Greenhouse gas mitigation potentials in the livestock sector

Mario Herrero[1,2*], Richard T. Conant[2,3], Petr Havlík[4], Alexander N. Hristov[5], Pete Smith[6], Pierre Gerber[7], Margaret Gill[6], Klaus Butterbach-Bahl[2,8], Benjamin Henderson[7] and Philip K. Thornton[9]

[1]Commonwealth Scientific and Industrial Research Organization, 306 Carmody Road, St Lucia, QLD 4067, Australia.
[2]International Livestock Research Institute, Old Naivasha Road, Nairobi 00100, Kenya
[3]Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO 80523-1499, United States.
[4]Ecosystems Services and Management Program, International Institute for Applied Systems Analysis, Laxenburg, Austria.
[5]Department of Animal Science, Pennsylvania State University, 324 Henning Building, University Park, PA16802, United States.
[6] Environment and Food Security, Institute of Biological & Environmental Sciences, University of Aberdeen, 23 St Machar Drive, Aberdeen AB24 3UU, UK.
[7]Food and Agriculture Organization of the United Nations, via delle Terme di Caracalla, Rome, Italy.
[8]Institute of Meteorology and Climate Research, Atmospheric Environmental Research (IMK-IFU) Karlsruhe Institute of Technology (KIT) Kaiserstraße 12, 76131 Karlsruhe, Germany.
[9]CGIAR Research Programme on Climate Change, Agriculture and Food Security, Rolighedsvej 21, DK-1958 Frederiksberg C, Copenhagen, Denmark.

*Corresponding author: Dr Mario Herrero, Commonwealth Scientific and Industrial Research Organization, 306 Carmody Road, St Lucia, QLD 4067, Australia.
Mario.Herrero@csiro.au

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 $GtCO_2eq/yr$*. 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 $GtCO_2eq/yr$, 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 $GtCO_2eq$, while modelled scenarios of reduced livestock product consumption provide a range up to 7.8 $GtCO_2eq$. 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[7].

Smith *et al.*[8] estimated that the technical mitigation potential of livestock systems was 1.7 $GtCO_2eq/yr$, 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 $GtCO_2eq$ 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[9] or developed using lifecycle analysis. Estimates using IPCC emissions guidelines[10-14] include direct non-CO_2 emissions of methane (enteric and manure) and nitrous oxide (manure management), while LCA approaches [15,16] 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[9], 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 $GtCO_2eq$/yr (Table 1). The most important sources of emissions were enteric methane (1.6-2.7 $GtCO_2eq$[10-14,16]), N_2O emissions associated with feed production (1.7 $GtCO_2eq$[16]) and land use for animal feed and pastures, including change in land use (1.6 $GtCO_2eq$[16]).

[Table 1 about here]

The level of disaggregation of global livestock emissions differs considerably between studies. Some estimates are based primarily on Tier 1 approaches[12,13,17], with Tier 2 sometimes being used for enteric fermentation[10,11]. FAO[16] and Herrero *et al.*[14] disaggregate emissions by country/region, species, production system and by product (milk, meat). FAO[16] use Tier 2 for the IPCC emissions categories and LCA methods for the other sources. Herrero *et al.*[14] 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 $GtCO_2eq$, 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 $GtCO_2eq$, C.V.=27%; mean = 0.29 $GtCO_2eq$, CV= 46%). Comparable values of uncertainties (11-145%) for CH_4 emissions from manure management for several European countries were also reported by

Rypdal and Winiwarter[18], Leip *et al.*[19] or Monni *et al.*[20] for Finland, whereas those for European CH_4 emissions from enteric fermentation are in agreement with the global level estimates (6-40%)[19]. For the EU member states, Leip[19] estimated that reported national N_2O emissions from manure management (storage only) are uncertain in the range of 21-414%, while direct and indirect N_2O emissions from agricultural land due to fertilizer application or soil N_2O emissions from grazing animals (e.g. urine patches) have a national level uncertainty of 57-424% (mean value: 156).

According to both FAO[16] and Herrero *et al.*[14], cattle production systems dominate the sector's emissions (64 and 78%, of respective totals). FAO[16], using LCA estimated cattle emissions from all sources to be about 4.6 Gt CO_2eq, of which 2.5 Gt CO_2eq from beef cattle and 2.1 Gt CO_2eq 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_2eq), poultry (0.7 Gt CO_2eq), buffalo (0.6 Gt CO_2eq), and small ruminants (0.5 Gt CO_2eq).

The developing world contributes to 70% of emissions from ruminants and 53% of emissions from monogastrics[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%[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)[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)[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[16].

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].

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, respectively[11, 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 grazing[23]. 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).

[Figure 1 about here]

Emissions intensities in livestock systems The global non-CO_2 emissions intensity of livestock products is estimated at 44 kgCO_2eq/kg protein, with a large range between 9-500 kgCO_2/kg[14]. 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 meats[14, 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 CO_2 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 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 $GtCO_2eq$. 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.*[8], 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 (ECH_4), and manure storage and application or deposition, and animal management options. A comprehensive description of these has been recently provided by Hristov *et al.*[26]. We estimated that the practices could help mitigate between 0.01-0.52 $GtCO_2eq$. In ruminant production systems, ECH_4 emissions usually comprise the largest proportion of GHG emissions and have been the main focus of animal-based mitigation research efforts[27-29].

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 ECH_4 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[30]. Another well-known option for decreasing ECH_4 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 ECH_4 emissions constant[30]. 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[30]. Our estimated technical mitigation potential of this practice is 0.68 $GtCO_2eq$, 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 $GtCO_2eq$ when considering the low adoption rates (20-25%) of improved feeding practices in the developing world over the last 20 years[30].

Forages with high-concentration of plant secondary metabolites (tannins, for examples) have also been shown to decrease ECH_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[31].

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[26, 32]. In subsistence agricultural systems, reduction of herd size would increase feed availability and productivity of individual animals and the total herd, thus lowering ECH_4 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_2O. Emission of N_2O due to agriculture activities is estimated at 2.8-6.2 Tg N_2O yr^{-1} equaling 20-40% of all sources[33-35], of which emissions associated with feed production may account for 1.3-2.0 $GtCO_2eq$ (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_2O 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_2O 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_2O management practice from manure management ranges from 0.01 to 0.075 $GtCO_2eq/yr$.

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_2O 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_2O 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 0.01-0.075GtCO2eq[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_2O losses to the environment[43, 44]. Even if N_2O 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_2O 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_2O 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_2O 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

$MtCO_2eq$ in the world's rangelands[16]. Much of this potential (two thirds, approximately 270 $MtCO^2eq$) arises in areas of developing countries. With about half of this (approximately 130 $MtCO_2eq$) 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.

Figure 4 around here

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[8]. But what would happen if the global population ate less meat? Stehfest *et al.*[56] 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 CO_2-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 CO_2-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[57]) 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 CO_2-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 CO_2-eq. stabilisation target by about 50% in 2050 compared to the reference case[56]. In another study, Popp *et al.*[12] simulated non-CO_2 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.*[7], explored similar scenarios to those considered by Erb *et al.*[58], 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 CO_2-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[59], 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[60, 61].

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[62-64]. Godfray *et al.*[63] 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.*[65] and Mueller *et al.*[66] 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.*[65] 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.*[65] 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 x 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 x 10^{15} kilocalories), which is an increase of 28%.

Crop yield improvement will play a critical role in future land use dynamics[67] and on livestock systems[26]. It will determine the requirements for additional cropland, and have a strong impact also on grassland expansion[26]. Havlík *et al.*[26] 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 (0.25$GtCO_2$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_2O emissions[68], 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.*[69]

estimate an annual reduction in livestock emissions of 163 $MtCO_2eq$ in response to a \$27tCO_2eq 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 signficant 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[71]. 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[72].

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).
2. Thornton P.K. Livestock production: recent trends, future prospects. *Phil. Trans. Royal Soc. B.* **365**, 2853-2867 (2010).
3. Herrero M., Thornton P.K., Gerber P. and Reid R.S. Livestock, livelihoods and the environment: understanding the trade-offs. *Curr. Opin. Env. Sust.* 1, 111-120 (2009).
4. FAO. *The State of Food and Agriculture. Livestock in the Balance.* Food and Agriculture Organization of the United Nations, Rome, Italy (2009).

5. Rosegrant M.W. *et al.* Looking into the future for agriculture and AKST (Agricultural Knowledge Science and Technology). In: *Agriculture at a Crossroads* Edited by McIntyre BD, Herren HR, Wakhungu J, Watson RT. Island Press: 307-376 (2009).
6. Capper, J.L., Cady, R.A. and Bauman, D.E.. The environmental impact of dairy production: 1944 compared with 2007. *J. Anim. Sci.* **87**, 2160- 2167 (2009).
7. Smith, P. et al. How much land based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Global Change Biology* (accepted for publication, 2013).
8. Smith P. *et al.* Greenhouse gas mitigation in agriculture. *Phil. Trans. R. Soc. B* **363**, 789–813 (2008).
9. IPCC. Emissions from livestock and manure management. In *2006 IPCC Guidelines for National Greenhouse Gas Inventories.* Volume 4: Agriculture, Forestry and Other Land Use. Edited by S. Eggleston, L. Buendia, K. Miwa, T. Ngara & K. Tanabe. Intergovernmental Panel on Climate Change, pp. 10.0–10.87. (Cambridge University Press 2006).
10. EC-JRC/PBL. Emission Database for Global Atmospheric Research (EDGAR), Release Version 4.2. http://edgar.jrc.ec.europa.eu. (2011).
11. US EPA. *Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990-2020.* United States Environmental Protection Agency, Washington D.C. (2006)
12. Popp A., Lotze-Campen H. and Bodirsky B. Food consumption, diet shifts and associated non-CO_2 greenhouse gases from agricultural production. *Glob. Env. Change* 20, 451–462 (2010).
13. Tubiello *et al.* The FAOSTAT database of greenhouse gas emissions from agriculture. Geophysical Research Letters, in press (2013).
14. Herrero, M. *et al.* High resolution bio-physical livestock data for global change and sustainability research. *PNAS,* forthcoming (2013).
15. FAO. Greenhouse gas emissions from the dairy sector. A life cycle assessment. (Food and Agriculture Organization of the United Nations, Rome, Italy FAO, 2010)
16. FAO, 2013. Greenhouse gas emission form livestock – Global patterns and mitigation options. (Food and Agriculture Organization of the United Nations, Rome, Italy, in preparation, 2013)
17. Bodirsky, B. L. *et al.* N2O emissions from the global agricultural nitrogen cycle – current state and future scenarios. *Biogeosci.* **9**, 4169–4197 (2012).

18. Rypdal, K., Winiwarter, W. Uncertainties in greenhouse gas emission inventories, evaluation, comparability and implications. *Environm. Sci. Pol.* 4, 107–116 (2001).

19. Leip A. *et al.* Evaluation of the livestock sector's contribution to the EU greenhouse gas emissions (GGELS) – final report. (European Commission, Joint Research Centre 2010).

20. Monni S., Perala P., Regina K. Uncertainty in agricultural CH4 and N2O emissions from Finland –possibilities to increase accuracy in emission estimates. *Mitigation Adapt Strat Global Change* **12**, 545–571 (2007).

21. US EPA. *Global Mitigation of Non-CO2 Greenhouse Gases Report* (update -March 2012). United States Environmental Protection Agency, Washington, D.C. (2012).

22. Westhoek, H. *et al.*, The Protein Puzzle, The Hague: PBL Netherlands Environmental Assessment Agency (2011).

23. Havlík, P. *et al.* Crop productivity and the global livestock sector: Implications for land use change and greenhouse gas emissions. *American Journal of Agricultural Economics* 95, 442-448 (2013).

24. de Vries, M and de Boer, I.J.M. Comparing environmental impacts of livestock 33 products. A review of life cycle assessments. *Livest. Sci.* **128**, 1-11 (2009).

25. Cederberg, C., Hedenus, F., Wirsenius, S., Sonesson, U. Trends in greenhouse gas emissions from consumption and production of animal food products - Implications for long-Term climate targets. *Animal* **7**, 330-340 (2013).

26. Hristov, A. N. et al. *Mitigation of Greenhouse Gas Emissions in Livestock Production. A Review of Technical Options for non-CO_2 Emissions.* FAO Technical Paper, pp. 220. (FAO, Rome, Italy, 2013).

27. Boadi, D., C. Benchaar, C., J. Chiquette, J. and D. Massé, D. Mitigation strategies to reduce enteric methane emissions from dairy cows: Update review. *Can. J. Anim. Sci.* **84**, 319-335 (2004).

28. Martin, C., Morgavi, D.P. and Doreau, M. Methane mitigation in ruminants: from microbe to the farm scale. *Animal* **4**, 351-365 (2010).

29. Cottle, D. J., Nolan, J.V. and Wiedemann, S.G. Ruminant enteric methane mitigation: a review. *Anim. Prod. Sci.* **51**, 491–514 (2011).

30. Thornton P.K. and Herrero M. The potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics. *PNAS* **107**, 19667–19672 (2010).

31. Hristov, A. N. Historic, pre-European settlement, and present-day contribution of wild ruminants to enteric methane emissions in the United States. *J. Anim. Sci.* **90**, 1371-1375 (2012).

32. Gill, M. Smith, P and Wilkinson, J. M. Mitigating climate change: the role of domestic livestock. *Animal* **4**, 323-333 (2010).

33. Fowler D. *et al.* Atmospheric composition change: Ecosystems – Atmosphere Interactions. *Atmosph. Env.* **43**, 5193-5267 (2009).

34. Davidson, E.A. The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. *Nature Geosci.* **2**, 659-662 (2009).

35. Reay D.S. *et al.* Global agriculture and nitrous oxide emissions. *Nature Clim. Change* **2**, 410-416 (2012).

36. Chadwick D. *et al.* Manure management: Implications for greenhouse gas emissions. *Anim. Feed Sci. and Technol.* **166-167**, 514-531 (2011).

37. Well K. and Butterbach-Bahl K. Indirect emissions of nitrous oxide from nitrogen deposition and leaching of agricultural nitrogen. In Smith K (ed.) *Nitrous oxide and climate change*, 162-89 pp. (Earthscan Ltd, London, 2010)

38. Oenema O, Velthof G.L., Yamulki S., Jarvis S.C. Nitrous oxide emissions from grazed grassland. *Soil Use Manag.* **13**, 288-295 (1997).

39. Smith P et al. Agriculture. In: *Climate Change 2007: Mitigation*. Edited by In B Metz, OR Davidson, PR Bosch, R Dave, LA Meyer. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, (Cambridge University Press, 2007).

40. Chadwick, D. Emissions of ammonia, nitrous oxide and methane from cattle manure heaps: effect of compaction and covering. *Atmos. Environ.* **39**, 87–799 (2005).

41. Thomsen, I.K., Pedersen, A.R., Nyord, T., Petersen, S.O. Effects of slurry pre-treatment and application technique on short-term N_2O emissions as determined by a new non-linear approach. *Agric. Ecosyst. Environ.* **136**, 227–235 (2010).

42. Clemens, J., Trimborn, M., Weiland, P., Amon, B. Mitigation of greenhouse gas emissions by anaerobic digestion of cattle slurry. *Agric. Ecosyst. Environ.* **112**, 171–177 (2006).

43. Van Groenigen J.W. *et al.* Nitrous oxide emissions from silage maize fields under different mineral nitrogen fertilizer and slurry applications. *Plant and Soil* **263**, 101–111 (2004).

44. Webb, J., Pain, B., Bittman, S., Morgan, J. The impacts of manure application methods on emissions of ammonia, nitrous oxide and on crop response—A review. *Agric. Ecosyst. and Environ.* **137**, 39-46 (2010).

45. Van Groeningen, J.W., Velthof, G.L., Oenema, O., Van Groeningen, K.J. Towards an agronomic assessment of N_2O emissions: a case study for arable crops. *Eur. J. Soil Sci.* **61**, 903–913 (2010)

46. Smith, K.A. and Conen, F. Impacts of land management on fluxes of trace greenhouse gases. *Soil Use Manag.* **20**, 255-263 (2004).

47. Snyder CS, Bruulsema TW, Jensen TL, Fixen PE. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. *Agric. Ecosyst. and Env*. **133**, 247-266 (2009)

48. Clough T.J. *et al.* The mitigation potential of hippuric acid on N_2O emissions from urine patches: An in situ determination of its effect. *Soil Biol Biochem* 41, 2222-2229 (2009).

49. Betram J.E. *et al.* Hippuric acid and benzoic acid inhibition of urine derived N_2O emissions from soil. *Global Change Biol.* **15**, 2067-2077 (2009).

50. Conant, R. T., Paustian, K. & Elliott, E. T. Grassland management and conversion into grassland: Effects on soil carbon. *Ecol. Applic.* **11**, 343-355 (2001).

51. Conant RT, Paustian K. Potential soil carbon sequestration in overgrazed 17 grassland ecosystems. *Global Biogeo. Cycles* **16**, 1143-1152 (2002).

52. Ojima, D.S. *et al.* Modeling the effects of climatic and CO_2 changes on grassland storage of soil C. *Water, Air, and Soil Poll.* **70**, 643-657 (1993)

53. Reid, R.S. *et al.* Is it possible to mitigate greenhouse gas emissions in pastoral ecosystems of the tropics? *Env. Dev. Sust.* **6**, 91-109 (2004).

54. De Fries R, Rosenzweig C. Toward a whole-landscape approach for sustainable land use in the tropics. *PNAS* **107**, 19627–19632 (2010).

55. Royal Society of London. *Reaping the Benefits: Science and the Sustainable Intensification of Global Agriculture*. London: Royal Society (2009).

56. Stehfest E. *et al.* Climate benefits of changing diet. *Clim. Change* **95**, 83-102 (2009).

57. Willett, W.C. *Eat, drink, and be healthy: the Harvard Medical School guide to healthy eating*. (New York: Simon & Schuster 2001).

58. Erb K.-H., Haberl H., Plutzar C. Dependency of global primary bioenergy crop potentials in 2050 on food systems, yields, biodiversity conservation and political stability. *Ener. Pol.* **47**, 260-269 (2012).

59. Smith, P. Delivering food security without increasing pressure on land. *Global Food Sec.* (online). doi: 10.1016/j.gfs.2012.11.008 (2012).

60. Schmidhuber, J., Tubiello, F. N. Global food security under climate change. *PNAS* **104**, 19703-19708 (2007).

61. Simelton, E. *et al.* The socioeconomics of food crop production and climate change vulnerability: a global scale quantitative analysis of how grain crops are sensitive to drought. *Food Sec.* **4**, 163-179.

62. Foresight Project. *The Future of Food and Farming. Final Project Report.* (The Government Office for Science, London 2011).

63. Godfray H.C.J. et al. Food security: the challenge of feeding 9 billion people. *Science* **327**, 812-818 (2010).

64. IAASTD. *International Assessment of Agricultural Knowledge, Science and Technology for Development*: Executive Summary of the Synthesis Report, http://www.agassessment.org/index.cfm. (2009)

65. Foley, J.A. *et al.* Solutions for a cultivated planet. *Nature* **478**, 337-342 (2011).

66. Mueller N. D. *et al.* 2012. Closing yield gaps through nutrient and water management. *Nature* **490**, 254-257 (2012).

67. Tilman, D., Balzer, C., Hill, J., Befort, B.L. Global food demand and the sustainable intensification of agriculture. *PNAS* **108**, 20260-20264 (2011).

68. Valin, H. *et al.* Agricultural productivity and GHG emissions in developing countries: what future trade-offs between mitigation and food security? *Env. Res. Lett.*, under consideration (2013).

69. Golub, A. *et al.* Global climate policy impacts on livestock, land use, livelihoods, and food security. *PNAS,* published online 26/09/2012 (2012).

70. Key N, Tallard G. Mitigating methane emissions from livestock: a global analysis of sectoral policies. *Clim. Change*, **12**: 387-414 (2012).

71. Herrero M. et al. Smart investments in sustainable food production: revisiting mixed crop-livestock systems. *Science* **327**, 822-825 (2010).

72. Vervoort J. *et al.* Food systems futures: towards adaptation pathways across multiple dimensions and levels. *Global Env. Change*, under consideration (2013).

73. Carvalho, J. L. N. et al. Potential of soil Carbon sequestration in different biomes of Brazil. *Rev. Bras. De Ciencia Do Solo* **34**, 277-289 (2010).

74. Lal. R. Soil Carbon sequestration impacts on global climate change and food security. *Science* **304**, 1623-1627. (2004).

75. Wang, S. *et al.* Management and land use change effects on soil carbon in northern China's grasslands: a synthesis. Agric. Ecosyst. Env. (2011).
76. Follett, R.F. and Schumann, G.E. Grazing land contributions to carbon sequestration. In Grassland: A Global Resource, p. 264-277. (2005).
77. Schuman, J.E., Janzen, H.H., Herrick, J.E. Soil carbon sequestration and potential carbon sequestration in rangelands. *Env. Poll.* **116**, 391-396 (2002).
78. Morgan, J. *et al.* Carbon sequestration in agricultural lands of the United States. *J. Soil and Water Cons.* **65**, 6-13. (2011)
79. Lal, R. Carbon sequestration in dryland ecosystems. *Env. Man.* **33**, 528-544, (2003).
80. Bellarby J., *et al.* Livestock greenhouse gas emissions and mitigation potential in Europe. *Global Change Biol.* **19**, 3-18. (2013).
81. Fitton, N. *et al.* Greenhouse gas mitigation potential of agricultural land in Great Britain. *Soil Use and Manag.* **27**, 491-501 (2011).

Acknowledgments

Financial support from the CGIAR Programme on Climate Change, Agriculture and Food Security (CCAFS) and the EU-FP7 AnimalChange project are acknowledged. PS is a Royal Society-Wolfson Research Merit Award holder.

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[10], EPA 2012[21], Globiom 2013[23].

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 kgCO_2eq/km2, Emissions intensities = Low = > 70 kg CO_2eq/kg protein, Medium = 41 – 69 kg CO_2eq/kg protein, High = < 40 kg CO_2eq/kg protein. Data from Herrero et al.[14]

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[16] and Smith *et al.*[8] b) improved digestibility impacts of 10% increased digestibility in all ruminants in the developing world, up-scaling values from Thornton and Herrero[30]. Direct application of this option to developed country situations was assumed to be too small to be considered. c) Data from Hristov *et al.*[26]. 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.*[26]. d) Avoided LUC from transitions from grazing to mixed crop-livestock systems as estimated by Havlik *et al.*[23] e) Animal management practices like improved health, reduced mortality from Hristov *et al.*[26]. Effects applied as c). f) Rangeland rehabilitation mitigation potentials from Conant et al 2002. g) manure management mitigation potentials from Smith *et al.*[8].

Figure 4. Mitigation potentials for carbon sequestration in grasslands through rangeland rehabilitation and grazing management in selected regions and globally[16, 39, 50, 73-81].

Table 1. Global greenhouse gas emissions from livestock (1995-2005)

Emissions source	Emissions (GtCO2eq)	Reference
Feed N_2O	1.3-2.0	Includes N_2O 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 $GtCO_2eq$ [10,14,16,17]
Feed CO_2 – LUC excluded	0.92	16
Feed CO_2 LUC	0.23	16
Pasture expansion CO_2 LUC	0.43	16
Feed CH_4 rice	0.03	16
Enteric CH_4[1]	1.6-2.7	10-14, 16
Manure CH_4[1]	0.2-0.4	10-14, 16
Manure N_2O[1]	0.2-0.5	10-14, 16, 17
Direct Energy CO_2	0.11	16
Embedded Energy CO_2	0.02	16
Post farm gate CO_2	0.023	16
Non-CO_2 emissions[1] **(IPCC guidelines)**	2.0-3.6	
Total emissions (LCA approach) [2]	5.3-7.5	

[1] Livestock emissions according to IPCC emissions guidelines[9]

[2] Range estimated using information from global analyses for key emissions source categories. LCA as implemented by FAO[16]

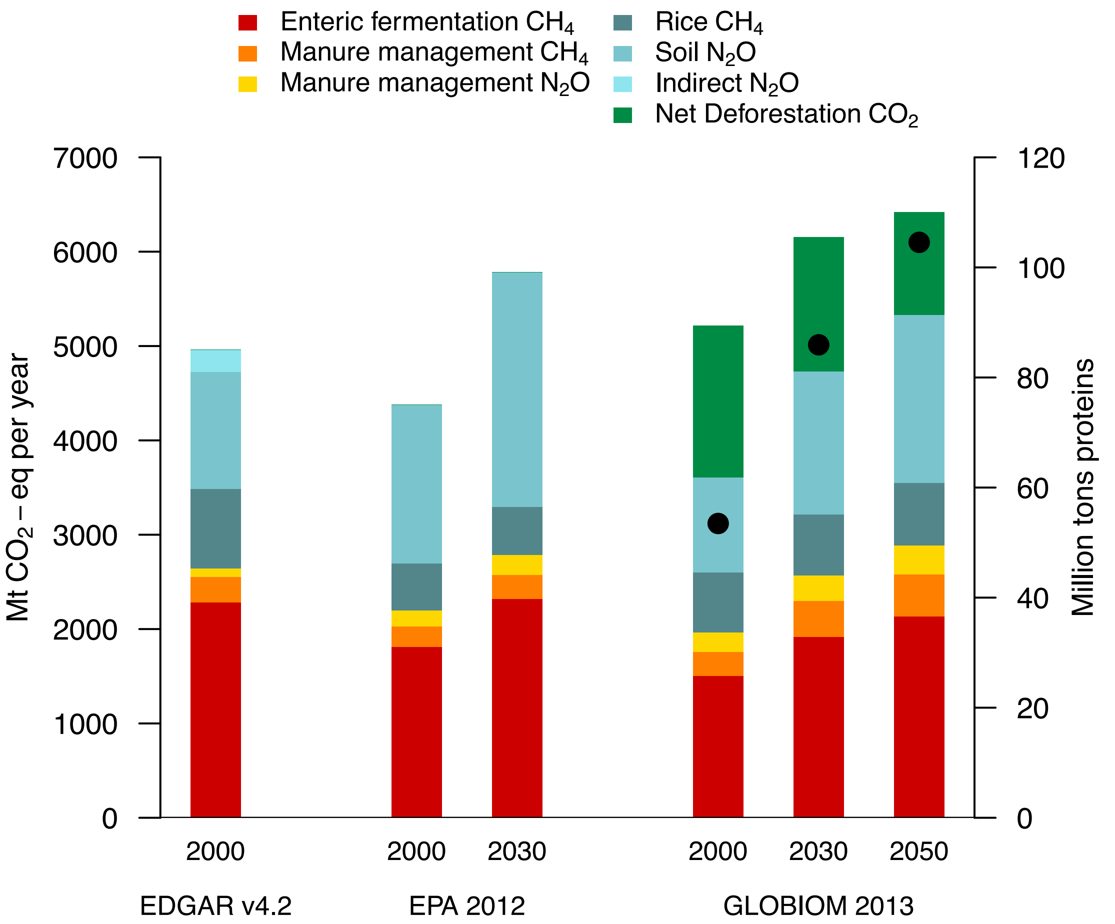

Figure 1. Baseline projections of greenhouse gas emissions for the main IPCC source categories for livestock and agriculture. The baseline projection represents a continuation of the current livestock product demand trends (black dots, converted to edible animal protein, all livestock products) Source: Edgar v4.2[10], EPA 2012[21], Globiom 2013[23].

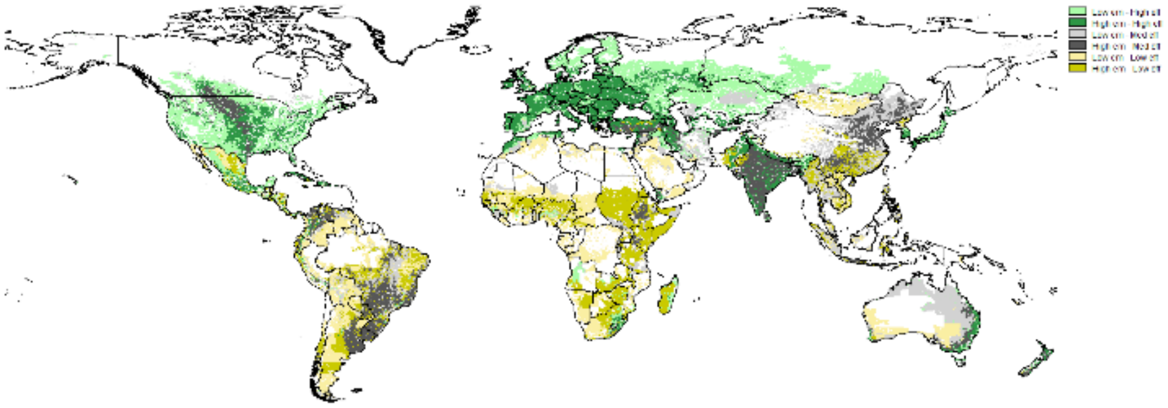

Figure 2. GHG emissions from ruminant livestock and emissions intensities per kg of protein from ruminant source foods (meat and milk combined). High Emissions = > 20 thousand kgCO_2eq/km2, Emissions intensities = Low = > 70 kg CO_2eq/kg protein, Medium = 41 – 69 kg CO_2eq/kg protein, High = < 40 kg CO_2eq/kg protein. Data from Herrero et al.[14]

We will submit a high quality figure in due course

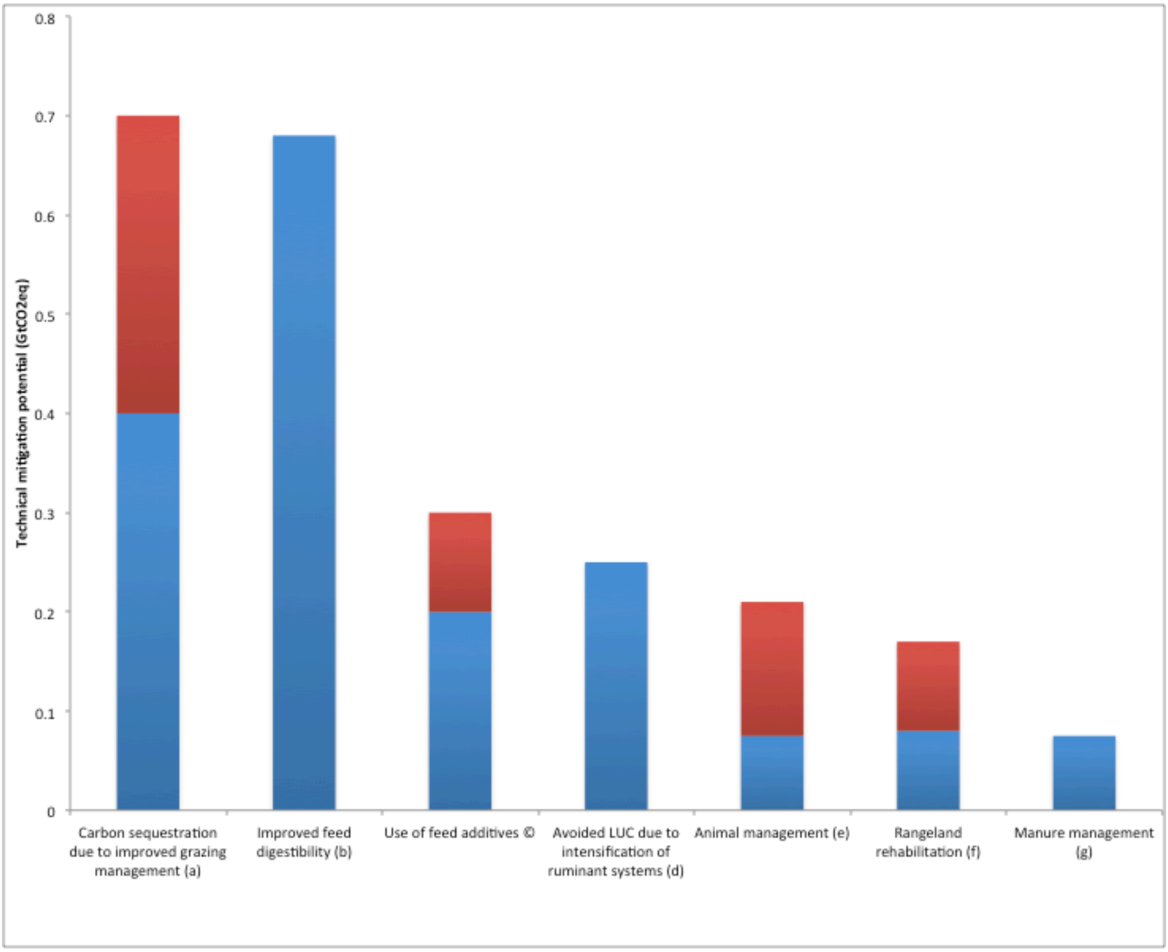

Figure 3. Technical mitigation potentials of supply-side options for reducing emissions from the livestock sector. Red parts represent the range for each practice. a) range defined by FAO[16] and Smith *et al.*[8] b) improved digestibility impacts of 10% increased digestibility in all ruminants in the developing world, up-scaling values from Thornton and Herrero[30]. Direct application of this option to developed country situations was assumed to be too small to be considered. c) Data from Hristov *et al.*[26]. 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.*[26]. d) Avoided LUC from transitions from grazing to mixed crop-livestock systems as estimated by Havlik *et al.*[23] e) Animal management practices like improved health, reduced mortality from Hristov *et al.*[26]. Effects applied as c). f) Rangeland rehabilitation mitigation potentials from Conant et al 2002. g) manure management mitigation potentials from Smith *et al.*[8].

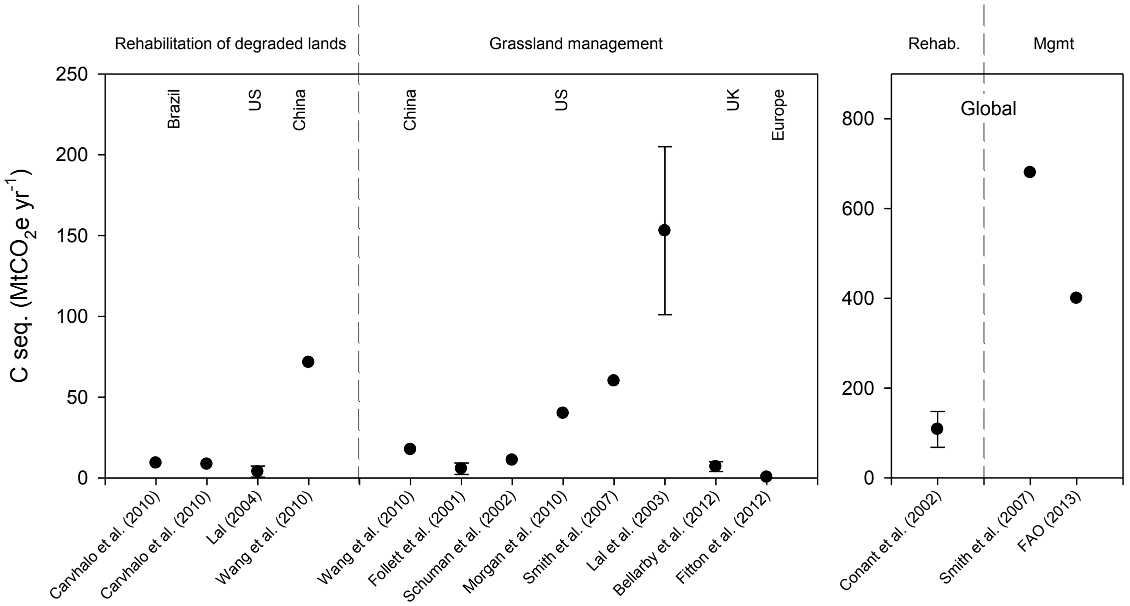

Figure 4. Mitigation potentials for carbon sequestration in grasslands through rangeland rehabilitation and grazing management in selected regions and globally[16, 39, 50, 73-81].