Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics

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Edited by Ruth S. DeFries, Columbia University, New York, NY, and approved July 30, 2010 (received for review November 10, 2009)

We estimate the potential reductions in methane and carbon dioxide emissions from several livestock and pasture management options in the mixed and rangeland-based production systems in the tropics. The impacts of adoption of improved pastures, intensifying ruminant diets, changes in land-use practices, and changing breeds of large ruminants on the production of methane and carbon dioxide are calculated for two levels of adoption: complete adoption, to estimate the upper limit to reductions in these greenhouse gases (GHGs), and optimistic but plausible adoption rates taken from the literature, where these exist. Results are expressed both in GHG per ton of livestock product and in Gt CO_2-eq. We estimate that the maximum mitigation potential of these options in the land-based livestock systems in the tropics amounts to approximately 7% of the global agricultural mitigation potential to 2030. Using historical adoption rates from the literature, the plausible mitigation potential of these options could contribute approximately 4% of global agricultural GHG mitigation. This could be worth on the order of \$1.3 billion per year at a price of \$20 per t CO_2-eq. The household-level and sociocultural impacts of some of these options warrant further study, however, because livestock have multiple roles in tropical systems that often go far beyond their productive utility.

bovines | intensification | mitigation | systems

Livestock are a global resource that provide substantial benefits to society, including food, income, soil nutrients, employment, a means of insurance and risk spreading, traction, and clothing. In the process, livestock use a large amount of natural resources: for example, livestock systems occupy approximately 30% of the planet's ice-free terrestrial surface area and account for 8% of the total use of fresh water (1). The demand for livestock products in developing countries will nearly double by 2050 as a result of human population increases, urbanization, and increasing incomes. Can future demand for livestock products be met in a sustainable way, and will future livestock production have poverty alleviation benefits? Many tradeoffs exist, competing demands for natural resources will intensify, and it will be a challenge to balance livestock production, livelihoods, and environmental protection (2).

At the same time, climate change will have significant negative impacts on livestock production systems (3, 4), particularly in the drier rangeland systems of the tropics. However, livestock are also a large contributor to the climate change problem (5). By some estimates they contribute 18% of global anthropogenic greenhouse gas (GHG) emissions (1). The main sources and types of greenhouse gases from livestock systems are carbon dioxide (CO_2) from land use and its changes (feed production, deforestation), which accounts for 32% of emissions from livestock; nitrous oxide (N_2O) from manure and slurry management, which accounts for 31%; and methane (CH_4) production from ruminants, which accounts for 25% of emissions.

Livestock systems will need to adapt in the future, requiring significant changes in production technology and farming methods in places, which could affect productivity as well as development goals (6). Agriculture and livestock in particular are likely to be required to play a much greater role than they have hitherto in reducing GHG emissions. Livestock keepers could mitigate some of these in various ways (7). Here we carry out analysis that attempts to quantify the extent to which several different options could mitigate GHGs from bovines in the mixed and rangeland-based livestock systems in the tropics. We concentrate on grazing systems and on the biophysical impacts and limits of some known mitigation options that people believe could work. The focus is on the mitigation of CO_2 and CH_4. The role of N_2O emissions from certain grazing systems is currently undergoing reevaluation (8).

Results

We estimated the impacts of adoption of improved pastures, intensifying ruminant diets, changes in land-use practices, and changing breeds of ruminants on the production of CH_4 and CO_2 for two levels of adoption: complete adoption, to estimate the upper limit to GHG reductions, and optimistic but plausible adoption rates taken from the literature, where these exist. Results for the six options summarized in Table 1 are shown in Table 2, in terms of the amount of CH_4 produced per ton of milk and meat, and the number of bovines needed to satisfy milk and meat demand in 2030 for the region and systems shown (i.e., it is assumed that demand for these livestock products is satisfied from within each system in each region). Methane production was calculated separately for milk and meat, with due regard to the estimated proportions of dual-purpose animals in each system and by splitting the herd into milk-producing animals (adult females) and meat-producing animals (males and replacement females) (*SI Text*). Results also are shown for the amount of CO_2 equivalent (CO_2-eq) mitigated in relation to the three pathways considered, where these come into play for the different options: a reduction in livestock numbers associated with diet improvement, the carbon sequestered via restoration of degraded rangelands, and the extra carbon sequestered as a result of land-use change, expressed as Mt CO_2-eq. Results for all options except 3a are shown for two levels of adoption: for 100% adoption rates in the systems and regions considered for each option, to define the upper limit of mitigation potential; and for an optimistic but plausible adoption rate taken from the literature, where possible.

Adoption of Improved Pastures in Latin America. Differences in CH_4 production per ton of milk between the natural cerrado vegeta-

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Author contributions: P.K.T. and M.H. designed research, performed research, analyzed data, and wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.0912890107/-/DCSupplemental.

Table 1. Mitigation options evaluated

Option	Region	System	Gas affected	Changes evaluated
1. Adoption of improved pastures	CSA	LGH	CH_4, CO_2	Cerrado vegetation to *Brachiaria* spp. pasture: digestibility increase, impacts on animal productivity Carbon sequestration (9) Restoration of degraded soils (10) Area adopted: best case from Central America, 1990–2003, 1.3% per year (30% to 2030); average of five countries, 0.6% per year (11)
2. Diet intensification				
(a) Stover digestibility improvement	SSA, SA	MRA, MRH, MRT, MIA, MIH, MIT	CH_4	Stover digestibility increase by 10%, impacts on animal productivity Adoption rate: 43%, maximum observed for genetically improved dual-purpose cowpea in West Africa (12); generally much lower rates (<10%) are observed or expected (13); 23% to 2030 used here (1% per year)
(b) Grain supplements	SSA, SA	MRH, MRT, MIH, MIT	CH_4	Grain supplement: increase from 0.5 to 2.0 kg per head per day, impacts on animal productivity Adoption rate: 23% to 2030 assumed (1% per year). In the absence of data, similar adoption rates to agroforestry-based supplements may be plausible
3. Land use				
(a) Carbon sequestration in rangelands	CSA, SSA	LGA, LGH, LGT	CO_2 (CH_4)	Changed carbon sequestration rates (10) (Methane production at intermediate stocking rates: not evaluated here) Complete adoption
(b) Increasing agroforestry practices	CSA, SSA, SA, SEA	MRH, MRT	CH_4, CO_2	*Leucaena* spp supplement of leaves, animal performance: Adoption rate: 1% per year, 23% to 2030 assumed, plausible for the best case (14) Carbon sequestration per ha: average lower limit for different tropical agroforestry systems (15)
4. Changing breeds of large ruminants	CSA, SSA, SA, SEA	LG (meat), MRH, MRT, MIH, MIT (dairy)	CH_4	Local to a cross-bred animal: animal productivity, meat in the LG systems and milk in the MRH/T and MIH/T systems Adoption rate: 29% to 2030 assumed, based on Kenya's adoption of crossbred dairy animals, the best case in East and Southern Africa (16)

CSA, tropical Central and South America; SA, South Asia; SEA, Southeast Asia; SSA, Sub-Saharan Africa; LG, rangeland-based systems; MI, mixed crop-livestock irrigated systems; MR, mixed crop-livestock rainfed systems; A, arid-semiarid systems (including hyper-arid); H, humid-subhumid systems; T, tropical highland systems.

tion and improved pastures can be large, but these depend on the level of adoption of improved pasture varieties. Although CH_4 production per animal (expressed as one tropical livestock unit, equivalent to a body weight of 250 kg) consuming *Brachiaria* pastures compared with natural grasslands is higher (38.7 compared with 31.2 kg CH_4 per year), milk production and liveweight gain per animal per day are three times higher (see *Materials and Methods* and *SI Text*). This results in a significant reduction in CH_4 production per unit of milk and meat produced and in total CH_4 produced. The number of animals required to satisfy demand is reduced under the improved pastures option, thus reducing pressure on natural resources. Adoption of improved deep-rooted pastures such as *Brachiaria* spp. has the additional advantage of sequestering 29.5 t per ha more carbon than natural rangeland vegetation (9). The direct and indirect impacts of this strategy and a plausible adoption rate (30%) represent mitigation of 29.8 Mt CO_2-eq; diet improvement and reduction of animal numbers account for 7% of the mitigation potential. This option could result in the use of less land as well as fewer animals to satisfy demand. This could translate into more CO_2 savings from deforestation avoided, although we have not included that effect here.

Diet Intensification Options. Diet improvements through increases in the quality of the basal diet or through supplementation are common strategies to intensify the diets of ruminants. In mixed systems in the developing world, stover from crops is widely used as a feed resource and can represent up to 50% of the diet of ruminants (17). Stover from different varieties of the same crop species has a wide range of digestibilities, and these differences are exploited by crop breeders to create dual-purpose crops with higher-quality residues. The two strategies tested here (options 2a and 2b) operate under similar principles as with the improvements of the diet through adoption of *Brachiaria* pastures. Better-quality diets reduce the CH_4 output per unit of product and therefore can reach a target quantity of animal product at lower CH_4 emissions and usually with fewer animals. Improving the digestibility of crop residues produces less milk (3.6 compared with 4.9 kg milk per day) and more CH_4 (33.0 compared with 31.7 kg CH_4 per year; *SI Text*) than supplementing the same basal diet with grain concentrates. However, both produce more milk, meat, and CH_4 than the control diet and can offset CH_4 production by a significant reduction in the numbers of animals to satisfy meat and milk demand. The total mitigation potential of crop residue digestibility improvements is higher than grain supplementation owing to its broader recommendation domain. This option is widely applicable across most rain-fed and irrigated mixed systems where large concentrations of animals exist and numbers are projected to increase. Therefore, significant reductions in the numbers of animals to meet demand can occur, whereas feeding grain concentrates is an option that is most appropriate to the humid and temperate mixed systems.

Land Use Options. We tested two options commonly believed to have a high mitigation potential: carbon sequestration through restoration of degraded rangelands in tropical Central and South America (CSA) and sub-Saharan Africa (SSA), and the use of agroforestry practices in mixed crop–livestock systems in humid

Table 2. Mitigation potentials for the options shown in Table 1

Option	CH_4 production (kg) per t of Milk	CH_4 production (kg) per t of Meat	No. of bovines (×10^6) needed to satisfy demand in 2030 for Milk	No. of bovines (×10^6) needed to satisfy demand in 2030 for Meat	Mitigation of CH_4 via reduction in bovine nos. (Mt CO_2-eq)	C sequestered via restoration of degraded pastures* (Mt CO_2-eq)	C sequestered via land-use change (Mt CO_2-eq)	Total mitigation (Mt CO_2-eq)
1. Adoption of improved pastures in LGH systems in CSA								
Cerrado	78	1,552	45.5	45.5	—	—	—	—
100% adoption[†] of *Brachiaria* pasture	31	713	14.7	16.8	7.4	23.5	13.5[‡]	44.5
30% adoption[†] of *Brachiaria* pasture	64	1,300	36.2	36.9	2.2	23.5	4.1[‡]	29.8
2a. Diet intensification: stover digestibility improvement in MR, MI systems in SSA, SA								
Baseline diet[§]	58	1,958	490.1	490.1	—	—	—	—
100% adoption[†] of stover with 50% digestibility (from 40%)	25	548	177.0	114.3	61.6	—	—	61.6
23% adoption[†] of stover with 50% digestibility (from 40%)	50	1,634	418.1	403.6	14.2	—	—	14.2
2b. Diet intensification: grain supplementation in MRH, MRT, MIH, MIT systems in SSA, SA								
Baseline diet[§]	58	1,958	148.0	148.0	—	—	—	—
100% adoption[†] of increasing grain supplementation from 0.5 to 2 kg/head/d	18	395	39.3	22.5	22.1	—	—	22.1
23% adoption[†] of increasing grain supplementation from 0.5 to 2 kg/head/d	49	1,598	123.0	119.1	5.1	—	—	5.1
3a. Land use: restoration of degraded pastures in the LG systems in CSA and SSA								
In CSA	—	—	—	—	—	53.6	—	53.6
In SSA	—	—	—	—	—	96.7	—	96.7
3b. Land use: increasing agroforestry practices in the MRH, MRT systems in CSA, SSA, SA, SEA								
Baseline diet[§]	58	1,958	287.6	287.6	—	—	—	—
1 kg Leucaena supplement replacing 0.5 kg stover and 0.5 kg concentrate (100% adoption[†])	25	523	103.9	59.2	40.3	—	102.7[¶]	143.0
1 kg Leucaena supplement replacing 0.5 kg stover and 0.5 kg concentrate (23% adoption[†])	50	1,628	245.3	235.1	9.3	—	23.6[¶]	32.9
4. Changing breeds of large ruminants in the LG (meat) and MRH, MRT, MIH, MIT (milk) systems in CSA, SSA, SA, SEA								
Local breeds	31	713	363.3	172.8	—	—	—	—
100% adoption[†] of crossbreeds	26	568	171.6	77.8	19.5	—	—	19.5
29% adoption[†] of crossbreeds	30	671	307.7	145.2	5.6	—	—	5.6

*Rates of carbon sequestration from ref. 10.

[†] "Adoption" refers to the proportion of total milk and meat production in 2030 that comes from implementing the option analyzed.

[‡] Carbon sequestration data from ref. 9.

[§] Baseline diet: grazing (1.3 kg DM), stover at 45% digestibility (2 kg DM), cut-and-carry (1 kg DM), grain concentrates (0.5 kg DM).

[¶] Carbon sequestration data from ref. 15.

and tropical highland areas of the developing world. Despite lower potential rates of carbon sequestration in SSA rangelands than in CSA (190 compared with 691 kg C per ha per year) (10), a higher proportion of degraded lands and a greater rangeland extent lead to a higher (almost double) mitigation potential for SSA rangelands than in CSA.

Agroforestry practices have dual mitigation benefits. Agroforestry species usually have a high nutritive value and can help to intensify diets of ruminants while they can also sequester carbon. In this example, replacing some concentrates and part of the basal diet with leaves of *Leucaena leucocephala* also intensifies diets so that animal numbers can be reduced to meet livestock product demand. Approximately 28% of the plausible mitigation potential of 32.9 Mt CO_2-eq for this option comes from the reduction in livestock numbers possible, compared with 72% contributed from the carbon sequestration effects.

Changing Breeds of Ruminants. At current adoption rates of improved breeds with higher milk production potential and higher body weights, only modest reductions in the amount of CH_4 produced per ton of milk can be obtained. This happens because of a body weight effect in which larger animals (500 kg compared with 250 kg) on the same diets will have higher intakes. As a result, differences in CH_4 production per animal are 38.7 kg CH_4 per year compared with 68.5 kg CH_4 per year, but the CH_4 output per unit of animal product does not change significantly. The larger animals produce more milk and meat, and as a result fewer animals are required to meet demand. This option potentially could be applied to many animals and across large areas, but the maximum mitigation potential is estimated to be a relatively modest 19 Mt CO_2-eq.

Comparisons Between the Different Options. Comparison of options at observed or plausible adoption rates suggest that restoration of degraded rangelands in SSA and CSA has the highest mitigation potential, owing to the magnitude of degradation and rangeland extent, although there may well be issues associated with its implementation. Next is the agroforestry option, which sequesters carbon and intensifies diet quality to reduce animal numbers. Improvements in the use of improved pastures and crop residue digestibility have the next-highest mitigation potentials owing to their broad recommendation domains and the marginal reductions in CH_4 production per unit of output that can be obtained.

Replacing breeds has the second-lowest mitigation potential of the options considered here, mainly because larger animals have higher intakes and produce significantly more CH_4 than smaller indigenous breeds, and this negates most of the benefit of increases in milk and meat production. Grain supplementation had the lowest mitigation potential, apparently mostly because of the relatively limited recommendation domain for this option.

Discussion

If we sum the various mitigation potentials (and subtract the restoration of degraded pastures in CSA in option 1, because this is already counted in option 3a), the total mitigation potential is 417 Mt CO_2-eq. This amounts to approximately 12% of the global livestock-related CH_4 and CO_2 emissions that are associated mainly with extensive livestock systems (1). The total mitigation potential using plausible adoption rates amounts to 214 Mt CO_2-eq, or 6% of the extensive livestock system-related CH_4 and CO_2 emissions. If some of these options were implemented in the same system simultaneously, further emission reductions might be obtained (for example, changing breed of animal together with supplementing the diet in several ways), but we have not estimated those effects here.

These estimates are highly indicative, because there are several limitations to the analysis. Although we attempted a breakdown by region and system, the true complexity of the changes examined is not comprehensively addressed. For example, option 2b, if adopted widely in a region, could have significant impacts on grain price, which could then translate into shifts in demand for grain for human food and for livestock feed. For most of the options considered, there may well be indirect impacts on natural resources that are not considered here, as well as impacts on (and of) livestock diseases, for example. Quantifying all of the potential impacts of systems' and land-use change is not straightforward, however. The replacement of cerrado vegetation with improved pastures, for example (option 1), could potentially reduce rates of future deforestation, because less land would be required to maintain fewer but more productive animals. The sowing of improved pasture in the forest margins, in areas that have already been deforested, could thus help to reduce future rates of deforestation.

All these mitigation options have costs associated. For example, restoration of degraded lands in the warm-dry and warm-moist climatic zones is estimated to cost \$50 per ha per year and \$15 per t CO_2-eq per year, whereas livestock feeding options in the same zones are estimated to cost \$60 per t CO_2-eq per year (18). There are many reasons for the gap between what could potentially be achieved and realized GHG mitigation, such as policy barriers, institutional, sociocultural, educational, and economic constraints, and particularly for the future, the price of CO_2 equivalents. Global agriculture could offset 5–14% (with a potential maximum of 20%) of total annual CO_2 emissions for prices ranging from \$20 to \$100 per t CO_2-eq (18). Even given the highly indicative nature of the numbers reported here, the mitigation potential of these strategies for the land-based livestock systems in the tropics amounts to approximately 7% of the (total) global agricultural mitigation potential to 2030. Using plausible adoption rates, this decreases to a contribution of approximately 4%. This could still be worth on the order of \$1.3 billion per year at a price of \$20 per t CO_2-eq (18), however. There are currently approximately 43 million livestock keepers living in the tropical rangeland-based systems on less than \$1 per day (19). Although the mitigation options looked at here may contribute only modestly to mitigation in relation to the global total from agriculture, such carbon payments could represent a meaningful amount of potential income for resource-poor livestock keepers in the tropics: an average of some \$30 per household per year would increase some household incomes by 15% or more.

How can we increase the contribution of tropical land-based livestock systems to global agricultural mitigation? The analyses here highlight the contribution that reducing the number of livestock could play in mitigating GHGs from land-based systems in the tropics. Most of the strategies investigated in this study involve significant reductions in animal numbers while increasing their productivity. However, there are likely to be sociocultural tradeoffs involved. For many pastoralist societies in Africa and Asia, wealth is measured at least partially in terms of livestock numbers (1). Options that propose reducing peoples' assets may not only affect households culturally, but they may also have unintended consequences on households' ability to manage risk. The value of livestock to livelihoods in marginal environments goes far beyond the direct impacts of their productive capacity. There are other options, however, that could still generate income for livestock-keeping households and from that perspective may well be worth seriously considering. This highlights the need to carry out household-level analysis to estimate what income levels these options might generate, in view of changes in production costs and production levels. Another option would be to improve adoption rates of these strategies and other mitigation options, via investments that reduce transaction costs and provide services and incentives to farmers so that they can adopt selected practices. These need to be accompanied by systems of payments for GHG efficiency at the farm gate (such as paying premiums for low emissions per kilogram of animal product produced) and also by establishing constraints on carbon emissions for the livestock sector.

Materials and Methods

Land Use and Livestock Systems Classification. We postulate large differences in mitigation potential between different livestock production systems, and so to disaggregate the results of the analysis here, we used a dynamic livestock production system classification scheme (20). The scheme characterizes grassland-based systems, in which more than 10% of the dry matter fed to animals is farm produced and in which annual average stocking rates are less than 10 temperate livestock units per ha of agricultural land; rain-fed mixed farming systems, in which more than 90% of the value of nonlivestock farm production comes from rain-fed land use, including the following classes; and irrigated mixed farming systems, in which more than 10% of the value of nonlivestock farm production comes from irrigated land use. These are further categorized on the basis of climate: arid–semiarid (with a length of growing period (LGP) <180 d), humid–subhumid (LGP >180 d), and tropical highlands/temperate regions. The classification scheme (Table S1) was mapped using proxies (21, 22) and has been updated using new datasets. The key proxies are cropland, LGP, and human population density. Cropland was estimated from the Global Land Cover (GLC) 2000 data layer (http://bioval.jrc.ec.europa.eu/products/glc2000/glc2000.php). Despite the age of GLC 2000, the estimates of cropland that are based on it have been shown to be no better or worse, in general, than estimates based on some other data products for Africa (23) and globally (24). Rangelands were defined according to certain land cover classes (22), modified according to whether areas had a human population density greater than 20 persons per square kilometer, as well as an LGP >60 d (which can occasionally allow cropping); in such cases, the areas were included in the mixed system categories. In our mapping of livestock systems, cropland areas from GLC 2000 may be overestimated in some situations, although using some other land-cover data products may result in underestimates (23, 24). Different estimates of cropland extent may affect the results of the analysis presented here, but probably only to a limited extent, given that livestock numbers were allocated to the different systems in such a way as to match national livestock statistics. The weaknesses of current land-cover datasets with respect to cropland identification are slowly being rectified through evaluation and harmonization of different datasets in different situations (see ref. 25, for example). The irrigated areas are based on the Food and Agriculture Organization (FAO) Aquastat map version 4.0.1 (26). For human population, we use the 1-km Global Rural-Urban Mapping Project (GRUMP) data (http://sedac.ciesin.columbia.edu/gpw/ancillaryfigures.jsp#1kmdens), which also defines urban areas. For 2030, the GRUMP population data are allocated pro rata according to the United Nations Population Division's medium-variant population data for each year by country (http://esa.un.org/unpp). Length of growing period data have been developed from the WorldClim 1-km data for the year 2000 (27), together with a new tropical highlands layer for the same year based on the same dataset, and for the year 2030 (28).

Livestock Numbers and Future Projections. For future projections of livestock numbers in the grazing systems of the tropics, we used a set of "reference world" simulations (29). These were derived using the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) combined with a global water simulation model based on global water databases (30). IMPACT is a partial equilibrium agricultural sector model and simulates food production (for 32 crop, livestock, and fish commodities) according to economic, demographic, and technological change. The model generates annual projections for irrigation, livestock, and nonagricultural water withdrawals and depletion, as well as irrigated and rain-fed crop area, yield, production, demand for food, feed, and other uses, prices, and trade; and livestock numbers, yield, production, demand, prices, and trade. The model also estimates the number of malnourished preschool children in developing countries as a proxy for poverty rates. A scenario has been simulated to 2050 that quantifies global economic growth and shifts in the demand and supply of agricultural products, which imagines a world developing in the coming decades much as it does today (the "reference world") (29). Economic growth assumptions and agricultural productivity estimates are largely based on those of the TechnoGarden scenario of the Millennium Ecosystem Assessment (31). The reference world assumes a set of energy use and production projections that lie in the middle of available energy projections. The GHG emissions scenario associated with this is the SRES B2 scenario (32), and climate projections to 2050 using the outputs from the Hadley Centre Coupled Model version 3, HadCM3 (33), were used to drive the various modeling tools (29). We use the same climate and human population data to modify the livestock system classification in the analyses here. We used reference world numbers of bovines for both 2000 and for 2030 (29). The data for 2000 are based on averages for the years 1999–2001 from the FAOSTAT database (http://faostat.fao.org/default.aspx), and these country-level data were then allocated pro rata according to the Gridded Livestock of the World dataset (34). For livestock in 2030, the livestock numbers that were generated as output from the IMPACT model were converted to live-animal equivalents using country-level ratios of live-to-slaughtered animals from FAOSTAT for the average of the 3 y centered on 2000. These future livestock numbers were then allocated to the modified system extents on a pro rata basis. In the reference run, although there are significant improvement in animal yields, growth in numbers will continue to be the main source of production growth in developing countries, reflecting recent trends (29). Numbers of bovines by region and system for 2000 and 2030 are shown in Table S2.

Estimating Emissions from Livestock Systems. Diets of domestic ruminants in the tropics are varied and depend to a great extent on the type of production system in which animals are kept. To account for these systems' and regional differences, we divided the tropics up into four regions: SSA, South Asia (SA), Southeast Asia (SEA), and tropical CSA. We omitted East Asia and West Asia–North Africa from the analysis because the great majority of the land-based livestock systems in these regions are subtropical rather than tropical. We estimated livestock diets using expert knowledge and literature reviews for each production system (17). Diets are made up of seven generic feeds: arid rangelands, humid rangelands, cooler tropical rangelands, stover (crop residues), cut-and-carry pastures, opportunistic feeds such as weeds and roadside grasses, and grains. The availability of these feeds and the complexity of diets depend on the level of intensification of the production system (35). Such dietary differences are essential in estimating differences in CH_4 production between systems and regions (17). We use a dynamic model for predicting feed intake and nutrient supply in ruminants, RUMINANT (36) (*SI Text*), as the basis of our calculations of CH_4 produced from enteric fermentation. The model estimates intake and supply of nutrients to the animal from fermentation kinetics and passage of carbohydrate and protein through the animal and subsequent excretion (37) and estimates the animal's nutrient requirements (38). The model can simulate animals of different body weights because of the incorporation of allometric rules for scaling passage rates (37), and it calculates stoichiometries (39). RUMINANT has been validated with a wide range of tropical and temperate diets. Because constraints on intake due to scarcity of feed resources are common in many farming systems (17), we assume that feed scarcity amounts to 25% of total feed intake for dry-season diets. For each system and region, RUMINANT was run for dry and wet season diets and the results multiplied by the number of days in each season to obtain yearly CH_4 production estimates per animal. These were then aggregated to the system level by multiplying by the number of livestock present in each system. Methane from ruminant manure management systems was assumed to be proportional to the CH_4 produced from enteric fermentation, amounting to 3% of the CH_4 coming from enteric fermentation (17, 40). RUMINANT was also used to estimate the impacts of dietary changes on meat production, and we estimated offtake rates by region from ref. 29) (*SI Text*).

Rationale for the Mitigation Options Assessed. We estimated the mitigation potential of six region- and system-specific options to 2030. The rationale for their selection follows.

Option 1: Intensifying rangeland productivity in the neotropics via adoption of improved pastures. Taken as a whole, CSA is the highest contributor to agricultural GHG emissions. At the same time, the region has human population densities that are sufficiently low to permit the expansion of ruminant livestock production. However, it is critical that any expansion of livestock production does not happen at the expense of forest loss. Considerable expansion of the areas in improved pasture we judge to be plausible, because improved pastures have been widely adopted in tropical CSA in recent times: the historical precedent exists. There is less scope for the widespread adoption of improved pastures in the tropics of SSA and Asia, however. For the former, there is little historical precedent, and substantial economic development of the rangelands is unlikely. In the tropical regions of Asia, pressure on land resources means that there is only limited scope for the expansion of land-based ruminant production systems (41). To evaluate this option, we assumed conversion of rangelands from native cerrado vegetation to an improved pasture such as *Brachiaria decumbens*, one of several species of cultivated grass of African origin that are already widely cultivated as a livestock feed in the tropics. We applied modified animal productivity parameters and calculated CH_4 emissions using the RUMINANT model. The results were scaled up to the whole of the humid–subhumid grassland-based system (LGH) in CSA by applying historical rates of improved pasture expansion to the total area (11). Expansion of improved pastures in the rangelands of CSA could also affect carbon sequestration rates, and we estimated this effect using data for *Brachiaria humidicola* (9). We estimated the added carbon sequestration potential that arises from restoration of degraded pastures in the region using existing data (10).

Option 2: Diet intensification in mixed systems in SSA and Asia. The manipulation of dietary components in ruminants is considered by many to be one of the most direct and effective ways of mitigating CH_4. Mixed crop–livestock systems in the tropics usually have complex diets that are amenable to modification. Productivity is inherently low in many of the mixed systems in SSA and Asia but could be substantially increased through diet intensification, about which a considerable body of research exists. Widespread application of different options is plausible in many situations. To assess the effects of diet intensification in the mixed systems in SSA and SA, we evaluated two options in relation to a common baseline large ruminant diet, made up of daily intakes per head of 1.3 kg dry matter (DM) of grazing, 2 kg DM of cereal stover with a digestibility of 45%, 1 kg DM of cut-and-carry forage, and 0.5 kg DM of a grain concentrate. Such a diet can support milk production of 1.3 kg per day and liveweight gain of 0.07 kg per day. The source of cereal stover changes, depending on the system and region, from maize in many parts of SSA to rice and sorghum in SA, for example. First (option 2a), we posited an increase in stover digestibility of 10 percentage points, which is well within the range of variation in digestibility that has been observed in sorghum, for example (42). We evaluated the impacts of this change in the diet and scaled up the results to all of the MR (mixed rain-fed) and MI (mixed irrigated) systems in SSA and SA. Adoption rates of up to 43% for genetically improved dual-purpose crops have been observed in some parts of West Africa (12). Although lower adoption rates may be expected in general, the potential domain for adopting this option is large and extends throughout the mixed systems of SA (13). Second (option 2b), we modified the basal diet by increasing the amount of grain fed as a supplement from 0.5 to 2 kg per animal per day. As for option 2a, we evaluated the impact of the change in diet on milk and CH_4 production. Unlike option 2a, we judged that this option would not be so applicable to the arid–semiarid mixed systems, given the importance of grain production for human consumption in these systems. Accordingly, the results were scaled up to the mixed humid–subhumid and tropical highland systems in SSA and SA, for the livestock numbers projected to 2030. We could find no direct adoption data in the literature and thus used a rate of 1% per year (some 23% to 2030), the same rate as for option 2a and for the agroforestry-based supplementation option (see below, option 3b).

Option 3: Land-related alternatives. We evaluated two options with a specific focus on land-use change: one that improved the sequestration of carbon in degraded rangelands (via some reduction in animal numbers to moderate stocking rates in these areas), and one that evaluated broad adoption of agroforestry options that can increase carbon sequestration and also provide improvements to ruminant diets via supplementation with highly digestible leaves.

Option 3a: Carbon sequestration in rangelands.

Globally, the rangelands occupy vast areas of land, and the potential for carbon sequestration has been amply demonstrated (10). Important social benefits could accrue in addition to the environmental benefits, by providing an additional source of income for the poor livestock producers that predominate in the tropics. There is considerable activity in this area, but uncertainties persist regarding the mechanisms that are needed to set up efficient and equitable payment schemes. We applied existing carbon sequestration rates (10) to the degraded proportion of the rangeland-based systems (LG) in SSA and SA and calculated total amount of extra carbon sequestered.

Option 3b: Increasing the uptake of agroforestry practices.

This option has both direct and indirect impacts on the environment and livestock. Increasing tree coverage can markedly increase the rate of carbon sequestration, depending on the system and region (15), while at the same time it can improve the diets of livestock because of the higher nutritive value and increased digestibility of some agroforestry species. This option can tackle CH_4 and CO_2 emissions simultaneously. To estimate the effects, we increased the area under agroforestry according to historical rates of adoption and scaled this up to the systems in which it is most like to be practiced: the mixed rain-fed humid/subhumid and tropical highland (MRH, MRT) systems in the tropics. We estimated the additional CO_2 captured in these systems. We ran RUMINANT with a modified diet that included the leaves of *L. leucocephala* as a supplementary feed for cattle in the dry season and quantified the CH_4 mitigated as a result. Adoption rates on the order of 1% per year of agroforestry practices such as improved fallows and boundary plantings have been observed in some situations (14), and we applied this here (23% to 2030).

Option 4: Shifts in breeds of ruminant livestock. Historically, the use of conventional livestock breeding techniques has been largely responsible for the increases in yield of livestock products observed over recent decades (43). Genetic improvement coupled with diet intensification could lead to substantial efficiency gains in livestock production and CH_4 output. This would result in fewer but more productive animals being kept, which could have positive consequences for CH_4 production and land use. To quantify this option, we changed the potential productivity of animals in the RUMINANT model to simulate a change in breed from a local cow to a cross-bred animal and estimated the impacts on both meat production in the rangeland (LG) systems and dairy production in the MR and MI systems. We excluded the arid–semiarid systems from this scaling up, because we assumed that adoption in these systems of such an option would be low. In the humid–subhumid and tropical highland systems, we assumed an adoption rate of 29% to 2030, based on the historical adoption rate of crossbred dairy animals in Kenya (16).

ACKNOWLEDGMENTS. We thank Rich Conant, Federico Holmann, Matthieu Lesnoff, Frank Place, Mark Rosegrant, and Russ Kruska for providing information and links to relevant literature.

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