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Greenhouse gas mitigation potentials in the livestock sector

Mario Herrero[1]*, Benjamin Henderson[1], Petr Havlík[2], Philip K. Thornton[1,3], Richard T. Conant[4], Pete Smith[5], Stefan Wirsenius[1,6], Alexander N. Hristov[7], Pierre Gerber[8,9], Margaret Gill[5], Klaus Butterbach-Bahl[10,11], Hugo Valin[2], Tara Garnett[12] and Elke Stehfest[13]

The livestock sector supports about 1.3 billion producers and retailers, and contributes 40–50% of agricultural GDP. We estimated that between 1995 and 2005, the livestock sector was responsible for greenhouse gas emissions of 5.6–7.5GtCO_2e yr^{-1}. Livestock accounts for up to half of the technical mitigation potential of the agriculture, forestry and land-use sectors, through management options that sustainably intensify livestock production, promote carbon sequestration in rangelands and reduce emissions from manures, and through reductions in the demand for livestock products. The economic potential of these management alternatives is less than 10% of what is technically possible because of adoption constraints, costs and numerous trade-offs. The mitigation potential of reductions in livestock product consumption is large, but their economic potential is unknown at present. More research and investment are needed to increase the affordability and adoption of mitigation practices, to moderate consumption of livestock products where appropriate, and to avoid negative impacts on livelihoods, economic activities and the environment.

The livestock sector is large. Twenty billion animals make use of 30% of the terrestrial land area for grazing, one-third of global cropland area is devoted to producing animal feed[1] and 32% of freshwater is used to provide direct livelihood and economic benefits to at least 1.3 billion producers and retailers[2,3]. As an economic activity, livestock contributes up to 50% of agricultural GDP globally[4].

The livestock sector is also very dynamic. Global per capita consumption of livestock products has more than doubled in the past 40 years[4]. Increasing human population, incomes and urbanization are projected to drive increases in the consumption of milk and meat over the next 20 years, at least at previously observed rates[1,5], with most of the growth projected to occur in the developing world. In response to these demand trends, the sector has managed to significantly increase production. Beef and milk production have more than doubled over the past 40 years and monogastric production (pigs and poultry) has grown in places by a factor of five or more[2]. Intensification of production, in terms of increased livestock and/or crop productivity, has played a pivotal role in raising the output per unit of land and animal[1]. For example, in the USA, 60% more milk is produced now than in the 1940s with about 80% fewer cows[6]. Although intensification has occurred in some regions, agricultural land expansion has also been an important component of production growth in places such as Africa and Latin America. These trends, if continued, could drive significant increases in greenhouse gas (GHG) emissions, deforestation, loss of biodiversity and other negative impacts on the environment[7].

Here we review the mitigation potential of a number of field-tested management options for mitigating GHG emissions in livestock production. Our Review incorporates new supply-side information, such as changes in the structure of livestock production systems, with information about how policies that reduce demand for animal protein might contribute to emissions reductions. This synthesis of supply- and demand-side mitigation potentials is central to understanding the ways in which the components of our food systems interact and how livestock emissions could evolve and be managed in the future. We focus on biogenic emission sources in livestock systems, so we do not address CO_2 from energy use.

Mitigation potentials were estimated for the following: (i) technical and management interventions; (ii) intensification and the associated structural changes of livestock systems; and (iii) moderation of demand for livestock products.

We estimate that these options have the technical potential to mitigate a substantial proportion of emissions from livestock. However, their economic mitigation potential may be far smaller due to adoption barriers and costs of the technical options, underinvestment in the livestock sector and a lack of effective policies or political will for promoting healthy levels of consumption of livestock products in the diets of developed and developing country populations. We conclude with a discussion on research needs for improving the feasibility and adoption of mitigation options in livestock systems to lower GHG emissions without hampering rural economies and livelihoods.

[1]Commonwealth Scientific and Industrial Research Organization (CSIRO), 306 Carmody Road, St Lucia, Queensland 4067, Australia. [2]Ecosystems Services and Management Program, International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria. [3]CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), ILRI, PO Box 30709, Nairobi 00100, Kenya. [4]Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, Colorado 80523-1499, USA. [5]Scottish Food Security Alliance—Crops, Institute of Biological & Environmental Sciences, University of Aberdeen, 23 St Machar Drive, Aberdeen AB24 3UU, UK. [6]Department of Energy and Environment, Chalmers University of Technology, SE-41296 Gothenburg, Sweden. [7]Department of Animal Science, Pennsylvania State University, 324 Henning Building, University Park, Pennsylvanie 16802, USA. [8]Animal Production and Health Division, FAO, Viale delle Terme di Caracalla, 00153 Rome, Italy. [9]Animal Production Systems Group, Wageningen University, PO Box 338, 6700 AH Wageningen, the Netherlands. [10]Institute of Meteorology and Climate Research, Atmospheric Environmental Research (IMK-IFU) Karlsruhe Institute of Technology (KIT), Kreuzeckbahnstr. 19, 82467 Garmisch-Partenkirchen, Germany. [11]International Livestock Research Institute, Old Naivasha Road, Nairobi 00100, Kenya. [12]University of Oxford, Oxford Martin School, Oxford OX13QY, UK. [13]PBL Netherlands Environmental Assessment Agency, Bilthoven 3720 AH, The Netherlands. *e-mail: Mario.Herrero@csiro.au

Table 1 | Current global greenhouse gas emissions from livestock (~1995–2005).

Emissions source	Emissions ($GtCO_2e$)	Reference
Feed N_2O	1.3–2.0‡	9,13,15,16–18
Feed CO_2 (LUC excluded)	0.92	15,17,18
Feed CO_2 (LUC)	0.23	15,17,18
Pasture expansion CO_2 LUC	0.43	15,17,18
Feed CH_4 rice	0.03	15,17,18
Enteric CH_4*	1.6–2.7	9–13,15,17
Manure CH_4*	0.2–0.4	9–13,15,17,18
Manure N_2O*	0.2–0.5	9–13,15–18
Direct energy CO_2	0.11	15,17,18
Embedded energy CO_2	0.02	15,17,18
Post-farm gate CO_2	0.023	15,17,18
Non-CO_2 emissions* (IPCC guidelines)	2.0–3.6	This Review
Total emissions (LCA approach)†	5.6–7.5	This Review

*Livestock emissions according to IPCC emissions guidelines[8]. †Range estimated using information from global analyses for key emissions source categories. LCA as implemented by FAO[15]. ‡Includes N_2O emissions from manures applied to pastures, and from fertilizers to croplands for both feed and pasture. Emissions from manure applied to pastures ranges from 0.42–0.95 $GtCO_2e$. LUC, land-use change.

GHG emissions from livestock

A key starting point for assessing the mitigation potential of the livestock sector is understanding the baseline levels of emissions associated with different livestock products, the key contributing greenhouse gases, their main sources and the regional differences in livestock production systems. We present these below.

Current emissions. Several global estimates of GHG emissions from livestock have been undertaken (Table 1). Here we classify studies as either following IPCC emissions guidelines[8], which include direct non-CO_2 emissions of methane (CH_4; enteric and manure) and nitrous oxide (N_2O, manure management)[9–13], or using life-cycle analysis (LCA)[14,15], which includes extra sources in the supply chain; from conception to retail, emissions arise from feed production and animal rearing as well as from the processing and transportation of livestock commodities to markets. Further emissions occur after sale associated with transportation, storage, cooking and consumption or possible disposal. Some of these LCA emissions are reported in the GHG inventories of other sectors (that is, fuels to transport products in the transport sector, energy used in processing in industry sector).

We estimate that total emissions from livestock from 1995 to 2005 were between 5.6 and 7.5 $GtCO_2e\ yr^{-1}$ (Table 1). The most important sources of emissions were enteric CH_4 (E_{CH_4}; 1.6–2.7 $GtCO_2e\ yr^{-1}$; refs 9–13,15), N_2O emissions associated with feed production (1.3–2.0 $GtCO_2e\ yr^{-1}$; ref. 15) and land use for animal feed and pastures, including change in land use (~1.6 $GtCO_2e\ yr^{-1}$; ref. 15). Figure 1 shows the spatial distribution of global livestock emissions[13].

The level of disaggregation of global livestock emissions differs considerably between studies (see Supplementary Information). Some estimates are based primarily on Tier 1 approaches (using default global or regional emission factors)[10–12,16], with Tier 2 approaches (using estimated regional or local emission factors) sometimes being used for enteric fermentation[9]. Some studies disaggregate emissions by country and region, species, production system and by product (milk, meat)[13,15]. FAO estimates[15,17,18] use Tier 2 methods for the IPCC emissions categories and LCA methods for the other sources. Herrero *et al.*[13] use Tier 3 methods (application of a rumen kinetics model) for E_{CH_4} and Tier 2 methods for the other source categories.

Cattle production systems dominate the sector's emissions (64–78% depending on the study[13,15,17]). FAO studies[17,18] using LCA estimated cattle emissions from all sources to be about 4.6 $GtCO_2e\ yr^{-1}$, of which 2.5 $GtCO_2e\ yr^{-1}$were from beef cattle and 2.1 $GtCO_2e\ yr^{-1}$from the dairy cattle herd (producing both milk and meat). The other species have much lower and similar levels of emissions: pig (0.7 $GtCO_2e\ yr^{-1}$), poultry (0.7 $GtCO_2e\ yr^{-1}$), buffalo (0.6 $GtCO_2e\ yr^{-1}$) and small ruminants (0.5 $GtCO_2e\ yr^{-1}$).

Soils are the dominant source within the global atmospheric budget of N_2O. Emissions of N_2O due to agriculture activities are estimated at 2.8–6.2 $TgN_2O\ yr^{-1}$, 20–40% of all sources[19–21], of which emissions associated with feed production may account for 1.3–2.0 $GtCO_2e\ yr^{-1}$ (Table 1). Nitrous oxide emissions are directly linked to the use of synthetic and organic fertilizers for food and feed production and to livestock manure management and urine excretion to grazed grasslands.

The developing world (non-Annex 1 countries; see Supplementary Information) contributes 70% of non-CO_2 emissions from ruminants and 53% from monogastrics[13], and this share is expected to grow as livestock production increases to meet demand growth in the developing world. Mixed crop–livestock systems dominate livestock emissions (58% of total emissions) largely because of their prevalence, whereas grazing-based systems contribute 19% (ref. 13). Industrial and other systems comprise the rest.

Taking an aggregate view of the sector, and using all LCA sources of emissions, animal feed production accounts for about 45% of the sector's emissions, with about half of these emissions related to fertilization of feed crops and pastures (manure and fertilizer included)[15]. The remaining animal feed emissions are shared between energy use and land use. Enteric fermentation contributes about 40% of total emissions, followed by manure storage and processing (~10% of emissions)[17,18].

Direct energy consumption on animal farms, energy consumption embedded in farm buildings and equipment and post-farm gate emissions account for less than 5% of the sector's emissions. However, when added to the energy consumption related to animal feed production, energy accounts for about 20% of the sector's emissions[15].

Methane (CH_4) accounts for 43% of emissions, and the remaining part is almost equally shared between N_2O (29%) and CO_2 (27%). These estimates exclude carbon sequestered in grazing land (rangeland and pastures)[16]. There is some consensus on the magnitude of E_{CH_4} emissions, irrespective of the approach used (mean 2.0 $GtCO_2e\ yr^{-1}$, coefficient of variation (CV) = 18%). Methane and N_2O emissions from manure management, although smaller in magnitude, are more uncertain at the global level (mean 0.28 $GtCO_2e\ yr^{-1}$, CV = 27%; mean = 0.29 $GtCO_2e\ yr^{-1}$, CV = 46%). Comparable uncertainties (11–145%) for CH_4 emissions from manure management for several European countries have also been reported[22–24], and those for European CH_4 emissions from enteric fermentation agree with the global level estimates (6–40%)[23,25,26]. Reported national N_2O emissions from manure management (storage only) are uncertain in the range of 21–414%, whereas direct and indirect N_2O emissions from agricultural land due to fertilizer application or soil N_2O emissions from grazing animals (for example, urine patches) have an uncertainty of 57–424% (mean value: 156) at the national level[23].

Baseline projections. Estimates of the emissions associated with the projected growth of the livestock sector to 2050 suggest that E_{CH_4}, CH_4 from manure management and N_2O from manure management are likely to grow at rates between 0.9–5%, 0.9–4%, 1.2–3% per year, respectively[10,11,16,27–29]. The ranges reflect different scenarios and assumptions about growth in demand for livestock products, animal numbers and type and productivity growth in livestock systems. A continuation of existing trends would lead to increases in

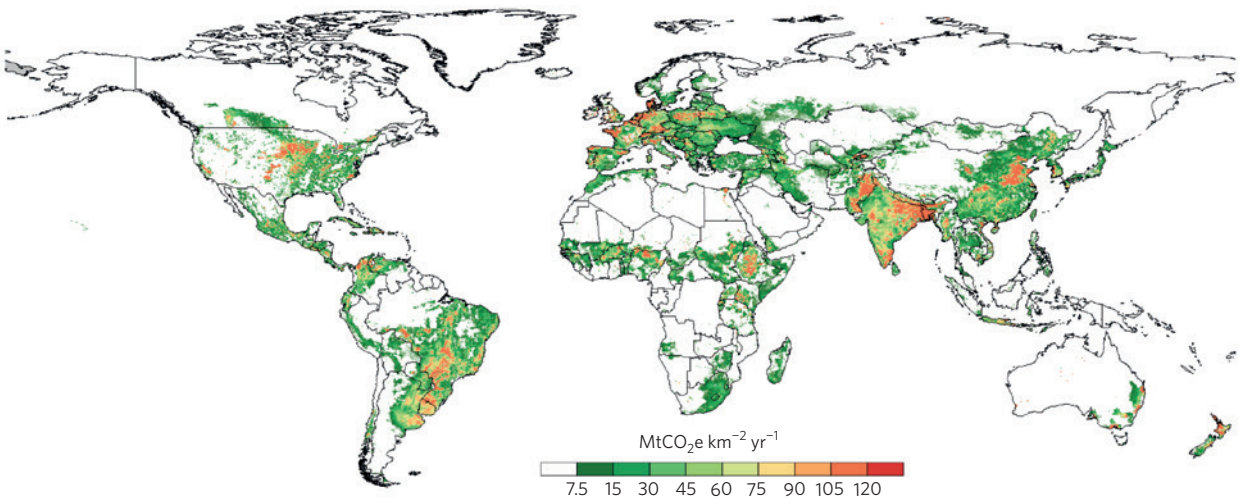

Figure 1 | GHG emissions from global livestock for 1995–2005. Using data from 2005, we have updated the version of this map used in ref. 13.

livestock emissions of between 1–1.5% per year across all sources other than land-use change (Fig. 2)[10,29]. Although not only attributable to livestock, emissions from deforestation over the same period are projected to grow at a slower rate of 0.8% yr^{-1} (ref. 29). Cropland area expansion is growing at a faster rate than pasture expansion, primarily due to the accelerated growth of pig and poultry production (>5% globally).

Emissions intensities in livestock systems. The global non-CO_2 emissions intensity of livestock products is estimated at 44 $kgCO_2e\ kg^{-1}$ protein, with a large range between 9–500 $kgCO_2\ kg^{-1}$ (ref. 13). The range reflects differences between livestock products, with monogastrics (pigs and poultry) at the lower end of the range, followed by milk and ruminant meats[13,15,30,31]. The developed world has high absolute emissions but significantly lower emissions intensities than the developing world due to improved livestock diets, genetics, health and management practices. These practices reduce CH_4 emissions intensities and CO_2 emissions intensities due to lower land-use requirements. Many parts of the developing world have high emissions from livestock, which are produced at high emissions intensities due to low productivity and large numbers of animals (for example, parts of Africa and Latin America)[13].

Mitigation options and their technical potential

The mitigation options presented below can be targeted towards the supply of livestock products. These include technical and management interventions, and practices for increasing crop and livestock productivity. Another group of options could target reductions in the consumption of livestock products.

Technical and management interventions

Several mitigation practices could be implemented within the livestock sector (emissions from crop production for livestock feed are not considered here) (Fig. 3). Animal-based GHG mitigation options for livestock can be categorized as targeting E_{CH_4}, manure storage and application or deposition and animal management. Hristov *et al.*[32] provides a comprehensive description of these. We estimate that these practices could help mitigate between 0.01–0.5 $GtCO_2e\ yr^{-1}$. In ruminant production systems, E_{CH_4} emissions usually comprise the largest proportion of GHG emissions and have been the main focus for animal-based mitigation research[33–35].

Use of feed additives. Several chemical compounds, such as alternative electron receptors, ionophoric antibiotics, enzymes and probiotic cultures, have been tested for their ability to decrease CH_4 emissions, mainly in short-term experiments[32]. Their effects are often much reduced in the long term due to adaptation of the rumen microbial ecosystem. In addition, there may be as yet unknown environmental concerns associated with some of these compounds, and issues around acceptance by the public may severely constrain widespread adoption. Nevertheless, recent experiments with new CH_4 inhibitors show promise for the future[36].

Improved feed digestibility. A well-studied E_{CH_4} mitigation option for ruminants is the provision of forages of higher digestibility. This is unlikely to yield many benefits in highly developed animal production systems but has considerable potential in developing countries[37]. Another well-studied option for decreasing E_{CH_4} emissions and increasing efficiency is inclusion of energy-dense feeds (for example, cereal grains) in the ration, with the greatest potential in production systems that utilize little or no grain to feed animals, as is common in many parts of the world. Widespread adoption of this practice depends on economic feasibility though improving the nutritive value of low-quality feeds but could have a considerable effect on herd productivity while keeping E_{CH_4} emissions constant[30]. To maximize the benefits of improved feed quality, reductions in animal numbers need to be part of the strategy. Fewer better-fed animals could reduce pressure on land and other resources, but greater economic return from more efficient systems may encourage farmers to keep more livestock[37]. Our estimated technical mitigation potential of this practice is 0.68 $GtCO_2e\ yr^{-1}$, when a 10% increase in digestibility of the basal diet is considered and is widely applied throughout the developing world. The economic mitigation potential, however, is closer to 0.12–0.15 $GtCO_2e\ yr^{-1}$ when considering the low adoption rates (20–25%) of improved feeding practices in the developing world over the last 20 years[37,38].

Forages with a high concentration of plant secondary metabolites such as tannins have also been shown to decrease E_{CH_4}, although results have been inconsistent. Inclusion of lipids or high-oil by-product feeds, such as distiller's grains, when available, may be an economically feasible mitigation practice[39]. Algae is another option that merits more investigation, as its high quality could lead to significant yield improvements and reduced land use, but current economic costs and logistics prevent its widespread uptake[40].

Manure management. Emissions can be reduced by decreasing N losses, for example, by storing manure or slurries appropriately, thereby minimizing losses due to volatilization or runoff[41]. Often simple measures can be taken to avoid nutrient losses to the environment such as compacting and covering farmyard manure[42,43].

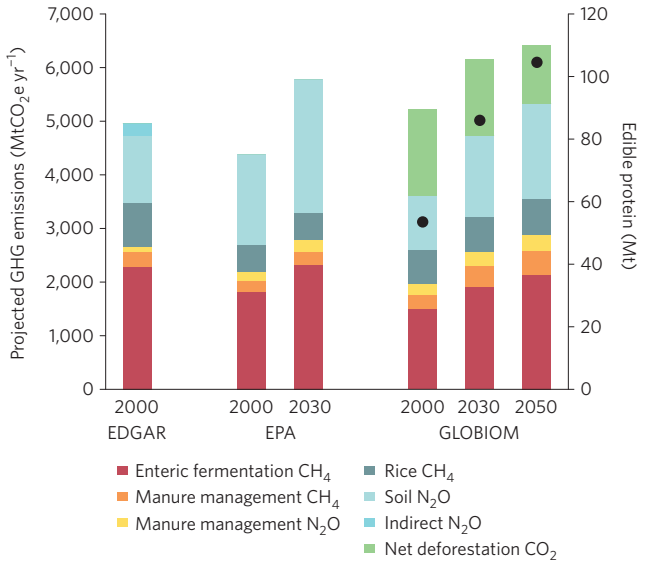

Figure 2 | Baseline projections of GHG emissions for the main IPCC source categories for the entire agricultural sector. The baseline projection represents a continuation of the current livestock product demand trends (black dots, converted to edible animal protein for all livestock products). EDGAR data are from ref. 9, EPA data from ref. 27 and GLOBIOM data from ref. 29.

Slurry may also be anaerobically digested before its application, which affects the organic matter content and the concentrations of volatile solids but N content is minimally affected. However, evidence for anaerobic digestion reducing field-scale N_2O emissions is mixed[44,45]. For most livestock systems worldwide, there is limited opportunity for manure management, treatment or storage[41]; most excretion happens in the field and collection for fuel or fertility amendment occurs after it is dry and CH_4 emissions are negligible. The greatest mitigation potential possibly derives from application of manures to the field; the N_2O mitigation potential ranges from 0.01–0.075 $GtCO_2e\ yr^{-1}$ (ref. 41) depending on timing and form of application[46,47]. Even if N_2O emissions increase following N application, the emissions per unit of product, which is the most important agronomic criterion[48], is likely to be reduced if manures are applied to match plant N demand at times that avoid heavy rains[49]. Other options for reducing N_2O include the use of nitrification inhibitors[50], which have been successfully tested for suitability in in reducing N_2O emissions from cropland and grassland in various climates[50–52].

Soil carbon sequestration in grasslands. Grazing-land management practices that affect species composition, forage consumption, nutrient and water inputs and fire can impact soil carbon stocks[53]. Excessive removal of aboveground biomass, continuous grazing at suboptimal stocking rates and other poor grazing management practices that result in a mismatch between forage supply and animal demands have led to the depletion of soil carbon stocks[53,54]. Much of the world's grazing land is still under pressure to produce more livestock through expansion and more intensive grazing, particularly in Africa[55]. However, good grassland management can potentially reverse historical soil carbon losses and sequester substantial amounts of carbon in grazing-land soils (Fig. 4a). Much of this sequestration potential may be economically feasible, because it can be realized by implementing practices that enhance forage production[41]. Changes in grazing management — increasing or reducing the forage consumption rate to maximize forage production — could lead to annual sequestration of up to 150 $MtCO_2e\ yr^{-1}$ in the world's grazing lands[56] (Fig. 4b). Much of this potential (81%, approximately 120 $MtCO_2e\ yr^{-1}$) is in developing countries, occurring in areas where production is predicted to increase following a period of de-stocking, that is, in areas where primary production can recover from overgrazing[56]. The use of legumes in pastures has been estimated to sequester 200 $MtCO_2e\ yr^{-1}$ globally, though this could increase soil N_2O emissions by 60 $MtCO_2e\ yr^{-1}$, offsetting 28% of the soil carbon sequestration benefits. Although recent evidence suggests that modest amounts of carbon can be sequestered, about half of the global net mitigation potential of this option is in developing countries[56]. Carbon sequestration in grazing lands should perhaps be considered a co-benefit of improving productivity and ecosystems services[57], rather than a primary objective for managing grazing land ecosystems.

Increased livestock and crop/pasture productivity

Practices that increase livestock, crop and pasture productivity have recieved significant attention in the past years, due to their multiple mitigation benefits. They can improve the GHG emission intensities of different livestock products, but they can also have indirect benefits associated with land use sparing, and could promote structural changes in the livestock sector. This section briefly describes these mitigation benefits.

Animal productivity and health. Improving the genetic potential of animals for production, their reproductive performance, health and liveweight gain rates are among the most effective approaches for reducing GHG emissions per unit of product[32,58]. In subsistence agricultural systems, reduction of herd size by increased reproduction rates increases feed availability as well as the productivity of individual animals and the total herd, thus lowering E_{CH_4} and overall GHG emissions per unit of product. Reducing the age at slaughter by increasing liveweight gain rates significantly decreases GHG emissions per unit of product in beef and other meat production systems. Improved animal health and reduced mortality and morbidity can increase herd productivity and reduce emissions intensity in all livestock systems. Adoption of modern reproductive management technologies, targeting increased conception rates, increased fecundity (in swine and small ruminants) and reduced embryo loss also provide a significant opportunity to reduce GHG emissions from the livestock sector, with appropriate attention to animal welfare considerations. We estimated that these improved animal management practices could reduce emissions in the livestock sector by 0.2 $GtCO_2e\ yr^{-1}$ by 2050.

Avoided deforestation due to intensification. A recent review by Smith[59] indicates that this involves addressing the many unsustainable practices already manifest in the global food system. Many options for sustainable intensification exist, ranging from adoption of new technology to improving the efficiency of current food production. At the high-tech end are options such as the genetic modification of living organisms and the use of cloned livestock and nanotechnology[60–62]. By 2050 it may be possible to manipulate the traits controlled by many genes and confer desirable traits (such as improved nitrogen and water-use efficiency in crops) with improved productive characteristics[61]. But the future role of genetic manipulation in sustainable intensification is heavily dependent on the softening of public opposition, which is widespread in places.

It may be possible in some regions to rebalance the distribution of inputs to optimize production and close yield gaps[63,64]. The benefits and impacts of irrigation and the water needed for crop production vary greatly across the globe, but addressing these imbalances could bring yields to within 95% of their current potential for 16 important food and feed crops, and adding 2.3 billion tonnes (5×10^{15} kcal) of new production (a 58% increase)[63]. Closing the yield gap of the same crops to 75% of their potential could increase global production by 1.1 billion tonnes (2.8×10^{15} kcal), an increase of 28% (ref. 63).

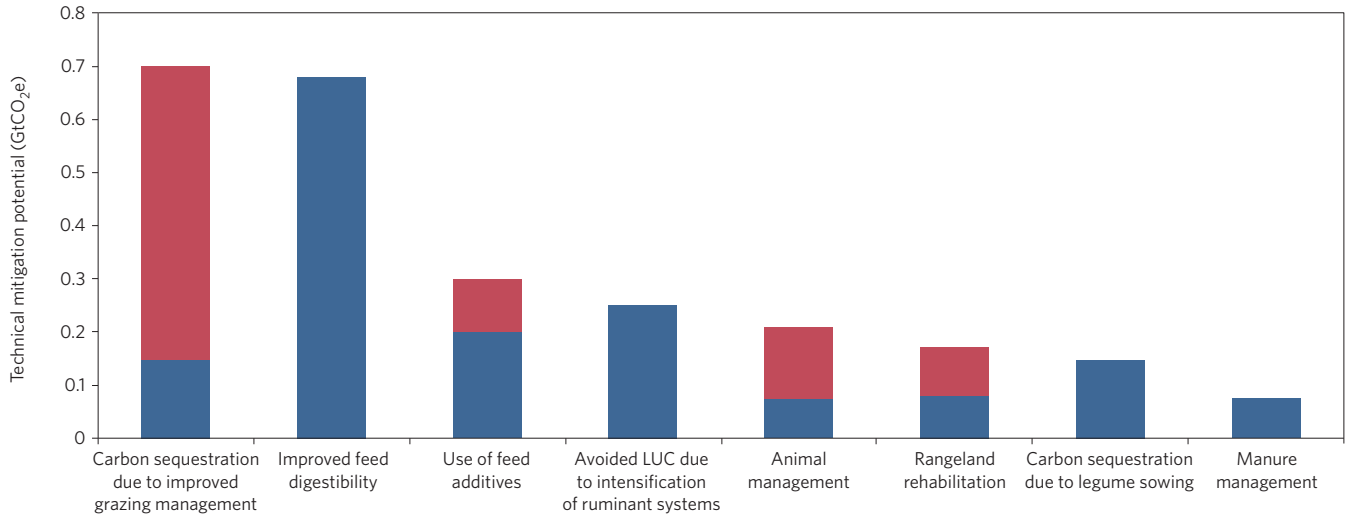

Figure 3 | Technical mitigation potentials of supply-side options for reducing emissions from the livestock sector. Red represents the range for each practice, where available. The range of mitigation potentials for carbon sequestration due to improved grazing management is defined by refs 41,56. The mitigation potentials for 10% improved digestibility in all ruminants in the developing world are shown, obtained by up-scaling values from ref. 37. Direct application of this option to developed country situations was assumed to be too small to be considered. Full adoption of the practice across all ruminants was assumed to obtain the technical mitigation potential for this practice, hence no range is presented . The mitigation potentials for use of feed additives are from ref. 32, and include inhibitors, ionophores, electron receptors, enzymes, plant bioactive compounds, lipids and manipulation of rumen microflora. These potentials are applied to breeding herds of cattle globally with effects on E_{CH_4} as described in ref. 32. The mitigation potentials of avoided land-use change from transitions from grazing to mixed crop–livestock systems are from ref. 79. The mitigation potentials for animal management practices such as improved health and reduced mortality are from ref. 32, and the effects applied as for feed additives. Rangeland rehabilitation mitigation potentials are from ref. 56. Manure management mitigation potentials are from ref. 41.

Crop yield improvements will play a critical role in future land-use dynamics[65] and livestock systems[32]. They will determine the requirements for extra cropland and strongly affect grassland expansion[32]. Compared with yield stagnation, maintaining past trends in crop yield growth would save 290 Mha of cropland and avoid further expansion of about 120 Mha of grassland by 2030[32]. This is caused by increasing crop yields, which lower crop prices, leading to shifts in ruminant production from grass-based systems to more intensive systems with forage-based diets supplemented with grains; and relocation of livestock production to the most cost-effective regions. Hristov *et al.*[32] found that GHG emissions decreased by more than 2 $GtCO_2e\ yr^{-1}$ when crop yields grew according to past trends, compared with yield stagnation. About 90% of the emissions reduction came from avoided land-use changes partly associated with livestock (0.25 $GtCO_2e\ yr^{-1}$). Emissions associated with feed production were also reduced due to improved productivity. Productivity increases based solely on higher fertilizer rates would reduce the overall positive balance through increased crop N_2O emissions[66].

Moderation of demand for livestock products

Projections of food demand that are based on growing populations and increasing per capita wealth suggest that demand for food will increase by 60–100% by 2050[67]. Given that the resource-use efficiency of livestock production is low in comparison with crops, and that about a third of the world's cereal production is fed to animals[1], reducing consumption of livestock products in some places could greatly reduce the need for more food. On average, the production of beef protein requires about 50 times more land than the production of vegetable proteins[68], and GHG emissions excluding land-use change are about 100 times higher. Although meat now represents only 15% of the total energy in the global human diet, approximately 80% of agricultural land is used for animal grazing or the production of feed and fodder for animals[1], but this does include extensive grasslands in areas where other forms of agriculture would be extremely challenging.

Increases in the demand for meat have been used in a wide range of scenario analyses of the agricultural sector[41,69] (see the Supplementary Information for a description of the scenarios tested). By contrast, with global adoption of healthy diets (following healthy eating recommendations[70]), adequate food production in 2050 could be achieved on less agricultural land than is used at present, allowing the regrowth of natural vegetation and resulting in a reduction of GHG emissions of 4.3 $GtCO_2e\ yr^{-1}$ relative to the baseline. More extreme scenarios would yield emissions reductions of 5.8, 6.4 and 7.8 $GtCO_2e\ yr^{-1}$, respectively, for no-ruminant meat, no-meat and no-animal product scenarios. In addition to reducing pressure on agricultural land, a global transition to a healthy, low-meat diet would reduce the mitigation costs, particularly in the energy sector, of achieving a 450 ppm CO_2e stabilization target in 2050[71]. Reducing the demand for livestock products is, at least in theory, a powerful mitigation option[11,72–75].

Reduced consumption could have substantial beneficial effects largely through its ability to create 'spare land' that can be used for either bioenergy or C sequestration by afforestation[7,76]. Switching to a low-animal-product diet that converges on the global average energy demand in the year 2000 (that is, 2,800 kcal per capita per day, compared with the global mean of 3,100 kcal per capita per day in the reference case) gave emissions reductions of 0.7–7.3 $GtCO_2e\ yr^{-1}$, if the spared land is used for bioenergy, and 4.6 $GtCO_2e\ yr^{-1}$ if afforestation is assumed.

Dietary changes might occur in various ways, such as through changes in consumer preferences or via stringent climate policies and emissions pricing in the food and agriculture sectors that change the relative prices in favour of low-emissions food and thereby cause a shift in consumption[77,78]. However, emissions pricing could push up global food prices and reduce consumption in low-income regions, with negative impacts on food security[79]. Such impacts on global prices could be avoided, however, by implementing emissions pricing on food consumed rather on food produced[77].

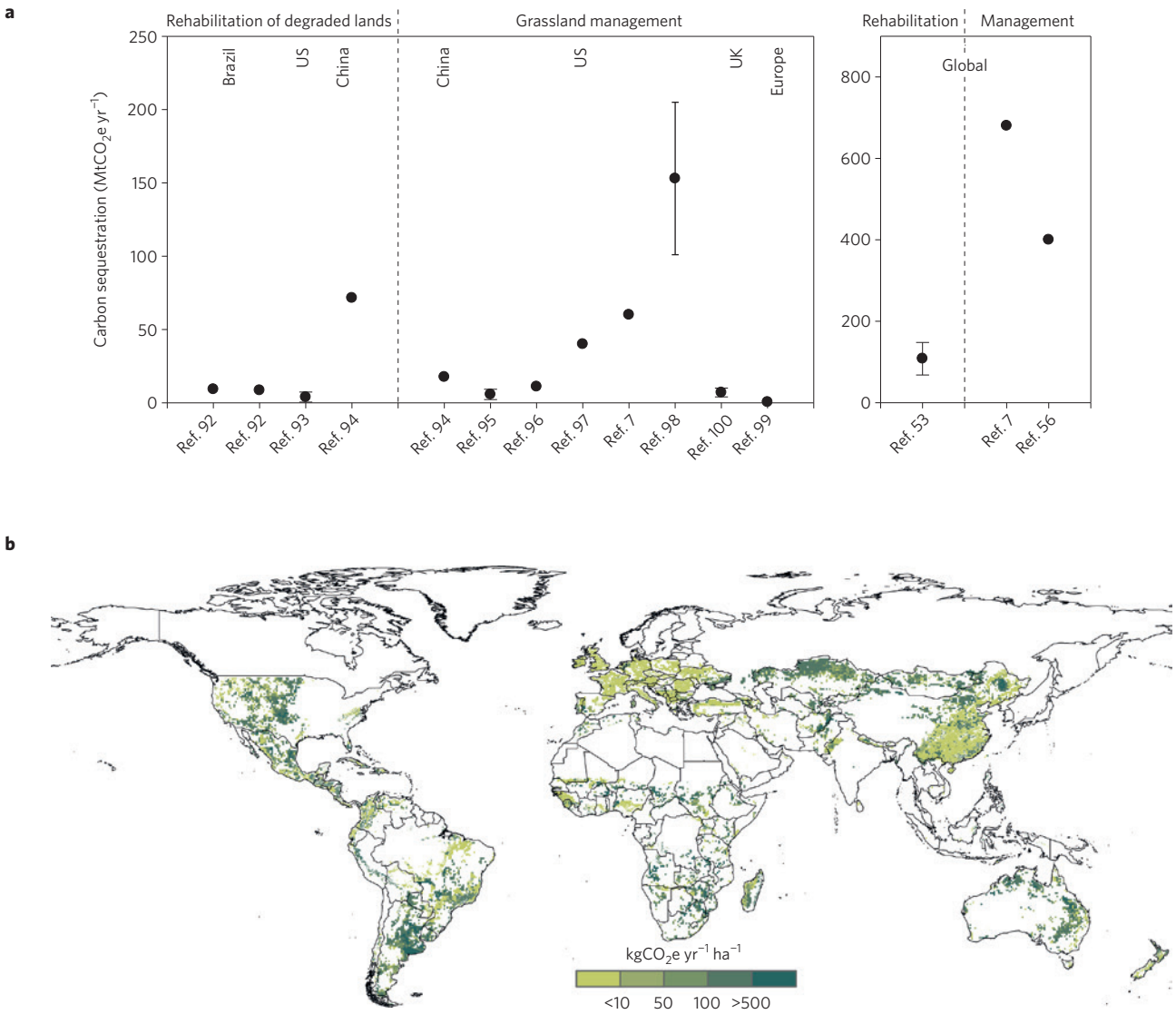

Figure 4 | The carbon sequestration potential of grazing lands. a, The mitigation potentials for carbon sequestration in grasslands through rangeland rehabilitation and grazing management are shown for selected regions (left) and the globe as a whole (right). Data are from the references indicated. **b**, The spatial distribution of the carbon sequestration potential in rangelands[56].

For demand-side options, determining a technical potential is not useful as it would be based on a rather implausible 'no animal products' scenario. Likewise, holding back consumption in the already low-meat diets of developing regions may be regarded as undesirable. With regard to plausible low-meat diets, we find a mitigation potential of 4.3–6.4 $GtCO_2e\ yr^{-1}$, with about 1–2 $GtCO_2e\ yr^{-1}$ coming from process emissions, mostly CH_4 and N_2O, and the remainder from land-use change CO_2 (see Supplementary Information). As assumptions on bioenergy grown on spare land would introduce another important source of uncertainty, we focus — where relevant — on afforestation of the abandoned land. In addition, we do not address waste reduction in the demand-side options, as this has mostly been analysed for the entire food system rather than for livestock specifically.

Mitigation potentials, market effects and trade-offs

The success of the practices described above in mitigating GHG from the livestock sector is largely dependent on their adoption. This in turn depends on public and private incentives, public policies and taxes, costs and logistics of implementation, and trade-offs between practices and with other sectors. Some of these critical factors and their ability to yield economically feasible mitigation alternatives are described below.

Economic supply-side mitigation potentials. Although the technical mitigation potential for livestock is substantial, the share that can be achieved at reasonable economic cost is likely to be much smaller. Our yardstick is a marginal abatement cost of up to US$50 per tCO_2e, which is higher than current carbon market prices and those of the recent past, but still lower than the carbon price needed to make significant impacts on global GHG emissions across all sectors[80].

The 2030 mitigation potentials for animal GHG emissions at unit costs of US$20, US$50 and US$100 per tCO_2e were estimated to be 175, 200 and 225 $MtCO_2e\ yr^{-1}$, respectively[81]. For measures targeting soil carbon sequestration in grazing lands, higher mitigation levels of 250, 375 and 750 $MtCO_2e\ yr^{-1}$ by 2030 were estimated at these prices. Another global assessment estimated that animal GHG emissions could be reduced by 136, 193 and 228 $MtCO_2e\ yr^{-1}$ by 2030 at unit costs of US$20, US$50 and US$100 per tCO_2e (ref. 27). The economic mitigation potentials in these studies were calculated without considering market

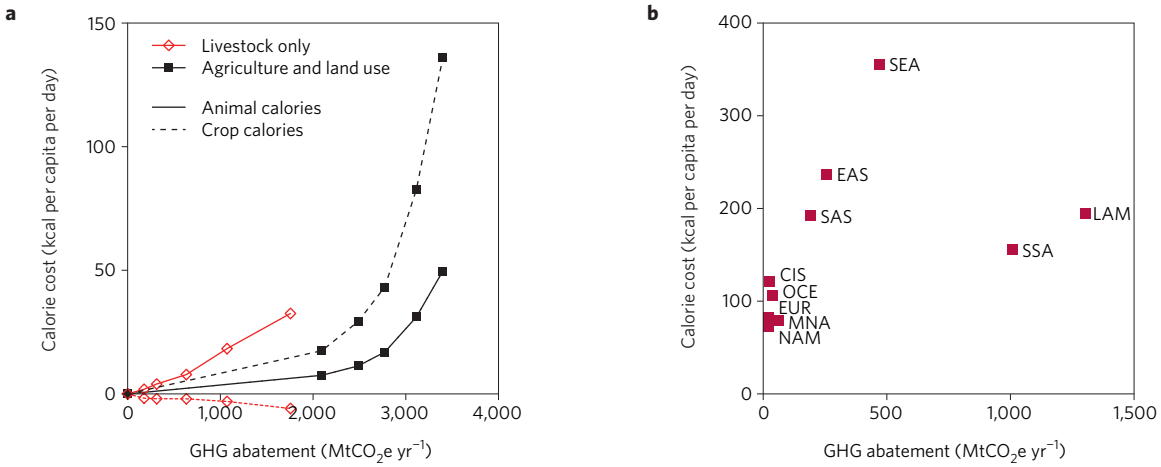

Figure 5 | Total abatement calorie cost (TACC) of mitigation policies. a, Policies targeting either the livestock sector only or all agricultural and land-use change GHG emissions with a carbon tax from US$0–100 per tCO_2e and decomposed by calorie source. The six plotted points (squares and diamonds) on each line correspond to the different levels of tax at US$0, 5, 10, 20, 50 and 100. **b**, The TACC values of a mitigation policy that targets both agricultural and land-use change emissions with a carbon tax of US$100 per tCO_2e are shown by region (calculations based on ref. 79). NAM, North America; MNA, Middle East and North Africa; EUR, Europe; OCE, Oceania; CIS, Commonwealth of Independent States; SAS, South Asia; EAS, East Asia; SEA, Southeast Asia; SSA, Sub-Saharan Africa; LAM, Latin America.

interactions and their effects on reallocating livestock production, trade, land use and nutrition in the presence of mitigation policies. Some important consequences of these market interactions are discussed below.

Emissions leakage. This occurs when the mitigation policies used to reduce livestock emissions in one region cause production to fall, increasing the imports of livestock commodities to that region, thereby raising production and associated emissions in the exporting regions. This market-based migration of production can potentially lower the efficacy of mitigation policies, but if policies rely on positive incentives such as mitigation subsidies rather than negative incentives such as a carbon tax, it may be possible to reduce emissions without lowering production and thereby prevent leakage. If negative incentives are used, leakage can only be eliminated if the incentives are applied to all global livestock emissions. Annual reductions in livestock emissions of 163 $MtCO_2e\ yr^{-1}$ have been estimated in response to a US$27 per tCO_2e carbon tax on agricultural emissions in industrialized (Annex I) countries[82]. However, 35% of this reduction in emissions is estimated to be offset by increased emissions in developing (non-Annex I) countries. A sensitivity analysis of the trade elasticities, which are critical determinants of the leakage rate, placed the mean leakage rate (with a 95% confidence) between 16% and 56%.

Two thirds of the emissions reduction achieved by a tax on livestock CH_4 emissions in industrialized (Annex I) countries could be leaked via increased emissions in developing countries[83]. Emissions leakage rates of 22–91% have been estimated for different economic scenarios in the EU[23,84].

Emissions leakage could also be a problem for demand-side mitigation policies that seek to reduce the consumption of livestock products in some countries. Farmers in these countries may try to export their surplus production at lower prices to minimize their losses, increasing consumption in other regions, at least over the short term. As with supply-side mitigation policies, emissions leakage can also limit the effectiveness of consumption-side policies. The magnitude of this response greatly depends on the flexibility of trade and the sensitivity of consumers to price changes, among other things[77,82]. These findings highlight the importance of coordinated global mitigation policies to control for emissions leakages.

Rebound effects. The responses of economic agents to new technologies and practices that lower production costs and output prices are known as rebound effects[80,84,85]. This is important for policies that aim to mitigate land-use change emissions by intensifying production, as lower prices will drive higher consumption levels. If developing regions improved livestock feed efficiency by 25%, 371 $MtCO_2e\ yr^{-1}$ could be avoided, but those savings could be up to three times larger if the demand for livestock products was held constant[66]. Similar rebound effects have been found for livestock efficiency improvements and waste reduction using different models[86]. In contrast, Cohn *et al.*[87] showed that policies fostering grassland intensification in Brazil were not significantly affected by rebound effects, and that global GHG savings from unilateral mitigation efforts by Brazil are only marginally affected. This demonstrates the importance of considering the attenuating influence of market interactions between economic agents and regions when assessing the effectiveness of mitigation policies.

Emissions pricing and demand-side potentials. Total abatement calorie cost (TACC) curves have been proposed as a measure of the change in food availability in response to emissions reductions from a GHG tax[79]. Figure 5a shows the strong relationship between GHG mitigation in the livestock sector and the availability of calories of animal origin. The overall abatement potential (considering all animal and land-use change emissions sources) under such a policy would be 1.8 $GtCO_2e\ yr^{-1}$ with a demand reduction of about 27 kcal per capita per day at US$100 per tCO_2e. This relatively minor calorie cost is due to the overall small share of calories of animal origin in human diets: 18% globally. When implementing the GHG tax on all agricultural non-CO_2 emissions and CO_2 emissions from land-use change, the total abatement potential at US$100 per tCO_2e is about 3.4 $GtCO_2e\ yr^{-1}$ and the corresponding calorie cost is about 190 kcal per capita per day. The calorie cost is low at taxes below US$20 per tCO_2e and most of the mitigation comes from avoided deforestation. Above this carbon price, further mitigation comes mostly from the agricultural sector, with significant impacts on food availability. The relationship between climate mitigation and food availability varies substantially across regions (Fig. 5b), which is a crucial consideration for targeting mitigation efforts.

Potential shifts in meat and dairy demand from the implementation of a GHG tax on food in the EU have been estimated[77]. Owing

to the relatively inelastic demand for meat and dairy products, the direct mitigation potential from GHG pricing of food was found to be small. For a climate tax on animal food equivalent to €60 per tCO_2e, the estimated emissions reduction was about 32 $MtCO_2e\ yr^{-1}$ — mainly from shifting from beef to other meats — which is about 7% of current GHG emissions in EU agriculture. However, this structural change in demand away from beef would also reduce total land requirements for food. If that spare land were used for bioenergy that is used as a substitute for fossil fuel energy, the mitigation effect of this policy intervention could be several times larger.

Discussion

The mitigation potential of the livestock sector could represent up to 50% of the global mitigation potential of the agriculture, forestry and land-use sector. This is significant, but most of this potential has yet to be realized, due to low adoption rates of technical practices and uncertainties and trade-offs associated with attempts to reduce the consumption of livestock products. At the same time, establishing the societal impacts of land-sparing opportunities, in terms of livelihoods, employment, economics, gender and equity, is essential for understanding their feasibility. This area needs to receive urgent attention due to its policy relevance.

There is also a need to increase investment in the livestock sector in the developing world so that it becomes more market-oriented[88]. This could catalyse the adoption of practices for sustainably intensifying the sector in addition to mitigating emissions. Understanding the interactions at global and local scales between mitigation and adaptation in livestock systems will also be essential for identifying the practices that create the largest synergies and reduce the trade-offs between these goals[89].

The continuing trend of increasing global consumption of meat is not compatible with reducing GHG emissions from agriculture. There is a need for research to understand what types of knowledge or interventions could limit the global growth in livestock consumption without threatening the food security or nutritional outcomes of people in developing countries. Public health policies offer one opportunity for moderating the overconsumption of livestock products by the growing middle classes that would be likely to have beneficial effects on both health and climate change mitigation[73]. On the other hand, the world food system has never had to react to planned, voluntary reductions in food consumption, so very few policy alternatives to reduce consumption equitably have been designed or tested[90].

Limiting the rise in emissions from the livestock sector is challenging. There are opportunities for simultaneously increasing productivity and decreasing emissions intensity, but these run the risk of successful farmers expanding production, thus limiting the benefits in terms of total emissions. Thus addressing leakage and rebound impacts with the livestock sectors, and between the livestock and other sectors, will be essential. Reducing the global consumption of livestock products would bring considerable benefits in terms of lower agricultural emissions, but much more research is needed on how this could be achieved without negative trade-offs in some parts of the livestock sector. Reducing the large and growing contribution of the livestock sector to climate change while also ensuring that global nutritional security and health needs are supported is an urgent global research and investment priority.

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Author contributions

M.H. conceived the study and prepared the manuscript. All authors analysed data and contributed to the writing and editing of the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence should be addressed to M.H.

Competing financial interests

The authors declare no competing financial interests.