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Understanding Changes in the UK's CO_2 Emissions: A Global Perspective

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The UK appears to be a leading country in curbing greenhouse gas (GHG) emissions. Unlike many other developed countries, it has already met its Kyoto obligations and defined ambitious, legally binding targets for the future. Recently this achievement has been called into question as it ignores rapidly changing patterns of production and international trade. We use structural decomposition analysis (SDA) to investigate the drivers behind annual changes in CO_2 emission from consumption in the UK between 1992 and 2004. In contrast with previous SDA-based studies, we apply the decomposition to a global, multiregional input—output model (MRIO), which accounts for UK imports from all regions and uses region-specific production structures and CO_2 intensities. We find that improvements from "domestic" changes in efficiency and production structure led to a 148 Mt reduction in CO_2 emissions, which only partially offsets emission increases of 217 Mt from changes in the global supply chain and from growing consumer demand. Recent emission reductions achieved in the UK are not merely a reflection of a greening of the domestic supply chain, but also of a change in the international division of labor in the global production of goods and services.

Introduction

Addressing the problem of climate change has moved high-up on the governments' agendas across the world. Despite initial efforts to curb greenhouse gas (GHG) emissions in the course of the Kyoto Protocol, global emissions are growing faster today than at the beginning of the 1990s. This has increased the pressure on policy makers to seal an ambitious deal for a post-2012 climate change regime, which holds the chance to limit warming to 2 °C relative to preindustrial levels, which has already been adopted as a guiding principle of climate change mitigation efforts by more than 100 countries (*1*).

In the current period of negotiations, the evaluation of industrialized (*Annex B*) countries' performance in meeting climate change targets is of renewed interest. In the United Nations Framework Convention on Climate Change (UNFCCC) a *territorial* or *production-based* accounting approach was applied for target setting and the monitoring of industrialized countries' emissions, including all GHG emissions released from a country's territory. With regard to international trade this includes the emissions released within a country for export production (*2, 3*). Motivated by concerns about "carbon leakage" for an adequate attribution of environmental responsibilities in times of an unprecedented integration of the global economy through expansion and changes in the pattern of international trade, and segmentation of production processes, recent research has recommended *consumption-based* emission inventories as a complement to production-based accounts. Such consumer emission accounts adjust conventional production-based emission inventories by subtracting export-related and adding import-related emissions (*3*).

In this general context, the UK economy deserves particular attention. Based on production accounting figures, the UK was one of the first countries to fulfill its Kyoto Protocol commitments. Already by 1999, GHG emissions were lowered by 12.5% compared to 1990 levels. These emission reductions in the UK occurred over a period of considerable structural changes in its economy, namely, the liberalization of the UK energy sector, which led to the so-called "dash for gas", as well as the continuing growth and differentiation of the service sector (*4*). Though still continuing in the 1990s, most of the decline in the energy-intensive manufacturing industries occurred in the 1970s and 1980s (*4*). Energy firms, in the newly competitive market, turned to the construction of gas turbine power stations, which could be built in a shorter period of time, to take advantage of improved technology, falling gas prices, and high interest rates (*4, 5*). The increasing specialization of the UK economy on service provision was driven by a large expansion, by international standards, of activities relying on the application of information technologies, such as financial, retail, communication, legal, advertising, and business services (*6*). We will henceforth refer to this as the "transition toward a service economy".

These developments took place in a period of sustained economic growth in the UK (*7*), and were also associated with a continuously deteriorating trade balance reflecting the country's growing dependence on imported products (*8*). In fact, it has been highlighted elsewhere that the UK is a country that has experienced a large increase in foreign outsourcing with one of the highest shares of imported to total intermediate inputs in the industrialized world (*9, 10*). (Ref *10* found that total outsourcing in terms of value-added increased from 38% in 1984 to 53% in 1995.) These trends indicate that the way trade-related emissions are accounted for will increasingly affect the evaluation of the UK's CO_2 emissions record. In fact, we show elsewhere that while territorial CO_2 emissions as accounted under the UNFCCC have been falling steadily (*11*), the global emissions released to meet final demands in the UK (consumer emissions) continue to rise (*12, 13*).

Rising consumer emissions call into question the seemingly positive developments in emission trends based on the UK's production accounts. In a context of a growing economy, with large and systematic shifts in production structure, consumer's preferences, and trade structure, knowledge of the quantitative significance of the various drivers behind changes in emissions is needed. The systemic nature of such transformations in production and consumption activities across the globe implies that regions cannot be considered in isolation, as changes depend jointly on dynamically changing domestic and external factors.

Structural decomposition analysis (SDA) is a technique frequently applied to quantify the impact of drivers behind changes in CO_2 emissions over time such as changes in energy

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efficiency, production structure of the economy, and consumer preferences. However, because of data limitations, most studies have either entirely focused on the analysis of domestic drivers behind emission changes (*14–19*) or have assumed that imported goods and services are produced using the same technology abroad and at home (*20–22*). The former approach fails to address the structural dependence of countries and results are impossible to interpret in terms of global net carbon effects. The latter approach will most likely provide substantially biased estimates of trends in global net carbon effects for the various decomposition factors. In both cases misleading policy implications might be derived.

This analysis adds to the existing literature by applying for the first time a SDA on a global, environmentally extended, multiregional input–output model (MRIO) to quantify the impact of several technological and economic drivers behind annual changes in the UK's consumption-based emissions for the period 1992–2004. By making use of more detailed accounts of emissions embedded in import flows to the UK over time, we are able to show how drivers behind UK consumer emission changes relate to changes in producer emissions across world regions.

The approach used here has been referred to as "unidirectional trade" MRIO model in recent input–output literature (*23–25*) and constitutes an approximation of a complete MRIO model. In fact, this approach dispenses of the simplifying "domestic technology" assumption associated with so-called "single region models" for calculating import-related CO_2 emissions, which has been shown could lead to significant errors in input–output computations (*23, 25–27*), by using region-specific production structures and CO_2 intensities. In particular, the domestic technology assumption can result in a systematic underestimation of import-related emissions for developed, open economies such as the UK, if imports are produced using more carbon-intensive procedures than available domestically (*28, 29*).

However, we do not believe that this paper is of interest to an international readership only for from this technical viewpoint. Instead we think that the UK case is also of interest as similar trends in trade patterns and structural economic developments have been observed for other key players in international climate change negotiations such as the U.S. (*30*), Japan (*31*), or the EU-27 as a whole (*32*).

In the next two Sections we briefly describe methods and data. We then turn toward the result discussion.

Methods and Data

Methods. Structural decomposition analysis of emission changes is based on environmentally extended input–output models. Such models are frequently used for life-cycle assessments, energy analysis, and the study of greenhouse gas emissions or other environmental pressures from final consumption (*18*). In the climate change context such consumption-based national emission inventories are often referred to as nations' "carbon footprints" (*33*).

As consumer emission analysis requires the estimation of CO_2 emissions associated with imported products, MRIO models have been increasingly used to relax the restrictive assumption that imported products are produced in the same way abroad as at home (*34, 35*). In the first part of this Section we will develop such a MRIO model for the UK before we will outline the SDA approach in the second part.

Even though our model is based on a supply and use approach, we use the notation of the standard Leontief model here for matters of notational simplicity. The interested reader is referred to the Supporting Information (SI) for all model details. Good introductions to input–output analysis can be found in refs *36* and *37*.

Environmentally extended input–output models are commonly used to estimate the emissions arising from economic activities. Mathematically, we can write emissions from economic activity, p, using the standard input–output equilibrium relationship as

$$p = \boldsymbol{f}'(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{y} \tag{1}$$

where p is pollution output, $\boldsymbol{A}$ is a technology matrix showing the inputs of sectors per unit of their output in monetary terms, $\boldsymbol{y}$ is a final demand vector, $\boldsymbol{I}$ is an identity matrix, $\boldsymbol{f}$ is an emission intensity vector showing sectoral emissions per unit of output, and $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ is the total requirement matrix also known as *Leontief Inverse*, henceforth denoted by $\mathbf{L}$. For the open economy, we can generalize eq 1 and explicitly consider imports. An augmented direct requirements matrix $\boldsymbol{A}^*$ can be derived from a MRIO transaction table in which interregional flows are explicitly included. Also, multiregion emission intensity and demand vectors, $\boldsymbol{f}^*$ and $\boldsymbol{y}^*$ can be derived from stacking demand in the UK of imported goods and total output in each region, respectively.

Here we build a trade model between the UK (u) and 3 foreign regions: Europe OECD (e), non-Europe OECD (o), and non-OECD (w). We assume that the UK trades with all other regions, but the other regions do not trade with each other. This means that this model cannot take into account feedback effects from international trade activities. However, the literature suggests that such simplification can still provide a good approximation of complete MRIO models (*23–25*). For our model this has been demonstrated in a model comparison exercise elsewhere (*12*). The interested reader is referred to the SI for all model details.

For the UK, there is evidence that its carbon footprint has been increasing continuously in recent years (*12, 13*). There are multiple factors contributing to this trend, such as changes in sectoral carbon intensities, changes in the structure of global supply chains of the products consumed in the UK, or changes in the composition or level of UK final demand. SDA can be used to quantify the relative contribution of these factors to the overall change in the UK's carbon footprint.

Formally, the change in emissions of eq 1, using multiregion factors, can be decomposed into separate contributions from changes in each variable as

$$\Delta p^* = \Delta \boldsymbol{f}^{*\prime}\boldsymbol{L}^*\boldsymbol{y}_c^*\boldsymbol{y}_l^* + \boldsymbol{f}^{*\prime}\Delta \boldsymbol{L}^*\boldsymbol{y}_c^*\boldsymbol{y}_l^* + \boldsymbol{f}^{*\prime}\boldsymbol{L}^*\Delta \boldsymbol{y}_c^*\boldsymbol{y}_l^* + \boldsymbol{f}^{*\prime}\boldsymbol{L}^*\boldsymbol{y}_c^*\Delta \boldsymbol{y}_l^* \tag{2}$$

where $\boldsymbol{y}_c^*$ and $\boldsymbol{y}_l^*$ are a further breakdown of the final demand vector $\boldsymbol{y}^*$ into a composition and a level component, respectively. Each contribution, or "effect", is the result of multiplying the "per unit impact" times "the total change" in the explanatory variable. These contributions can provide an insight into the driving forces underlying the relationship between emissions and technological, affluence, and population factors, where the latter have been omitted in eq 2 for simplicity.

One problem to address is the existence of a plethora of equally acceptable decompositions depending on the choice of time index, a ubiquitous problem in scientific computing when dealing with discrete approximation of derivatives. To address this "non-uniqueness" problem we compute the average of all possible decomposition (*15, 18, 38, 39*). As pointed out in ref *38* there is considerable variation in change terms that appear in the decomposition equation. A sensitivity analysis of the choice of time index is provided in the SI, where we also justify the choice to report the range of the estimates to provide a conservative approach in the representation of variability in the computed results as recommended in ref *15*.

Data. Our analysis is based on a time series of supply-and-use tables for the UK covering consecutive years from

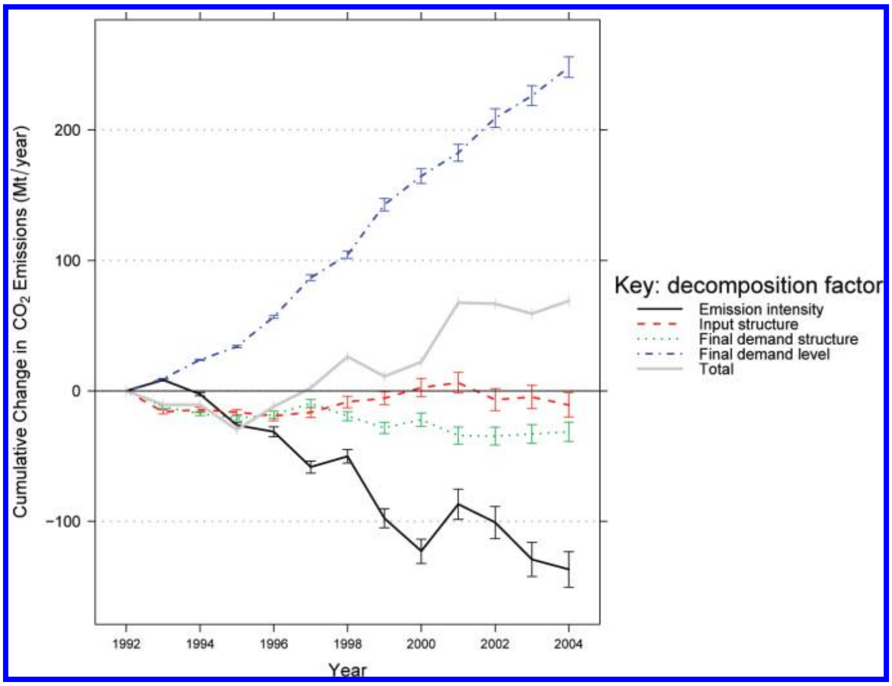

FIGURE 1. Four-factor decomposition of annual changes in the UK's carbon footprint for the 1992−2004 period (in million tonnes of CO_2 per year). The patterned colored lines represent the cumulative annual contributions to changes (figures in parentheses represent total changes over the period) from emission intensity (f^*), solid black (−136.8 Mt, −26.6%), production structure (L^*), dashed red (−10.8 Mt, −2.1%), final demand structure (y_c^*), dotted green (−31.4 Mt, −6.1%), final demand level (y_l^*), dash-dotted blue (248 Mt, +48.5%), and total emissions (p^*), solid bold gray (69 Mt, +13.5%). The error bars are based on the range of the decomposition estimates.

1992 to 2004. In the absence of published input−output data, which is suitable for modeling, this data set has been produced by the Stockholm Environment Institute and the University of Sydney from the official supply-and-use table publication of the UK Office for National Statistics (*40*) in a recent project for the UK's Department of Environment, Food and Rural Affairs (DEFRA). The tables distinguish 123 sectors, and values are recorded in current basic prices. For each year, bilateral trade matrices were constructed for UK imports from OECD Europe, OECD non-Europe, and non-OECD, at the same aggregation level (*12*). UK's CO_2 data were taken from the officially published Environmental Accounts (*11*).

For the foreign regions in the model we used tables from the GTAP5 (*41*) and GTAP6 (*42*) databases aggregated to 30 sectors and 3 regions. The data cover the time periods 1997 and 2001, respectively. For years 1998 to 2000 we used weighted averages of 1997 and 2001 data. For time periods prior to 1997 we assumed constant 1997 technology and for periods 2002−2004 we assumed the use of 2001 technology. These are strong assumptions, which can only be justified by the lack of global input−output data. This issue will be further discussed later. We fully account for changes in the import structure associated with UK production, which is the most important issue in the context of this paper. CO_2 emission data for the rest of the world was taken from the International Energy Agency (IEA) database covering consecutive years from 1992 to 2004 (*43*). Emission intensities were derived by imputing new output vectors for non-UK regions using sectoral GDP statistics from UN statistics (*44*). By using a model based on emission intensities we avoid the problems associated with the mixing of data in different units (hybrid unit models) in the context of SDA (*45*).

All monetary values were converted from current into basic prices using the double deflation method, as customary in the input−output literature (*15*, *19*). We use detailed sectoral price deflators provided by the UK Office for National Statistics for the deflation of UK related tables (domestic and imports) (*46*, *47*). For non-UK regions we used price index data provided by UNSTAT (*48*). More details on data sources, preparation, and modeling approach can be found in the SI. A complete description of the data is provided in ref *12*.

Results

The four-factor SDA presented in Figure 1 gives a first overall impression of the results. Between 1992 and 2004, CO_2 emissions released globally in the production of goods and services consumed by final demand entities in the UK increased by 69 Mt, 13% of the level in 1992. Figure 1 shows that this increase was driven by rising final consumption levels in the UK, which are a reflection of a period of sustained economic growth in the UK. Overall, increased final spending on goods and services in the UK led emissions to grow by 248 Mt (+48.5%). A further decomposition of these factors shows that more than 4/5 of these (196 Mt) were due to increases in per household spending levels. The remaining fifth was caused by the shrinking household size (from 2.5 persons per household to 2.3) in the UK and the rising resident population (from 57.6 to 59.8 million). Interestingly, the former is more important than the latter in the UK context with 31 Mt and 21 Mt CO_2 emissions, respectively. The corresponding six-factor decomposition is provided in the SI. Concomitantly, improvements in the carbon efficiency of global production processes saved a total of 137 Mt (−27%) of annual CO_2 emissions between 1992 and 2004. Further reductions were brought about by changes in the global supply chain (11 Mt, −2%), as well as changes in the composition of the average consumption basket of UK residents (31 Mt, −6%). The general finding that CO_2 emissions are driven up by final spending levels and mitigated by efficiency improvements has been observed in many previous SDA-based studies (*18*, *38*, *49*, *50*). On further reflection, this "empirical regularity" might not be coincidental. There could be many explanations, not necessarily mutually exclusive, for this recurrent pattern. For instance,

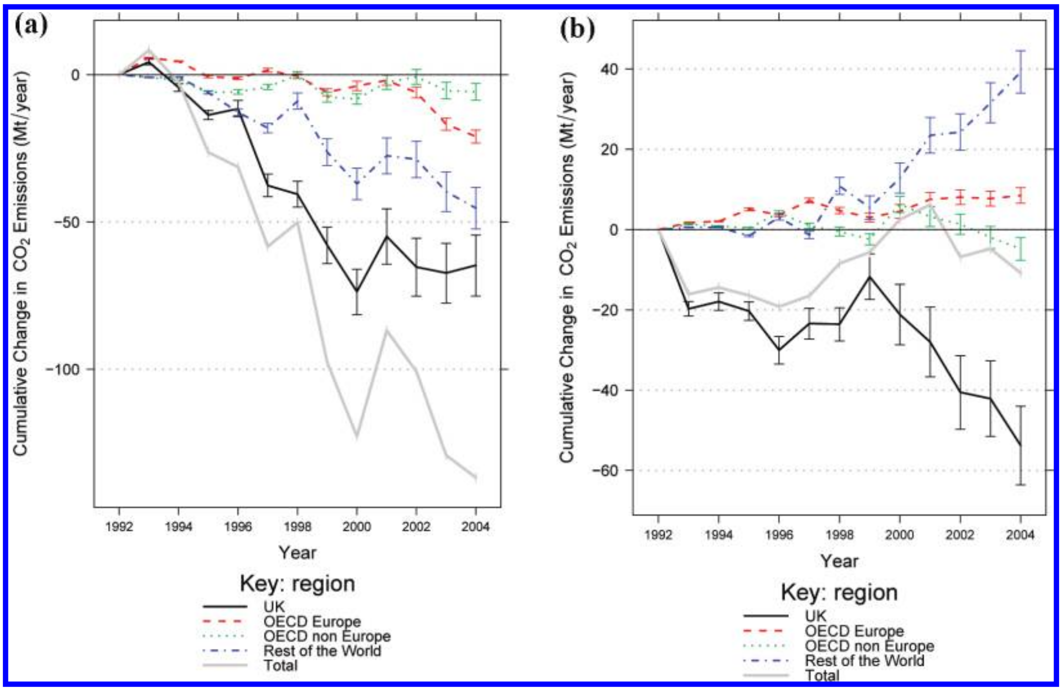

FIGURE 2. Four-factor decomposition of annual changes in the UK carbon footprint for the 1992−2004 period (in million tonnes of CO_2 per year) by world regions. The error bars are based on the range of the decomposition estimates. (a) Cumulative changes in regional CO_2 emission sources from changes in global emission intensity, *f. The patterned colored lines represent the *regional* contribution to emission changes (figures in parentheses represent total changes over the period) from the UK, solid black (−64.7 Mt, −18.8%), OECD Europe, dashed red, (−21 Mt, −47.9%), OECD non-Europe, dotted green (−5.8 Mt, −13.1%), the "Rest of the World", dash-dotted blue (−45.3 Mt, −57%), and total factors, solid gray (−136.8 Mt, −26.8%). (b) Cumulative changes in regional CO_2 emission sources from changes in global input structure, *L**. The patterned colored lines represent the *regional* contributions to emission changes (figures in parentheses represent total changes over the period) from the UK, solid black (−53.7 Mt, −15.6%), OECD Europe, dashed red (8.5 Mt, +19.4%), OECD non-Europe, dotted green (−4.8 Mt, −10.8%), the "Rest of the World", dash-dotted blue (39.2 Mt, +49.4%), and total factors, solid gray (−10.8 Mt, −2.1%).**

assuming causality in one direction, expanding sectors might be able to avail themselves of newer, more energy efficient technologies resulting in decreasing average energy intensity. On the other hand, if causality is reversed, this could be explained as the result of the so-called *rebound effect* referring to behavioral responses (such as "increased consumption") that tend to offset the beneficial effects of the introduction of more efficient technologies.

While the effects from changes in decomposition factors are most important in aggregate terms, the multiregion nature of our model allows us to differentiate the contribution from each region. We will therefore focus on a more detailed analysis that can provide further insight into the determinants of emissions.

Figure 2 shows regional contributions for the first two decomposition factors of Figure 1: emission intensity (a) and production structure (b). The graphs of the other decomposition factor results are omitted to conserve space and are provided in the SI. Figure 2a shows that about half, 64.7 Mt (−18.8%), of the cumulative savings from changes in sectoral CO_2 intensities were realized in the UK. The sharp decreases during the 1990s are a consequence of the "dash for gas", the major fuel mix shift from coal to gas in the electricity-generating sector. Due to dwindling domestic gas reserves and rising oil prices, this effect has started to level off in more recent years increasing the pressure for new developments in the reduction of territorial CO_2 emissions in the UK (*4*). Also all non-UK regions contributed to cumulative emissions savings from sectoral carbon efficiency improvements: 21 Mt (−48%) in Europe OECD, 6 Mt (−13%) in non-Europe OECD, and 45 Mt (−57%) in the non-OECD regions.

While changes in the input structure across the global supply chains of products consumed in the UK contributed only very modestly to changes in CO_2 emissions from consumption in the UK, the regional breakdown in Figure 2b highlights that this actually is the result of two opposing trends. Considerable reductions in CO_2 emissions were made in the UK's domestic supply chain (54 Mt, −15.6%). However, these reductions were offset by emission increases outside the UK from changes in the global input structure and trade patterns, 8.5 Mt for OECD-Europe (+19.4%) and 39 Mt for ROW (+49.4%).

A similar, but quantitatively less pronounced pattern can be observed for structure changes in final demand (please see the SI for details). Through shifts in the composition of the consumption basket of the average UK resident, a total of 45 Mt (−13.2%) in the cumulative annual CO_2 emissions was saved in the UK. However, these emission reductions were partially offset through an increased reliance on consumer goods from overseas. This caused additional CO_2 emissions of 14 Mt in the rest of the world and 3 Mt in Europe OECD over the period 1992−2004 (+17.8% and +5.7% respectively).

Figure 3a and b present a further "5-sector" breakdown of emission changes for the UK and the non-OECD regions of the "input structure" effects of Figure 2b. To conserve space we limit our analysis to one factor, production input structure, for the UK and ROW. A similar analysis could be presented for all other regional components of each factor. We refer to the SI for more details. The significant emission reductions from structural change in UK domestic production are largely driven by the UK's continuous development toward a service economy. Figure 3a shows how, even though the share of services in the UK domestic supply chain increased from 52% in 1992 to 65% in 2004 (*40*), CO_2 emissions from these shifts increased by only slightly less than 5 Mt (+8%). At the same time the "hollowing out" of manufacturing decreased emissions in the UK by 25.5 Mt (−35%). Additional

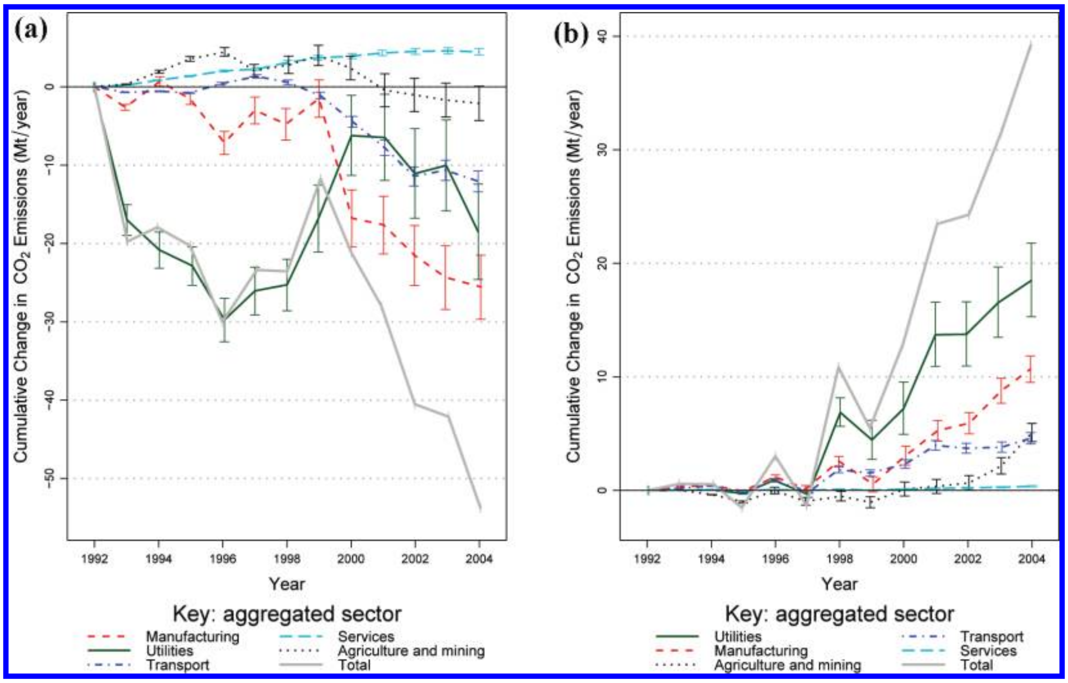

FIGURE 3. Cumulative changes in *sectoral* CO_2 emissions due to changes in the "input structure" for the 1992−2004 period (in million tonnes of CO_2 per year), for the UK and the ROW. The error bars are based on the range of the decomposition estimates. (a) Changes in *sectoral* CO_2 emission sources from changes in the "input structure", L^*, in the UK. The patterned colored lines represent the *sectoral* contribution to emission changes (figures in parentheses represent total changes over the period) from the following: Manufacturing, short-dashed red (−25.5 Mt, −35.2%), Utilities, solid green (−18.5 Mt, −11.3%), Services, long-dashed cyan (4.5 Mt, +8.1%), Transport, dash-dotted blue (−12.1 Mt, −33.2%), Agriculture and Mining, dotted black (−2.1 Mt, −13.0%), and Total emissions, solid gray (−53.7 Mt, −15.6%). (b) Changes in *sectoral* CO_2 emission sources from changes in the "input structure", L^*, in the ROW. The patterned colored lines represent the *sectoral* contribution to emission changes (figures in parentheses represent total changes over the period) from the following: Manufacturing, short-dashed red (10.7 Mt, +34.8%), Utilities, solid green (18.5 Mt, +69.2%), Services, long-dashed cyan (0.4 Mt, +20.9%), Transport, dash-dotted blue (4.6 Mt, +36.9%), Agriculture and Mining, dotted black (5.1 Mt, +65.2%), and Total emissions, solid gray (39.2 Mt, +49.4%).

tables in the SI show that, for example, one major contributor of this fall is the ferrous metal sector whose production declined sharply after 1997 (*74*).

Moreover, a shift toward less carbon intensive service industries allowed for additional reductions in CO_2 emissions of 18.5 Mt (−11%) in the UK's domestic supply chain from the Utilities sector. Tables in the SI clearly show that the energy supply sector is responsible for most of the changes in this sector. The large reductions from early 1990s in the UK are mainly associated with the "dash for gas". Emissions from energy supply started to increase after energy production from nuclear power peaked in 1997. Emissions started declining again in the last years as the share of gas increased, except for 2003 where consumption of coal rose by +6% (*51*, *52*).

Looking at the "Rest of the World" region in Figure 3b, the UK effects are almost mirrored providing evidence of regionalization of the division of labor and of evolving structural complementarity. Manufacturing activities, for example, in the global supply chain of products consumed in the U.K., are increasingly carried out in the rest of the world.

This caused an increase in annual emissions in this region of 10 Mt (+35%) between 1992 and 2004. Increased manufacturing activities are accompanied by increased demands on utilities in the foreign regions, mainly for the generation of electricity required to produce the various manufactured goods and services required in the production for UK consumer goods and services. This increased annual CO_2 emissions from UK consumption by almost 20 Mt (+69%).

Uncertainties. Results from input−output models are associated with a whole range of uncertainties, which have been previously discussed in the literature. These uncertainties are, for example, associated with the aggregation level of the input−output tables, (the quality of) the source data or the representation of production processes in monetary rather than physical units (*53*−*55*). In an uncertainty assessment specifically focusing on SDAs, Weber (*56*) shows, based on a Monte Carlo experiment using U.S. data, that results can vary considerably with aggregation levels. It is shown that structural changes appear considerably more important with decreasing aggregation, whereas efficiency shows the opposite trend. However, assuming that the more detailed data provides the most accurate description of sectoral emissions, the simulations demonstrate that although structural changes are consistently underestimated whereas emission intensity changes are overestimated, the bias is considerably reduced as soon as aggregation is undertaken in a meaningful way.

MRIO models can deal with one major source of uncertainties attached to input−output based consumer emission studies: that is the domestic technology assumption associated with the estimation of import-related emissions. At the same time some new uncertainties are added associated with currency conversion, the valuation of import and export data, regional aggregation, data availability, and type of MRIO model chosen or the treatment of the rest of the world. Good discussions of uncertainties associated with multiregional models are provided elsewhere (*23*, *30*, *33*, *57*−*59*).

In our model particularly the source data uncertainty is likely to be higher than in standard input−output models, because the UK input−output data used do not live up to the quality standards of tables officially published by Statistical Authorities. The same holds for the GTAP data used for modeling production activities in the foreign regions

(*60*), which is aggravated by its high sectoral and regional aggregation level (*25*) as well as the incomplete time coverage.

Because of the potentially large uncertainties involved in any MRIO model, a thorough uncertainty assessment was carried out during the model development phase. This included qualitative components such as a result comparison, as well as a quantitative component in form of a Monte Carlo simulation (*58, 61*). In fact, the Monte Carlo simulation is the first of its kind in the context of environmentally extended multiregional input−output modeling. This provides us with a systematic evaluation of model sensitivities.

The estimated relative standard error for total UK consumer emissions ranges between 3.3% in 1994 and 5.5% in 2004. However, these error margins can be substantially higher for detailed sector estimates. Given the high uncertainties associated with non-UK regions, it is not surprising that this is particularly the case in sectors where traded emissions are substantive. In general, the study shows that uncertainty increases with sector detail.

We apply this knowledge for an informed response in the application of these results to policy: often we only present aggregate results or provide simple disaggregations by regions. We never show results for more than five sectors in each region in the main section of this paper. For such high level analysis, errors typically tend to cancel out (*55, 58, 61*). Such a conservative approach in utilizing the results is even more important due to the added uncertainties from the deflation (*62*) and the SDA itself (*15*). Moreover, the uncertainties from currency conversion based on market exchange rate underlying the GTAP data is difficult to reduce given data availabilities as pointed out in this journal (*30*). An alternative conversion based on purchasing power parity would lead to a closing of the wealth gap between the richer (UK, OECD Europe, OECD non-Europe) and the poorer (non-OECD) regions in the model, but is unlikely to affect our qualitative conclusions.

Ultimately, as Weber (*59*) points out, MRIO models come with their own uncertainties and should not be seen, per se, as the panacea for modeling the impacts of global trade. Therefore, the choice of a MRIO model with a more aggregated description of the rest of the world over a sectorally very detailed input−output model with simplified trade modeling depends, in terms of uncertainties, on the subject of the analysis. Given the purpose of this study to analyze the differential regional contributions to drivers behind changes in UK consumer CO_2 emissions, we believe that taking a global, MRIO approach is necessary. Applying a domestic technology assumption based on more detailed knowledge of domestic technology for imputing import-related emissions would just amplify results from structural changes in the UK and undermine the purpose of the analysis (see SI). We thereby acknowledge the limitations posed by applying a "unidirectional trade" MRIO. However, the added uncertainties appear modest and manageable, particularly as the proposed model will lead to conservative estimates rather than overestimations. In this context the high regional aggregation is of advantage as fewer regions lend themselves to smaller under-estimations (*25*). Still, we encourage future research to study the effects of neglecting feedback effects from international trade on SDA results, where adequate data are available. Further quantitative research is required to study the specific uncertainties associated with MRIO models, also in the context of SDA exercises.

Discussion

Our analysis contributes to the growing streams of literature on the analysis of the CO_2 emissions embodied in countries' trade patterns (*30, 35, 60, 63*) as well as the analysis of the drivers behind changes in countries' CO_2 emissions (*18, 19, 22, 50, 64, 65*). Even though multiregional models are increasingly becoming the dominant "currency" for emission studies under full consideration of trade (*34*), decomposition studies have either focused entirely on the analysis of domestic drivers behind emission changes or assumed that goods and services imported are produced in the same way abroad as at home.

In this study we apply structural decomposition analysis (SDA) in a global, multiregional input−output (MRIO) model to understand annual changes in UK consumer CO_2 emissions between 1992 and 2004. By doing so we are able to capture the different regional (i.e., UK and non-UK) contributions to changes in individual technological and socio-economic emission determinants such as the carbon intensity of production, the production and trade structure, or consumer preferences. This allows us to study how changes in emissions from UK final consumption arise in the context of changing global production patterns, i.e., how the different drivers behind changes in UK consumer emissions relate to changes in territorial (or producer) emissions across the globe. By doing so a link between the UK's consumer emission accounts and producer emission accounts in other world regions is established for each emission determinant. To our best knowledge, such an analysis has not been attempted before.

The UK government has set out a plan in its Sustainable Development Strategy to reduce the global environmental impacts from production and consumption acknowledging that "there would be little value in reducing the environmental impacts within the UK if the results were merely to displace those impacts overseas or close off benefits at home or abroad" (*67*). The government suggests an eco-efficiency approach ("doing more with less") as the means to achieve this goal focusing on three priority areas: better products and services, which reduce the environmental impacts from the use of energy, resources, or hazardous substances; cleaner more efficient production processes, which strengthen competitiveness; and shifts in consumption toward goods and services with lower impacts.

We show in this paper that, in terms of CO_2 emissions, reducing the global environmental impacts might require reversing a trend as consumer emissions have been growing, at least between 1992 and 2004. Because the individual (or groups of) SDA factors related well to three eco-efficiency measures proposed by the government, our results enable to analyze past trends and would be well-suited to monitor progress in the future. The presented evidence shows that improvements were made in all three priority areas. However, the resulting emission reductions were not sufficiently large to offset the additional CO_2 from growing consumption.

Regardless of the honorable ambition of avoiding emission displacements, we illustrate how displacement effects, beside the well-known effects from the liberalization of the energy sector in the UK with the associated "dash for gas", are one key reason the UK managed to reduce its producer CO_2 emissions and therefore fulfill its Kyoto commitments. These displacements effects are particularly visible for the "structural components" (production and demand structures), which consider relative changes in production and consumption activities, respectively.

For example, examining changes in the UK's domestic production structure in isolation, CO_2 emissions of UK industries were reduced by 54 Mt. This is a typical result which would have been derived from a domestic SDA. However, the systemic nature of changes in production (as well as other SDA factors) implies that the UK cannot be considered in isolation. Taking also into account the associated changes in the production structure in other world regions as well as their exports to the UK, we show that these reductions are almost completely substituted by emissions in other parts of the world, which have replaced domestic production activities (see Figure 2b). Emission reductions in the UK through changes in the production structure are therefore not a reflection of a greening domestic supply chain, but of structural shifts in the international division of labor in the global production of goods and services.

With regard to the choice of modeling approach it should be noted that our results depend on choosing a multiregional model setup over a model applying a "domestic technology" assumption for estimating import related CO_2 and for approximating structural change in production in the rest of the world. A counter-factual experiment (see SI) shows that the domestic technology assumption leads to an increase of 18.6 Mt of CO_2 emissions over 1992−2004, which is about 73% lower than our reported estimate. Hence, as foreign regions in such a model are approximated by UK data, structural effects are replicated and further CO_2 emission reductions are derived from changes in the production structure of non-UK regions as frequently done in the literature. Hence, while domestic models provide an incomplete picture, a domestic technology assumption for calculating import-related CO_2 arrives at qualitatively different results for structural decomposition factors. In both cases misleading policy implications might be derived.

The structural shifts in the international division of labor manifest in the UK in terms of a continuing transition toward a service economy. We demonstrate how this increasing specialization on service provision have helped to reduce CO_2 emissions in the UK due to their low direct emission component, but led to additional emissions elsewhere where a growing share of primary and secondary production activities are undertaken as a result. The fact that the service transition in the UK seems to be just part of a larger reshuffling in global production and associated emissions raises considerable doubts to whether the service economy can be seen as a "wedge" to mitigate climate change. In fact, when all indirect emission components in other sectors across the globe are accounted for, the final consumption of services is responsible for more than 40% of the growth in CO_2 emissions from UK final consumption. In this sense, we add new evidence to an increasing body of literature urging for a careful evaluation of the role of services in the context of climate change mitigation (*13, 22, 68, 69*).

From an international policy perspective, the growth in UK consumer emissions is of concern, especially in the light of a declining manufacturing sector and a growing trend of production fragmentation in the UK (*9, 10*). Significant cost reductions in international coordination have increasingly allowed producers to take advantage of differences in technologies, factor prices, and laxer environmental standards, by relocating parts or all of their production processes overseas, mostly to *non-Annex B* countries, which do not have emission targets under the Kyoto Protocol. As almost all of the non-OECD countries in our model are *non-Annex B* countries, the alleged "greening of the UK supply chain" and the increased dependence on production in the non-OECD region might have contributed in driving global emissions upward (*60, 70*).

For any post-2012 international climate change regime it will be important to recognize the importance of international trade and the fragmentation of production processes. It is important to establish mechanisms making sure that shifting trade patterns will not undermine the effectiveness of the new international climate change regime. An extension of the Clean Development Mechanism (CDM) is only one among a variety of options for achieving this (*70, 71*). This could also be a point of departure, if the UK government is serious about the avoidance of displacement effects in other parts of the world. It is the responsibility of developed countries to assist developing countries by sharing and facilitating the use of new and cleaner technologies through investment and trading and in promoting better environmental standards.

Apart from such concerns about carbon leakage, emission displacements have also a fairness dimension as more carbon intensive production activities tend to be shifted from developed to less developed economies (*60*). In this sense analysis as presented here provides important evidence to support international climate change negotiations.

We believe this analysis to be of general interest for the international climate change discussion because the observed trends associated with the service transition and emission displacement are not a UK-specific phenomenon. However, more evidence from other countries is required to confirm our findings. We hope that these findings will stimulate further much needed research to support the climate change debate using similar decomposition exercises based on multiregional input−output models that include more regions with improved quantity and quality of data.

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Supporting Information Available

Additional technical details about the model, data, and methodology; additional tables and figures for other decomposition factors; sensitivity analysis of methodology. This material is available free of charge via the Internet at http://pubs.acs.org.

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