Greenhouse gas mitigation potentials in the livestock sector

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The livestock sector is the largest anthropogenic land user. It supports about 1.3 billion producers and retailers, and contributes to 40-50% of agricultural GDP. We estimated that between 1995 and 2005, the livestock sector was responsible for greenhouse gas emissions ranging between 5.6-7.5 GtCO₂eq/yr. If current projections of increases in
consumption of animal source foods are correct, these emissions could potentially double in the future. The technical mitigation potential of livestock systems ranges between 0.1-7.8 GtCO$_2$eq/yr, which is up to 50% of the mitigation potential of the agriculture, forestry and land use sectors. Technical options that sustainably intensify livestock production, that promote carbon sequestration in rangelands, or that reduce emissions from manures account for 2.4 GtCO$_2$eq, while modelled scenarios of reduced livestock product consumption provide a range up to 7.8 GtCO$_2$eq. The economic mitigation potential of these options is low due to numerous trade-offs and constraints to their adoption. More research and investment are needed to increase adoption rates of technical mitigation practices, and for establishing the levels of consumption of animal source foods that are sustainable, and that do not have negative impacts on livelihoods, economic activities and our ecosystems.

The livestock sector is large. Seventeen billion animals make use of 30% of the ice-free terrestrial mass for grazing, a third of the global cropland as feed$^1$, and 32% of freshwater to provide direct livelihoods and economic benefits to at least 1.3 billion producers and retailers$^{2,3}$. As an economic activity, livestock contributes between 40-50% 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 last 40 years$^4$. Projections driven by increased human population, incomes and urbanization, show that the consumption of milk and meat will continue to grow in the next twenty years, at least at previously observed rates$^{1,5}$, with most of the growth projected to occur in the developing world. Against these demand trends, the sector has managed to respond by significantly increasing production. Beef and milk production have more than doubled over the same period and monogastric production (pigs and poultry) has grown in places by a factor of five or higher$^2$. Intensification of production has played a pivotal role in improving productivity and feed efficiency of domestic animals$^1$. For example, in the United States there is 60% more milk produced now than in the 1940s with about 20% of the cows$^6$. While intensification has been possible in places, land expansion has been an important component of production growth in places like Africa and Latin America. These trends and projections, if continued, could drive significant changes in the land use sector that could lead to
increased greenhouse gas emissions (GHG), deforestation and loss of biodiversity amongst other negative impacts on the environment. Smith et al. estimated that the technical mitigation potential of livestock systems was 1.7 GtCO$_2$eq/yr, with grazing management contributing over 80% of this potential. This review revisits the mitigation potentials already proposed for a number of known technical options using the latest data available, and incorporates information not available at the time of the IPCC AR4, such as changes in human diets and in the structure of livestock production systems to provide a synthesis of the mitigation potential in the livestock sector. These options are central to the way the components of our food systems interact and largely determine how they could evolve in the future.

We review the most recent global estimates for methane, nitrous oxide and carbon dioxide emissions from domestic livestock. We examine the contribution of different species, livestock products and production systems, and also present information on GHG efficiencies per unit of edible protein from livestock product.

Greenhouse gas technical mitigation potentials were estimated for the following: technical interventions (improved feeding practices, increases in feed digestibility, use of feed additives, manure management); sustainable intensification and the associated structural changes of the livestock sector, carbon sequestration in rangelands and hypothetical reductions in consumption of livestock products. The technical potential of these options combined could help mitigate up to 7.8 GtCO$_2$eq by 2050. However, their economic mitigation potential is small due to significant barriers to their adoption, lack of investment in the livestock sector and lack of sophisticated policies to differentiate and promote healthy levels of animal source foods in the diets of developed and developing countries. We conclude with a discussion on research needs for improving the feasibility of GHG mitigation in livestock systems without hampering rural economies and livelihoods.

Greenhouse gas emissions from livestock
Several global estimates of greenhouse gas emissions from livestock are available (Table 1). Methodological differences exist between studies, and for this review we have classified them as either following IPCC emissions guidelines or developed using lifecycle analysis. Estimates using IPCC emissions guidelines include direct non-CO₂ emissions of methane (enteric and manure) and nitrous oxide (manure management), while LCA approaches include additional sources. Taking the supply chain from conception to retail, emissions arise from feed production, animal rearing as well as from the processing and transportation of livestock commodities to markets. After retail, further emissions occur, associated with the transportation of animal products by consumers, their preparation (including cooking) and consumption or possible disposal. In contrast with LCA approaches, and according to IPCC guidelines, some of these sources are reported in GHG inventories of other sectors (i.e. fuels used to transport products are reported under the transport sector, and emissions from energy used in processing are reported under the industry sector).

We estimate that total emissions from livestock 1995-2005 were between 5.6 and 7.5 GtCO₂eq/yr (Table 1). The most important sources of emissions were enteric methane (1.6-2.7 GtCO₂eq), N₂O emissions associated with feed production (1.7 GtCO₂eq) and land use for animal feed and pastures, including change in land use (1.6 GtCO₂eq).

The level of disaggregation of global livestock emissions differs considerably between studies. Some estimates are based primarily on Tier 1 approaches, with Tier 2 sometimes being used for enteric fermentation. FAO and Herrero et al. disaggregate emissions by country/region, species, production system and by product (milk, meat). FAO use Tier 2 for the IPCC emissions categories and LCA methods for the other sources. Herrero et al. use Tier 3 for enteric methane and Tier 2 methods for the other source categories. There is reasonable consensus on the magnitude of methane emissions, irrespective of the approach used (mean 2.0 GtCO₂eq, C.V. = 18%). Methane and nitrous oxide emissions from manure management, while smaller sources of emissions, show higher uncertainty at global level (mean 0.28 GtCO₂eq, C.V.=27%; mean = 0.29 GtCO₂eq, CV= 46%). Comparable values of uncertainties (11-145%) for CH₄ emissions from manure management for several European countries were also reported by...
Rypdal and Winiwarter\textsuperscript{18}, Leip \textit{et al.}\textsuperscript{19} or Monni \textit{et al.}\textsuperscript{20} for Finland, whereas those for European CH\textsubscript{4} emissions from enteric fermentation are in agreement with the global level estimates (6-40\%)\textsuperscript{19}. For the EU member states, Leip\textsuperscript{19} estimated that reported national N\textsubscript{2}O emissions from manure management (storage only) are uncertain in the range of 21-414\%, while direct and indirect N\textsubscript{2}O emissions from agricultural land due to fertilizer application or soil N\textsubscript{2}O emissions from grazing animals (e.g. urine patches) have a national level uncertainty of 57-424\% (mean value: 156).

According to both FAO\textsuperscript{16} and Herrero \textit{et al.}\textsuperscript{14}, cattle production systems dominate the sector’s emissions (64 and 78\%, of respective totals). FAO\textsuperscript{16}, using LCA estimated cattle emissions from all sources to be about 4.6 Gt CO\textsubscript{2}eq, of which 2.5 Gt CO\textsubscript{2}eq from beef cattle and 2.1 Gt CO\textsubscript{2}eq from the dairy cattle herd (producing both milk and meat). The other species have much lower, and similar levels of emissions: pig (0.7 Gt CO\textsubscript{2}eq), poultry (0.7 Gt CO\textsubscript{2}eq), buffalo (0.6 Gt CO\textsubscript{2}eq), and small ruminants (0.5 Gt CO\textsubscript{2}eq).

The developing world contributes to 70\% of emissions from ruminants and 53\% of emissions from monogastrics\textsuperscript{14}, and this share is expected to grow as livestock production increases in the developing world to meet demand increases. Mixed crop-livestock systems dominate livestock emissions (58\% of total emissions), while grazing-based systems contribute 19\%\textsuperscript{14}. 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 fertiliser included)\textsuperscript{16}. The rest of animal feed emissions are shared between energy use and land use. Enteric fermentation represents the next category of emissions, contributing about 40\% of total emissions, followed by manure storage and processing (about 10\% of emissions)\textsuperscript{16}.

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 energy consumption related to animal feed production, energy accounts for about one fifth of the sector’s emissions\textsuperscript{16}. 

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CH₄ accounts for 43% of emissions, and the remaining part is almost equally shared between N₂O (29%) and CO₂ (27%). These estimates exclude carbon sequestered in grazing land (rangeland and pastures)¹⁶.

Emissions projections. Estimates of emissions associated with the projected growth of the livestock sector to 2050 suggest that methane from enteric fermentation, methane from manure management and nitrous oxide from manure management are likely to grow at rates between 0.9-5%, 0.9-4%, 1.2-3% per year, respectively¹¹,¹²,¹⁷,²¹-²³. The range reflects different scenarios and assumptions about growth in demand for livestock products, animal numbers and the magnitude of productivity growth in livestock systems. A continuation of existing trends would lead to rates of growth of livestock emissions between 1-1.5%/year across sources (Figure 1)¹¹,²³. Although not only attributable to livestock, emissions from deforestation over the same period are projected to grow at 3.5%/yr, suggesting significant land expansion for feed production and grazing²³. Cropland area expansion is growing at a faster rate than pasture expansion primarily due to the accelerated growth of pig and poultry production (growing at rates higher than 5% globally).

Emissions intensities in livestock systems The global non-CO₂ emissions intensity of livestock products is estimated at 44 kgCO₂eq/kg protein, with a large range between 9-500 kgCO₂/kg¹⁴. Figure 2 shows the magnitude of livestock emissions and their emissions intensities (data from Herrero et al.¹⁴). The range reflects differences between livestock products, with monogastrics (pigs and poultry) at the lower end of the range, followed by milk, and red meats¹⁴,¹⁶,²⁴,²⁵. The developed world has high emissions but significantly lower emissions intensities than the developing world due to improved livestock diets, genetics, health and management practices, which reduce methane emission intensities and CO₂ emissions intensities due to lower land use requirements. Considerable parts of the developing world have high emissions from livestock produced at high emissions intensities due to low productivity of high numbers of animals (i.e. large parts of Africa and some in Latin America, dark yellow areas in Figure 2).

[Figure 1 about here ]

[Figure 2 about here]
Mitigation options and potentials in livestock systems

For the purpose of this review, mitigation options for the livestock sector can be classified into two types: 1) those directly associated with the supply of livestock products: these include improved grazing and feeding practices and other ways of intensifying livestock production, carbon sequestration and manure management amongst others; and 2) those reducing the demand for livestock products (i.e. changes in consumption of animal source foods). The technical mitigation potential of these options combined ranges from 0.1 – 7.8 GtCO₂eq. This section examines them in detail.

Supply-side livestock sector mitigation potentials

The following text describes an update on the range of technical options with potential to mitigate GHG in livestock systems reviewed by Smith et al., with the mitigation potentials presented in figure 3.

Animal-based mitigation options Animal based greenhouse gas mitigation options for livestock can be categorized as targeting enteric methane (E₇CH₄), and manure storage and application or deposition, and animal management options. A comprehensive description of these has been recently provided by Hristov et al. We estimated that the practices could help mitigate between 0.01-0.52 GtCO₂eq. In ruminant production systems, E₇CH₄ emissions usually comprise the largest proportion of GHG emissions and have been the main focus of animal-based mitigation research efforts.

A number of chemical compounds, like alternative electron receptors, ionophoric antibiotics, enzymes and probiotic cultures, have been tested for their ability to decrease methane emissions, mainly in short-term experiments. However, their long-term effects are usually much reduced, due to adaptation of the rumen microbial ecosystem. In addition, environmental issues and acceptance by the public are either unknown, or likely to prevent their future adoption.

[Figure 3 about here]
A very important and well-studied ECH₄ mitigation option for ruminants is the provision of forages of higher digestibility. This is unlikely to yield much benefit in well-developed animal production systems, but there is considerable potential in developing agricultural systems. Another well-known option for decreasing ECH₄ emission and increasing overall efficiency is inclusion of energy-dense feeds in the ration (e.g. cereal grains). Again, significant progress in this area is expected mostly in production systems, which utilize little or no grain to feed animals; however, in many parts of the world, widespread adoption of this practice may not be economically feasible. In these situations, improving the nutritive value of low-quality feeds can have a considerable benefit on herd productivity, while keeping ECH₄ emissions constant. To maximize the benefits of improving feed quality as a mitigation practice, reductions in animal numbers need to be considered as part of this 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. Our estimated technical mitigation potential of this practice is 0.68 GtCO₂eq, when a 10% increase in digestibility of the basal diet is considered and is widely applied throughout the developing world, where this practice has a higher potential to increase productivity. However, we estimate that its economic mitigation potential is closer to 0.12-0.15 GtCO₂eq when considering the low adoption rates (20-25%) of improved feeding practices in the developing world over the last 20 years.

Forages with high-concentration of plant secondary metabolites (tannins, for examples) have also been shown to decrease ECH₄, 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.

**Animal Management** Improving the genetic potential of animals for production, their reproductive efficiency and lifespan, health, and lifetime productivity are highly effective approaches for enhancing animal production efficiency and thus reducing GHG emissions per unit of product. In subsistence agricultural systems, reduction of herd size would increase feed availability and productivity of individual animals and the total herd, thus lowering ECH₄ and overall GHG emissions per unit of product. Reducing age at slaughter of finished cattle and the number of days that animals are on feed in the feedlot can have a significant impact in deceasing GHG emissions in beef and other meat animal production.
systems. Improved animal health, and reduced mortality and morbidity are expected to increase herd productivity, and reduce emission intensity in all livestock production 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, provided livestock numbers are not increased as a consequence of more efficient systems.

Nitrous oxide mitigation in livestock systems Soils are the dominant source within the global atmospheric budget of N$_2$O. Emission of N$_2$O due to agriculture activities is estimated at 2.8-6.2 Tg N$_2$O yr$^{-1}$ equaling 20-40% of all sources$^{33,35}$, of which emissions associated with feed production may account for 1.3-2.0 GtCO$_2$eq (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. Production of manure and slurry is inherent to livestock production and both contain large amounts of inorganic N and easily degradable carbon sources with a narrow C:N ratio$^{36}$. Manure-related N$_2$O emissions can be observed during storage or at and following application. Emission can be direct, i.e. directly bound to the site of storage or application, or indirect, i.e. following NH$_3$ volatilization and deposition or leaching of NO$_3$ or dissolved organic N to water bodies and further microbial conversion at sites apart from its original source$^{37}$. Furthermore, in grazed pastures urine patches are the main sources of N$_2$O emissions and nitrate leaching$^{38}$.

The key for reducing emissions is to tighten N losses to the environment, e.g. by storing manure/ slurries appropriately thereby minimizing losses due to volatilization or leaching$^8$. The mitigation potential associated with N$_2$O management practice from manure management ranges from 0.01 to 0.075 GtCO$_2$eq/yr.

Often simple measures can be taken to avoid nutrient losses to the environment. E.g. Chadwick (2005$^{36}$, 2011$^{40}$) showed that by compacting and covering farmyard manure, emissions of NH$_3$ as well as N$_2$O can be reduced significantly. Slurry may also be anaerobically digested prior of its application. This affects organic matter content and concentrations of volatile solids, while N amounts are only a little or not affected. However, there are conflicting reports as to whether anaerobic digestions indeed reduce
field scale N$_2$O emissions$^{41,42}$. However, as Smith et al. (2008)$^8$ state, for most livestock systems worldwide, there is limited opportunity for manure management, treatment or storage; excretion happens in the field and handling for fuel or fertility amendment occurs when it is dry and methane emissions are negligible. The highest mitigation potential is possibly linked to the application of manures to the field and its mitigation potential ranges from 0.01-0.075GtCO$_2$eq$^8$. Choosing the right timing and form of application, e.g. subsurface application of manures by injection or drilling at times when crop or grassland N demands are high, will increase plant N use efficiency and limit N$_2$O losses to the environment$^{43,44}$. Even if N$_2$O emissions may increase following N application, the emission per product, which is the most important agronomic criteria$^{45}$, is likely to be reduced if manures are applied according to plant N demand and if e.g. periods with heavy rains or non-growing seasons are avoided$^{46}$. Other options for reducing N$_2$O not only from agricultural land but also from grazed pastures include the use of nitrification inhibitors$^{47}$. Nitrification inhibitors have been successfully tested for various climates and for its suitability to reduce N$_2$O emissions from cropland as well as grassland$^{47-49}$. If animal numbers were to decrease due to other suggested mitigation practices, it is likely that N$_2$O emissions could increase due to increased conversion of land to cropland and increased fertilizer use.

Revised potentials for carbon sequestration in rangelands Grazing-land management practices that affect species composition, offtake, nutrient and water inputs, and fire can impact soil carbon stocks$^{51}$—either releasing or taking up CO$_2$ from the atmosphere. Excessive removal of above-ground biomass, continuous grazing at suboptimal stocking rates, and other poor grazing management practices which result in a mismatch between forage supply and animal demands, are particularly important human-controlled factors that influence grassland production and have led to depletion of soil carbon stocks$^{51,52}$. Much of the world’s grazinglands are still under pressure to produce more livestock through expansion and more intensive grazing, particularly in Africa’s rangelands$^{53}$. However, good grassland management can potentially reverse historical soil carbon losses and sequester substantial amounts of carbon in grazing-land soils (Figure 4). Much of this sequestration potential may be economically feasible because it can be realized through implementation of practices capable of enhancing forage production$^8$. Recent research suggests that changes in grazing management – increasing or reducing offtake rate in order to maximize forage production – could lead to sequestration of as much as 400
MtCO$_2$eq in the world’s rangelands$^{16}$. Much of this potential (two thirds, approximately 270 MtCO$_2$eq) arises in areas of developing countries. With about half of this (approximately 130 MtCO$_2$eq) coming from rangelands that have been degraded due to historic overgrazing, but a significant share also comes from increasing offtake in areas now lightly grazed. Interestingly, much of the sequestration potential arises from areas in which production seems likely to increase following a period of de-stocking – areas where primary production can recover from grazing$^{16}$. Improved management of planted pastures - sowing improved, deep-rooted forage species, and making investments to enhance production (e.g., by enhancing soil fertility through sowing legumes or using mineral fertilizers) in nutrient poor pastures could all lead to sequestration and may be achieved at modest cost where there are strong synergies between carbon sequestration and increased forage production.

The modest mitigation potentials of carbon sequestration in rangelands summarized here suggest that this option could be considered a co-benefit of improving productivity and ecosystems services$^{54}$, rather than a primary objective for managing rangeland ecosystems.

Reducing demand: what is the hypothetical global mitigation potential of reducing livestock product consumption? Projections of food demand, which include population changes and also changes in per-capita wealth, suggest that we will need 70-100% more food by 2050$^{55}$. Part of this increase in demand is driven by a greatly increased demand for livestock products (meat and dairy) in growing economies. Given that the resource use efficiency of livestock production is low in comparison to crops, and that about a third of the world’s cereal production is fed to animals$^1$, it has been hypothesized that a reduction in the livestock product consumption could greatly reduce the need for more food. On average, the production of beef protein requires over five times more land and water than the production of vegetable proteins, such as cereals$^{56}$. While meat currently represents only 15% of the total energy in the global human diet, approximately 80% of the agricultural land is used for animal grazing or the production of feed and fodder for animals$^1$. It should be noted that this includes extensive grasslands in areas where other forms of agriculture would be extremely challenging.
Given the strong relationship between increasing wealth (from a low start) and consumption of livestock products, the increased food demand driven by the increasing prosperity of developing countries has been taken as a given, and has been used in various scenario analyses of the agricultural sector. But what would happen if the global population ate less meat? Stehfest et al. examined these questions. Under the most extreme scenario, where no animal products are consumed at all, adequate food production in 2050 could be achieved on less land than is currently used, allowing considerable forest regeneration, and reducing land based greenhouse gas emissions to one third of the reference “business-as-usual” case for 2050, a reduction of 7.8 Gt CO₂-eq. yr⁻¹.

The largest decreases are projected to occur in grassland area, but decreases in cropland could also be achieved. Other variants (no ruminant meat, no meat) had slightly smaller impacts (5.8, 6.4 Gt CO₂-eq. yr⁻¹, respectively), but reduced grassland area significantly (80%) and cropland area as well. Another scenario, examining the hypothetical adoption of a healthy diet (following healthy eating recommendations) globally, also saw significant global reduction in ruminant numbers, and reductions in cropland (-135 Mha) and grassland (-1360 Mha) areas, with emission reductions of 4.3 Gt CO₂-eq. yr⁻¹ compared to the reference case. In addition to reducing pressure on agricultural land, a global transition to a low meat, balanced diet would reduce the mitigation costs to achieve a 450 ppm CO₂-eq. stabilisation target by about 50% in 2050 compared to the reference case. In another study, Popp et al. simulated non-CO₂ GHG emissions under different assumptions of food demand. They too found that reduced demand for livestock products would significantly decrease emissions, and when comparing technical vs. reduced consumption, found that reduced consumption would be far more effective due to potential land sparing impacts.

Smith et al., explored similar scenarios to those considered by Erb et al., showing that reducing consumption could have substantial beneficial effects, again in particular through their ability to create ‘spare land’ that can be used for either bioenergy or C-sequestration through afforestation. A scenario in which a switch to a low-animal product diet converging to the global average energy demand in the year 2000 (i.e. 2800 kcal/cap/d, compared to the global mean of 3100 kcal/cap/d in the reference case), gave emission reductions of 0.7-7.3 Gt CO₂-eq. yr⁻¹, depending on how the ‘spare land’ is used.
These scenarios, while important to determine the magnitude of the technical potential for mitigation from livestock, are largely infeasible for many reasons. The large regional discrepancies in consumption needs between the developed and the developing world have not been considered, and they need to be put in a nutritional diversity framework that takes into account healthy, varied diets for different parts of the world. Establishing the societal impacts of land sparing opportunities, in terms of livelihoods, economics, gender and equity, is also essential to understand their feasibility. This area warrants further research. On top of that, the world food system has never had to react to planned, voluntary, reductions in food consumption. Therefore, very few successful policy alternatives to reduce consumption equitably have been designed, tried and tested. Nevertheless, notable examples are being considered in Scandinavia.

**Sustainable intensification** Sustainable intensification has recently been reviewed by Smith, and will involve addressing the many unsustainable practices already manifest in the global food system, but will also need to future-proof against threats such as the adverse impacts of projected climate change in many regions, which if uncontrolled, could counteract any benefits accruing from sustainable intensification.

There are many options for sustainable intensification, ranging from the 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. Godfray et al. suggest that by 2050, it will be possible to manipulate traits controlled by many genes and confer desirable traits (such as improved nitrogen and water use efficiency in crops, or use of cloned animals) with improved productive characteristics. Genetic manipulation, then, could play a role in future sustainable intensification, should the public opposition to genetic modification, widespread in some regions of the world, change.

Foley at al. and Mueller et al. examined the closure of the theoretical yield gap as a mechanism of sustainable intensification (in some regions) by rebalancing the distribution of inputs to optimise production. Foley et al. also showed that benefits and impacts of irrigation are not evenly distributed and that water needed for crop production varies greatly across the globe. Foley et al. suggest that redistributing these imbalances could
largely close the yield gap, and show that bringing yields to within 95% of their potential
for 16 important food and feed crops could add 2.3 billion tonnes ($5 \times 10^{15}$ kilocalories) of
new production, which represents a 58% increase. Closing the yield gap of the same crops
to 75% of their potential, would give a global production increase of 1.1 billion tonnes
($2.8 \times 10^{15}$ kilocalories), which is an increase of 28%.

Crop yield improvement will play a critical role in future land use dynamics and on
livestock systems. It will determine the requirements for additional cropland, and have a
strong impact also on grassland expansion. Havlík et al. illustrated that compared with
yield stagnation, maintaining past trends in crop yield growth would save 290 Mha of
cropland and avoid additional expansion of about 120 Mha of grassland by 2030. The
latter is caused by the fact that increasing crop yields leads to lower crop prices and hence
to the intensification of ruminant production from grass based systems to systems with
forage-based diets supplemented with grains. In their study, GHG emissions decreased by
more than 2 GtCO$_2$-eq per year when crop yields grew according to the past trends as
compared to yield stagnation. About 90% of the emissions reduction came from avoided
land use changes, with a part associated to livestock (0.25GtCO$_2$-eq); but also emissions
directly linked to the livestock sector were reduced due to the improved productivity.
They also found that productivity increases solely based on higher fertilizer rates, would
reduce the overall positive balance through increased N$_2$O emissions, which are a key
source of emissions in livestock systems.

Emissions leakage If mitigation policies used to reduce livestock emissions in one region
cause production to fall, this will increase the importation of livestock commodities to that
region, thereby raising the production and associated emissions in the regions supplying
these imports. This is known as emissions leakage and it can significantly reduce the
efficacy of mitigation policies in regulated regions. If such policies rely on positive
incentives such as mitigation subsidies, rather than negative incentives such as a carbon
tax, it can be possible to reduce emissions without lowering production, and thereby
prevent leakage. However, if negative incentives are used, leakage can only be eliminated
if the incentives are applied to all global livestock emissions.

There are few studies that estimate the leakage of livestock emissions in response to
mitigation policies. Using a computable general equilibrium (CGE) model, Golub et al.
estimate an annual reduction in livestock emissions of 163 MtCO$_2$eq in response to a $27tCO_2$eq carbon tax set on agricultural emissions in industrialized (Annex I) countries. However, 35% of this reduction in emissions is estimated to be offset by increased emissions in developing (non-Annex I) countries. Sensitivity analysis of the trade elasticities, which are critical for the leakage rates in the model, allowed placement of this mean leakage figure of 35% between 16% and 56% with 95% confidence. Using a partial equilibrium model (Aglink-Cosimo), Key and Tallard$^70$ estimate that two thirds of the emission reduction achieved by a tax on livestock CH$_4$ emissions in industrialized (Annex I) countries, is leaked via increased emissions in developing countries. Leip et al.$^{19}$ also use a partial equilibrium model (CAPRI), but estimate a lower emission leakage rate of 22%, following the application of a tax on livestock animals in the EU. These findings on the leakage illustrate the importance of coordinated global mitigation policies.

Conclusions

The technical mitigation potential of the livestock sector could represent up to 50% of the global technical mitigation potential of the agriculture, forestry and land use sectors. This is significant, but most of this potential is still hypothetical, due to low adoption of technical practices and the uncertainties and trade-offs associated with any attempts to reduce the consumption of livestock products.

There is little evidence of government success in changing food preferences and good evidence for a positive link between increasing incomes and the consumption of livestock products. Yet the evidence is strong that continuation of the trend of recent decades of increasing consumption of meat in particular, is not compatible with reducing greenhouse gas emissions from agriculture. In addition, the livestock sector is an increasingly important contributor to global agricultural trade. There is a need for research to understand what types of knowledge or interventions could contribute to limiting global demand for livestock products.

Understanding the socio-economic impacts of land sparing on food systems and value chains, is of paramount importance for designing intensification and nutritional scenarios
of increased feasibility, where public policy could play a significant role in driving their implementation.

There is also a need to increase investment in the livestock sector in the developing world so that it becomes more market orientated. This could prove a catalyst to increase the adoption of practices for sustainably intensifying the sector while mitigating emissions. Understanding the interactions between mitigation and adaptation in livestock systems will be essential to remove constraints to adoption of the practices that create the largest synergies, and to reduce the trade-offs associated with some practices. Scenario development at multiple scales, from global to local will be required to elucidate these effects.

Our overall conclusion therefore is that limiting the rise in emissions from the livestock sector is particularly challenging. There are opportunities for capturing synergies of increasing productivity and decreasing emission intensity, but these run the risk of resulting in successful farmers keeping more animals and thus limiting the benefits in terms of total emissions. Reducing global consumption of livestock products would bring considerable benefits in terms of agricultural emissions, but there is little evidence as to how this might be achieved without negative trade-offs. This is therefore an area in need of urgent research.

References

1. FAO. *Livestock's Long Shadow: Environmental Issues and Options.* (Food and Agriculture Organization of the United Nations, Rome, Italy. 2006).


Acknowledgments

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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.

Competing financial interests

The authors declare no competing financial interests.
Figure legends

Figure 1. Baseline projections of greenhouse gas emissions for the main IPCC source categories for livestock and agriculture. The baseline projection represents a continuation of the current livestock product demand trends (black dots, converted to edible animal protein, all livestock products) Source: Edgar v4.2, EPA 2012, Globiom 2013.

Figure 2. GHG emissions from ruminant livestock and emissions intensities per kg of protein from ruminant source foods (meat and milk combined). High Emissions = > 20 thousand kgCO₂eq/km², Emissions intensities = Low = > 70 kg CO₂eq/kg protein, Medium = 41 – 69 kg CO₂eq/kg protein, High = < 40 kg CO₂eq/kg protein. Data from Herrero et al.

Figure 3 - Technical mitigation potentials of supply-side options for reducing emissions from the livestock sector. Red parts represent the range for each practice. a) range defined by FAO and Smith et al. b) improved digestibility impacts of 10% increased digestibility in all ruminants in the developing world, up-scaling values from Thornton and Herrero. Direct application of this option to developed country situations was assumed to be too small to be considered. c) Data from Hristov et al. Includes inhibitors, ionophores, electron receptors, enzymes, plant bioactive compounds, lipids and manipulation of rumen micro-flora. Applied to breeding herds of cattle globally with effects on enteric methane as described in Hristov et al. d) Avoided LUC from transitions from grazing to mixed crop-livestock systems as estimated by Havlik et al. e) Animal management practices like improved health, reduced mortality from Hristov et al. Effects applied as c). f) Rangeland rehabilitation mitigation potentials from Conant et al 2002. g) manure management mitigation potentials from Smith et al.

Figure 4. Mitigation potentials for carbon sequestration in grasslands through rangeland rehabilitation and grazing management in selected regions and globally.
Table 1. Global greenhouse gas emissions from livestock (1995-2005)

<table>
<thead>
<tr>
<th>Emissions source</th>
<th>Emissions (GtCO2eq)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed N₂O</td>
<td>1.3-2.0</td>
<td>Includes N₂O emissions from manures applied to pastures, and from fertilisers to both cropland for feed and pasture. Emissions from manure applied to pastures ranges from 0.42-0.95 GtCO₂eq[^10,^14,^16,^17]</td>
</tr>
<tr>
<td>Feed CO₂ – LUC excluded</td>
<td>0.92</td>
<td>16</td>
</tr>
<tr>
<td>Feed CO₂ LUC</td>
<td>0.23</td>
<td>16</td>
</tr>
<tr>
<td>Pasture expansion CO₂ LUC</td>
<td>0.43</td>
<td>16</td>
</tr>
<tr>
<td>Feed CH₄ rice</td>
<td>0.03</td>
<td>16</td>
</tr>
<tr>
<td>Enteric CH₄[^1]</td>
<td>1.6-2.7</td>
<td>10-14, 16</td>
</tr>
<tr>
<td>Manure CH₄[^1]</td>
<td>0.2-0.4</td>
<td>10-14, 16</td>
</tr>
<tr>
<td>Manure N₂O[^1]</td>
<td>0.2-0.5</td>
<td>10-14, 16, 17</td>
</tr>
<tr>
<td>Direct Energy CO₂</td>
<td>0.11</td>
<td>16</td>
</tr>
<tr>
<td>Embedded Energy CO₂</td>
<td>0.02</td>
<td>16</td>
</tr>
<tr>
<td>Post farm gate CO₂</td>
<td>0.023</td>
<td>16</td>
</tr>
<tr>
<td>Non-CO₂ emissions[^1] (IPCC guidelines)</td>
<td>2.0-3.6</td>
<td></td>
</tr>
<tr>
<td>Total emissions (LCA approach)[^2]</td>
<td>5.3-7.5</td>
<td></td>
</tr>
</tbody>
</table>

[^1]: Livestock emissions according to IPCC emissions guidelines
[^2]: Range estimated using information from global analyses for key emissions source categories.
[^10]: LCA as implemented by FAO[^16]
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We will submit a high quality figure in due course
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