has also been suggested by: Boone,1994; Milchunas et al, 1985; Norby and Cotrufo,1998; all cited in Rasse *et al*, 2005. 4. A simulation study suggested maize root systems contribute 1.8 times more carbon to soils than the above-ground biomass: Molina et al, 2001; cited in Rasse *et al*, 2005. 5. Gale *et al*, 2000; cited in Puget & Drinkwater, 2001. 6. German study of the annual weed *Amaranthus retroflexus L.* found a positive effect of roots on soil carbon levels but a negative effect of the leaves and stems; "Mechanisms of soil carbon storage in experimental grasslands," S. Steinbeiss, V. M. Temperton, and G. Gleixner, Biogeosciences Discussions, 4, 3829–3862, 2007.

[653] Root biomass carbon as % of total (root + above-ground) plant biomass carbon, tCO2/ha: organic 1.7/6.23 = 27.3%; non-organic 0.99/ha/6.19 = 16.0%. Table 8, "The Role of Organic Agriculture in Mitigating Climate Change,"J. Kotschi & K. Müller-Sämann, IFOAM, May 2004. Original reference: Haas G and Köpke U (1994): Vergleich der Klimarelevanz ökologischer und konventioneller Landbewirtschaftung. In: Enquete Kommission Schutz der Erdatmosphäre des Deutschen Bundestages (ed): Schutz der Grünen Erde, Klimaschutz durch umweltgerechte Landwirtschaft und Erhalt der Wälder. Bonn, Economica Verlag.

[654] Difference = 1.7/0.99 x 100 = +72%.

[655] Rasse *et al*, 2005.

[656] Oral communication, Pete Douglas, Soil Association Producer Services department, 1 September 2008.

[657] Email communication, Rob George, Soil Association, 21 January 2009.

[658] "Organic alfalfa production," http://attra.ncat.org/attra-pub/PDF/alfalfa.pdf

[659] Baritz *et al*, 2004, Task group 5 Land Use Practices and SOM, http://ec.europa.eu/environment/soil/pdf/vol3.pdf.

[660] Baritz *et al*, 2004, Task group 5 Land Use Practices and SOM, http://ec.europa.eu/environment/soil/pdf/vol3.pdf.

[661] Compared to UK yields reported in 'Agriculture in the UK 2008', Defra, UK Government.

[662] 1. English organic yields are: for potatoes, 28t/ha (vs. the 19.4t/ha cited in the table); for sugar beet, 59t/ha (vs. the 50t/ha cited in the table); for wheat, c.5.4t/ha (vs. the 4.5t/ha cited in the original table for wheat yield without straw, not shown here), and for barley, c.4.7t/ha (which is similar to that cited in the original table for barley yield without straw, not shown here); page 31, "England and Wales under organic agriculture – How much food could be produced", University of Reading, 2009. 2. In a study of a long-established biodynamic farm in the Netherlands, winter wheat yields were 5t/ha/yr and potato yields were 30t/ha/yr, while the non-organic yields were 9t/ha/yr and 54t/ha/yr respectively; Pulleman *et al*, 2003. 3. In a trial in southern Sweden, the average yields of a three-year grass ley in an organic system were 11t/ha/yr.

[663] A dense layer of soil below the topsoil that is impervious to water, causing water-logging.

[664] 1. Oral communication, Dr Paul Hepperly, New Farm Training and Research Manager, The Rodale Institute, Pensylvania, 9 January 2005, at the Soil Association's annual conference in Newcastle. 2. For example, Reganold JP (1995): Soil quality and profitability of biodynamic and conventional farming systems: A review. American Journal of Alternative Agriculture 10: 35-44.

[665] Increasing the total root biomass on organic farms by around 15%, on top of that from the main crops and weeds, according to the data in the study cited in the previous paragraph.

[666] Kirchmann *et al*, 2007.

[667] For instance, traditional 'organic' grass leys included a mixture of perennial ryegrasses, Timothy, Meadow Fescue, Cocksfoot, white clover and herbs to increase diversity, production and resistance to diseases; "Organic beef and dairy production: an introductory guide," June 2008, Soil Association food and farming department. For example, though this is probably more than normal, one organic farmer, Peter Segger in Wales, has 16 types of herb in his grass; oral communication, soil carbon workshop, Soil Association conference, 18 November 2008.

[668] Higher plant biodiversity leads to larger plant biomass production: Balvanera *et al*, 2006; Lambers *et al*, 2004; Roscher *et al*, 2005. All cited in, "Mechanisms of soil carbon storage in experimental grasslands," S. Steinbeiss, V. M. Temperton, and G. Gleixner, Biogeosciences Discussions, 4, 3829–3862, 2007.

[669] "Managing soil" subsection of the Soil Association organic standards (Soil Association, 2005).

[670] For example, see data for "microbial quotient", Table 6, Liebig & Doran, 1999.

[671] "Jenkinson and Ladd (1981) have demonstrated a close positive association between soil organic C and N levels and soil microbial biomass." Cited in Fraser *et al*, 1988.

[672] 1. The mucigels released by rhizosphere (rootzone) microflora contribute to aggregate stability; Haynes *et al*, 1991. Cited by Shepherd *et al*, 2002. 2. Root systems increases the soil microbial biomass which produces polymers that act as binding agents; Jastrow *et al*, 1998; Tisdall & Oades, 1979. Cited by Rasse *et al*, 2005. 3. Tisdall & Oades, 1982; cited by Wells *et al*, 2000.

[673] Fungal hyphae link soil particles together and impart aggregate stability; Haynes & Naidu, 1998. Cited by Shepherd *et al*, 2002.

[674] Elliott, 1986; Oades, 1988. Cited in: Puget P. & L.E.Drinkwater, Short-term dynamics of root-and shoot-derived carbon from a leguminous green manure, Soil Sci. Soc. Am J.. 65:771-779 (2001).

[675] Swaby, 1950; Scullion & Malik, 2000; Scullion *et al*, 2002. All cited in Pulleman *et al*, 2003.

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[676] In Switzerland, the FiBL DOK trial found a significantly higher soil carbon content for the biodynamic than the non-organic 'integrated' system down to 60cm. In Pennsylvania, the Rodale Institute trial found organic farming had higher soil C levels than non-organic farming down to 30cm. In the UK, Armstrong et al, 2000, found that organic permanent grasslands had double the topsoil depth of non-organic grasslands. Increases in both topsoil and subsoil carbon content with organic farming are also reported for Diez *et al*, 1991; Raupp, 1995b; Welp, 1993; and Løes & Øgaard, 1997 (for the last two, confirmation is needed of the level of change, and if the study really represents organic farming); cited in Stolze *et al*, 2000. See section 6.6.

[677] Miller & Jastrow, 1990; Wright *et al*, 1999. Cited in Pimental *et al*, 2005.

[678] Troeh, R. Frederick & Louis Milton Thompson, "Soils and Fertility," 2005. Published by Wiley-Blackwell.

[679] Paul Hepperly, Jeff Moyer, David Pimental, David Douds Jr., Kristine Nichols & Rita Seidel, "Carbon Sequestration in Organic Maize/Soybean Cropping Systems," paper for the 16th IFOAM Organic World Congress, Modena, Italy, June 16-20, 2008. Archived at http://orgprints.org/view/projects/conference.html

[680] Hepperly *et al*, 2008.

[681] Pimentel, D; Hepperly, P; Hanson, J; Douds, D; Seidel, R. (2005) "Environmental, Energetic, and Economic Comparisons of Organic and Conventional Farming Systems" *BioScience* 55: 573–582).

[682] Hepperly *et al*, 2008.

[683] Troeh, R. Frederick & Louis Milton Thompson, "Soils and fertility," 2005. Published by Wiley-Blackwell.

[684] Langley & Hungate, 2003. Rasse *et al*, 2005.

[685] Hole *et al*, 2005. Also, "reduced organic matter availabilty negatively affect earthworm populations, epsecially anecic species," [vertical-burrowing earthworms],' Pulleman *et al*, 2003.

[686] Elliott, 1986; Oades, 1988. Cited in: Puget P. & L.E.Drinkwater, Short-term dynamics of root-and shoot-derived carbon from a leguminous green manure, Soil Sci. Soc. Am J.. 65:771-779 (2001).

[687] Rasse *et al*, 2005.

[688] Galvez *et al*, 1995. Cited in Pimentel, D; Hepperly, P; Hanson, J; Douds, D; Seidel, R. (2005) "Environmental, Energetic, and Economic Comparisons of Organic and Conventional Farming Systems" *BioScience* 55: 573–582).

[689] The grass ley has several benefits for soil, including the provision of mycorrhizal fungi. Dr Christine Watson, Scottish Agricultural College, Soil Association conference, Edinburgh, 9 January 2008.

[690] Bolton *et al*, 1985; Fraser *et al*, 1988.

[691] Ansorge, 1966; Meiklejohn, 1968; Waksman, 1952. All cited in Fraser *et al*, 1988.

[692] Fontaine et al., 2003; Kramer and Gleixner, 2006. Cited in Steinbeiss *et al*, 2007.

[693] Hooper *et al*, 2000; Stephan *et al*, 2000; Wardle *et al*, 1999. Cited in Steinbeiss *et al*, 2007.

[694] 1. "The depressive effects of inorganic fertilizers on soil microbial biomass and some enzyme activities generally occur where regular inorganic fertilizer applications cause soil acidifcation (ph<5) and/or salt toxicity (Dick, 1992; Witter *et al.*, 1993)"; cited in Nguyen *et al*, 1995. 2. In trials where 80kg/ha of N fertiliser was applied, the microbial population fell by 25%; this was thought to be due to a change in soil pH from pH 5.4 to pH 4.5. Also, applications of liquid nitrogen fertiliser have temporary negative effects on microbial activity, and the system takes a minimum of 5-6 weeks to recover from a single application. "Life in the soil – The relationship between agriculture and soil organisms," http://www.nano.csiro.au/files/files/pcz9.pdf

[695] Gerard & Hay, 1979. Cited by Pulleman *et al*, 2003.

[696] Bollen, 1961; Chandra, 1964. Cited in Fraser *et al*, 1988.

[697] Greaves et al, 1976; cited in Fraser *et al*, 1988. Note, some researchers have attributed this negative effect of herbicides on soil microbes to a reduction in organic residues inputs from the weed control, rather than a toxic effect.

[698] Pimental, 2005; cited in Pimental *et al*, 2005. See also results of the FiBL trial below.

[699] 1. Baveco JM & De Roos AM, 1996, Assessing the impact of pesticides on lumbricid populations: an individual-based modelling approach, Journal of Applied Ecology 33, 1451-1468; cited by Pulleman *et al*, 2003. 2. Agrochemicals may affect earthworm populations as juveniles feed close to the surface: D.G. Hole, A.J. Perkins, J.D. Wilson, I.H. Alexander, P.V. Grice, A.D. Evans, "Does organic farming benefit biodiversity?", Biological Conservation 122 (2005) 113–130.

[700] The soil microbial biomass level can be enhanced by high soil water levels; research indicates that 60% water-filled pore space is the optimum water content for maximum aerobic microbial activity. Fraser *et al*, 1988.

[701] See section 6.2 for more details and references of the studies mentioned.

[702] In 1998, at the end of the third rotation, the soil microbial biomass carbon had these levels: biodynamic 360mg C/kg of soil, organic 313mg/kg, integrated 267 mg/kg, and 218 mg/kg. Table 5. Fließbach, A., H.R. Oberholzer, L. Gunst & P. Mäder, 2007, "Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming," Agriculture Ecosystems & Environment 118:273-284.

[703] Mäder *et al*, 2006. Cited in: Niggli, U., Fließbach, A., Hepperly, P. and Scialabba, N. 2009. Low Greenhouse Gas Agriculture: Mitigation and Adaptation Potential of Sustainable Farming Systems. FAO, April 2009, Rev. 2 – 2009.

[704] Mäder, P., A. Fließbach, A. Dubois, L. Gunst, P.Fried & U. Niggli, 2002, "Soil fertility and biodiversity in organic farming," Science 296:1694-1697.

[705] Microbial biomass C was 214.9µg/g on the organically managed plots vs. 147.0 µg/g on the 'District Practice' plots..

[706] Average of 1,280kgC/ha of microbial biomass carbon on the organic farms, vs. 889kgC/ha on the non-organic farms, for the top 30.5cm of soil. Table 6, Liebig & Doran, 1999.

[707] On the three farm pairs in Nebraska where earthworm activity was measured, the levels were 'moderate', 'high' and 'high' on the organic farms, and 'low', 'moderate' and 'moderate' on the non-organic farms, respectively. Table 5, Liebig & Doran, 1999.

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[708] The rhizosphere is the ecologically distinct zone that exists around plant root hairs and which has, for instance, a higher microbial activity than the rest of the soil.

[709] Page 1103 and Fig. 1, Drinkwater *et al*, 1995. See section 6.2 for details of study.

[710] Douds, D., Janke, R., & Peters, S. (1993). VAM fungus spore populations and colonization of maize and soybean roots under conventional and low input sustainable agriculture. *Agriculture, Ecosystems and Environment* 43: 325 – 335. Cited in: Hepperly *et al*, 2006.

[711] Hepperly *et al*, 2008.

[712] David Douds, Kristine Nichols, Paul Hepperly, and Rita Seidel , "Exploring the Role of Arbuscular Mycorrhizal Fungi in Carbon Sequestration in Agricultural Soil ," 2008 Joint Annual Meeting, Celebrating the International Year of Planet Earth, 7 October 2008.

[713] Fraser *et al*, 1988. See section 6.2.

[714] John P. Reganold, Alan S. Palmer, James C. Lockhart, A. Neil Macgregor, Soil Quality and Financial Performance of Biodynamic and Conventional Farms in New Zealand, SCIENCE, 16 April 1993, Volume 260, pp. 344-349.

[715] D.G. Hole, A.J. Perkins, J.D. Wilson, I.H. Alexander, P.V. Grice, A.D. Evans, "Does organic farming benefit biodiversity?", Biological Conservation 122 (2005) 113–130.

[716] 1. Section 3, Johnston *et al*, 2009, *in press*. 2. According to these studies inorganic N fertiliser does not generally increase SOM levels: Leigh and Johnston, 1994, Jenkins *et al*, 1994, Raupp, 1991 and many others; cited in, "The Role of Organic Agriculture in Mitigating Climate Change - a Scoping Study," by Johannes Kotschi and Karl Müller-Sämann, IFOAM, February 2004. 3. According to this review of long-term farming experiments around the world, inorganic N fertilisers have minimal effects on SOC levels: Glending & Powlson, 1995. Cited in email communication, Pete Smith, Royal Society-Wolfson Professor of Soils & Global Change, Institute of Biological and Environmental Sciences, University of Aberdeen; 21 November 2008.

[717] See section 9.3.

[718] Tove Heidmann, Bent T. Christensen and Svend E. Olesen, "Changes in soil C and N content in different cropping systems and soil types," in "Greenhouse Gas Inventories for Agriculture in the Nordic Countries," Proceedings from an international workshop, Helsingør, Denmark 24-25 January 2002. The –150kg figure for soil C losses on land receiving inorganic fertiliser is a Soil Association figure, taken by reading off the chart in Figure 4.

[719] Oral communication, Dr Paul Hepperly, New Farm Training and Research Manager, The Rodale Institute, Pennsylvania, 9 January 2005, at the Soil Association's annual conference in Newcastle. Also,

[720] Vandasselaar AV & Lantinga EA, 1995, Modeling the carbon cycle of grassland in the Netherlands under various management strategies and environmental conditions, Netherlands Journal of Agricultural Science 43, 183-194. Cited in Baritz *et al*, 2004.

[721] The average amount of carbon that remained in the soil was 50% when only compost and no inorganic N fertiliser was used, but only 36% when N fertiliser was also applied at standard rates. Table 5, Bhoghal *et al*, 2007, Defra Project SP0561.

[722] At the 33t/ha/yr compost application rate and without N fertiliser, the soil carbon sequestration rate was 96kgC/ha/yr and the 'soil carbon conversion rate' was 66% (ie. 66% of the applied carbon was retained in the soil as stable carbon); for the same compost application rate but with N fertiliser, the figures were 41kgC/ha/yr and 30%, a reduction of 55%. At the higher 50t/ha/yr compost application rate and without N fertiliser, the soil carbon sequestration rate was 50kgC/ha/yr and the 'soil carbon conversion rate' was 34%; for the same compost application rate but with N fertiliser, the figures were 61kgC/ha/yr and 41%, an increase of 22%. (Note, the effects were also not consistent over all four sites: at one of the four sites, the inverse was true, with N fertiliser causing a large increase in the carbon sequestration rate at the lower compost application rate and a small decrease at the higher compost application rate.) The lower application rate in the trials is cited as 21.6t/ha/yr dryweight, and the higher rate as 32.5t/ha/yr dryweight. Using a 65% dry matter content (Table 2), this is freshweight equivalents of 33.2t/ha/yr and 50t/ha/yr. Table 5, Bhoghal *et al*, 2007, Scientific report for Defra Project SP0561.

[723] Table 5, Bhoghal *et al*, 2007, Scientific report for Defra Project SP0561.

[724] Nguyen *et al*, 1995.

[725] 1. Dick, R.P., 1992. A review: long-term effects of agricultural systems on soil biochemical and microbial parameters. Agric. Ecosytems Environ., 40:25-36. Cited in Nguyen *et al*, 1995. 2. Witter, E., Martensson, A.M., Garcia, F.V., 1993. Size of the microbial biomass in a long-term field experiment as affected by different N-fertilizers and organic manures. Soil Biol. Biochem., 25:659-669. Cited in Nguyen *et al*, 1995. 3. In trials where 80kg/ha of N fertiliser was applied, the microbial population fell by 25%; this was thought to be due to a change in soil pH from pH 5.4 to pH 4.5. Also, applications of liquid nitrogen fertiliser have temporary negative effects on microbial activity, and the system takes a minimum of 5-6 weeks to recover from a single application. "Life in the soil – The relationship between agriculture and soil organisms," http://www.nano.csiro.au/files/files/pcz9.pdf

[726] Khan *et al*, 2007.

[727] 1. Section 2.1.2, Johnston *et al*, 2009. 2. CLIMSOIL report for the European Commission, December 2008.

[728] Soil carbon levels fell on the unfertilised plots, because fertilisation of any kind increases plant biomass production, in this case increasing the crop root and stubble levels. Section 2.1.2 and Figure 3, section 3, Johnston *et al*, 2009, *in press.*

[729] CLIMSOIL report for the European Commission, December 2008.

[730] 36t/ha (freshweight) of green waste compost supplies 250kg/ha of nitrogen to the soil; Table 8, Bhogal *et al*, 2007, Defra Project SP0561. Therefore, as well as being a physically large amount, any application of amounts higher than 36t/ha would risk breaching the 250kgN/ha/year limit from organic manures that applies in the UK Nitrate Vulnerable Zones (averaged over the farm area and over a rolling year), and that is also the recommended N application limit for farmland elsewhere in the UK.

[731] Defra, "Agriculture in the United Kingdom, 2006", table 6.1, Defra, 2007.

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[732] Defra, "Agriculture in the United Kingdom, 2005," Defra, 2006.

[733] The expanding international demand for soya is a major driver of the conversion of natural habitats to arable land in South America. This is a cause of soil carbon losses. For instance, the Argentine pampas has been a, "net source of greenhouse gas … in response to the conversion of natural grasslands into grazing lands and croplands." IPCC, GPG-LULUCF, 2003.

[734] See information on grass (point 1), root systems (point 6) and on maize (5.10).

[735] Pulleman *et al*, 2000, found 14% higher SOC levels for grassland (3 comparisons). Shepherd *et al*, 2002, found 16% higher levels on grassland (6 comparisons; but its 'non-organic' samples were mostly unconverted fields on the organic farms rather than 'mainstream' non-organic grassland farms, so this could be conservative). Armstrong et al, 2000, found 11% lower SOC levels on grassland but just over double the topsoil depth.

[736] There is still some use of arable-based feeds in organic systems, mainly to 'finish' livestock. Livestock can be finished on grass and clover. However, for example, as the forage quality declines in the autumn, it can be necessary to supplement the diet with concentrates and cereals to continue the animals' growth. Section 6.4, "Finishing organic beef and lamb," Soil Association Technical Guide.

[737] Butler *et al* (2008) 'Fatty acid and fat-soluble antioxidant concentrations in milk from high and low input conventional and organic systems: seasonal variation', *Journal of the Science of Food and Agriculture J Sci Food Agric* 88:1431–1441. Also, quote by Gillian Butler, livestock production manager at Nafferton Ecological Farming Group, who led the research, in "Cows that eat outdoors produce healthier milk,"Independent, 28 May 2008.

[738] Section 5.2, "Finishing organic beef and lamb," Soil Association Technical Guide.

[739] Currently half of the world's pork production occurs in landless industrial systems, and for poultry meat the share is over 70%. Steinfeld, H., Gerber, P., Wassenaar, T., Rosales, M. and de Haan, C. 2006. Livestock's long shadow. Environmental issues and options. FAO, Rome.

[740] Pig and poultry production has greatly increased in western societies, and more recently in many developing societies, with the development of intensive indoor livestock systems producing cheap white meat and eggs (at great cost to animal welfare). Under widespread organic farming, there would be a large reversal in the production of these products. Based on the production records of 176 organic farms, an initial assessment of one scenario of food production under widespread organic farming in England and Wales has concluded that chickenmeat and pork production would fall by around 70%, and eggs by 27%. "England and Wales under organic agriculture: how much food could be produced?", by Philip Jones with Richard Crane **,** Centre for Agricultural Strategy, Policy and Development, University of Reading, see Press Release, 24 June 2009, http://www.rdg.ac.uk/about/newsandevents/releases/PR21951.asp

[741] Peter Melchett, Policy Director and organic farmer, Soil Association, email communication, 9 October 2009.

[742] Report by EBLEX (English beef and lamb executive),"In the Balance? - The future of the English beef industry,"2009.

[743] However, the UK currently imports beef and veal equivalent to an additional 31% of UK production, according to Agriculture n the United Kingdom 2006 (Defra), so the excess would be only 37%. Page 53, An initial assesment of one scenario for food production under widespread organic farming in England and Wales, based on the production records of 176 organic farms. "England and Wales under organic agriculture: how much food could be produced?", by Philip Jones with Richard Crane **,** Centre for Agricultural Strategy, Policy and Development, University of Reading, see Press Release, 24 June 2009, http://www.rdg.ac.uk/about/newsandevents/releases/PR21951.asp

[744] Currently feed-lot systems are allowed under the US Government organic farming standards which is totally against organic farming principles and is recognised as a serious abberation that needs to be corrected. Under EU standards and elsewhere such systems are illegal under organic farming standards. 'Organic beef production' in this report refers only to systems that are based on grazing and feeding of forage (grass or other roughage), not grain-based, in line with true organic farming priniciples.

[745] In 2006, compared to national average yields, English organic yields were about 33% lower for wheat, about 35% lower for potatoes, about 20% lower for barley, about 48% lower for oats and 4% higher for sugar beet. FBS data, page 31, "England and Wales under organic agriculture – How much food could be produced", University of Reading, 2009.

[746] In 2007, 71% of the UK organic farmland area was permanent grass and 16% was temporary grass; Organic Food and Farming Market report, Soil Association, 2007. This high level of permanent grass is, however, greatly exaggerated by the fact that there is a large imbalance in the UK organic sector, with a much higher rate of grassland (ruminant livestock) farmers having so far converted to organic farming than arable farmers. Nevertheless, the fact that organic 'arable' farmers are based on mixed systems with livestock (usually mainly or including ruminants) should mean that many organic 'arable' farms have some permanent grassland as well and so there should (inherently) be a higher level of permanent grass with organic farming, than non-organic farming. Farms which raise predominantly ruminant livestock farmers will mostly have a high proportion of permanent grass.

[747] M. Pulleman, A. Jongmans, J. Marinissen & J. Bouma, "Effects of organic versus conventional arable farming on soil structure and organic matter dynamics in a marine loam in the Netherlands," Soil Use and Management (2003) 19, 157-165.

[748] Note, these figures are for illustrative purposes. They are the average carbon stock levels of existing grassland and croplands, and it cannot be presumed that conversion of any area of cropland would produce grassland of the same average tC/ha as existing grassland, given that the land would have different soil/climate conditions etc. Also, organic cultivated land already has higher soil carbon levels, so it could be suggested that the gain would be less than on conversion of non-organic cropland to permanent grassland. However, it also possible – as suggested by the three comparative soil carbon studies on organic grassland – that organically managed permanent grassland has higher soil carbon levels than non-organic grassland and that the difference would therefore be (more or less) similar to that for conversion of non-organic cropland to grassland.

[749] Page 18, table 1-22, CEH *et al*, 2008 http://www.edinburgh.ceh.ac.uk/ukcarbon/docs/2008/Defra_Report_2008.pdf

[750] Jones and Donnelly, 2004, cited on page 59, CLIMSOIL report for the European Commission, December 2008.

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[751] Jones & Donnelly, 2004, cited on page 59, CLIMSOIL report for the European Commission, December 2008.

[752] Based on the soil C measurement data, if there is a sequestration rate of 0.5tc/ha over, say, 10 million ha of permanent grassland = 5 million tC/yr, compared to UK agriculture's official annual GHG emissions of 13.8million tC. Similarly, a modelling study estimated total soil C gains for the UK grasslands of 6million tC/yr using a figure of 670kgC/ha. The method used data for national grassland yields and levels of deposited manure, and UK decomposition rate data, to estimate C inputs and outputs; Janssens *et al*, 2009. The study ignored applied FYM/slurry and other management effects, so will not be totally reliable (though FYM application would just have a further positive effect). Also if it is not an estimate for the whole soil profile and has just consided the top soil layer (30cm or less), or if the decomposition rate data is not derived from the same sites that provide the productivity/deposition data, then this is unlikely to be reliable.

[753] Bellamy *et al*, 2005. Note, 'significantly' refers to significant in real/policy terms, not to statistical significance.

[754] Pulleman *et al*, 2000, found 14% higher SOC levels for grassland (3 comparisons). Shepherd *et al*, 2002, found 16% higher levels on grassland (6 comparisons; but its 'non-organic' samples were mostly unconverted fields on the organic farms rather than 'mainstream' non-organic grassland farms, so this could be conservative). Armstrong et al, 2000, found 11% lower SOC levels on grassland but just over double the topsoil depth.

[755] Conant *et al.*, 2001; 2005; Freibauer *et al.*, 2004; Conant and Paustian, 2002; Reeder *et al.*, 2004. CLIMSOIL report for the European Commission, December 2008.

[756] Conant *et al*, 2001, 2005; Conant & Paustian, 2002; Freibauer *et al*, 2004; Reeder *et al*, 2004. Cited in Smith *et al*, 2007.

[757] References for previous information: eg. Conant and Paustian, 2002; Fuhlendorf *et al*, 2002; cited in Baritz *et al*, 2004.

[758] For example: in North Wales, soil carbon density is believed to be significantly affected by the intensity of sheep grazing "Wales' carbon - managing climate change", by John Farrar, Chris Freeman and Davey Jones, University of Wales, Bangor, July 2003. Briefing paper for Welsh Assembly Government officials.

[759] B. Emmett, unpublished data; cited on page 91, CLIMSOIL report for the European Commission, December 2008.

[760] "Paper for information - Paper 8 – Livestock production subsidy schemes and cross-compliance provisions," Agricultural Use And Management Of Common Land Stakeholder Working Group, December 2002. http://www.defra.gov.uk/WILDLIFE-COUNTRYSIDE/issues/common/manage/pdf/swg2paper8.pdf

[761] Page 92, CLIMSOIL report for the European Commission, December 2008.

[762] Page 92, CLIMSOIL report for the European Commission, December 2008.

[763] Standard 8.2.4, Compendium of organic standards, 2006, Defra.

[764] The maximum number of livestock allowed per hectare cannot exceed that which would mean that on average more than 170kgN/ha are deposited on the land via the manure. This means there are maximum stocking levels for each type of animal. These are listed in Annex VII, Livestock Equivalance Table, Compendium of organic standards, 2006, Defra. http://www.defra.gov.uk/foodfarm/growing/organic/standards/pdf/compendium.pdf

[765] Email communication, Richard Young, 11 May 2009.

[766] Anna Bassett, Soil Association livestock adviser, oral communication, 16 July 2008.

[767] Agriculture in the United Kingdom 2006, and 2007, Defra.

[768] According to the UK organic standards," "composting" shall mean the process whereby materials are fermented aerobically in order to encourage the breeding of bacteria and to kill off weed seeds and pathogens. The heap should heat up to a temperature of at least 60°C." Compendium of Organic Standards, September 2006, Defra.

[769] "Ancient Wisdom Meets Modern Science - Studies & Advances in Composting," by Paul Hepperly, Ph.D. & Christine Ziegler Ulsh, ACRES USA, September 2007, Volume 37, no.9.

[770] Section 5.2.3, page 24, Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561.

[771] According to this recent review for the UK Government, contrary to their conclusions for other organic materials such as straw and biosolids, the authors considered that the use of compost probably does represent genuine additional carbon storage potential as compost additions are largely a result of diversions from landfill. Bhogal *et al*, 2007.

[772] 2007 data, UK Emissions of Carbon Dioxide, Methane and Nitrous Oxide by National Communication Source Category, http://www.defra.gov.uk/environment/statistics/globatmos/gagccukem.htm Landfill emissions have reduced 59% since 1990, but were steady since 2005. 2007 UK Greenhouse Gas emissions, final figures, 3 February 2009 - Statistical Release .

[773] Section 5.4.1, page 30, Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561.

[774] Phosphate (P) and potash (K) fertiliser prices have risen from around £150/t and £135/t respectively in 2005, to £500-700/t and £390-590/t respectively in 2008, to £640/t and £560/t in February 2009. Farmers Weekly on-line, fertiliser price reports, www.fwi.co.uk Eg. a farmer growing 100ha of potatoes may normally apply around 180kgP/ha, which at current prices means spending £11,500 a year on P fertiliser; "What will limit crop yields in the future?" presentation by Professor Carlo Leifert, Soil Association conference, November 2008, http://92.52.112.178/Web/SA/saweb.nsf/leifert_workshop5.pps

[775] Based on the results of four recent trials, 33.2t/ha of green waste compost (freshweight, or 21.6t/ha dryweight) applied in the absence of N fertiliser would produce an average carbon sequestration rate of 2.07tC/ha/yr in English conditions. With inorganic N fertiliser use, the sequestration rate of the compost was only an average of 880kgC/year. This compares to rates of 1,862 and 1,741kgC/ha/yr for conversion of farmland to woodland or biomass energy crops (willow). Table 5 and Section 6, Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561.

[776] Standard 4.7.38, Soil Association organic farming standards. When manure is stacked for several months it will rot slowly; if turned twice during this time, oxygen is introduced and the process is aerobic. Full composting involves more turning and usually a well-balanced mixture of organc residues (such as manure and crop residues).

[777] See section 5.2.

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[778] Oral communication, Peter Segger, organic farmer, Wales, chair of soil carbon workshop at Soil Association conference, 18 November 2008.

[779] Shepherd *et al*, 2002.

[780] Fließbach, A., and Mäder, P. (2000): Microbial biomass and size-density factions differ between soils of organic and conventional agricultural systems. *Soil Biology & Biochemistry* **32**, 757-768.

[781] Shepherd *et al*, 2002.

[782] For example: 1) The 18-year 'Market Garden experiment' comparing the effects of compost, FYM and biosolids on soil carbon levels, carried out on a sandy loam in Woburn, UK (1942+), in which compost achieved the best results. Section 2.1.1, "Soil Organic Matter: Its Importance in Sustainable Agriculture and Carbon Dioxide Fluxes," Edward Johnston, Paul R. Poulton, and Kevin Coleman, 2009, Chapter 1, Vol 101, Advances in Agronomy, *in press*. 2) In this 34-year study of soil and SOM formation, for nearly all years and nearly all SOM fractions studied, the carbon concentration was greatest for compost, then FYM, then straw and then inorganic fertiliser. Leinweber P & Reuter G, 1992. Cited in Sleutel *et al*, 2003.

[783] Results of the 'Market Garden experiment', Woburn,12% clay content soil, Johnston *et al*, 2009, *in press*. Two types of compost were tested, a vegetable compost and a biosolids/straw compost.

[784] Additionally, it is possible what is considered to be a good quality compost, ie. comprising a mix of plant and animal remains and with a mix of 'brown' and 'green' plant residues, would produce better results.

[785] Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561. The compost had a dry matter level of 65%.

[786] Crop residues produced soil carbon retention rates of 8%, 9%, 15%, and 14-21%, respectively in four US studies reviewed in Kong *et al*, 2005. C retention rates of 8% and 10% were found for wheat straw in a 7-year study in Ohio, US, Duiker & Lal, 1999. The average C retention rates of straw in the UK is 7%, Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561.

[787] Nine-year trial by US researchers from the Rodale Institute and USDA. References: 1. "Compost, Manure and Synthetic Fertilizer Influences Crop Yields, Soil Properties, Nitrate Leaching and Crop Nutrient Content," by Paul Hepperly, Don Lotter, Christine Ziegler Ulsh, Rita Seidel, and Carolyn Reider, October 2008. 2. "Ancient Wisdom Meets Modern Science - Studies & Advances in Composting," by Paul Hepperly, Ph.D. & Christine Ziegler Ulsh, ACRES USA, September 2007, Volume 37, no.9.

[788] Amount of compost applied was 14t/ha dry matter in years producing pepper crops (once every three years); additionally from 1992-1996, 29t/ha dry matter was applied in years producing maize crops.

[789] Presentation, "Reversing climate change – feeding the world," by Dr Paul Hepperly, Research Director, The Rodale Institute, Pennsylvania, at the IFOAM conference in Modena, Italy, 2008. Results of the Compost Utilization Trial, 1993 to 2002.

[790] One part dairy cattle manure and bedding (straw or newspapers) to 4 parts leaves, by volume; C:N ratio 18.8. A compost based on chicken litter was also trialled but did not have the same benefits, producing a soil carbon increase but from a lower starting level and ending with the same soil carbon level (2%) as the plots treated with inorganic fertiliser or raw manure. "Compost, Manure and Synthetic Fertilizer Influences Crop Yields, Soil Properties, Nitrate Leaching and Crop Nutrient Content," by Paul Hepperly, Don Lotter, Christine Ziegler Ulsh, Rita Seidel, and Carolyn Reider, October 2008.

[791] Table 10, "Compost, Manure and Synthetic Fertilizer Influences Crop Yields, Soil Properties, Nitrate Leaching and Crop Nutrient Content," by Paul Hepperly, Don Lotter, Christine Ziegler Ulsh, Rita Seidel, and Carolyn Reider, October 2008.

[792] "Ancient Wisdom Meets Modern Science - Studies & Advances in Composting," by Paul Hepperly, Ph.D. & Christine Ziegler Ulsh, ACRES USA, September 2007, Volume 37, no.9.

[793] "Ancient Wisdom Meets Modern Science - Studies & Advances in Composting," by Paul Hepperly, Ph.D. & Christine Ziegler Ulsh, ACRES USA, September 2007, Volume 37, no.9.

[794] Hepperly *et al*, 2008.

[795] Kong *et al*, 2005. See section 6.2 for more details.

[796] 1.85% in 1995, compared to 1.19% in 1992. Wells *et al*, 2000. See section 6.2.

[797] Wallace, 2005 & 2007; cited section 5.2.3 and table 5, pages 24-25, Bhogal *et al*, 2007, Defra Project SP0561.

[798] King *et al*, 2004. Cited in Section 6, Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561.

[799] 36t/ha freshweight (or 23t/ha dryweight) of green waste compost supplies 250kgN/ha; Table 2, page 18, Bhogal *et al*, 2007, Defra Project SP0561. Applications of organic matter to farmland in the UK and Europe are limited by the amount of N they supply. This is the UK situation. The Code of Good Agricultural Practice recommends a general N loading limit of 250kgN/ha/yr. However, for land within Nitrate Vulnerable Zones (NVZs), which now cover much of England, 250kgN/ha/yr (rolling year) is the new legal limit for all applications of organic materials, including compost, food waste and sewage sludge (but excluding manure deposited by grazing livestock). For the previously established NVZ areas (1996 and 2002), this limit has applied since the start of 2009, but for the newly designated NVZ areas, it applies from the start of 2010 (reference at end of this endnote). However, for livestock manures (excluding manure deposited by grazing livestock, but presumably including composted livestock manure), for all organic farmland and for non-organic farmers in NVZs, applications are limited to 170kgN/ha averaged over the whole farm area. There is an exception for grassland non-organic farms in the UK NVZs, whereby a 250kgN/ha limit applies to manure applications as long as no legumes, other than grass/legume mixtures, are grown in the rotation. "Field application of organic manures," Leaflet 8, Guidance for Farmers in Nitrate Vulnerable Zones," www.defra.gov.uk/environment/water/quality/nitrate

[800] Fließbach, A., H.R. Oberholzer, L. Gunst & P. Mäder, 2007, "Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming," Agriculture Ecosystems & Environment 118:273-284.

[801] This is based on a carbon loss rates of 20% for organic composting, and an average soil carbon conversion rate of 50% for composting in the absence of N fertiliser (Table 5, Bhogal *et* al, 2007). Thus, the amount of carbon in the original material used for composting that ends up as soil carbon is: 80% x 50% = 40% (ie. 5.7 times as much as the 7% carbon conversion rate for UK straw). Note, the conversion rates may be different for organic compost, so this is just a preliminary estimate.

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[802] To achieve a suitable C:N ratio, such as around 30:1.

[803] Email communication, 7 January 2009. Peter Segger, organic farmer, Wales, and chair of soil carbon workshop at Soil Association conference, 18 November 2008. The compost is made of: 30% manure (mostly local horse stables), 30%+ green waste (mostly from the farm), and the remainder is high-carbon inputs. The brown or carbon inputs are a mixture of wood chips from the farm and cardboard from local organic shops. The farmer conducts large numbers of SOM tests and monitors the volume of compost. Soil types are varied: medium loams, silty loams; average clay content is 18-23%.

[804] Oral communication, Pete Douglas, Soil Association Producer Services department, 3 September 2008.

[805] ADAS, "The Environmental Impact of Livestock Production – Review of research and literature," report for Defra, February 2008.

[806] http://www.bio.bris.ac.uk/research/insects/dung.html

[807] Lee C. M.; Wall R. Cow-dung colonization and decomposition following insect exclusion. Bulletin of entomological research, 2006, vol. 96, n°3, pp. 315-322.

[808] Wall R, Strong L: Environmental consequences of treating cattle with the antiparasitic drug ivermectin. *Nature* 1987, **327:**418-421.

[809] "Conservation considerations regarding the use of Avermection animal health products," RSPB Project Information Note, May 2006.

[810] Oral communication, Peter Melchett, Policy Director and organic farmer, Soil Association; and nods of agreement to this point from the audience, at soil carbon workshop, Soil Association conference, 18 November 2008.

[811] Macrocyclic Lactones in Antiparasitic Therapy By J. Vercruysse, Robert S. Rew. Published by CABI Publishing, 2003.

[812] Sommer *C,* Bibby BM (*2002*). The influence of veterinary. medicines on the decomposition of dung organic matter in. soil. Eur J Soil Biol 38:155–159.

[813] L. E. Iglesias, C. A. Saumell, A. S. Fernández, L. A. Fusé, A. L. Lifschitz, E. M. Rodríguez, P. E. Steffan, and C. A. Fiel. Environmental impact of ivermectin excreted by cattle treated in autumn on dung fauna and degradation of faeces on pasture. Parasitol Res (2006) 100:93– 102.

[814] Westergaard K, Muller AK, Christensen S, Bloem J, Sorensen SJ (2001) Effects of tylosin on the soil microbial community. *J Soil Biol Biochem* **33**: 2061–2071.

[815] 1. Wall R, Strong L: Environmental consequences of treating cattle with the antiparasitic drug ivermectin. *Nature* 1987, **327:** 418-421. 2. L. Strong, R. Wall, A. Woolford and D. Djeddour**.** The effect of faecally excreted ivermectin and fenbendazole on the insect colonisation of cattle dung following the oral administration of sustained-release boluses**.** Veterinary Parasitology Volume 62, Issues 3-4, April 1996, Pages 253-266.

[816] S D Wratten, A B Forbes. Environmental assessment of veterinary avermectins in temperate pastoral ecosystems. Annals of Applied Biology Volume 128 Issue 2, Pages 329 – 348**.** Published Online: 28 Jun 2008.

[817] Macrocyclic Lactones in Antiparasitic Therapy By J. Vercruysse, Robert S. Rew. Published by CABI Publishing, 2003.

[818] The research is summarised in: S-O Dimander**,** J Höglund and PJ Waller, Disintegration of Dung Pats from Cattle Treated with the Ivermectin Anthelmintic Bolus, or the Biocontrol Agent *Duddingtonia flagrans, Acta Veterinaria Scandinavica* 2003, 44**:**171-180.

[819] Albert Kollmann, Isabelle Touton, Agathe Brault, Michel Alvinerie, Pierre Galtier, and Christian Mougin. Effect of the endectocide ivermectin on filamentous fungi. Environmental Chemistry Letters (2004) 1:215–218.

[820] Macrocyclic Lactones in Antiparasitic Therapy By J. Vercruysse, Robert S. Rew. Published by CABI Publishing, 2003.

[821] Eg. the review: Reganold, John, P., Soil Quality & Profitability of Biodynamic & Conventional Farming Systems, Organic Farming & Biodynamic Agriculture Training resource book.

[822] Granstedt, A. & L. Kjellenberg, Organic and biodynamic cultivation - a possible way of increasing humus capital, improving soil fertility and providing a significant carbon sink in Nordic conditions. http://orgprints.org/12625/01/Granstedt_12625_ed.doc

[823] Koepf, H.H., 1981. The principles and practice of biodynamic agriculture. In: B.Stonehouse (Editror), Bioligical Husbandry, Butterworths, London, pp. 237 – 250. Cited in Nguyen *et al*, 1995.

[824] Annex IIA of the EU regulation: "Peat: Use limited to horticulture (market gardening, floriculture, arboriculture, nursery)."

[825] Soil Association standards 4.07.04 ("You may only use peat in propagating media, but you should use alternatives to peat where possible. Ideally these should be from sustainable UK produced materials"), 5.2.15 (in potted herbs and plants), and 7.01.04 (in mushroom production).

[826] Email communication, Rob George, Technical manager, Producer Certification, Soil Association, 10 August 2009.

[827] Email communication, Jim Aplin, organic grower, 7 August 2009.

[828] Email communication, Jim Aplin, organic grower, 7 August 2009.

[829] "Organic farming and climate change," UNCTAD/WTO report, 2007.

[830] "Carbon Sequestration and Trace Gas Emissions in Slash-and-Burn and Alternative Land-Uses an The Humid Tropics," C. A. Palm, TSBF; P. L. Woomer, University of Nairobi; J. Alegre, ICRAF; L. Arevalo, ICRAF; C. Castilla, D. G. Cordeiro, EMBRAPA; B. Feigl, CENA; K. Hairiah, Brawijaya University; J. Kotto-Same, IRAD; A. Mendes, EMBRAPA; A. Moukam, IRAD; D. Murdiyarso, BIOTROP; R. Njomgang, IRAD; W. J. Parton, Colorado State University; A. Ricse, INIA; V. Rodrigues, EMBRAPA; S. M. Sitompul, Brawijaya University; and M. van Noordwijk, ICRAF. ASB CLIMATE CHANGE WORKING GROUP, FINAL REPORT, PHASE II, Reprinted November, 2000, Nairobi, Kenya. This report is one of a series detailing results from the Alternatives to Slash-and-Burn (ASB) Programme, of the Consultative Group on International Agricultural Research (CGIAR). The ASB programme seeks to reconcile agricultural production and development with mitigation of the adverse environmental effects of deforestation. Research sites are located in humid tropical forest margins in Cameroon, Brazil, Peru, Indonesia and Thailand.

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[831] 1. Chadd S.A., Davies W.P. & Koivisto J.M., 2002. 'Practical production of protein for food animals', Protein sources for the animal feed industry, Expert Consultation and Workshop, FAO Animal Production and Health. 2. Bajjalieh N., 2002, 'Proteins from oilseeds', In**:** Protein Sources for the Animal Feed Industry. Expert consultation and workshop. Bangkok, 29 April - 3 May 2002; (Proceedings); FAO Animal Production and Health Proceedings, no. 1*; FAO Expert Consultation and Workshop on Protein Sources for the Animal Feed Industry*, Bangkok, 29 Apr - 3 May 2002 / FAO. Animal Production and Health Div. , 2004, p.141-159. 3. The two preceeding sources suggest that the soya meal (for animal feed) represents a large majority, 72%, of the value of the soya bean. The following suggested that feed use represents a lower level of around 60% of the value of soya, with soya oil for food representing the remaining 40%: oral communication, Tony Bell, BOCM Pauls, 25.9.2007.

[832] 1. "The Global GM Market, Implications for the European food chain," G.Brookes, N.Craddock & B.Kniel, 2005; 2. "Should we worry about soya in our food?" The Guardian, Felicity Lawrence, 25 July 2006.

[833] New Soil Association standard 4.1.4 says that, "Any land that was primary habitat or an area of High Conservation Value (HCV) after January 2007 must **not** be cleared or used for organic farming. Note – we will implement these standards for palm oil and its derivatives from 2011. For other products we will introduce a timeline for compliance when this standard is reviewed in 2011." (Previously, SA standards only prohibited the clearance of primary habitats on already certified land). The standard will be implemented by the use of a positive list of approved suppliers of organic palm oil and derivatives. This year, to inform the organic industry, Soil Association certification is writing to all producers and licencees that use or trade in these ingredients, and to all organic certification bodies that control the suppliers in the relevant countries. The list of approved suppliers will be drawn up in 2010, and it will be required to be used from 2011. The same process will start for soya in 2010.

[834] Independent newspaper list of all companies and supermarkets, and their policies on palm oil: http://www.independent.co.uk/environment/green-living/big-brands-palm-oil-policy-1677480.html

[835] Many researchers have observed a significant relationship between soil erodibility and aggregate stability (Wischmeier & Mannering, 1969), and that aggregate stabilty increases significantly with organic C content (Kemper & Koch, 1966). Cited in Mulla *et al*, 1992.

[836] Huntington, 2006. Cited in: Hepperly, Paul Reed Ph.D, "The Impact of Agriculture and Food Systems on Greenhouse Gas, Energy Use, Economics and the Environment," The Rodale Institute.

[837] Mäder, P., A. Fließbach, A. Dubois, L. Gunst, P.Fried & U. Niggli, 2002, "Soil fertility and biodiversity in organic farming," Science 296:1694-1697.

[838] "Soil Association- How Organic Farming Delivers Biodiversity," http://www.beechenhill.co.uk/PDF/204_How_org_delivers_bio.pdf

[839] "Winter Cover Crops", Charles B. Sperow, January,1995, West Virginnia University Extension Service.

[840] "Managing soil" subsection of the Soil Association organic standards (Soil Association, 2005).

[841] Peter Melchett, Policy Director and organic farmer, Soil Association, email communication, 6 October 2009.

[842] Oral communication, Pete Douglas, Soil Association Producer Services department, 3 September 2008.

[843] "The State of Scotland's Farmed Environment," 2005. http://www.macaulay.ac.uk/LINK/

[844] Bhogal *et al*, 2009, Scientific Report for Defra Project SP0561.

[845] Section 5.3, Bhogal, A.,. Chambers, B.J., Whitmore, A.P. &. Powlson, D.S. (2007). *The effects of reduced tillage practices and organic material additions on the carbon content of arable soils.* Scientific Report for Defra Project SP0561.

[846] "Soils can only increase carbon sequestration up to a point. Retained carbon increases until it reaches a new equilibrium state that reflects the new management environment." Curbing Greenhouse Gases: Agriculture's Role, Bruce A. McCarl, Professor , Department of Agricultural Economics, Texas A&M University.

[847] Eg. clay particles and calcium are needed for carbon sequestration . Oral communication, Dr Paul Hepperly, New Farm Training and Research Manager, The Rodale Institute, Pennsylvania, 9 January 2005, at the Soil Association's annual conference in Newcastle.

[848] For instance, a 30% increase means a soil that initially had 50tC/ha would have sequestered 15t of carbon, but a soil with 80tC/ha would have sequestered 24t of carbon.

[849] Volume 4, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, IPCC, 2007. http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html

[850] eg.1. The average topsoil SOC content of cultivated land in England and Wales was 2.8% in 1995 (Webb *et al*, 2001). 2. The average soil carbon content of Scottish arable soils is around 3.6% (Scottish Soils database. Jan Dick, Pete Smith, Ron Smith, Allan Lilly, Andrew Moxey, Jim Booth, Colin Campbell, Drew Coulter, "Calculating farm scale greenhouse gas emissions," 2008.

[851] Cool climates with heavy annual rainfall enhance the accumulation of soil organic matter. Løes & Øgaard, 1997.

[852] Batjes NH 1999. Management options for reducing CO2-concentrations in the atmosphere by increasing carbon sequestration in the soil. Report 410±200±031, Dutch National Research Programme on Global Air Pollution and Climate Change & Technical Paper 30, International Soil Reference and Information Centre Wageningen.

[853] "Arable soils are relatively depleted in carbon and so have the potential to increase greatly if managed carefully," presentation by Professor Pete Smith & Annette Freibauer, "The Carbon Cycle in European Arable Land." http://www.bgc-jena.mpg.de/public/carboeur/workshop/files/Arable_Freibauer.pdf

[854] Section 1, Baritz *et al*, 2004, Task group 5 Land Use Practices and SOM, http://ec.europa.eu/environment/soil/pdf/vol3.pdf.

[855] These are the actual carbon sequestration rates of organic farming, not the rates relative to the non-organic systems, which might be slightly lower as the non-organic systems also gains small amounts in the K-trial and FST trial, and marginal amounts in the LTRAS and Michegan University trials, but lost more carbon than the organic system in the DOK trial. However, the rate for the Michegan trial is likely to be a large under-estimate given that only the top 7.5cm of the soil was sampled. For a review of

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the comparative effects such as this, ideally only comparative data would be considered. However, the relative sequestration rates are not normally reported by researchers. This shows a weakness of using sequestration data unlike the % differences in soil carbon levels that were reviewed in Chapter 6, which are always the comparative effect.

[856] For the 28 years to 2005, the average change in soil carbon levels per ha/year are reported as: -207kgC/ha/yr for the inorganic fertiliser-only plots, -123kgC/ha/yr for the organic plots, -84kgC/ha/yr for the integrated plots, while the biodynamic plots gained +42kgC/ha/year. However, the starting soil carbon levels varied as follows: 1.6% for the 'intensive non-organic' and biodynamic, c.1.5% for the organic, and 1.4% for the integrated. Mäder, P., Fliessbach, A., Dubois, D., Gunst, L., Jossi, W., Widmer, F., Oberson, A., Frossard, E., Oehl, F., Wiemken, A., Gattinger, A., Niggli, U. (2006): The DOK experiment (Switzerland). In the book: Long-term field experiments in organic farming. Raupp, J., Pekrun, C., Oltmanns, M., Köpke, U. (eds.). pp 198. Koester, Bonn. Cited in,"Low Greenhouse Gas Agriculture: Mitigation And Adaptation Potential Of Sustainable Farming Systems," FAO, May 2008. Author's note: although these figures have been cited in other reports, since all systems ended with the same soil carbon levels except the biodynamic system, the differences should be ascribed to the different starting levels, not the impacts of the systems, except for the biodynamic system, so really a sequestration rate of 0kgC/ha/yr would be more representative of the organic system. Also, relative to the inorganically fertilised plots (which started with the same soil carbon level), the biodynamic plots actually gained 249kgC/ha/yr. However, for consistency, as all the other figures in this table are of the absolute rates of carbon sequestration, not the rates relative to the non-organic systems, we have not cited these more positive figures.

[857] Pimentel *et al*, 2005. Table 2, Hepperly *et al*, 2006. Note, different figures have been cited for this. Figures of 1,218kg, 857kg, and 217kg are the mean rate of three recent years (2002, 2004, 2006), not the average over the trial.

[858] Robertson G.P., E.A Paul & R.R. Harwood, 2000, "Greenhouse Gases in Intensive Agriculture: Contributions of Individual Gases to the Radiative Forcing of the Atmosphere," Science, Vol 289, pages 1922-1925, 15 September 2000. www.sciencemag.org. Calculation by Soil Association: 29-soil C/(19-fuel + 56-N20) x100 = 39%.

[859] The farm has been running an organic system (legume-based, with livestock density of 1.4LUs/ha) and a non-organic system (continuous cropping, inorganic fertiliser of 145N/ha/yr) since 1990. Different figures have been reported for the soil carbon sequestration/loss levels, perhaps representing different years: 1) The organic was sequestering 180kgC/ha/yr and the non-organic losing 120kgC/ha/yr, cited in: "Low Greenhouse Gas Agriculture: mitigation and adaptation potential of sustainable farming systems," FAO April 2009, rev.2 - 2009; reference: Rühling *et al.* 2005 (in German). 2) The organic was sequestering 370kgC/ha/yr, and the non-organic losing 250kgC/ha/yr, according to the researchers Küstermann *et al*, 2008.

[860] Küstermann, B., Wenske, K. and Hülsbergen, K.-J. (2007): Modellierung betrieblicher C- und N-Flüsse als Grundlage einer Emissionsinventur [Modelling carbon and nitrogen fluxes for a farm based emissions inventory]. Paper presented at Zwischen Tradition und Globalisierung - 9. Wissenschaftstagung Ökologischer Landbau, Universität Hohenheim, Deutschland, 20-23.03.2007. Archived http://orgprints.org/9654/ Cited: "Organic farming and climate change," UNCTAD/WTO report, 2007. Note, the offset would probably have been larger: the organic system suffered from low yields (43% less than the non-organic system) as it was sited on poorer soil than the non-organic system (reference: "Low Greenhouse Gas Agriculture: mitigation and adaptation potential of sustainable farming systems," FAO April 2009, rev.2 – 2009).

[861] Cited in: "Low greenhouse gas agriculture: mitigation and adaptation potential of sustainable farming systems," FAO May 2008. Reference: Küstermann, B., Kainz, M., Hülsbergen, K.-J. (2008): Modeling carbon cycles and estimation of greenhouse gas emissions from organic and conventional farming systems. *Renewable Agriculture and Food Systems* **23**, 38-52.

[862] We calculate that UK cultivated land contains an average of **81.6tC/ha** in the 0-30cm layer (compared to 67tC/ha for English arable soils). This was derived by calculating that 63% of the 0-1m soil carbon in UK cropland occurs in the top 30cm, which was derived by using the % of C in the 0-30cm out of the total 0-1m depth cropland C stock for each UK country (page 18, table 1-22, CEH *et al*, 2008) and weighting these by the size of the carbon stock in each UK country (page 17, CEH *et al,* 2008). Applying this 63% to the total 738million tC in UK cropland (Page 17, table 1-21, CEH *et al*, 2008), gives a carbon stock of 465milliontC for the 0-30cm layer of UK cultivated land, or 465milliontC/5.7 million ha = 81.6tC/ha.

[863] The top 0-30cm of 'all' cropland soils in England contains 67tC/ha; page 18, CEH *et al*, 2008.

[864] UK arable area is 5.7 million ha: "Agriculture in the United Kingdom, 2007," Defra.

[865] This is almost 8 times UK agriculture's official annual GHG emissions (13.8MtC/yr). In 2007, as an end user, UK agriculture was officially responsible for 50.6million tCOe, which x44/12 is 13.8million tC/yr (2008 UK Greenhouse Gas emissions, provisional figures, 26th March 2009 - Statistical Release; Annex B- Emissions of all greenhouse gases, carbon dioxide, methane and nitrous oxide by source and end-user, Defra.)

[866] 64million/20 years = 3.2milliontC/yr.

[867] According to the IPCC soil carbon guidelines, typically, for continuously cropped land in cool, moist, temperate regions, clay soils have 59-66tC/ha in the top 30cm (85-95t x 0.69 factor for annual cropping), sandy soils have around 49tC/ha (71t x 0.69 factor for annual cropping).

[868] In 2007, as an end user, UK agriculture was officially responsible for 50.6million tCOe, which x12/22 is 13.8million tC/yr (2008 UK Greenhouse Gas emissions, provisional figures, 26th March 2009 - Statistical Release; Annex B- Emissions of all greenhouse gases, carbon dioxide, methane and nitrous oxide by source and end-user, Defra.)

[869] http://www.decc.gov.uk/en/content/cms/publications/lc_trans_plan/lc_trans_plan.aspx

[870] We calculate that UK cultivated land contains an average of 81.6tC/ha in the 0-30cm layer (compared to 67tC/ha for English arable soils). This was derived by calculating that 63% of the 0-1m soil carbon in UK cropland occurs in the top 30cm, which was derived by using the % of C in the 0-30cm out of the total 0-1m depth cropland C stock for each UK country (page 18, table 1-22, CEH *et al*, 2008) and weighting these by the size of the carbon stock in each UK country (page 17, CEH *et al,* 2008). Applying this 63% to the total 738million tC in UK cropland (Page 17, table 1-21, CEH *et al*, 2008), gives a carbon stock of 465milliontC for the 0-30cm layer of UK cultivated land, or 465milliontC/5.7 million ha = 81.6tC/ha. If we had used this figure

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of 81.6tC/ha (instead of the lower figure for the top 18cm of English cropland), then a 28% increase would mean a total sequestration of 0.28 x 81.6/20 = **1.14tC/ha/yr** and 0.28 x 465 million =130.2 million t of C, or **6.5 milliontC/year for UK over 20 years**, double our estimates of 563kgC/ha/yr and 3.2milliontC/year.

[871] Page 18, Table 1-22, CEH *et al*, 2008. This figure for 'all' English grassland, 0-30cm, is likely to give an underestimate of the average tC/ha increase with organic farming, as the tC/ha in the top 30cm of grassland is higher in Scotland and Northern Ireland than in England, though it is lower in Wales.

[872] There is 6.0million ha of grassland over 5 years old in the UK, excluding rough grazing. Table 3.1, Agriculture in the United Kingdom, 2008, Defra.

[873] 12.45 x 6.0million ha = 74,700,000tC extra in UK managed grasslands. The area of grassland over 5 years, excluding rough grazing is 6.0million ha; Table 3.1, "Agriculture in the United Kingdom, 2008," Defra.

[874] Janssens *et al*, 2003; cited on page 59, CLIMSOIL report for the European Commission, December 2008. http://ec.europa.eu/environment/soil/pdf/climsoil_report_dec_2008.pdf

[875] UK methane emissions per dairy cattle per year are: 105kg from enteric fermentation plus 25.8kg from manure (based on average cattle weight 577kg). Assuming a stocking level of 2 dairy cattle per ha, this means dairy cattle release: 2 x (105 + 25.8) x 21 (conversion factor for methane to C02) x 12/44 (conversion to carbon equivalent) = 1,498kgCeq/ha/yr of methane. So, grassland would give an offset of 670/1498 x 100 = 45% offset. Beef cattle emissions are 39% of those of dairy cattle, per animal. Reference for methane emission data for cattle from page 374, Annexes of the UK Greenhouse Gas Inventory, 2007: http://www.airquality.co.uk/reports/cat07/0905131425_ukghgi-90-07_Annexes_Issue2_UNFCCC_Final.pdf

[876] 560kgC x44/12 = 2,053kgCO2eq. CO2eq means the total warming effect of all greenhouse gas emissions (CO2, nitrous oxide and methane) expressed in terms of the amount of carbon dioxide that would have the same effect.

[877] Using Cranfield's August 2007 figures for organic crops/t, kgCO2eq: wheat – 620; oilseed rape: 1,310; potatoes: 180. Assuming that energy use accounts for following proportion of total organic GWP: wheat: 14%; oilseed rape: 19%; potatoes: 49% (Williams *et al*, 2006). We reduced the energy use by 15%, which gives the following reduced GHG figures for organic crops : wheat: 620 – (0.15 x 0.14 x 620) = 607; oilseed rape: 1,310 – (0.15 x 0.19 x 1310) = 1,273; potatoes: 180 – (0.15 x 0.49 x 180) = 167.

[878] in 2006, the average organic farming yields of all English regions were 5.1t/ha for wheat. This probably under-estimates the national average organic farming wheat yield as this figure is not weighted by production levels in each region; if the NE and NW regions are excluded, the average of 5.4t/ha for wheat may be more representative, we assume. In 2006, the average organic yields for potato production in three English regions (the only regions for which there was data) was 28t/ha. Page 31, "England and Wales under organic agriculture – How much food could be produced", University of Reading, 2009. For oilseed rape, we assumed that UK organic yields would be 35% less than UK average yields for oilseed rape of 3.4t/ha (Agriculture in the United Kingdom, 2007, Defra), ie. 2.2t/ha. Taking the inverse of these yields give areas of: wheat 0.185ha/t, oilseed rape 0.454ha/t, and potatoes 0.036ha/t.

[879] Based on production data used by Cranfield University, see Tables 37 & 38, Williams *et al*, 2006.

[880] "Feed and Food, Statistical Yearbook 2004," European Feed Manufacturers Federation (FEFAC), 2005.

[881] One tonne of maize produces a total 836kg of co-products (including 241kg of 21% protein gluten feed), so each t of co-products requires 1000/836 = 1.2t of maize. Iowa Corn at http://www.iowacorn.org/cornuse/cornuse_3.html Cited in: "Maize International Market Profile," page 9, FAO, http://siteresources.worldbank.org/INTAFRICA/Resources/257994-1215457178567/Maize_Profile.pdf

[882] US organic yields compared to non-organic: maize – 6% less (69 sets of data); soya – 6% less (55 sets of data). Survey of results of replicated farming trials from seven state universities and two independent research facilities, for different parts of the US, including rain-fed and irrigated regions, Bill Liedhardt, University of California.

[883] 0.96 x US soya yield average of 2.8t/ha = 2.69t/ha. 0.96 x US maize yield average of 8.8t/ha = 8.45t/ha. Note, yields may be lower from other regions but a higher assumption of yield gives a more conservative soil C sequestration figure.

[884] 550kgC x 44/12 = 2,017kgCO2eq.

[885] Pig and poultry production has greatly increased in western societies, and more recently in many developing societies, with the development of intensive indoor livestock systems producing cheap white meat and eggs (at great cost to animal welfare). Under widespread organic farming, there would be a large reversal in the production of these products. Based on the production records of 176 organic farms, an initial assessment of one scenario of food production under widespread organic farming in England and Wales has concluded that chickenmeat and pork production would fall by around 70%, and eggs by 27%. "England and Wales under organic agriculture: how much food could be produced?", by Philip Jones with Richard Crane **,** Centre for Agricultural Strategy, Policy and Development, University of Reading, see Press Release, 24 June 2009, http://www.rdg.ac.uk/about/newsandevents/releases/PR21951.asp

[886] Bhogal, A., Chambers, B.J., Whitmore, A.P. &. Powlson, D.S. (2007). *The effects of reduced tillage practices and organic material additions on the carbon content of arable soils.* Scientific Report for Defra Project SP0561.

[887] The authors best estimate is that the adoption of min-till practices temporarily raises soil carbon levels by around 160kgC/ha/yr for 3 or 4 years, in English and Welsh conditions. This implies a total temporary SOC increase of 480-640kgC/ha, or an increase of just around 1% of the total arable soil carbon level during those 3-4 years (eg. 0.64tC increase on 60tC/ha soil = +1.1%). If, on average, the arable land subject to min-till is roughly half-way to this level at any one time, this suggests that the actual effect of the adoption of min-till is an increase in the arable soil carbon store on this land of just 0.5% of the total, or so.

[888] King, J.A., R.I. Bradley, R. Harrison, and A.D. Carter. 2004, "Carbon sequestration and saving potential associated with changes to the management of agricultural soils in England." Soil Use and Management 20:394-402.

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[889] P. Smith, R. Milne, D.S. Powlson, J.U. Smith, P. Falloon, K. Coleman, Revised estimates of the carbon mitigation potential of UK agricultural land, Soil Use and Management, Vol. 16, No. 4, ages 293-295, 2000. Published on-line 19 January 2006.

[890] Due to the combined effects of: the growing unpredictability of seasonal weather, droughts, crop damage by torrential rain and flooding events, shortages of water for irrigation, and the spread of pests and disease. Plus the effects of other major imminent threats to agricultural production: depletion of 'fossil water' aquifers that supply irrigation water in several major agricultural regions (eg. USA and India), 'Peak Oil' impacts on fertiliser prices, and tightening P and K fertiliser supplies.

[891] An initial assesment of food production under widespread organic farming England and Wales, based on one scenario from the production records of 176 organic farms, has concluded that chickenmeat and pork production would fall by around 70%, and eggs by 27%, while red meat production could increase considerably (beef +68%, lamb +55%), and there would be as much cereals for human consumption as is available now and 43% more potatoes. "England and Wales under organic agriculture: how much food could be produced?", by Philip Jones with Richard Crane , Centre for Agricultural Strategy, Policy and Development, University of Reading. See Press release, 24 June 2009, http://www.rdg.ac.uk/about/newsandevents/releases/PR21951.asp

[892] eg. Williams et al, 2007; UK Cormack & Metcalfe, 2000; Pelletier et al, 2008; Pimentel, 2006; Pimental et al, 2005.

[893] See section 7.17.

[894] FAO, 2002, "World agriculture towards 2015/30". Summary report. ISBN: 9251047618 FAO, Rome.

[895] Original concept and calculation provided by Craig Sams. Note, this does not take account of the fact that a large increase in the global arable area is forecast [which would mean more losses of carbon from land use change, but a greater soil carbon storage value from widespread organic farming instead of non-organic farming]; Bruinsma JE., Ed. Agriculture: Towards 2015/2030. A FAO Perspective. London: Earthscan; 2003. p. 432.

[896] 1.5billion tC/yr is 11.2% of the total global annual anthropogenic GHG emissions of 13.4tC billion tCeq by man's activites: in 2004, global GHG emissions were 49.0billiontCO2eq; Figure 2.1, page 36, IPCC 4th Assessment Report:Climate Change 2007:Synthesis Report, http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf This 11% offset figure of all anthropogenic GHG emissions assumes no increase or decrease in emissions in future. The precise offset % in future years will depend on the level of GHG emissions and any changes in the biological capacity of the soil to sequester carbon. If, as should and will hopefully happen, GHG emissions progressively decline in future, this offset figure will increase in proportion to the decline in emissions. If, however, as is feared, rising temperatures reduce the ability of soils in some regions to store carbon (see 4.3), then this would reduce the global average sequestration rate and counter the positive effects (on the level of the offset) of declining emissions. Improvements in farming practices will be another factor.

[897] The world's soils are estimated to have lost around 44 billion tonnes of carbon (tC) since 1850, see section 4.1.

[898] IPCC (Intergovernmental Panel on Climate Change) 2007. Synthesis Report. In Metz, O.R.D., Bosch, P.R., Dave, R., Meyer, L.A. (ed.). Fourth Assessment Report: Climate Change 2007. Cambridge University Press, Cambridge, United Kindom and New York, NY, USA.

[899] There have been many comparative studies of organic farming energy use, eg. Williams et al, 2007; Cormack & Metcalfe, 2000 (Energy use in organic farming systems, MAFF project OF0182); Pelletier et al, 2008; Pimentel, 2006; Pimental et al, 2005.

[900] "Organic farming offers a very high mitgation potential in particular regarding nitrogen and N2O, since this type of agriculture is claimed to be self-sufficient in nitrogen due to a highly efficient recycling of manures fom livestock and crop residues by composting as as well as use of leguminous crops to deliver additional nitrogen. The obligatory ban on mineral nitrogen, the reduced livestock units per hectare and the diversified crop rotation with manure leads to reduced emissions of nitrous oxide." Ana Frelih-Larsen, Anna Leipprand, Sandra Naumann (Ecologic) and Olivier Beucher(Baastal), 2008, "Background Paper for Stakeholder Consultation Workshop Climate Change Mitigation in Agriculture – Policy Options for the Future June 2008." See PICCMAT project website: http://www.climatechangeintelligence.baastel.be/piccmat/files/PICCMAT_policy_paper_June08.pdf

[901] The four other analyses of the global soil C sequestration potential of agriculture are: IPCC (1996, TAR); Lal , 2003 – 2004a); IPCC (2000; SR-LULUCF); and Manne & Richels, 2004. The range quoted is taken from Table 7, Smith *et al*, 2007.

[902] Smith P., Martino D., Cai Z., Gwary D., Janzen H.H., Kumar P., McCarl B., Ogle S., O'Mara F., Rice C., Scholes R.J., Sirotenko O., Howden M., McAllister T., Pan G., Romanenkov V., Schneider U., Towprayoon S., Wattenbach M. and Smith J.U. Greenhouse fas mitigation in agriculture. *Philosophical Transactions of the Royal Society of London Series B Biological Sciences* (2008) 363, 789-813. Published on-line 6 September 2007.

[903] For details about the flaws in current soil carbon models, see sections 4.5 and 9.3.

[904] Watson RT, Noble IR, Bolin B, Ravindranth NH, Verado D, Dokken DJ., Eds. IPCC Special report on Land Use, Land-Use Change, and Forestry. Cambridge: Cambridge University Press; 2000. p. 377. Cited by Minnen *et al*, 2008. Since the date of this estimate, there has been a finding that trees and other vegetation apparently also emit significant quantities of methane, possibly accounting for 10-30% of global methane emissions; research by the Max Planck Institute in Heidelberg, Germany, published in Nature and corroborated by studies of the Amazon. "Plants revealed as methane source," 11 January 2006. http://news.bbc.co.uk/1/hi/sci/tech/4604332.stm. Author's note: if confirmed this might reduce the presumed soil carbon sequestration potential of forestry by a few percentage (20% of the 15% of global warming currently due to methane = 3%. 3% compared to the sequestration potential of global plantations over the long-term of about 50% of projected cumulative GHG emissions, is 3/50 x 100 = 6%. This level of methane emissions is from the existing vegetation, however, and presumably the proposed plantations would not add as much again, so any reduction is likely to be less than 6%).

[905] eg. The UK's Stern Review (www.sternreview.org.uk) warned that unless action is taken within the next 10-20 years, the environmental damage caused by climate change later in the century could cost between 5 and 20% of global GDP every year.

[906] Jelle G van Minnen, Bart J Strengers, Bas Eickhout, Rob J Swart, and Rik Leemans, Quantifying the effectiveness of climate change mitigation through forest plantations and carbon sequestration with an integrated land-use model, Carbon Balance Manag. 2008; 3: 3, Published online 2008 April 15.

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[907] The disappearance of humus is hastened in warm and moist climates, which explains why most tropical soils are so poor in organic matter and suffer from both lack of good structure and available nutrients. Tiessen, H., Cuevas†, E., Chacon, P., 2002. The role of soil organic matter in sustaining soil fertility. Nature 371:783-785. Cited in, "Humus", Wikipedia.

[908] Also, page 118: "Banse and Grethe (2008) used the ESIM model to forecast the impact of a 10% target for biofuels on production and demand for biofuels within the EU. … Results indicate that a substantial part of the policy-induced demand for biofuels is likely to be met by imports of biofuels and biofuel substrates, especially following the implementation of a potential Doha agreement. In particular, imports of plant oils were forecast to increase. … globally there are particular concerns about biofuel production from palm oil. … The authors conclude that 'In the long run, the political perspective for biofuels in the EU is questionable." And from page 119: "." Section 7.4, page 118 and 119, CLIMSOIL report for the European Commission, December 2008. http://ec.europa.eu/environment/soil/pdf/climsoil_report_dec_2008.pdf

[909] For example, Drinkwater *et al*, 1995 (US study of organic and non-organic tomato-producing farms found no difference in yield levels); Garcia *et al*, 1989 (study of biodynamic and non-organic avocado plantations, the yields of biodynamic plantation were "good" for the area), and Melero *et al*, 2006 (Spanish trial of vegetable production, 66% higher yields per ha with organic farming). There was no difference in organic and non-organic farming tomoto yields in a survey of results of replicated farming trials from seven state universities and two independent research facilities, for different parts of the US, rain-fed and irrigated areas, Bill Liedhardt, University of California. Also, a report by Reading University found that UK organic sugar beet yields are 9% higher than non-organic farming: "England and Wales under organic agriculture: how much food could be produced?", by Philip Jones with Richard Crane , Centre for Agricultural Strategy, Policy and Development, University of Reading. See Press release, 24 June 2009, http://www.rdg.ac.uk/about/newsandevents/releases/PR21951.asp.

[910] For example, the estimated Global Warming Impact is much lower for potatoes (0.16tCO2e/t product) than arable crops (0.6tCO2e/t), white meat and eggs (4-5tCO2e/t), and very much lower than red meat (16tCO2e/t) – results of Cranfield University's Life Cycle Analysis for Defra, August 2007. Draft figures received by email from Cranfield University, August 2007, intermediate results from the project,"Developing and delivering environmental Life-Cycle Assessment (LCA) of agricultural systems", Defra project (IS0222), an updated version of the earlier LCA study Williams *et al*, 2006.

[911] For example, Wells *et al*, 2000. See section 6.2.

[912] Under the IPCC soil carbon guidelines, horticultural land is given the lowest default soil carbon level for cropland, 8% lower level than continuously cropped arable land. The use of any organic matter input practice would raise the level to 'medium', the same as continuously cropped land, but no higher. Table 5.5, Volume 4, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, IPCC, 2007. Note, as organic management would almost certainly raise the actual level much more than this, these guidelines greatly under-estimate the positive soil carbon impact of organic horticulture.

[913] Johnston *et al*, 1998, Table 8. Cited in section 2.1.2, Johnston *et al*, 2009, *in press*.

[914] Koerber G R, Edwards-Jones G, Hill P W, Milà i Canals L, Nyeko P, York E H, Jones D L. (2009). Geographical variation in carbon dioxide fluxes from soils in agro-ecosystems and its implications for life-cycle assessment, *Journal of Applied Ecology, 46, 306–314*. [Note, the soil carbon balances (annual soil carbon inputs minus losses) estimated by this study for different field crops appear be unreliable, as the same national figure for soil carbon losses by heterotrophic soil respiration was used for all crops and all three UK locations, ignoring the site-specific factors which influence soil carbon losses (soil clay and water content, temperaures and existing SOC levels) and despite using crop/site-specific figures for the rest of the inputs/outputs calculation, so the soil carbon losses would have been over- or under-estimated in most of the cases.]

[915] Armstrong Brown *et al*, 2000; Melero *et al*, 2006; Garcia *et al*, 1989; Drinkwater *et al*, 1995 (organic field horticulture vs. non-organic vegetable/arable systems); and Wells *et al*, 2000. See section 6.2.

[916] Smith, A., Watkiss, P., Tweddle, G., McKinnon, A., Browne, M., Hunt, A., Treleven, C., Nash, C. & Cross, S. (2005) *The Validity of Food Miles as an Indicator of Sustainable Development*, Final Report produced for Defra. AEA Technology Environment, Oxon , UK.

[917] For 16 comparisons, 3 studies in Northern Europe. Pulleman *et al*, 2000, found a 14% higher soil carbon (SOC) content for organic grassland in the Netherlands (3 comparisons). Shepherd *et al*, 2002, found a 16% higher SOC content for fields on 6 predominantly grassland organic farms, compared to unconverted fields (mostly on the same organic farms, ie. the differences may not represent the general differences between the organic and non-organic sector). Armstrong Brown *et al*, 2000, found a 11% lower SOC content but twice the depth of topsoil for 7 organic and non-organically managed permanent pasture sites in the UK (suggesting overall more soil carbon storage). See section 6.2.

[918] These reasons are: 1) lower average grazing levels in organic systems, 2) the use of deeper-rooting plant species in organic managed grasslands such as red clover, 3) perhaps greater levels of soil organisms (eg. fungal mycorrhizae and earthworms), 4) non-use of inorganic fertilisers which tends to reduce plant root growth, 5) greater level of permanent grassland, and 6) avoidance of avermectin wormers which might be affecting dung decomposition. The effect of the important differences in manure management are not clear: on the one hand, organic farming involves lower manure production/application rates per hectare of grassland (lower stocking rates and manure from livestock housing transferred arable land) but, on the other hand, a higher proportion of the manure is in solid form (deposited manure from grazing animals and application of farmyard manure) rather than slurry, and also the applied manure will be spread more evenly over the grassland area in organic farming. Another possible difference could be in the effects of using more grazing as opposed to more cutting for silage, such as if one practice is better at promoting root growth than the other. It could be considered that N fertiliser use might have a positive effect on topsoil carbon levels (even if not necessarily on total soil carbon levels) by increasing grass biomass production in the topsoil. Actually, organic and non-organic grass productivity is similar if a sufficiently high clover percentage is maintained, and it is the difference in root biomass that is relevant. A long-term UK trial found that the use of N-fertiliser on grass has the same effect on topsoil carbon levels as grazed grass-clover (the trial used sheep grazing and cattle grazing might have a different effect); 36-year Rothamsted 'Ley-arable experiment', Johnston *et al*, 2009, *in press*. On the other hand, Dutch researchers have found that high

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rates of N fertiliser reduce soil carbon increases [high rates are often used in NW European dairy farming], compared to low to moderate N fertiliser rates, as root growth is greater in conditions of N stress; Vandasselaar & Lantinga, 1995.

[919] Comprising: 5,965,000ha managed grass over 5 years ('improved' grass not in an arable rotation), 4,313,000ha private rough grazing, and 1,238,000ha common rough grazing = 11,516,000 ha. Agriculture in the United Kingdom, 2007, Defra.

[920] Based just on the results of the NSI survey, Bellamy *et al*, 2005. Limitations in the methodology, such as the non-measurement of soil depth or soil density, mean the results need to be treated with caution. Eg. if there has been widespread soil compaction due to over-grazing during the period of the survey then, at the re-sampling stage, the 15cm samples would have included a greater proportion of lower-carbon soil from the deeper layer, reducing the average carbon content and giving the impression of small but widespread soil carbon losses. The subject therefore needs further research.

[921] Bengtsson J, Ahnstrom J, Weibull AC (2005) "The effects of organic agriculture on biodiversity and abundance: a meta-analysis," *Journal of Applied Ecology*, 42, 2, 261-269.

[922] According to the East African Standard for organic farming, trees shall be present and hedges should be encouraged; East African Community 2007. The Pacific Organic Standard requests properties over 5 hectares to set aside a minimum of 5% of the certified area for wildlife, unless the property is following a traditional agroforestry or polyculture approach; Secretariat of the Pacific Community 2008. Pacific organic standard. Prepared by the Regional Organic Task Force.

[923] For example, in this tropical study, the total biomass produced rose from 8.2tC/ha/season for growing okra alone to 16.4rC/ha/season for inter-cropping of okra and cucumber; while the yield/hectare rose 59%; average of results of two spacing treatments and two seasons. "Biological efficiency of intercropping in okra (Abelmoschus esculentus (L.) Moench), Susan Anna John and C. Mini, Journal of Tropical Agriculture 43 (1-2): 33-36, 2005.

[924] For example, growing a mixture of three barley varieties produced a biomass/hectare increase of 5-6% after 100 days and a yield increase of 2%. Preliminary BAR-OF-WP4 report on,"Do nutrient uptakes and grain yields differ between spring barley varieties grown for organic farming as mono-crop and in mixture? Characteristics of spring barley varieties for organic farming", Niels Erik Nielsen, Ingrid Kaag Thomsen and Jørgen Berntsen. Experimental details in Nielsen *et al*, 2003.

[925] Presentation slides by Thomas Harttung, from Denmark, at soil carbon workshop, Soil Association, 18 November 2008.

[926] Poulton *et al*, 2003. Cited in Johnston *et al*, 2009, *in press.*

[927] There is a "long period needed to compensate for emissions through the establishment of the plantations" and this is greater in northern latitudes because of the slower growth rates; Minnen *et al*, 2008. Author's note: in Europe, for example, new plantations require: growing and transporting the sapling, fencing the area, weeding and thinning. Presumably, these establishment emissions are greater in Europe than, say, in less industrialised countries. This is presumably less of an issue with individual trees and farm woodlands (less weeding and thinning?) but it may nevertheless take years before sequestration starts.

[928] Bhogal, A., Chambers, B.J., Whitmore, A.P. &. Powlson, D.S. (2007). *The effects of reduced tillage practices and organic material additions on the carbon content of arable soils.* Scientific Report for Defra Project SP0561.

[929] 1. "Conversion to organic management may be a way to increase soil C sequestration. However increases in SOM derived from use of organic amendments, crop rotation, and legumes might be undercut by organic systems' reliance on tillage," Macilwain, 2004; cited in Mariott & Wander, 2006. 2. "Organic farming, despite its emphasis on building organic matter, was thought to actually endanger soil because it relies on tillage and cultivation." In," Organic Farming Beats No-Till?," by Don Comis, 10 July 2007. Article on USDA Agricultural Research Service website, http://www.ars.usda.gov/is/pr/2007/070710.htm

[930] SOM contributes to favourable soil structure, thus improving rooting patterns and soil aeration. Pulleman *et al*, 2000.

[931] Teasdale *et al*, 2007.

[932] Balesdent et al, 2000, Relationship of soil organic matter dynamics to physical protection and tillage, Soil and Tillage Research, Volume 53, Issues 3-4, February 2000, Pages 215-230.

[933] Mineralisation is the conversion of nutrients in the organic form (i.e. stored in SOM) into inorganic forms - unpublished paper on soil carbon and organic farming, provided to the Soil Association by Dr Julia Cooper, Newcastle University, 9 October 2007. SOM 'oxidation' is when soil carbon is converted to atmospheric CO2.

[934] Peter Melchett, Policy Director and organic farmer, Soil Association, 7 October 2009.

[935] See point 9.2 on minimum tillage.

[936] In 2007, 71% of the UK organic farmland area was permanent grass and 16% was temporary grass; Organic Food and Farming Market report, Soil Association, 2007. This high level of permanent grass is, however, greatly exaggerated by the fact that there is a large imbalance in the UK organic sector, with a much higher rate of grassland (ruminant livestock) farmers having so far converted to organic farming than arable farmers. Nevertheless, the fact that organic 'arable' farmers are based on mixed systems with livestock (usually mainly or including ruminants) should mean that many organic 'arable' farms have some permanent grassland as well and so there should (inherently) be a higher level of permanent grass with organic farming, than non-organic farming. Farms which raise predominantly ruminant livestock farmers will tend to have a high proportion of permanent grass.

[937] Armstrong Brown *et al*, 2000; Liebig & Doran, 1999; Gardner & Clancy, 1996; Wells *et al*, 2000. Liebig & Doran said there was less frequent tillage on the five organic farms they studied compared to five non-organic farms, in Nebraska & North Dakota. Gardner & Clancy said that the use of reduced tillage had widely replaced the plough in the region studied (North Dakota, Great Plains), but the three conventional farms in their study used more tillage than the organic farms. In the vegetable production trial in Australia by Wells *et al*, the organic and non-organic systems were designed to represent commercial practices; the organic system used minimum tillage while the non-organic 'District Practice' system used multiple tillage (rotary-hoe); the researchers remarked that "conventional vegetable farming often involves repeated tillage." See section 6.2.

[938] 1. Organic Arable Farming Trial Gladbacherhof, Hesse, Germany, 1998- : Schulz, F., Brock, C. & Leithold, G.**, "**Effects of Farm Type and Different Intensities of Soil Tillage on Cash Crop Yields and Soil Organic Matter**,"** proceedings of the 2nd ISOFAR-

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Conference in Modena in 2008 (Vol.1, pp. 580+). 2. A comprehensive survey of the effects of ploughing in 7 long-term organic farming trials in Germany: Manuel Krawutschke, Einfluss differenzierter Bodenbearbeitung auf Gehalt und Dynamik der organischen Bodensubstanz in Ackerböden sowie deren Bedeutung für die Humusbilanzierung, January 2007; the full publication can be downloaded at http://geb.uni-giessen.de/geb/volltexte/2007/4516/; an English summary was published in the proceedings of the 10th "Wissenschaftstagung Oekologischer Landbau"Zurich, 2009, http://orgprints.org/13987/ ("total C quantity did not differ significantly between tillage treatments in all trials even though a high C accumulation in the reduced tillage system was visible in one trial."). Note, the Gladbacherhof trial was one of the seven trials in this survey.

[939] Chan *et al*, 2002; Sainju *et al*, 2002; Clapp *et al*, 2000; Franzluebbers *et al*, 1994; Doran *et al*, 1980. Cited in Rasse *et al*, 2005.

[940] Cited in Rasse *et al*, 2005.

[941] Van Meirvenne M Pannier J Hofman G & Louwagie G 1996. Regional characterisation of the long-term change in soil organic carbon under intensive agriculture. Soil Use and Management 12, 86-94.

[942] In this Danish survey, there was an overall increase in arable soil carbon levels. The increase was nearly all occurring in the 25-50cm depth of the sandy soils (below the standard sampling depth). The SOC gains were occurring in the coarse sandy soils, which were receiving more cattle manure and had more grass and catch crops in the rotation than the loamy soils, which were losing carbon. This management difference also implies that the coarse soils were being ploughed more than the loamy soils, to incorporate the manure, grass and cover crops. Thus, an explanation for the finding that the increase was occurring in the deeper soil layer, as opposed to the top soil layer or at all, is that perhaps the deep incorporation of organic matter by ploughing or an increase in the depth of ploughing had resulted in more soil carbon entering the deeper soil layers, increasing the total soil carbon store. An alternative explanation could be the deep deposition of carbon from the grass and cover crop roots. Tove Heidmann, Bent T. Christensen and Svend E. Olesen, "Changes in soil C and N content in different cropping systems and soil types," in "Greenhouse Gas Inventories for Agriculture in the Nordic Countries," Proceedings from an international workshop, Helsingør, Denmark 24-25 January 2002.

[943] Soil degradation due to tillage and water erosion is common in Mediterranean cereal-growing regions and has been shown to be linked with decreased levels of SOC. Masciandaro and Ceccanti, 1999; Evrendilek et al., 2004. Cited in D.L. Boellstorff, Estimated soil organic carbon change due to agricultural land management modifications in a semiarid cereal-growing region in Central Spain, Journal of Arid Environments 73 (2009) 389–392.

[944] See section 6.2 for more details of these studies.

[945] Marriott & Wander, 2006. Note, although most of the organic systems in the trials were using more intensive tillage methods than the organic systems, it should be noted that this did not involve mouldboard ploughing in all cases, and in at least two trials, the organic systems used min-till methods. See section 6.2 for other details.

[946] The general adoption of the mouldboard plough (which turns the topsoil over to one side) appears to have accompanied the adoption of the three-field system in the late eight and nineth century in Europe. White, *Medieval Technology*, pp. 69-78.

[947] Soils under cultivation have historically lost about 1% of their carbon each year. "Carbon Sequestration in Organic Maize/Soybean Cropping Systems," Paul Hepperly, Jeff Moyer, David Pimental, David Douds Jr., Kristine Nichols & Rita Seidel, paper for the 16th IFOAM Organic World Congress, Modena, Italy, June 16-20, 2008. Archived at http://orgprints.org/view/projects/conference.html

[948] Soils under permanent vegetation cover in general have higher SOM levels, partially due to the higher residue inputs (roots and exudates). Baritz *et al*, 2004, Task group 5 Land Ue Practices and SOM, http://ec.europa.eu/environment/soil/pdf/vol3.pdf.

[949] Section 3.1.2, page 15, "Soil Organic Matter: Its Importance in Sustainable Agriculture and Carbon Dioxide Fluxes," Edward Johnston, Paul R. Poulton, and Kevin Coleman, 2009, Chapter 1, Vol 101, Advances in Agronomy, *in press*.

[950] In England and Wales, soil cultivation is mainly by deep (mouldboard) ploughing to 20-25cm, followed by secondary cultivations (eg. harrowing, powered tillage and discing/tining) to create a seedbed for drilling. Minimum tillage or min-till involves just the use of these secondary cultivation types, while zero tillage or no-till involves no cultivation and the seeds are either directly drilled into the soil or are broadcast over the soil surface. Bhogal *et al*, 2007, Defra Project SP0561.

[951] Bhogal, A.,. Chambers, B.J., Whitmore, A.P. &. Powlson, D.S. (2007). *The effects of reduced tillage practices and organic material additions on the carbon content of arable soils.* Scientific Report for Defra Project SP0561.

[951] Defra, oral communication in meeting with Defra soil policy and research team, 8 May 2007.

[952] Bhogal, A.,. Chambers, B.J., Whitmore, A.P. &. Powlson, D.S. (2007). *The effects of reduced tillage practices and organic material additions on the carbon content of arable soils.* Scientific Report for Defra Project SP0561. 48 pp.

[953] According to Cranfield University, for non-organic bread wheat and oilseed rape, the ratios are: ploughing 50-57%, 'min-till' 41-45% and 2-5% for no-till (direct drilling). However, we believe the levels are lower – see below. Table 19, Williams, A., Audsley, E., Sandars, D. 2006. "Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities." Main Report. Defra Research Project IS0205.

[954] For example, the Stern report on the economics of climate change in 2006 cited reduced tillage as a means of increasing the storage of carbon in agricultural soils, citing the example of 4-year+ commitments on the Chicago Climate Exchange.

[955] 294 pounds/acre/year, according to this meta-analysis of no-till systems. West, T.O., and G. Marland. 2002. New carbon fl ux from agricultural ecosystems: methodology for full carbon analyses. Env. Poll. 116:439-444.

[956] Oral communication, Dr Paul Hepperly, Research Director, The Rodale Institute,, International conference "Organic agriculture and climate change," Enita Clermont, France, 17-18 April 2008. It has been estimated that conventional no-till can offset around 10% of the world's current carbon emissions, "Developments in Organic No-Till Agriculture - The Best of Both Worlds?," by Paul Hepperly, Jeff Moyer & Dave Wilson, ACRES U.S.A., September 2008, pages 16-19.

[957] See Michegan University example below.

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[958] Balesdent *et al*, 2000, Relationship of soil organic matter dynamics to physical protection and tillage, Soil and Tillage Research, Volume 53, Issues 3-4, February 2000, Pages 215-230.

[959] Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561.

[960] Both studies cited in Berner *et al*, 2008.

[961] Assuming a minimum soil carbon level of 40tC/ha: 2/40 x 100 = 5%.

[962] Barker *et al*, 2007, cited in Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561.

[963] Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561.

[964] 1. The soil carbon level was similar over a depth of 60cm after 10 years of conservation tillage at eight sites; Angers *et al*, 1993. 2. Vanden Bygaart *et al*, 2002, Rücknagel *et al*, 2003; cited in "The Role of Organic Agriculture in Mitigating Climate Change - a Scoping Study," by Johannes Kotschi and Karl Müller-Sämann, IFOAM, February 2004.

[965] Robertson G.P., E.A Paul & R.R. Harwood, 2000, "Greenhouse Gases in Intensive Agriculture: Contributions of Individual Gases to the Radiative Forcing of the Atmosphere," Science, Vol 289, p. 1922-1925, 15 September 2000. www.sciencemag.org

[966] Baritz *et al*, 2004, task group 5 Land Use Practices and SOM, http://ec.europa.eu/environment/soil/pdf/vol3.pdf.

[967] Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561.

[968] 1. Gilley & Doran, 1997; cited in Baritz *et al*, 2003, Task group 5 Land Use Practices and SOM. 2. Angers, D.A., N'dayegamiye, A., Coˆte´ , D., 1993. Tillage-induced differences in organic matter of particle-size fractions and microbial biomass. Soil Sci. Soc. Am. J. 57, 512–516. Cited in Berner *et al*, "Crop yield and soil fertility response to reduced tillage under organic management", Soil & Tillage Research 101 (2008) 89–96.

[969] Angers *et al*, 1993; cited in Berner *et al*, 2008.

[970] Page 5.19, Volume 4, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, IPCC, 2007.

[971] Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561.

[972] Goulding *et al*, 2007, have completed a 2-year study measuring CO2 fluxes by Eddy Covariance from adjacent ploughed and reduced tillage fields in Hertfortshire, and found the CO2 emissions from the ploughed fields were 35% more than from the reduced tillage fields. Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561.

[973] Because of the build-up of weed and disease problems, and soil compaction, the use of no-till is limited to specific crops and specific soil conditions in the UK, such as oilseed rape on heavy soils. Bhogal *et al*, 2007, Defra Project SP0561.

[974] If the adoption of min-till practices temporarily raises soil carbon levels by around 160kgC/ha/yr for 3 or 4 years, in English and Welsh conditions, this implies a total temporary SOC increase of 480-640kgC/ha, or an increase of just around 1% of the total arable soil carbon level during those 3-4 years (eg. 0.64tC increase on 60tC/ha soil = +1.1%). If, on average, the arable land subject to min-till is roughly half-way to this level at any one time, this suggests that the actual effect of the adoption of min-till is an increase in the arable soil carbon store on this land of just 0.5% of the total, or so.

[975] For instance, a study in England found that the N20 emissions increased five-fold by an amount equivalent to 170kgC02-C/ha/yr (210 versus 40 kg/haCO2-C/yr for ploughed fields), Goulding *et al*, 2007, cited in Bhogal *et al*, 2007.

[976] "Nationally, SOC in arable/ley soils showed a pattern of greater decreases with increasing soil wetness, except for the wettest soils, which showed no change in SOC." J. Webb, P. J. Loveland, B. J. Chambers, R. Mitchell and T. Garwood, "The impact of modern farming practices on soil fertility and quality in England and Wales," Journal of Agricultural Science, Cambridge (2001), **137**, 127–138.

[977] Baritz *et al*, 2004, task group 5 Land use Practices and SOM, http://ec.europa.eu/environment/soil/pdf/vol3.pdf.

[978] Although there are concerns about the system's heavy reliance on herbicides.

[979] Uptake of reduced tillage in Europe is mainly in the southern, semi-arid area [presumably because of the water conservation benefits]. Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561.

[980] For instance, based on data from all the tillage experiments in organic farming systems, Hampl (2005) concluded that occasional use of the mouldboard plough is inevitable for weed control. Cited in: Berner *et al*, 2008.

[981] A dense layer of soil below the topsoil that is impervious to water, causing water-logging.

[982] Mackay & Kladivko, 1985; Berry & Karlen, 1993. Both cited in Pulleman *et al*, 2003.

[983] Using deep curved tines to crumble the soil without turning it over and 'duck-feet' hoes for weed control; oral communication, Richard Gantlett, biodynamic farmer, 18 November 2008. See article "The Ploughless Farmer," Organic Farming magazine.

[984] See section 6.2 and previous point on Ploughing for more details.

[985] See section 6.2 for details.

[986] Teasdale, J.R., C.B. Coffmann & Ruth W. Magnum (2007): Potential Long-Term Benefits of No-Tillage and Organic Cropping Systems for Grain Production and Soil Improvement. Agronomy Journal: 99, 1297-1305.

[987] Teasdale *et al*, 2007. Cited, Niggli et al, FAO, April 2009.

[988] Table 4, Teasdale *et al*, 2007.

[989] The organic system had 28% lower maize yields than the non-organic system, which is significant as US organic cereal yields are normally very close to non-organic levels. Additionally, it was choked by weeds after the 9 years, so presumably the system could not be continued much longer. The Rodale Institute, which has since been taking this work forward, has very good experience with producing organic systems that have comparable yields to non-organic systems.

[990] "Carbon Sequestration in Organic Maize/Soybean Cropping Systems," Paul Hepperly, Jeff Moyer, David Pimental, David Douds Jr., Kristine Nichols & Rita Seidel, paper for the 16th IFOAM Organic World Congress, Modena, Italy, June 16-20, 2008. Archived at http://orgprints.org/view/projects/conference.html.

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[991] A comprehensive survey of the effects of ploughing in 7 long-term organic farming trials in Germany: Manuel Krawutschke, Einfluss differenzierter Bodenbearbeitung auf Gehalt und Dynamik der organischen Bodensubstanz in Ackerböden sowie deren Bedeutung für die Humusbilanzierung, January 2007; http://geb.uni-giessen.de/geb/volltexte/2007/4516/ An English summary was published in the proceedings of the 10th "Wissenschaftstagung Oekologischer Landbau"Zurich, 2009, http://orgprints.org/13987/ ("total C quantity did not differ significantly between tillage treatments in all trials even though a high C accumulation in the reduced tillage system was visible in one trial.")

[992] Organic Arable Farming Trial Gladbacherhof, Hesse, Germany, 1998-: Schulz, F., Brock, C. & Leithold, G.**, "**Effects of Farm Type and Different Intensities of Soil Tillage on Cash Crop Yields and Soil Organic Matter**,"** proceedings of the 2nd ISOFAR-Conference in Modena in 2008 (Vol.1, pp. 580+).

[993] Berner, A., Hildermann, I., Fließbach, A., Pfiffner, L., Niggli, U., Mäder, P. (2008): Crop yield and soil fertility response to reduced tillage under organic management. *Soil & Tillage Research* 101, 89-96. Cited in: Niggli, U., Fließbach, A., Hepperly, P. and Scialabba, N. 2009, Low Greenhouse Gas Agriculture: Mitigation and Adaptation Potential of Sustainable Farming Systems. FAO, April 2009, Rev. 2 – 2009. Note, the site has a very high soil clay content of 45%.

[994] Soil Association figure, based on the reported increase of 2tC/ha over 2 years and 5.5 months.

[995] Berner *et al*, 2008.

[996] Niggli *et al*, 2009, FAO, Rev. 2 – 2009. It is not clear if this is a more recent result than reported in Berner *et al*, 2008.

[997] Table 5, Berner *et al*, 2009. This was not statistically significant so the authors stated that vertical burrowing earth-worms were "not influenced" by the tillage system. But it would be more correct to say that there was no *proof* that they were.

[998] 1,717kg/yr vs. 1,624kg/yr. Table 2, Berner *et al*, 2009.

[999] Peter Melchett, Policy Director of the Soil Association and organic farmer, email communication, 5 November 2009, following a visit to FiBL.

[1000] This is a statement that is mainly encountered in the agricultural industry. However, many researchers make similar statements. For example, "Studies have shown that increase in SOC levels are directly linked to the return of fresh organic material to the soil … Agronomic practices that influence crop yields and, therefore, affect the proportion of crop residues returned to the soil, are likely to influence C levels in agricultural soils." Kong *et al*, 2005. Soil carbon modelling is currently also based on this assumption – see statements below.

[1001] 1**.** "Most studies agree that mineral fertilization increases yield, consequently litter input, and consequently SOM." Baritz *et al*, 2004, Task group 5 Land Practices and SOM. 2. Paustian, K., O. Andren, H.H. Janzen, R. Lal, P. Smith, G. Tiad, H. Tiessen, and M. Van Noordwijk, 1997. "Agricultural soils as a sink to mitigate CO_2 emissions," Soil Use and Management 13:230-244. 2.

[1002] For instance, all of these modelling studies are mainly based on the concept that the soil carbon input to the soil is proportional to the crop yields: Janssens *et al*, 2005; Zaehle *et al*, 2007; Smith *et al*, 2005; and Gervois *et al*, 2008.

[1003] This refers more clearly to the time since the introduction of inorganic fertilisers; previously yields were dependent on fertile soils and so there tended to be a positive correlation between soils with high organic matter levels and yields, although methods (such as N-fixing crops) were gradually developed to enhance the ability of soils to produce good yields.

[1004] For the yield results of the trial, see Fig.1, Guide to the Classical and other Long-term Experiments, Datasets and Sample Archive, Rothamsted Research, http://www.rothamsted.bbsrc.ac.uk/resources/ClassicalExperiments.html. For the soil carbon results, see Figure 3, page 12, "Soil Organic Matter: Its Importance in Sustainable Agriculture and Carbon Dioxide Fluxes," Edward Johnston, Paul R. Poulton, and Kevin Coleman, 2009, Chapter 1, Vol 101, Advances in Agronomy, *in press*. The yields stayed steady in all of the plots for most of the trial but started to rise sharply after a hundred and twently years (due to the introduction of new varieties and pesticides). However, the soil carbon levels showed a completely independent response, increasing significantly in the *first 70 years* on the plots receiving only farmyard manure (and rising gently thereafter), while showing *no change* on the inorganically fertilised plots during the whole trial, even though these were producing the highest yields by the end. It should be pointed out that the straw was baled and removed from all plots, although the input from stubble and root biomass remained (but this is very unikely to explain the results – see point below about crop residues).

[1005] As well as the standard application rates, all treatments were trialled at x1.5 application rates as well. See text and figure 18.1, Christensen, B.T. & Johnston, A.E. (1997) Soil organic matter and soil quality – Lessons learned from long-term experiments at Askov and Rothamsted. In: *Soil Quality for Crop Production and Ecosystem Health.* Developments in Soil Science 25, 349-430.

[1006] Baritiz *et al*, 2004, Task group 5 Land Use Practices and SOM..

[1007] Cited in Baritz *et al*, 2004, Task group 5 Land Use Practices and SOM. See also IPCC, 2000.

[1008] Baritz *et al*, 2004, Task group 5 Land Use Practices and SOM, http://ec.europa.eu/environment/soil/pdf/vol3.pdf.

[1009] See section 5.5 and Chapter 7 (eg. sections 1, 4, 5 & 6).

[1010] Smith *et al*, 2007.

[1011] For instance, Alvarez, 2005. Cited in Smith *et al*, 2007.

[1012] Irrigation in arid and semi-arid regions may increase soil carbon by 50-150gkC/ha/yr; Lal *et al*, 1998 – cited by Baritz *et al*, 2004. However, because irrigation can enhance decomposition, the increase "could be partially offset"; Baritz *et al*, 2004.

[1013] Only if the total soil carbon level was as low as 42tC/ha, would 2.1tC/ha be a 5% increase. 2.1/42 x 100 = 5%.

[1014] Cited in "The Role of Organic Agriculture in Mitigating Climate Change - a Scoping Study," by Johannes Kotschi and Karl Müller-Sämann, IFOAM, February 2004.

[1015] Glending & Powlson, 1995. Cited in email communication, Pete Smith, Royal Society-Wolfson Professor of Soils & Global Change, Institute of Biological and Environmental Sciences, University of Aberdeen; 21 November 2008.

[1016] For instance, in this recent review for the UK Government, it was reported that 'topsoil organic carbon increases … [have been] measured following both the application of organic manures and inorganic fertilisers," page 18, Bhogal *et al*, 2007. Of the

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three references quoted, two referred to the Askov and Rothamsted trials (see above). In the third reference (the only one to find an increase), one site found an 8% increase over 11 years with inorganic fertiliser use, and another site found no effect. This interpretation may have arisen from the fact that inorganic fertiliser use usually produces a higher soil carbon level than unfertilised soils, but that is not the relevant comparison for UK agricultural situations.

[1017] Vandasselaar AV & Lantinga EA, 1995, Modeling the carbon cycle of grassland in the Netherlands under various management strategies and environmental conditions, Netherlands Journal of Agricultural Science 43, 183-194. Cited in Baritz *et al*, 2004.

[1018] "Ancient Wisdom Meets Modern Science - Studies & Advances in Composting," by Paul Hepperly, Ph.D. & Christine Ziegler Ulsh, ACRES USA, September 2007, Volume 37, no.9.

[1019] Ingrid Hartmann, Hailu Araya & Sue Edwards, "Food security, Livelihoods and Options for Organic Agriculture in Ethiopa," paper presented at the "International Conference on Organic Agriculture and Food Secuity," 3-5 May, 2007, FAO, Italy. ftp://ftp.fao.org/paia/organicag/ofs/OFS-2007-INF-rev.pdf

[1020] Obviously, there are many developing country regions where farmland is currently unfertilised, but all attempts to improve agricultural production methods would anyway be based on a major improvement in soil fertility, ideally by organically-fertilised agro-ecological methods.

[1021] US organic yields compared to non-organic: maize – 6% less (69 sets of data); soya – 6% less (55 sets of data). Survey of results of replicated farming trials from seven state universities and two independent research facilities, for different parts of the US, including rain-fed and irrigated regions, Bill Liedhardt, University of California.

[1022] Ingrid Hartmann, Hailu Araya & Sue Edwards, "Food security, Livelihoods and Options for Organic Agriculture in Ethiopa," paper presented at the "International Conference on Organic Agriculture and Food Secuity," 3-5 May, 2007, FAO, Italy. ftp://ftp.fao.org/paia/organicag/ofs/OFS-2007-INF-rev.pdf

[1023] Soil respond linearly to increasing rates of residue or carbon additions, in both short- and long-term experiments. Eg. studies cited in Kong *et al*, 2005.

[1024] Rasse, D.P., Rumpel, C. & Dignac, M.F. 2005. Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. Plant and Soil, 269, 341-356.

[1025] Rasse *et al*, 2005.

[1026] Some studies have even found that maize and wheat tend to decrease soil aggregate stability. See studies cited in Puget & Drinkwater, 2001.

[1027] Page 285. Shepherd M.A., Harrison R., Webbs J., 2002: Managing soil organic matter – implications for soil structure on organic farms. Soil Use and Management no. 18, 284-292.

[1028] At least in non-organic systems. See studies cited in Puget & Drinkwater, 2001.

[1029] For instance, all of these modelling studies are mainly based on the concept that the soil carbon input to the soil is proportional to the crop yields: Janssens *et al*, 2005; Zaehle *et al*, 2007; Smith *et al*, 2005; and Gervois *et al*, 2008.

[1030] Puget & Drinkwater, 2001.

[1031] The reference given for this assumption is Sylvester-Bradley *et al,* 2002. UK Emissions by Sources and Removals by Sinks due to Land Use, Land Use Change and Forestry Activities, Report, June 2007. Centre for Ecology & Hydrology, University of Aberdeen, Forest Research Alice Holt, National Soil Resources Institute, Centre for Terrestrial Carbon Dynamics (Universities of Sheffield, Edinburgh, York & University College London), Agri-Food & Biosciences Institute, Queen's University Belfast.

[1032] This study attempted to predict the long-term effects of organic and non-organic management on soil carbon levels, using the CENTURY model; it used measurements of the harvested crop yields as an indicator for the level of crop biomass returned to the soil. The study used standard parameters of crop and grass biomass production developed for the CENTURY model (Table 1, from Metherell *et al*, 1993) and then, apparently, adapted these using yield data from a long-term farming trial. However, the farming trial was not an organic farming trial and the same initial parameters were used for the organic and non-organic systems. This is clearly a major factor in the study's predictions: the researchers say, "As correct prediction of production level is important for the accuracy of the soil organic matter predictions, future development of the model should be focussed on improving the crop growth model." Bente Foereid and Henning Høgh-Jensen, "Carbon sequestration potential of organic agriculture in northern Europe – a modelling approach", Nutrient Cycling in Agroecosystems 68: 13–24, 2004.

[1033] For example, "Environmental Footprint and Sustainability of Horticulture (including potatoes) - a comparison with other agricultural sectors", by the University of Warwick, Best Foot Forward, HDRA and Robert Gordon, 2007. To include soil carbon in its CO2 balance in way that is consistent with the approach, one would presumably need to compare the average per ha carbon storage level of the farming system with that of forestry.

[1034] An exception might be the REPRO soil model, which has been recently developed in Germany and validated by data from a long-term comparative organic farming trial – see section 6.5.

[1035] Defra, oral communication in meeting with Defra soil policy and research team, 8 May 2007.

[1036] Baritz *et al*, 2004, Task group 5 Land Use Practices and SOM, http://ec.europa.eu/environment/soil/pdf/vol3.pdf. Earlier in the report, however, the authors appear to recognose some positive aspects of livestock production, with the statement, "Traditional practices to restore SOM from rotational principles in combined livestock-farming systems have been lost."

[1037] Drinkwater *et al*, 1998.

[1038] Hepperly, P.R., D. Douds, Jr. & R. Seidel*,* 2006, "The Rodale Institute Farming Systems Trial 1981 to 2005: long-term analysis of organic and conventional maize and soybean cropping systems", p. 15-31. Chapter in: J. Raupp, et al., eds. Long-term Field Experiments in Organic Farming. International Society of Organic Agriculture Research (ISOFAR), Bonn, Germany.

[1039] See summary in section 6.2.

[1040] See section 6.2.

[1041] Carter, 2002; Parton et al, 1996. Cited in Fließbach, A., H.R. Oberholzer, L. Gunst & P. Mäder, 2007, "Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming," Agriculture Ecosystems & Environment 118:273-284.

[1042] The rates of soil carbon accumulation in this report are from on a database of results of long-term experiments.

[1043] Table 12, page 35, Bhogal *et al*, 2007, Defra Project SP0561. This is supported by many other sources – see Chapter 7

[1044] Fließbach, A., H.R. Oberholzer, L. Gunst & P. Mäder, 2007, "Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming," Agriculture Ecosystems & Environment 118:273-284.

[1045] Fließbach *et al*, 2007

[1046] Rasse, D.P., Rumpel, C. & Dignac, M.F. 2005. Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. Plant and Soil, 269, 341-356.

[1047] Puget & Drinkwater, 2001.

[1048] Most of the information in this paragraph is from Shepherd *et al*, 2002 and Puget & Drinkwater, 2001. Information on the ability of root carbon and crop residues to affect soil carbon levels, and more information on lignin, is from Rasse *et al*, 2005.

[1049] Puget & Drinkwater, 2001.

[1050] Drinkwater, L.E., Wagoner, P., Sarrantonio, M., 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature 396, 262–264.

[1051] Galvez *et al*, 1995. Cited in Pimental *et al*, 2005.

[1052] Mineralisation is the conversion of nutrients in the organic form (ie. in SOM) into inorganic forms.

[1053] Concern expressed in meeting with Defra soil policy and research team, 8 May 2007.

[1054] Only in one study was a lower level found for organic farming compared to non-organic farming, but the difference was very small (4% less) and not statistically significant, so this may have been simply due to natural variation and an artifact of the uncertainties in the study, rather than a product of organic farming.

[1055] 1. In a comparison of an organically managed field and a non-organically managed field, Marinari *et al* (2007) found a 70% higher soil microbial biomass and 76% higher labile SOM level on the organic field and that the soil under organic management was characterised by a rapid mineralization of labile SOM, which is released from SOM turnover. 2. Vazquez *et al* (2003) observed faster decomposition of SOM due to higher metabolic activity and abundance of soil decomposers with organic farming (cited by Marinari *et al*, 2007). 3. Armstrong Brown *et al*, 2000 (page 38) state, "There is also evidence for … a faster rate of decomposition of SOM and nutrient release" in organic farming. 4. See also the study Drinkwater *et al*, 1995, for supporting evidence (findings of a higher microbial activity and a three times greater N-mineralisation potential than on non-organic farms).

[1056] 1. According to Wander *et al*, 1994, an active soil microflora and a considerable pool of accessible nutrients are two important priorities in organic farming; cited by Marinari *et al*, 2007. 2. "Greater microbial activity or biomass have been found in a variety of cropping systems under ORG management (Bolton et al. 1985, Doran et al. 1987, Reganold et al. 1993, Wander et al. 1994; Scow et al., *in press*) reflecting the increased role of decomposers in determining N availability in ORG [organic] systems"; Drinkwater *et al*, 1995. 3. "In organic farming systems, where no inorganic N is applied with fertiliser, N availability is heavily dependent on the mineralisation of organic N compounds," Freidel *et al*, 2000.

[1057] "Jenkinson and Ladd (1981) have demonstrated a close positive association between soil organic C and N levels and soil microbial biomass." Cited in Fraser *et al*, 1988.

[1058] Sparling, 1997. Cited in Breland, T.A., and R. Eltun. 1999. Soil microbial biomass and mineralization of carbon and nitrogen in ecological, integrated and conventional forage and arable cropping systems. Biol. Fertil. Soils 30:193–201.

[1059] This study in California found that indicators of active soil carbon fractions "were three times greater" in the organic as the non-organically managed soils, yet the organic soils produced 28% higher SOM levels; Drinkwater *et al*, 1995, though the researchers said this could be due to either greater total C inputs or greater retention of soil C during decomposition. See the long-term trials by the Rodale Institute and Kong *et al*, 2005 for evidence of a higher soil carbon stabilisation rate compared to non-organic farming.

[1060] Korschens *et al*, 1998; cited by Shepherd M.A., Harrison R., Webbs J., 2002: Managing soil organic matter – implications for soil structure on organic farms, Soil Use and Management no. 18, 284-292. Also Tate, 1987; cited by Marinari *et al*, 2007.

[1061] Email communication, Pete Smith, Royal Society-Wolfson Professor of Soils & Global Change, Institute of Biological and Environmental Sciences, University of Aberdeen; 21 November 2008.

[1062] Elliott, 1986; Oades, 1988. Cited in: Puget P. & L.E.Drinkwater, Short-term dynamics of root-and shoot-derived carbon from a leguminous green manure, Soil Sci. Soc. Am J.. 65:771-779 (2001).

[1063] See Chapter 2 and section 7.6.

[1064] Langley & Hungate, 2003. Rasse *et al*, 2005.

[1065] Cited in Shepherd et al, 2002.

[1066] Several studies have now shown that soil aggregation strongly influences soil carbon sequestration, and carbon cycling. Chaney & Swift, 1984; cited in Shepherd *et al*, 2002. Also, Tisdall & Oades, 1982; Jastrow, 1996; Six *et al*, 1998; Gale *et al*, 2000; Puget *et al*, 2000; Denef *et al*, 2004; all cited in Kong *et al*, 2005.

[1067] See section 6.2 for more details and references of all studies mentioned here.

[1068] Average of 1,280kgC/ha of microbial biomass carbon on the organic farms, vs. 889kgC/ha on the non-organic farms, for the top 30.5cm of soil. See Table 6 and page 1607, Liebig & Doran, 1999.

[1069] The rhizosphere is the ecologically distinct zone that exists around plant root hairs and which has, for instance, a higher microbial activity than the rest of the soil.

[1070] Page 1103 and Fig. 1, Drinkwater *et al*, 1995.

[1071] Microbial biomass C was 214.9µg/g on the organically managed plots vs. 147.0 µg/g on the 'District Practice' plots..

[1072] The reason for why there could be some cases of a higher microbial level without a higher soil carbon level in organic farming, could be due to the greater diversity of the microbial population in organic farming, so that a higher microbial biomass can be supported by the same level of carbon input – see point on microbial diversity below. However, normally both soil carbon and microbial levels are higher in organic farming, and this is one of the minority of comparisons where an organic system did not produce a higher soil carbon level, which was presumably because all the plots had the same diverse crop rotations, which would not normally be the case and certainly not, say, in the UK. It is also possible that the higher microbial levels were having an unidentified positive effect, for example if there were differences in topsoil depth. Also, it is possible that there were positive effects *within the system* (even if not overall): the non-organic systems had higher yields and so may have been returning more crop biomass to the soil, in which case the fact that the organic systems had the same final soil carbon level could then indicate that they were converting a higher proportion of their carbon input into humus than the non-organic systems. See section 6.2.

[1073] Email communication, Pete Smith, Royal Society-Wolfson Professor of Soils & Global Change, Institute of Biological and Environmental Sciences, University of Aberdeen; 21 November 2008.

[1074] "Soil respiration is the sum of heterotrophic respiration and root respiration." Koerber *et al*, 2009.

[1075] Franzluebbers, K., Franzluebbers, A. J., Jawson, M. D. Environmental Controls on Soil and Whole-ecosystem Respiration from a Tallgrass Prairie Soil Sci Soc Am J 2002 66: 254-262.

[1076] 81mg CO2 per kg soil in the organic arable system versus only 34mgCO2/kg in the non-organic system. Wander *et al*, 1994; Harris *et al*, 1994. Cited in Hepperly *et al*, 2006.

[1077] See section 6.5. Pimentel *et al*, 2005. Hepperly *et al*, 2006.

[1078] An average of 464mgC/kg for the organic system vs. 264 mgC/kg for the non-organic system. Table 2, Pulleman *et al*, 2003.

[1079] Sebastiana Melero, Juan Carlos Ruiz Porras, Juan Francisco Herencia, Engracia Madejon, "Chemical and biochemical properties in a silty loam soil under conventional and organic management," 2006, Soil & Tillage Research 90 (2006) 162–170.)

[1080] Author's proposal.

[1081] Breland & Eltun, 1999.

[1082] Hopkins, D.W., Shiel, R.S., 1996. Size and activity of soil microbial communities in long-term experimental grassland plots treated with manure and inorganic fertilizers. Biol. Fertil. Soils 22, 66–70. Cited in Melero *et al*, 2006.

[1083] Results for July 1982, 0-7.5cm, Tables 2 & 4. Also Fig. 2. Fraser *et al*, 1988.

[1084] Fraser *et al*, 1988.

[1085] Anderson 1994. Cited in Breland & Eltun, 1999.

[1086] This might explain why some comparative studies found the increase in the microbial level can be greater than the increase in the soil carbon level in organic farming, ie. because greater diversity means a higher microbial biomass can be supported by the same level of carbon input.

[1087] Different groups of soil microorganisms, such as bacteria or fungi, use different carbon sources (Fontaine et al, 2003; Kramer and Gleixner, 2006), and a higher plant diversity increases the variability of compounds available as a nutrient source (Hooper et al, 2000; Stephan et al, 2000; Wardle et al, 1999). Cited in, "Mechanisms of soil carbon storage in experimental grasslands," S. Steinbeiss, V. M. Temperton, and G. Gleixner, Biogeosciences Discussions, 4, 3829–3862, 2007.

[1088] For example, this concern is stated by Kirchmann *et al*, 2007, and they give the example of two studies which found higher soil carbon levels but were using some imported organic matter (Clark et al, 1998; Bullock et al, 2002). Holger Kirchmann, Lars Bergström, Thomas Kätterer, Lennart Mattsson and Sven Gesslein, "Comparison of Long-Term Organic and Conventional Crop–Livestock Systems on a Previously Nutrient-Depleted Soil in Sweden," Published in Agron J 99:960-972 (2007).

[1089] Bhogal, A.,. Chambers, B.J., Whitmore, A.P. &. Powlson, D.S. (2007). *The effects of reduced tillage practices and organic material additions on the carbon content of arable soils.* Scientific Report for Defra Project SP0561.

[1090] Liebhardt *et al*, 1989, Clark *et al*, 1999. Cited in, Kirchmann *et al*, 2007.

[1091] If anything, the three legume-based organic systems had a marginally higher soil carbon level (about +2%) than the manure-based organic systems (even though one of each was the Rodale Institute trial systems where the legume-based system had slightly less than the manure-based system). Fig 1, Marriott & Wander, 2006.

[1092] For more details, see chapter 6, sections 2 and 5. Holger Kirchmann, Lars Bergström, Thomas Kätterer, Lennart Mattsson and Sven Gesslein, "Comparison of Long-Term Organic and Conventional Crop–Livestock Systems on a Previously Nutrient-Depleted Soil in Sweden," Published in Agron J 99:960-972 (2007). Published online 5 June 2007. Note, the researchers take a very different focus to that we have taken here (and come to different conclusions). In this paper, they compare a theoretical 'improved' version of non-organic farming to the theoretical self-sufficient version of organic farming, while we are always comparing the organic system (with or without external inputs) to the original non-organic farming system used in the trial. The latter is the relevant comparison for assessing the contribution of imported carbon to the difference in soil carbon level between *current* organic and non-organic farming systems.

[1093] "The amount of solid manure applied to the organic system … was… 50% greater than the animal desnity that could be supported from yield levels." Page 961, Kirchmann *et al*, 2007.

[1094] The final long-term SOC 'equilibrium' values would be 15gC/kg vs. 12gC/kg. Table 3, Kirchmann *et al*, 2007.

[1095] In the trial, the organic system involved the incorporation of the straw into the soil and the consequent importation of extra straw for livestock bedding. The authors say this practice, "does not represent realistic management of an organic system. In reality, the straw from at least one cereal crop per rotation needs to be removed and used as animal bedding." P. 966, Kirchmann *et al*, 2007.

[1096] Soil Association standard 4.7.19: "You must treat your non-organic manure and plant waste as follows: …"

[1097] Oral communication, Phil Stocker, Director of Farmer and Grower Relations, Soil Association, 11 February 2009. Most of the imported manure is cattle manure, though a few growers import poultry manure.

[1098] Page 69, The British Survey of Fertiliser Practice, 2008, Defra.

[1099] Oral communication, Phil Stocker, Director of Farmer and Grower Relations, Soil Association, 11 February 2009.

[1100] Oral communication, Rob George, Soil Association, 23 January 2009.

[1101] Oral communication, Phil Stocker, Director of Farmer and Grower Relations, Soil Association, 11 February 2009.

[1102] Organic pigs and poultry can be fed up to 10% non-organic feed but *only* if this feed is one of the few types permitted for non-organic origin (only certain refined derivatives and other products such as maize gluten meal, potato protein, sugar beet pulp etc.), and if there is no organic source available, and they have shown their organic certifier that it is not available.[1102] Although some of the carbon in feed is lost in respiration or removed in the meat or eggs, some will be excreted in the pig and poultry manure and be a soil carbon input on the organic land. Organic pig and poultry systems are free-range, so presumably most of this small amount of 'non-organic' carbon is deposited onto the grazing land, which would normally form part of a mixed arable/livestock rotation. This 10% non-organic feed 'allowance' for pigs and poultry ends at the end of 2009, after which it falls to 5% until the end of 2011, after which organic pigs and poultry will have to be fed a 100% organic diet. "Sources of organic animal feed 2008," Fact sheet, Soil Association, June 2008, www.soilassociation.org

[1103] See section 9.4 ("Concern: Higher organic matter additions have little effect on soil carbon levels.")

[1104] Based on the findings that compost produces the best soil carbon results – see section 7.12.

[1105] The majority of the land area that currently makes up the UK organic farming sector is grassland, with mixed (arable and livestock) farms and specialist horticultural operations comprising a minority. This is because of the relative ease of converting all-grassland farms and already-mixed non-organic farms to organic methods, but it is more difficult and costly to convert all-arable farms to organic farming (most non-organic arable production is on all-arable farms), as more fundamental changes are required (need to reintroduce livestock). Many all-arable farmers are now starting to convert, but future policies to support organic farming conversion will need to be tailored to better support these farmers to undergo conversion.

[1106] Concern expressed by Professor Pete Smith, Royal Society-Wolfson Professor of Soils & Global Change, Institute of Biological and Environmental Sciences, University of Aberdeen; at soil carbon workshop, Soil Association conference, 18 November 2008.

[1107] Root exudates account for 7-8% of total photosynthetic carbon; Farrare *et al*, 2003 (cited in Rasse *et al*, 2005). Other studies have speculated that assimilated C partitioned into the rhizosphere is approximately 30% of Net Primary Production. (NPP is the total carbon fixed by photosynthesis over the year minus the carbon lost in plant respiration, ie. the biomass at any one time, plus total root exudates, litterfall and allocation to symbiotic organisms over the year); Clark *et al*. 2001 (study of forests), Chapin & Eviner 2005 (cited in Koerber *et al*, 2009).

[1108] There is the well established inverse relationship between the size of farms and the amount of food they produce per hectare, with smaller farms generally having greater yields. Discovery first made in 1962 by the Nobel economist Amartya Sen, and since confirmed by several studies. For example, in 2000, the Institute for Food and Development Policy, reviewed data from every country for which data was available: for every country, smaller farms were from 200 to 1,000% more productive (output per unit area) than larger farms [note, these output figures are apparently for value, but tonnage was also greater on small farms]. Reasons are the growing of crop mixtures rather than monocultures, integration of different aspects of the farm (eg. crops & livestock), less bare soil as less need to accommodate machinary, and more and better quality of labour investment in small farms; "Small Farms Are More Efficient & Sustainable**,"** Multinational Monitor, July/August 2000, Volume 21, Number 7& 8, The Case for Small Farms - An Interview with Peter Rosset, executive director of the California-based Institute for Food and Development Policy. Author's note: the 'problem' is that small farms are not competitive economically (profit margin/ha) and they provide smaller amounts of each product per farm (so are disadvantaged in international markets vs. local markets). Organic farming systems have some characteristics of small farms (integration, more labour) but are not inherently large or small, and in practice largely replace the existing size structure and extent of mechanisation (with some differences): so, in the West, they tend to be fairly 'large' and mechanised.

[1109] Survey of results of replicated farming trials from seven state universities and two independent research facilities, for different parts of the US, rain-fed and irrigated areas, Bill Liedhardt, University of California.

[1110] 1. For example, Drinkwater *et al*, 1995 (US study of organic and non-organic tomato-producing farms found no difference in yield levels); Garcia *et al*, 1989 (study of biodynamic and non-organic avocado plantations, the yields of biodynamic plantation were "good" for the area), and Melero *et al*, 2006 (Spanish trial of vegetable production, 66% higher yields per ha with organic farming). 2. The survey by Bill Liedhardt of the University of California (see above) found no difference in tomoto yields. 3. Also, a report by Reading University found that UK organic sugar beet yields are 9% higher than non-organic: "England and Wales under organic agriculture: how much food could be produced?", by Philip Jones with Richard Crane , Centre for Agricultural Strategy, Policy and Development, University of Reading. See Press release, 24 June 2009, http://www.rdg.ac.uk/about/newsandevents/releases/PR21951.asp.

[1111] See section 6.2 for more details. In this UK survey, the nine organic horticultural farms had 58% higher soil carbon levels than the three non-organic horticultural farms; Armstrong Brown *et al*, 2000. In this six-year trial in Spain, organic vegetable production produced 138% higher soil carbon levels and 66% higher yields levels; Melero *et al*, 2006. Also, Garcia *et al*, 1989.

[1112] 1. This review of 133 studies found organic farming produced 80% higher crop and livestock yields: Badgley, C., Moghtader, J., Quintero, E., Zakem, E., Jahi Chappell, M., Avilés-Vázquez, K., Samulon, A. and Perfecto, I. (2007): Organic agriculture and the global food supply. Renewable Agriculture and Food Systems: 22(2); 86-108. 2. In the Tigray Province, one of the most degraded parts of Ethiopia, agricultural productivity was doubled over one million hectares through agroforestry, application of compost and introduction of leguminous plants into the crop sequence (yields were increased to a much greater extent at both farm and regional level than by using purchased mineral fertilisers); Edwards, S. (2007): The impact of compost use on crop yields in Tigray,

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Ethiopia. Institute for Sustainable Development (ISD). Proceedings of the International Conference on Organic Agriculture and Food Security. FAO, Rom. Obtainable at: ftp://ftp.fao.org/paia/organicag/ofs/02-Edwards.pdf

[1113] Average organic wheat yields are 5.4t/ha in England (excluding North-east & North-west regions), vs. UK average yields of 8t/ha. Average organic potato yields in England are 28t/ha vs. UK average of 43t/ha (maincrop). Organic yields derived from (i): by applying regional organic yields for 2006 (FBS farm data) to 2006 non-organic production levels in each region of England & Wales, the University of Reading have shown that organic per ha production levels (weighted by the distribution of non-organic production) are 32% less for wheat, 32% less for all cereals, and 33% less for potatoes. As an alternative method, (ii) If regional organic yields are simply averaged (with, for wheat, just the exclusion of the North-east and North-west regions, where non-organic production is lower than in other regions presumably because of less suitable conditions; organic wheat yields are also slightly lower in these regions), without considering current production distribution (except partially for wheat, as explained), then the same organic yield figures for potatoes and wheat are produced. However, because of differences in the balance of production of different crops under UK organic farming, actual national production levels would be different, with much less wheat (but same amounts available for human consumption), and much more potatoes and oats (unless production was scaled back), it was estimated (based on current organic production balances). Pages 31 and 32 etc., "England and Wales under organic agriculture: how much food could be produced?", by Philip Jones with Richard Crane, Centre for Agricultural Strategy, Policy and Development, University of Reading; Press release, 24 June 2009, http://www.rdg.ac.uk/about/newsandevents/releases/PR21951.asp. UK average yields from 'Agriculture in the United Kingdom 2008," Defra.

[1114] For example, the rate of carbon sequestration compared to the above-ground carbon input was 2 to 3 times higher in organic farming than non-organic farming in the Rodale Institute trial, see point 4.

[1115] Korschens *et al*, 1998; cited in Shepherd *et al*, 2002. In UK studies, a yield response to higher SOM levels (irrespective of the level of N applied) has been found with root crops and spring-sown cereals, and sometimes but not always with autumn-sown cereals; section 4, 'Soil organic matter and crop yields,' Johnston *et al*, 2009, *in press.*

[1116] Section 5.4, Bhogal *et* al, 2007. A soil's tendancy to aggregate is primarily a function of its soil organic matter content. Soil aggregation creates pores throughout the soil which hold water, as well as the hollow spheres of the aggregated clumps of soil particles which hold nutrients and water; Hepperly, P. & Ziegler Ulsh, C., Studies & Advances in Composting Technology - Ancient Wisdom Meets Modern Science, reprinted from ACRES, September 2007, Vol. 37, No. 9. These also increase the soil's surface area to retain water; Gupta *et al*, 1977; cited in Sheperd *et al*, 2002. SOM improves aggregation mainly in clay soils; in sandy soils, it does not create stable aggregates but still provides structural benefits for the seed-bed; Johnston *et al*, 2009, *in press.*

[1117] Shepherd *et al*, 2002. Rapid root growth is important for spring-sown crops which have to grow quickly to reach their yield potential; autumn-sown crops have plenty of time to develop an adequate root system; in sandy soils, SOM also provides a better seed-bed structure for seedling emergence which helps yield levels, as it avoids the formation of the hard surface 'crust' that occurs with inorganic fertiliser use and which restricts root growth; Sections 4 and 5, Johnston *et al*, 2009, *in press.*

[1118] Section 5.4, Johnston *et al*, 2009, *in press.* P is phosphate and K is potassium.

[1119] Section 4, 'Soil organic matter and crop yields,' Johnston *et al*, 2009, *in press.* The mass of fine roots left after grass leys also improves the seed bed, ie. helps seedling emergence; Section 5, Johnston *et al*, 2009, *in press.*

[1120] "Green manures," Stockfree Organic, Vegan-Organic Information Sheeet #8 www.networkforclimateaction.org.uk

[1121] For instance, 'in degraded/eroded dry and semi-arid Mediterranean soils, a significant increase in SOM would be expected to increase plant productivity," Baritz *et al*, 2004, Task group 5 on Land use and SOM.

[1122] For example, these two comparative studies found higher soil carbon levels on the organic farms than the non-organic farms, and also a positive correlation between soil organic matter levels and available soil nutrients. 1. Garcia *et al*, 1989 (study of organic avocado plantation in Tenerife). 2. Alvarez *et al*, 1988 (study of organic banana plantation in Tenerife).

[1123] Most organic matter additions provide a valuable source of plant available nutrients. Section 5.4, Bhogal *et al*, 2007.

[1124] Microbial decomposition of SOM may release nutrients (N,P, S and trace elements), "at times during the growing season and positions" that are "difficult to mimic the effect with a fertilizer application; Section 5, Johnston *et al*, 2009, *in press.*

[1125] Pimental *et al*, 2005.

[1126] Augé *et al*, 2000. Cited in Pimental *et al*, 2005.

[1127] For example, in the Rodale trial in Pennsylvania, in the drought year for soya, the organic soya yielded 53% more than the non-organic soya (the yield of which fell 66%), while in the four drought years for maize, the organic maize yielded on average 27% more than the conventional maize. Pimentel D, Hepperly P, Hanson J, Douds D, and Seidel R (2005), Environmental, energetic, and economic comparisons of organic and conventional farming systems, BioScience. Research in Tigray, Ethiopia found that organically managed crops last a fortnight longer in droughts before wilting than minerally fertilised crops, which can mean the difference between achieving a harvest and not; for details on this project, see: Edwards, S. (2007): The impact of compost use on crop yields in Tigray, Ethiopia. Institute for Sustainable Development (ISD). Proceedings of the International Conference on Organic Agriculture and Food Security. FAO, Rom. Obtainable at: ftp://ftp.fao.org/paia/organicag/ofs/02-Edwards.pdf. Similar results have been reported by organic and non-organic farmers in drought conditions in the UK.

[1128] Olness, A., Archer, D., 2005. Effect of organic carbon on available water in soil. Soil Science 170:90-101. Note, another sources says that every kg of SOM has the ability to absorb 20x its weight in water: Huntington, T. 2006, Available water capacity and soil organic matter. Encyclopedia of Soil Science, Taylor & Francis, 2nd edition. www.informaworld.com; cited in: Hepperly, Paul Reed Ph.D, "The Impact of Agriculture and Food Systems on Greenhouse Gas, Energy Use, Economics and the Environment," The Rodale Institute, undated (received 13 July 2009). In the UK, studies have found that higher SOM levels provide a 9-22% increase in the soil's Available Water Capacity, with the higher levels being for sandy soils, section; 5.5,

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Johnston *et al*, 2009, *in press*. [Note, for clay soils, the increase will be from the structural benefits of SOM *plus* the increase in water-holding capacity of humus. For sandy soils, it is mainly from the water-holding capacity of humus].

[1129] Troeh, R. Frederick & Louis Milton Thompson, "Soils and Fertility," 2005. Published by Wiley-Blackwell.

[1130] See section 7.6.

[1131] For instance in the Broadbalk wheat trial, which tested the effects of FYM and various levels of inorganic NPK fertiliser, until fungicides were used, levels of foliar fungal diseases especially powerdy mildew, were most severe on plots given most nitrogen and this curtailed yield levels; Guide to the Classical and other Long-term Experiments, Datasets and Sample Archive, Rothamsted Research, http://www.rothamsted.bbsrc.ac.uk/resources/ClassicalExperiments.html. A reduction in fungal diseases is also a common (if surprising) experience of farmers who convert to organic farming. This is believed to be because N fertiliser promotes faster crop growth which causes thinner plant cell walls that are more susceptible to fungal attack.

[1132] According to the long-term Broadbalk wheat trial, yields of wheat grown after a two-year break can be more than 2 t/ha larger than yields of continuous wheat, almost certainly because of the effects of soil borne pests and disease; Rothamsted Research, http://www.rothamsted.bbsrc.ac.uk/resources/ClassicalExperiments.html.

[1133] In principle the return of humun waste to the soil meets the organic principles of 'closing the nutrient cycle' and there has always been interest in using this resource. However, although biosolids are now applied by some non-organic farmers, the use of sewage sludge (biosolids) is prohibited in organic farming because of the problem of heavy metal contamination by the mixing of the sewage with with waste dirty water. Another problem for this as a source of soil carbon input is that most of the carbon is lost from the product in the sewage handling process. Ways need to be found to return human waste much more directly to the soil, without mixing by other waste water and with much less loss of much carbon. In the developed world, this requires, for instance, different town planning and building design to keep the toilet waste and other waste water streams separate. This is something, however, that can be relatively easily done in developing countries in rural regions because there the practice is not limited by the existence of sewage systems. Eg. see, "Toilets That Make Compost: Low-cost, sanitary toilets that produce valuable compost for crops in an African context," http://www.ecosanres.org/toilets_that_make_compost.htm

[1134] For example, red clover is a deeper-rooting plant. Red clover silage has been found to lead to significant improvements in animal growth compared to feeding grass silage, with a 17% increase in the live weight gain of steers found in one study. Randby, 1992; cited in "Finishing organic beef and lamb," Soil Association Technical Guide.

[1135] In the case of this tropical study, in which the total biomass produced rose from 8.2tC/ha/season for growing okra alone to 16.4rC/ha/season for inter-cropping of okra and cucumber; while the yield/hectare rose 59%; average of results of two spacing treatments and two seasons. "Biological efficiency of intercropping in okra (Abelmoschus esculentus (L.) Moench)", Susan Anna John and C. Mini, Journal of Tropical Agriculture 43 (1-2): 33-36, 2005.

[1136] For example, growing a mixture of three barley varieties produced a biomass/hectare increase of 5-6% after 100 days and a yield increase of 2%. Preliminary BAR-OF-WP4 report on,"Do nutrient uptakes and grain yields differ between spring barley varieties grown for organic farming as mono-crop and in mixture? Characteristics of spring barley varieties for organic farming", Niels Erik Nielsen, Ingrid Kaag Thomsen and Jørgen Berntsen. Experimental details in Nielsen *et al*, 2003.

[1137] "Weed management in organic crops," Defra report OF0315.

[1138] Higher plant biodiversity leads to larger plant biomass production: Balvanera *et al*, 2006; Lambers *et al*, 2004; Roscher *et al*, 2005. All cited in, "Mechanisms of soil carbon storage in experimental grasslands," S. Steinbeiss, V. M. Temperton, and G. Gleixner, Biogeosciences Discussions, 4, 3829–3862, 2007.

[1139] "What will limit crop yields in the future?" presentation by Professor Carlo Leifert, Soil Association conference, November 2008, http://92.52.112.178/Web/SA/saweb.nsf/leifert_workshop5.pps

[1140] Greenpeace, 2008, "Cool Farming: Climate impacts of agriculture and mitigation potential."

[1141] 1. Currently half of the world's pork production occurs in landless industrial systems [which are prohibited in organic farming], and for poultry meat the share is over 70%. Steinfeld, H., Gerber, P., Wassenaar, T., Rosales, M. and de Haan, C. 2006. Livestock's long shadow. Environmental issues and options. FAO, Rome. 2. Based on the production records of 176 organic farms, an initial assessment of food production of one scenario under widespread organic farming in England and Wales concluded that chickenmeat and pork production would fall by around 70%, and eggs by 27%; because of the consequent reduced use of cereals for animal feed, there would be as much cereals for human consumption as is available now; and there would be 43% more potatoes, and also more oats and other 'minor' cereals. "England and Wales under organic agriculture: how much food could be produced?", by Philip Jones with Richard Crane**,** Centre for Agricultural Strategy, Policy and Development, University of Reading, see Press Release, 24 June 2009, http://www.rdg.ac.uk/about/newsandevents/releases/PR21951.asp

[1142] See section 7.18 for details.

[1143] Badgley, C., Moghtader, J., Quintero, E., Zakem, E., Jahi Chappell, M., Avilés-Vázquez, K., Samulon, A. and Perfecto, I. (2007): Organic agriculture and the global food supply. Renewable Agriculture and Food Systems: 22(2); 86-108.

[1144] 1. In the Tigray Province, one of the most degraded parts of Ethiopia, agricultural productivity was doubled over one million hectares through agroforestry, application of compost and introduction of leguminous plants into the crop sequence, and the yields were increased to a much greater extent at both farm and regional level than by using purchased mineral fertilisers; Edwards, S. (2007): The impact of compost use on crop yields in Tigray, Ethiopia. Institute for Sustainable Development (ISD). Proceedings of the International Conference on Organic Agriculture and Food Security. FAO, Rom. Obtainable at: ftp://ftp.fao.org/paia/organicag/ofs/02-Edwards.pdf 2. Organic farming methods (eg. using composting) produce similar yields in average conditions but higher yields in dry conditions; Ingrid Hartmann, Hailu Araya & Sue Edwards, "Food security, Livelihoods and Options for Organic Agriculture in Ethiopa," paper presented at the "International Conference on Organic Agriculture and Food Secuity," 3-5 May, 2007, FAO, Italy. ftp://ftp.fao.org/paia/organicag/ofs/OFS-2007-INF-rev.pdf .

[1145] Page 100, CLIMSOIL report for the European Commission, December 2008.

[1146] The global potential of nitrogen producton for agriculture through biological N fixation is calculated to be 140 million t N/yr (by growing legumes between the cropping seasons, eg. grass/clover leys or other green manure crops, or during cropping ie. intercropping). Plus 160 million t N/yr from the manure from the current 18 billion livestock, equals 300 million t N/year. Compared to the current production of mineral nitrogen of 90-100 million t N/year. Niggli, U., Fließbach, A., Hepperly, P. and Scialabba, N. 2009. Low Greenhouse Gas Agriculture: Mitigation and Adaptation Potential of Sustainable Farming Systems. FAO, April 2009, Rev. 2 – 2009. Author's note: inorganic fertiliser only accounts for about half of the food produced in the world today. Also livestock numbers would be lower under organic farming, hence "two to three times greater."

[1147] In Central and Eastern Europe, Caucasus and Central Asia, agricultural production is now only 60-80% of 1990 levels; Greenpeace, 2008, "Cool Farming: Climate impacts of agriculture and mitigation potential."

[1148] Eg. in Australia, consumer demand for chicken meat has been growing steadily over the last decade. "Climate Change: Implications for Water Utilisation in animal Agriculture and Poultry, in Particular," Feedinfo News Service – 02/03/2009.

[1149] 1. Chadd S.A., Davies W.P. & Koivisto J.M., 2002. 'Practical production of protein for food animals', Protein sources for the animal feed industry, Expert Consultation and Workshop, FAO Animal Production and Health. 2. Bajjalieh N., 2002, 'Proteins from oilseeds', In**:** Protein Sources for the Animal Feed Industry. Expert consultation and workshop. Bangkok, 29 April - 3 May 2002; (Proceedings); FAO Animal Production and Health Proceedings, no. 1*; FAO Expert Consultation and Workshop on Protein Sources for the Animal Feed Industry*, Bangkok, 29 Apr - 3 May 2002 / FAO. Animal Production and Health Div. , 2004, p.141-159. 3. The two preceeding sources suggest that the soya meal (for animal feed) represents a large majority, 72%, of the value of the soya bean. The following suggested that feed use represents a lower level of around 60% of the value of soya, with soya oil for food representing the remaining 40%: oral communication, Tony Bell, BOCM Pauls, 25.9.2007.

[1150] Many processed foods contain ingredients derived from soya. The main product used in food is soya oil , which is commonly modified by the industrial process of 'hydrogentation' and used in various processed foods including margarine and commercial frying fats. Soya lecithin is used in a wide variety of foods such as chocolate, dairy products and bread. References: 1. "The Global GM Market, Implications for the European food chain," G.Brookes, N.Craddock & B.Kniel, 2005; 2. "Should we worry about soya in our food?" The Guardian, Felicity Lawrence, 25 July 2006.

[1151] See 7.18. "How the Palm Oil Industry is Cooking the Climate," Greenpeace report, November 2007, and follow-up report, "How Unilever palm oil suppliers are burning up Borneo." www.greenpeace.org.uk/media/reports/cooking-the-climate

[1152] N refers to nitrogen, P to phosphate (P_2O_5) and K to potash (K_2O).

[1153] Inorganic N fertiliser is made from fossil fuel (natural gas ie. methane) as the raw material, and the manufacturing process also requires alot of energy. Gas and N fertiliser prices were fairly steady for years until 1999, after which both started rising. With the gas crisis in 2005, UK fertiliser prices reached a highest ever level of £160/t (for ammonium nitrate) in October 2005. Since September 2007, with increases in energy costs and growing demand for fertiliser (Latin America, Asia and Africa) prices rose again two-fold and were around £330/t in 2008 (with a high of £390/t). February 2009 prices were £280/t. Fertiliser price reports, Farmers Weekly on-line, www.fwi.co.uk. Chapter 6, Agriculture in the United Kingdom 2007, Defra.

[1154] P fertiliser is mined as rock phosphate; with current global usage at 125million t/yr and reserves estimated at 4-8billion t, supplies are estimated to last for only 30-40 years more (at worst) to 60-90 years (at best); Fantal *et al*, 1985, Natural resources forum; cited in presentation "What will limit crop yields in the future?" by Professor Carlo Leifert, Soil Association conference, November 2008, http://92.52.112.178/Web/SA/saweb.nsf/leifert_workshop5.pps Potash (K) has similar supply problems, but in addition the refiners have the problem of escalating costs of ammonia and sulphur, which are needed for the manufacturing process. "More volatility in heated fertiliser market," 29 April 2008, Farmers Weekly on-line, www.fwi.co.uk

[1155] Phosphate (P) and potash (K) fertiliser prices have risen from around £150/t and £135/t respectively in 2005, to £500-700/t and £390-590/t respectively in 2008, to £640/t and £560/t in February 2009. Farmers Weekly on-line, fertiliser price reports, www.fwi.co.uk Eg. a farmer growing 100ha of potatoes may normally apply around 180kgP/ha, which at current prices means spending £11,500 a year on P fertiliser; "What will limit crop yields in the future?" presentation by Professor Carlo Leifert, Soil Association conference, November 2008, http://92.52.112.178/Web/SA/saweb.nsf/leifert_workshop5.pps

[1156] "Crop Watch North: Workload demands priority setting, says David Cairns", 2 March 2009. Special report, www.fwi.co.uk

[1157] Chapter 6, Agriculture in the United Kingdom 2007, Defra. Phosphate application rates have been declining since the 1980s and reached half the 1983 rate in 2008 (31kg/ha vs. 60kg/ha, on cultivated soils in Great Britain); potash rates have dropped a third since 1998 (43kg/ha vs. 65kg/ha, on GB cultivated soils); p24, British Survey of Fertiliser Practice 2008, Defra.

[1158] 1. If farmers are not applying P and K fertiliser, they are slowly reducing their soil reserves, which will start to affect yields at some point; Farmers Weekly on-line, www.fwi.co.uk. 2. Once P levels fall below a threshold level, yields fall dramatically and can be expected to fall by a half without P fertiliser, "What will limit crop yields in the future?" presentation by Professor Carlo Leifert, Soil Association conference, November 2008, http://92.52.112.178/Web/SA/saweb.nsf/leifert_workshop5.pps 3. N application rates depend on the breakeven ratio between the cost per unit of N fertiliser and the value of extra grain produced. This ratio jumped from 3:1 in 2000, to 7:1 in 2008, leading to lower fertiliser application recommendations; "Economic optimum N expected to fall as fertiliser prices rise," 22 May 2008.

[1159] For example, Webb, J., P. Bellamy, P.J. Loveland, and G. Goodlass. 2003, "Crop Residue Returns and Equilibrium Soil Organic Carbon in England and Wales", pp. 928-936, Vol. 67.

[1160] Page 2.38, Volume 4, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, IPCC, 2007. Note, a fall in soil C follows a slightly different pattern, with a steep decline occurring immediately after a mangement change, before levelling out.

[1161] Email communication, Pete Smith, Royal Society-Wolfson Professor of Soils & Global Change, Institute of Biological and Environmental Sciences, University of Aberdeen; 21 November 2008.

[1162] Section 5.3, Bhogal, A.,. Chambers, B.J., Whitmore, A.P. &. Powlson, D.S. (2007). *The effects of reduced tillage practices and organic material additions on the carbon content of arable soils.* Scientific Report for Defra Project SP0561.

[1163] Bhogal *et al*, 2009, Scientific Report for Defra Project SP0561.

[1164] Volume 4, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, IPCC, 2007.

[1165] Email communication by Eric Audsley, Cranfield University, 4 July 2008.

[1166] http://www.independent.co.uk/environment/climate-change/un-climate-conference-the-countdown-to-copenhagen-1242601.html

[1167] Soil geology, By Dr J Floor Anthoni (2000) www.seafriends.org.nz/enviro/soil/geosoil.htm

[1168] Soil geology, By Dr J Floor Anthoni (2000) www.seafriends.org.nz/enviro/soil/geosoil.htm

[1169] Factors Of Soil Formation - A System Of Quantitative Pedology, by Hans Jenny, 1994. http://www.soilandhealth.org/01aglibrary/010159.Jenny.pdf

[1170] For example, in the Palouse region of eastern Washington is one of the most productive dryland wheat-, lentil- and dry-pea-growing regions in the world. Yet, every winter millions of tonnes of fertile topsoil are washed off the steep loessial hills (U.S. Department of Agriculture, 1978). Cited in Mulla *et al*, 1992.

[1171] Six comparative studies have looked at soil depth and all found the topsoil was on average deeper under organic farming; this could be due to erosion (or greater erosion) on the non-organic farms or soil build-up on the organic farms. 1. Armstrong *et al*, 2000 found that the topsoil depth was 13% greater on the organic horticulture farms and double in organic grassland in England than on the non-organic horticulture/arable farms respectively, but 5% lower on the organic arable farms (no differences were statistically significant). 2. Liebig & Doran, 1999, found a 2-15cm greater topsoil depth on three organic farms in Nebraska (+43%, +9%, +9%, compared to the non-organic farms), only part of which might be due to a lower topsoil bulk density (3-4% less, 0-7.6cm depth). 3. Gerhardt,1997, found a significantly greater topsoil depth on an organic farm in Iowa, US. 4. Gardner & Clancy, 1996, found that three organic farms in North Dakota had an overall average 12% higher topsoil depth than three non-organic farms, which was mostly negated by lower soil bulk densities. 5. Reganold *et al*, 1993, found a statistically significant 11% increase in topsoil depth with biodynamic farming, partially due to a 7% decrease in bulk density, in New Zealand. 5. Reganold, 1987, found a 16cm thicker topsoil on the organic farm than an adjacent non-organic farm. See section 6.2.

[1172] Page 2.39, Volume 4, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, IPCC, 2007.

[1173] Assuming a soil carbon stock of 60tC/ha in arable soils (typically, clay soils have 59-66tC/ha, sandy soils have around 49tC/ha, according to the IPCC). O.33% of 60tC/ha = 198kgC/ha. With 5 million ha of arable land in the UK, this gives an annual loss of 1 million t C ha/year.

[1174] See Fig.4, page 12, "Soil Organic Matter: Its Importance in Sustainable Agriculture and Carbon Dioxide Fluxes," Edward Johnston, Paul R. Poulton, and Kevin Coleman, 2009, Chapter 1, Vol 101, Advances in Agronomy, *in press*.

[1175] See page 59, CLIMSOIL report for the European Commission, December 2008. Experimental evidence comes from Jones & Donnelly, 2004; modelling evidence comes from Janssens *et al*, 2003. Janssens et al, 2003 predict an average grassland carbon sequestration of 670kgC/ha for Europe. For the UK grasslands (except peatlands), Jansssens et al, 2005 estimate total annual soil carbon gains of 6 million tC/yr (derived from the figure in Table1, by multiplying by the UK land area). This is a modelling study: it used the CESAR soil dynamic model, FAO figures of national grassland yields and levels of deposited manure, and UK decomposition rate data, to estimate the balance of C inputs and C outputs. It ignores direct effects of other management aspects (such as regular cultivation and re-seeding, and FYM applications).

[1176] Jones & Donnelly, 2004, cited on page 59, CLIMSOIL report for the European Commission, December 2008.

[1177] This refers to the ten long-term comparative studies of organic farming (where increases over the study period were found in eight of the studies, see section 6.1) and the two UK long-term non-comparative monitoring studies, where the soil C levels remained stable (see section 6.4). Note, one of these comparative studies followed the effects of organic farming on ploughed-up grassland, and an increase in soil C could not have been expected in this case.

[1178] Figures 10-11, page 16: http://www.jdb.se/sbfi/publ/k-trial.pdf The results from the soil surveys were published in: Pettersson & v.Wistinghausen, 1977; Pettersson, Brinton & v.Wistinghausen, 1979; and Pettersson, Reents & v.Wistinghausen, 1992.

[1179] Figures 10-11, page 16: http://www.jdb.se/sbfi/publ/k-trial.pdf The results from the soil surveys were published in: Pettersson & v.Wistinghausen, 1977; Pettersson, Brinton & v.Wistinghausen, 1979; and Pettersson, Reents & v.Wistinghausen, 1992.

[1180] See section 6.2, Results of studies on the comparative soil carbon levels.

[1181] Email communication, 7 January 2009. Peter Segger, organic farmer, Wales, and chair of soil carbon workshop at Soil Association conference, 18 November 2008. The compost is made of: 30% manure (mostly local horse stables), 30%+ green waste (mostly from the farm), and the remainder is high-carbon inputs. The brown or carbon inputs are a mixture of wood chips from the farm and cardboard from local organic shops. The farmer conducts large numbers of SOM tests and monitors the volume of compost. Soil types are varied: medium loams, silty loams; average clay content is 18-23%.

[1182] The so-called 'Land-Use, Land-Use Change & Forestry' (LULUCF) measures. Jelle G van Minnen, Bart J Strengers, Bas Eickhout, Rob J Swart, and Rik Leemans, Quantifying the effectiveness of climate change mitigation through forest plantations and carbon sequestration with an integrated land-use model, Carbon Balance Manag. 2008; 3: 3. Online 2008 April 15.

[1183] "Organic farming and climate change," UNCTAD/WTO report, 2007.

[1184] Baritz *et al*, 2004, Task group 5 Land Use Practices and SOM. Original reference cited: Dick *et al*, 1998.

[1185] Stevenson, 1994. Cited in Marriott & Wander, 2006.

[1186] The mean age of carbon at 60-80cm is several millenia. Jean-François Soussana, INRA Clermont, France. Workshop on soil at International conference "Organic agriculture and climate change," Enita Clermont, France, 17-18 April 2008.

[1187] Freibauer *et al*, 2004; cited in Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561.

[1188] For example, the 'ley-arable' experiment by Rothamsted (1948-2002), Figure 6, page 20, Johnston *et al*, 2009, *in press.*

[1189] Figure 6-3, Jenkinson, 1965. Cited in Troeh, R. Frederick & Louis Milton Thompson, "Soils and Fertility," 2005.

[1190] Hoosfield spring barley long-term trial (1852+), on a silty clay loam, Rothamsted, Johnston *et al*, 2009, *in press*.

[1191] Market Garden experiment (1942-67), sandy loam soil (12% clay), Woburn; section 2.1.1, Johnston *et al*, 2009, *in press*.

[1192] See section 6.6.

[1193] eg. The UK's Stern Review (www.sternreview.org.uk) warned that unless action is taken within the next 10-20 years, the environmental damage caused by climate change later in the century could cost between 5 and 20% of global GDP every year.

[1194] For instance, soil carbon losses may occur in a brief period following afforestation, when C loss by soil microbial respiration and C gain by litterfall are imbalanced. Tree planting leads to soil disturbance and can stimulate the mineralization of soil organic matter (SOM). Additionally, whilst topsoils generally gain C when afforestation occurs (following the establishment phase), underlying mineral soils may lose C. Page 86, CLIMSOIL report for the European Commission, December 2008.

[1195] Minnen *et al*, 2008.

[1196] We realise this is a controversial issue, but we are completely confident that this position is supported by the large available body of scientific evidence. Several scientific reviews show that organic farming produces higher average mineral levels in food. 1. Worthington V. Nutritional quality of organic versus conventional fruits, vegetables, and grains, Journal of Complimentary Medicine 2001; 7 No. 2: 161–173. This found that found that organic crops had significantly higher levels of all 21 nutrients analysed compared to non-organic produce, including statistically significant higher levels of iron (21% more), magnesium (29% more) and phosphorus (14% more). 2. Soil Association (2001) Organic Farming, food quality and human health: a review of the evidence. 3. FSA, 2009. Contrary to the long-standing political position of the UK Food Standards Agency that organic food has no health benefits, their own review shows that organic food have higher average mineral levels. Almost all of the studies reviewed that found differences between organic and non-organic food found higher nutritional levels in organic food and this includes the majority of the studies where the diifference was statistically significant; the FSA put this information in Appendix12 and dismissed it as not 'important' in the main text of their report. Such a consistent trend over so many studies is highly unlikely to be just due to chance, as the FSA would like to think (and certainly has not been scientifically established to be due to chance).

[1197] Baritz *et al*, 2004, Task group 5 Land Use Practices and SOM, http://ec.europa.eu/environment/soil/pdf/vol3.pdf.

[1198] Oral communication, Professor Pete Smith, Royal Society-Wolfson Professor of Soils & Global Change, Institute of Biological and Environmental Sciences, University of Aberdeen; at soil carbon workshop, Soil Association conference, 18 November 2008.

[1199] Volume 4, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, IPCC, 2007. http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html

[1200] For cropland, the three main 'soil carbon stock change factors' are: continuous cropping with fertilisation ('medium' organic matter input) – 1; an additional organic matter input practice but no regular manure use (eg. grass leys in the crop rotation, green manures, high-residue crops, or irrigation; 'high' input) – 1.11; regular animal manure use ('high with manure') – 1.44.

[1201] Inventory and Projections of UK Emissions by Sources and Removals by Sinks due to Land Use, Land Use Change and Forestry, Annual Report, July 2008. Centre for Ecology & Hydrology, University of Aberdeen, Forest Research Alice Holt, National Soil Resources Institute, Centre for Terrestrial Carbon Dynamics (Universities of Sheffield, Edinburgh, York & University College London), Agri-Food & Biosciences Institute, Queen's University Belfast.

[1202] Williams, A., E. Audsley, & D. Sandars, 2006. "Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities." Main Report. Defra Research Project IS0205. Cranfield University and Defra.

[1203] PAS-2050 (2008) BSI Standards Solutions, Defra and the Carbon Trust. PAS 2050 – assessing the life cycle greenhouse gas emissions of goods and services. http://www.bsi-global.com/en/Standards-and-Publications/How-we-can-help-you/Professional-Standards-Service/PAS-2050/.

[1204] Koerber *et al*, 2009.

[1205] The CALM (Carbon Accounting for Land Managers) calculator designed, developed and funded by the CLA (Country, Land and Business Association), Savills, EEDA and Increment Ltd.

[1206] In 2007, as an end user, agriculture was officially responsible for 50.6milliontCOe, which x44/12 is 13.8million tC/yr (2008 UK Greenhouse Gas emissions, provisional figures, 26th March 2009 - Statistical Release; Annex B- Emissions of all greenhouse gases, carbon dioxide, methane and nitrous oxide by source and end-user, Defra.)

[1207] "Agriculture in the United Kingdom 2006," Defra, 2007.

[1208] "Food Security and Agricultural Mitigation in Developing Countries: Options for Capturing Synergies"*;* UN Food and Agriculture Organisation; Rome; November 2009.

[1209] Humus can hold the equivalent of 80–90% of its weight in moisture, so higher levels increase the soil's capacity to hold water and withstand drought conditions; Olness, A., Archer, D., 2005. Effect of organic carbon on available water in soil. Soil Science 170:90-101. In addition, the aggregation of the soil particles by humus creates pores throughout the soil, which also holds water.

[1210] Schnug E, Rogasik J, Panten K, Paulsen HM and Haneklaus S 2004. Oekologischer Landbau erhoeht die Versickerungsleistung von Boeden – ein unverzichtbarer Beitrag zum vorbeugenden Hochwasserschutz. Oekologie & Landbau 32 (132): 53-55:

[1211] This study was based on interviews of 7 organic and 7 non-organic potato farmers in East Anglia, the main area of organic and non-organic potato growing in the UK. Most farmers rely on judgement for when to use irrigation. The organic farmers used an average of 174.1m^3/t of potatoes, vs. 234.7 m^3/t for non-organic farmers, a difference of 26%. As the organic farmers had 22.5% lower per ha yields, the per ha use of water was even lower. Apart from the presumed differences in soil quality (which this study did not investigate), the study established that two differences in irrigation practice are probably contributing to the lower use of irrigation by organic farmers (to maximise water uptake, their per hour rates of water supply were twice as slow as the non-organic farmers, and also half of the non-organic farmers irrigated at night to reduce evaporation losses, while all non-

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organic farmers irrigated in the day). "Irrigation management in organic and non-organic potato production - a case study on the East Anglia region, UK," Soil Association, 2008.

[1212] 1. The Rodale Institute in the US found that, while the yields of non-organic farming were highly susceptible to drought, organically managed crops fared better. In the five drought years for maize, the two organic systems yielded on average 33% more maize than the non-organic maize (6.9t/ha and 7.2t/ha for the organic manure and legume systems respectively vs. 5.3t/ha), while in the drought year for soya, the two organic systems yielded an average of 78% more soya (1.8t/ha and 1.4t/ha) than the non-organic soya (the yield of which fell 66% to 0.9t/ha). Pimentel D, Hepperly P, Hanson J, Douds D, and Seidel R (2005). Environmental, energetic, and economic comparisons of organic and conventional farming systems, BioScience. 2. This issue is particularly important for drought-prone regions of developing countries. Experience in the Tigray province of Ethiopia, one of the most degraded parts of Ethiopia, for example, found that organically managed crops lasted a fortnight longer in droughts before wilting than inorganically fertilised crops, which could mean the difference between achieving a harvest and not. For details on this project, see: Edwards, S. (2007): The impact of compost use on crop yields in Tigray, Ethiopia. Institute for Sustainable Development (ISD). Proceedings of the International Conference on Organic Agriculture and Food Security. FAO, Rom. See: ftp://ftp.fao.org/paia/organicag/ofs/02-Edwards.pdf

[1213] Lotter, D., Seidel, R. & Liebhardt, W. (2003): The Performance of Organic and Conventional Cropping Systems in an Extreme Climate Year. American Journal of Alternative Agriculture 18(3): pp- 146-154.

[1214] 1. Much of the world's food production is in semi-arid areas (often irrigated); Bruinsma, 2003; cited by Kirchmann *et al*, 2007. 2. About 70% of the land in dry areas of the world is considered to be degraded; Dregne, H.E. and Chou, N.T. 1994. Global desertification dimensions and costs. In H.E. Dregne (ed.). Degradation and restoration of arid lands. Lubbock, USA; Texas Technical University. 3. Even small increases in SOM will take low-carbon Mediterranean soils back from the brink of desertification. Baritz *et al*, report of Task group 5 Land use Practices and SOM, 2004, http://ec.europa.eu/environment/soil/pdf/vol3.pdf.

[1215] Organic matter additions provide a valuable source of plant availabl nutrients, in particular: P, K, S and Mg. Bhogal *et al*, 2007.

[1216] There are already serious price and supply problems, which are only expected to get worse. The four-fold increase in P and K fertiliser prices in the last few years means some UK non-organic farmers are not applying P and K this year. This is also an important issue for organic farms. Although organic farming methods boost soil mineral supplies, there are concerns that organic farms are nevertheless often using up soil reserves of P and K, by not sufficiently replenishing these nutrients.

[1217] eg. Ceccanti and Garcia, 1994. Cited by Marinari *et al*, 2007.

[1218] Several scientific reviews show that organic farming produces higher average mineral levels in food. 1. Worthington V. Nutritional quality of organic versus conventional fruits, vegetables, and grains, Journal of Complimentary Medicine 2001; 7 No. 2: 161–173. This found that found that organic crops had significantly higher levels of all 21 nutrients analysed compared to non-organic produce, including statistically significant higher levels of iron (21% more), magnesium (29% more) and phosphorus (14% more). 2. Soil Association (2001) Organic Farming, food quality and human health: a review of the evidence. 3. FSA, 2009. Contrary to the long-standing political position of the UK Food Standards Agency that organic food has no health benefits, their own review found that in almost all cases studied organic foods had higher beneficial nutrients, and this includes the majority of the studies where the difference was statistically significant (however, the FSA put this information in Appendix12 and dismissed it as 'not important' in the main text of their report). 4. Review compiled for the national French food agency AFSSA, by Denis Lairon of the University of Aix-Marseille, concluded that organic crops contain more dry matter (are more nutrient dense) and more minerals – such as iron and magnesium, published in 2009 in the journal Agronomy for Sustainable Development.

[1219] Mäder, P., A. Fließbach, A. Dubois, L. Gunst, P.Fried & U. Niggli, 2002, "Soil fertility and biodiversity in organic farming," Science 296:1694-1697.

[1220] Ceccanti and Garcia, 1994; cited by Marinari *et al*, 2007.

[1221] Reganold, J.P., L.F. Elliott, and Y.L. Unger. 1987, "Long-term effects of organic and conventional farming on soil erosion," Nature 330:370-372.

[1222] In its technical report to the European Commission, Task group 5 proposed the development of a set of regional "target SOC values" for Europe's soils, which would probably comprise hundreds of different values across Europe, derived from existing information about soil and climate types in the EU. Baritz *et al*, 2004, http://ec.europa.eu/environment/soil/pdf/vol3.pdf.

[1223] Smith, P., Goulding, K.W., Smith, K.A., Powlson, D.S., Smith J.U., Falloon, P.D. & Coleman, K. 2000, "Including trace gas fluxes in estimates of the carbon mitigation potential of UK agricultural land." Soil Use and Management 16: 251-259.

[1224] Bhogal *et al*, 2007, Scientific Report for Defra Project SP0561.

[1225] Apparently, CERS were trading at 24 a tonne . Email communication, Craig Sams, 13 August 2008.

[1226] Liebig, M. A.; Doran, J. W. 1999: Impact of organic production practices on soil quality indicators. Journal of Environmental Quality 28: 1601-1609. http://jeq.scijournals.org/cgi/content/abstract/28/5/1601

[1227] 30% of the forest carbon store is typically attributed to the soil and 70% to the forest biomass. See Janssens *et al*, 2003.

[1228] Ivan A. Janssens, Annette Freibauer, Philippe Ciais, Pete Smith, Gert-Jan Nabuurs, Gerd Folberth, Bernhard Schlamadinger, Ronald W. A. Hutjes, Reinhart Ceulemans, E.-Detlef Schulze, Riccardo Valentini, A. Johannes Dolman. "Europe's Terrestrial Biosphere Absorbs 7 to 12% of European Anthropogenic CO2 Emissions", Published on-line in Science,Vol 300, 6 June 2003, www.sciencemag.org. Note, Janssens *et al*, 2005 is update of this study.

[1229] Bellamy P.H., P.J. Loveland, R.I.Bradley, R.M. Lark & G.J.D. Kirk, "Carbon losses from all soils across England and Wales 1978-2003", Nature, Vol 437, 245-248, 8 September 2005. Notes on methodology: the top 15cm of soil of almost 6000 sites spaced 5km apart across England and Wales were sampled between 1978 and 1983, and about 40% of the sites (2179) were re-sampled in three phases between 1994 and 2003. The arable and rotational grass sites were re-sampled in 1994-95 (853 of the

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original 2,578 sites), the managed permanent grassland sites re-sampled in 1995-1996 (771 of 1,579), and the other sites in 2003. The loss/gain values for the sites that were not re-sampled were obtained by applying a loss rate factor that had been derived from the re-sampled sites in relation to the original SOC content. The estimate for the UK was derived by applying the average 'gC/kg of soil' loss rate found for England and Wales for 15cm depth (this carbon store is given as 864mtC), to the estimated soil carbon store of the whole of the UK for 30cm (given as 2,542mtC), ie i*gnoring* the study's finding of a higher g/kg loss rate for higher-carbon soils (which would predominate in Scotland).

[1230] The researchers used the 'Loss on Ignition' method for measuring the SOC content of the organic soils (soils >15% SOC content). This method is suitable for mineral soils, but not for organic soils where the soils are mostly made of carbon and should not therefore show a significant change; changes in soil carbon in these soils occur as changes in soil quantity, such as changes in depth, which the survey did not measure. Also, too few samples of the organic soil types were taken [most of these soils are in the peatlands of Scotland, which were not surveyed]. See Pete Smith *et al*, 2007.

[1231] Converting measurements of the SOC content into estimates of the change in the total soil C stock, or the loss in tC/ha, depends on applying a figure for the bulk density of soil. In the NSRI study, bulk density was not measured but was estimated from the measurement of the soil carbon content, using a pedotransfer function. This is considered unreliable and a small error here can produce a large difference in the SOC %. Email communication, Pete Smith, 31 May 2008, Professor of Soil & Global Change, Institute of Biological and Environmental Sciences, University of Aberdeen.

[1232] "Climate change cannot be entirely responsible for soil carbon loss observed in England and Wales, 1978-2003," Pete Smith, Stephen J. Chapman, W. Andy Scott, Helaina I. J. Black , Martin Wattenbach, Ronnie Milne , Colin D. Campbell, Allan Lilly, Nick Ostle, Peter E . Levy , David G. Lumsdon, Peter Millard, Willie Towers, Sönke Zaehle, and Jo U. Smith. Global Change Biology (2007) 13, 2605–2609.

[1233] Bellamy *et al*, 2005.

[1234] The rate of gain was 1.43% of the SOC content/year for soils with starting SOC contents of 0-2% and a very small gain of 0.14%/year for soils with starting SOC contents of 2-3%. Most of the gains in the low SOC content soils are in the 'rough grazing and other soils' category, with smaller gains in the managed soils. Figure 3, Bellamy *et al*, 2005.

[1235] Section 2, Johnston *et al*, 2009, *in press.*

[1236] Figure 3, Bellamy *et al*, 2005.

[1237] Results for England and Wales, 1980 to 1995. J. Webb, P. J. Loveland, B. J. Chambers, R. Mitchell and T. Garwood, "The impact of modern farming practices on soil fertility and quality in England and Wales," Journal of Agricultural Science, Cambridge (2001), **137**, 127–138.

[1238] We don't know if equivalent national surveys of grassland have been done in other countries. Or if the conclusion by European researchers that grasslands are gaining soil carbon is mainly based on modelling.

[1239] Data received from Guy Kirk and Patricia Bellamy, National Soil Resources Institute, Cranfield University, 19 August 2008.

[1240] In fact, we presume that the survey period for these soils was only about 17 years, as the arable and managed grassland sites were re-sampled in 1994/96, before the other sites. Bellamy *et al*, 2005.

[1241] See earlier summary of the UK NSI soil survey.

[1242] For arable/ley: 95% confidence range: -0.25 to -0.42g/kg/year; median: -0.07g/kg/yr. For permanent grassland, the loss rate is an average of –0.40g/kg/year, 95% confidence range: -0.31 to –0.49g/kg/year; median: -0.23g/kg/yr.

[1243] Data from the National Soil Inventory of England and Wales, 1978-2003, provided by the National Soil Resources Institute, Cranfield University, 19 August 2008.

[1244] Rate of change in C content (g/kg/yr) = (re-sampled OC - original OC) / time interval, where OC is in units g/kg and time interval in yr. This was calculated for each NSI site and then averaged.

[1245] The average soil carbon content for all 898 resampled arable/ley sites fell from 3.4% in 1980 to 2.8% in 1995, and for the 771 resampled managed permanent grass sites from 5% to 4.2%,. J. Webb, P. J. Loveland, B. J. Chambers, R. Mitchell and T. Garwood, "The impact of modern farming practices on soil fertility and quality in England and Wales," Journal of Agricultural Science, Cambridge (2001), **137**, 127–138.

[1246] The average soil carbon content for the 898 resampled arable/ley soil sites fell from 3.4% in 1980 to 2.8% in 1995, a total fall of 17% of the original amount over fifteen years, and for the 771 resampled managed permanent grass sites from 5% to 4.2%, a total fall of 16% of the original value over fifteen years, ie. a loss of 1.1% of the 1980 topsoil carbon content on each of arable/ley land and managed permanent grass each year. J. Webb, P. J. Loveland, B. J. Chambers, R. Mitchell and T. Garwood, "The impact of modern farming practices on soil fertility and quality in England and Wales," Journal of Agricultural Science, Cambridge (2001), **137**, 127–138.

[1247] The UK's arable soil carbon store for the top 30cm is approximately 465milliontC (derived from pages 17 & 18, CEH *et al*, 2008; see chapter 2). The arable topsoil carbon store for the top15cm will be at least half of this, so an annual loss of over 1% would mean an annual loss of over 0.5 x 465million x 0.01 = over 2.3milliontC/yr.

[1248] See Chapter 2 for details.

[1249] The soil bulk density was not measured but was estimated from the soil carbon content using a pedo-transfer function from: Howard PJA, Loveland PJ, Bradley RI *et al.* (1995) The carbon content of soil and its geographical-distribution in Great Britain. *Soil Use and Management*, **11,** 9–15.

[1250] Janssens IA, Freibauer A, Schlamadinger B, Ceulemans R, Ciais P, Dolman AJ, Heimann M, Nabuurs G-J, Smith P, Valentini R, Schulze E-D. 2005. The carbon budget of terrestrial ecosystems at country-scale—a European case study. Biogeosciences 2:15–26.. http://www.biogeosciences.net/2/15/2005/bg-2-15-2005.pdf

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[1251] Zaehle *et al* estimated that arable soil C losses are 19.3 million tC/yr for the EU15, Norway and Switzerland. Janssens *et al* estimated that arable soil C losses are 46 million tC/yr for the 34 countries of geographical Europe (exc. European Russia). We have therefore assumed a level of 'around 30 million tC/ha/yr' for the EU25, Norway & Switzerland arable area.

[1252] These figures are for the EU25, Norway & Switzerland, from: Smith, J.U., Smith, P., Wattenbach, M., Zaehle, S., Hiederer, R., Jones, R.J.A., Montanarella, L., Rounsevell, M.D.A., Reginster, I. , Ewert, F., (2005). Projected changes in mineral soil carbon of European croplands and grasslands, 1990-2080. Global Change Biology, 11(12), 2141-2152.

[1253] Rising temperatures only increase soil carbon mineralisation in conditions of sufficient soil moisture - see 4.3.

[1254] The mean temperature across England and Wales increased by about 0.5°C and there were also changes in rainfall distribution; Hulme *et al*, 2002, cited in Bellamy *et al*, 2005. It is now believed that the warming effects of climate change have been enhanced by up to 25% in Europe since the 1970s - especially in Northern and Eastern Europe - due to a reduction in haze from the fall in air pollution; study by Dr Vautard *et al* in Nature Geoscience, 18 January 2009.

[1255] Mean annual temperatures have risen from about 9°C (1878-1990) to 10.3°C in 2000-2005. See Fig.10, Guide to the Classical and other Long-term Experiments, Datasets and Sample Archive, Rothamsted Research, http://www.rothamsted.bbsrc.ac.uk/resources/ClassicalExperiments.html.

[1256] For the soil carbon results of the Broadbalk winter wheat trial, see Fig.3, "Soil Organic Matter: Its Importance in Sustainable Agriculture and Carbon Dioxide Fluxes," Edward Johnston, Paul R. Poulton, and Kevin Coleman, 2009, Chapter 1, Vol 101, Advances in Agronomy, *in press*. The researchers say the recent fluctuations,"Almost certainly … reflect the difficulties encountered when trying to measure long-term changes in soil organic matter; these problems include soil variability, changes in sampling techniques, analytical error, changes in analytical techniques etc. … I do not think that we have any evidence to suggest that soil C levels in our long-term experiments are changing as a result of the undoubted increase in temperature that we have observed.", email communication, Paul Poulton, Senior Research Scientist, Rothamsted, 12 February 2009.

[1257] Janssens IA, Freibauer A, Schlamadinger B, Ceulemans R, Ciais P, Dolman AJ, Heimann M, Nabuurs G-J, Smith P, Valentini R, Schulze E-D. 2005. The carbon budget of terrestrial ecosystems at country-scale—a European case study. Biogeosciences 2:15–26.. http://www.biogeosciences.net/2/15/2005/bg-2-15-2005.pdf

[1258] "Europe's Terrestrial Biosphere Absorbs 7 to 12% of European Anthropogenic CO2 Emissions", by Ivan A. Janssens, Annette Freibauer, Philippe Ciais, Pete Smith, Gert-Jan Nabuurs, Gerd Folberth, Bernhard Schlamadinger, Ronald W. A. Hutjes, Reinhart Ceulemans, E.-Detlef Schulze, Riccardo Valentini, A. Johannes Dolman. Published on-line in Science, Vol 300, 6 June 2003, www.sciencemag.org

[1259] Note, these figures are cited in Zaehle *et al*, 2007, and referenced to Janssens *et al*, 2005. However, we could not find these European-wide estimates in the Janssens *et al* paper.

[1260] Zaehle, S., Bondeau, A., Carter, T., Cramer, W., Erhard, M., Prentice, I.C., Reginster, I., Rounsevell, M.D.A., Sitch, S., Smith, B., Smith, P.C., Sykes, M. (2007): Projected changes in terrestrial carbon storage in Europe under climate and land-use change, 1990-2100. Ecosystems 10(3) 380-401.

[1261] Smith, J.U., Smith, P., Wattenbach, M., Zaehle, S., Hiederer, R., Jones, R.J.A., Montanarella, L., Rounsevell, M.D.A., Reginster, I. , Ewert, F., (2005). Projected changes in mineral soil carbon of European croplands and grasslands, 1990-2080. Global Change Biology, 11(12), 2141-2152. [Smith et al, 2005a, or Jo Smith et al, 2005]

[1262] Gervois, S., P. Ciais, N. de Noblet-Ducoudré, N. Brisson, N. Vuichard, and N. Viovy (2008), Carbon and water balance of European croplands throughout the 20th century, *Global Biogeochem. Cycles*, 22, GB2022, doi:10.1029/2007GB003018.

[1263] Fig 1. Pete Smith, Stephen J. Chapman, W. Andy Scott, Helaina I. J. Black , Martin Wattenbach, Ronnie Milne , Colin D. Campbell, Allan Lilly, Nick Ostle, Peter E . Levy , David G. Lumsdon, Peter Millard, Willie Towers, Sönke Zaehle, and Jo U. Smith. Global Change Biology (2007) 13, 2605–2609.

[1264] Mineralisation is the conversion of nutrients in the organic form (i.e. stored in SOM) into inorganic forms - unpublished paper on soil carbon and organic farming, provided to the Soil Association by Dr Julia Cooper, Newcastle University, 9 October 2007. SOM 'oxidation' is when soil carbon is converted to atmospheric CO2.

[1265] We raised this issue of a correlation with agricultural management with the authors of the paper, who agreed that this did not seem to have been identified and that although they had not considered it, it was a possibility, although there was also a possibility that it was just a sampling error.

[1266] Based on production data used by Cranfield University, see Tables 37 & 38, Williams et al, 2006.

[1267] In 2006, the average organic farming yields of all English regions for were 5.1t/ha for wheat and 4.7t/ha for barley. This probably under-estimates the national average organic farming wheat yield as this figure is not weighted by production levels in each region; if the NE and NW regions are excluded, the average of 5.4t/ha for wheat may be more representative, we assume. Page 31, "England and Wales under organic agriculture – How much food could be produced", University of Reading, 2009.

[1268] Agriculture in the United Kingdom 2006', Defra, 2007. The egg production figure is only eggs for consumption (not hatching eggs) and has been adjusted to account for the fact that Cranfield's GHG figures are per 20,000 while Defra production statistics are per 12 million.

[1269] Figures for the volume of manufactured feed used per sector (including feed used by poultry integrators): pigs: 1,561,000t; poultrymeat: 4,358,000t; eggs: 1,125,000t; dairy: 2,804,000t. From: table: "*Raw materials usage in retail production of animal feedingstuffs of Great Britain*," in *"GB animal feed statistical notice,"* February 2006 – 2007, Defra. Feed for poultry integrators was included; feed for calves and feed for home-mixing was excluded.

[1270] 0.52 factor represents proportion of manufactured feed that is wheat or barley; see Table 34, page 53, Williams *et al*, 2006. We assumed the proportions for each sector were the same as the proportion of the total quantities of manufactured feed used by each sector, ie. we did not adjust by using a specific inclusion rate for each sector. Applying this factor to the total amount of manufactured feed used by these sectors (inc. feed used by poultry integrators) gives a total of only: 5,120,960t. However, the

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current amounts of each feed crop used in the UK are double this: wheat: 6,868,000t; barley: 3,115,000t; oats: 228,000t; giving a total of 10,211,000t. Assuming an arbitrary 10% is used for other sectors, leaves 0.9x 10,211,000 = 9,189,900t used by the pig, poultry and dairy sectors. (All 2006 data from Agriculture in the UK 2006, Defra, 2007.) This is 1.794 times the amount of manufactured wheat/barley feed total for these sectors of 5,120,960, so to account for the feed that is not manufactured feed or used by the poultry integrators, we have increased the amounts for each sector by a second factor of 1.794.

[1271] Using organic yields: wheat: 5.4t/ha; barley: 4.7/ha. A notional average UK yield for organic cereal feed production is then calculated as follows: [(5.4 x 6,868,000) + (4.7 x 3,115,000)] divided by total feed currently used in UK of (6,868,000 wheat + 3,115,000 barley = 10,211,000) = 5.07t/ha. Inverse of this = 0.197ha/t.

[1272] "Feed and Food, Statistical Yearbook 2004," European Feed Manufacturers Federation (FEFAC), 2005.

[1273] One tonne of maize produces a total 836kg of co-products (including 241kg of 21% protein gluten feed), so each t of co-products requires 1000/836 = 1.2t of maize. Iowa Corn at http://www.iowacorn.org/cornuse/cornuse_3.html Cited in: "Maize International Market Profile," page 9, FAO, http://siteresources.worldbank.org/INTAFRICA/Resources/257994-1215457178567/Maize_Profile.pdf

[1274] Agriculture in the United Kingdom 2006', Defra, 2007.

[1275] The calculation is presented in the Soil Association report, "Silent Invasion – the hidden use of GM crops in animal feed," 2007, page 32. The amounts of maize gluten feed were derived by multiplying the following two sets of figures. 1) Figures for the volume of manufactured feed used per sector were the same as in the soya feed calculation (see before). 2) Assumed % of the total feed that is maize gluten for each sector: pigs – 3%; poultrymeat – none; eggs – none; dairy- 15%; based on data from "*Results of the survey into the composition of main compound feed rations as used in Great Britain during the six month period: July to December 1995*," prepared by the Government Statistical Service, MAFF, 1996.

[1276] This accounts for the remaining 31% of maize gluten that is not from outside the EU. Derived by multiplying the figures in column 3 by 0.31.

[1277] UK/EU maize yields assumed to be 7.2t/ha (see p.36, Williams *et al*). Organic maize yields are assumed to be 66% of this, ie. 4.8t/ha, giving an area of 0.210ha/t. This is multiplied by 1.2 to allow for waste in processing (see above), giving a value of 0.253ha/t of organic maize gluten.

[1278] "Feed and Food, Statistical Yearbook 2004," European Feed Manufacturers Federation (FEFAC), 2005.

[1279] One tonne of maize produces a total 836kg of co-products (including 241kg of 21% protein gluten feed), so each t of co-products requires 1000/836 = 1.2t of maize. Iowa Corn at http://www.iowacorn.org/cornuse/cornuse_3.html Cited in: "Maize International Market Profile," page 9, FAO, http://siteresources.worldbank.org/INTAFRICA/Resources/257994-1215457178567/Maize_Profile.pdf

[1280] US organic yields compared to non-organic: maize – 6% less (69 sets of data); soya – 6% less (55 sets of data). Survey of results of replicated farming trials from seven state universities and two independent research facilities, for different parts of the US, including rain-fed and irrigated regions, Bill Liedhardt, University of California.

[1281] 0.96 x US soya yield average of 2.8t/ha = 2.69t/ha. 0.96 x US maize yield average of 8.8t/ha = 8.45t/ha. Note, yields may be lower from other countries but a higher assumption of yield gives a more conservative soil C sequestration figure.

[1282] Based on production data used by Cranfield University, see Tables 37 & 38, Williams et al, 2006.

[1283] Agriculture in the United Kingdom 2006', Defra, 2007.

[1284] The calculation is presented in the Soil Association report, "Silent Invasion – the hidden use of GM crops in animal feed," 2007, page 32. The amounts of soya feed were derived by multiplying the following two sets of figures. 1) Figures for the volume of manufactured feed used per sector: pigs: 1,561,000t; poultrymeat: 4,358,000t; eggs: 1,125,000t; dairy: 2,804,000t. From: table: "*Raw materials usage in retail production of animal feedingstuffs of Great Britain*," in *"GB animal feed statistical notice,"* February 2006 – 2007, Defra. Feed for poultry integrators was included; feed for calves and feed for home-mixing was excluded. 2) % of the total feed that is soya for each sector. We started with the following percentages: pigs – 15.5%; poultrymeat – 15.9%; eggs – 8.5%; dairy- 3.3%; based on data from "*Results of the survey into the composition of main compound feed rations as used in Great Britain during the six month period: July to December 1995*," prepared by the Government Statistical Service, MAFF, 1996 (it is hard to get current figures). This gives soya inclusion rates of: pigs – 21%; poultry – 21.5%; laying hens – 11.5%; dairy – 4.5%. Applying these rates to the volumes of manufactured feed in 1) would suggest an average soya inclusion rate of 15.4%. However, Defra and the feed company BOCM Pauls say the level has fallen to 11-12%, so the figures were all reduced in proportion, by 36%, to give an average soya inclusion rate of 11.4%.

[1285] We understand that the current US soya yields are 2.8t/ha, giving an area of (1/2.8) = 0.36ha/t. However, Cranfield University assumed a value of 0.384/0.424 for processed soya meal with hulls/without hulls (page 82, Williams *et al*, 20060 so we have used a value of 0.4 for non-organic soya feed production, which allows for a portion to be discarded during processing of the soya into its consistent parts including soya meal. Allowing for 6% lower yields with organic production gives a value of 0.42ha/t.

[1286] Agriculture in the United Kingdom 2006', Defra, 2007.

[1287] See figures for maize gluten feed in the calculation of UK/EU origin maize gluten feed.

[1288] We understand that the current US maize yields are 8.8t/ha and that US organic maize yields are 96% of this, 8.45t/ha, giving an area of (1/8.45) = 0.1183ha/t. This needs to be multiplied by 1.2 to allow for waste in processing (see above), giving a value of 0.142ha/t of maize gluten.

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