Livestock and the Environment: What Have We Learned in the Past Decade?

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Abstract

The livestock and environment nexus has been the subject of considerable research in the past decade. With a more prosperous and urbanized population projected to grow significantly in the coming decades comes a gargantuan appetite for livestock products. There is growing concern about how to accommodate this increase in demand with a low environmental footprint and without eroding the economic, social, and cultural benefits that livestock provide. Most of the effort has focused on sustainably intensifying livestock systems. Two things have characterized the research on livestock and the environment in the past decade: the development of increasingly disaggregated and sophisticated methods for assessing different types of environmental impacts (climate, water, nutrient cycles, biodiversity, land degradation, deforestation, etc.) and a focus on examining

the technical potential of many options for reducing the environmental footprint of livestock systems. However, the economic or sociocultural feasibility of these options is seldom considered. Now is the time to move this agenda from knowledge to action, toward realizable goals. This will require a better understanding of incentives and constraints for farmers to adopt new practices and the design of novel policies to support transformative changes in the livestock sector. It will also require novel forms of engagement, interaction, and consensus building among stakeholders with enormously diverse objectives. Additionally, we have come to realize that managing the demand trajectories of livestock products must be part of the solution space, and this is an increasingly important research area for simultaneously achieving positive health and environmental outcomes.

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1. INTRODUCTION

The past decade has produced a significant body of research on livestock and the environment, mainly driven by two events. First, we recognize that the livestock sector is large, increasingly competes for resources, and causes widespread environmental pressures in many parts of the world (1, 2). This topic was comprehensively addressed by the Food and Agriculture Organization (FAO) in their highly influential *Livestock's Long Shadow* (3), which has set the stage and provided impetus for a lot of subsequent work. Although it was light on the positive impacts of livestock, it set the benchmark for improving the estimates of environmental impacts by livestock. Second, given increased consumption of animal source food (ASF) caused by human population growth, increasing incomes, and urbanization over the past 50 years at least, the sector has been growing at an accelerated rate, and it is expected to continue growing. This phenomenon is often termed the Livestock Revolution (4).

How to achieve this growth with a lower environmental footprint, without sacrificing the livelihood and economic benefits that livestock bring, has dominated the agendas of those aiming at designing more sustainable patterns of global food supply and demand. Traditionally, most efforts were concentrated on increasing productivity per animal and/or per hectare. The goal then shifted toward sustainable intensification, that is, reducing impacts per unit of animal product generated, which came to dominate the agenda (5). More recently, our perspectives on the solution space for sustainably feeding the world have expanded (6). There is widespread acknowledgment that waste reduction could play a significant role (7). Additionally, movement of the food security agenda toward nutritional security has seen reductions in livestock consumption by some age groups of the human population as an attractive option for the joint delivery of health and environmental benefits (5).

This article reviews the major advances on livestock and the environment in the past five to eight years. It provides a brief account of resource use by livestock (for land, biomass, nitrogen, and water), climate change adaptation, and mitigation challenges for the livestock sector. We discuss options for reducing the environmental footprint of livestock and provide guidance for building a responsive research agenda on this topic for the coming years.

2. A BRIEF OVERVIEW OF THE DEMAND AND SUPPLY DYNAMICS FOR LIVESTOCK PRODUCTS

Any synthesis of livestock and the environment needs to be elaborated in the context of the past and future trends of global food consumption and its dynamics. **Table 1** presents information on patterns of food demand for different food groups to 2050 (8).

The key characteristics of these patterns are (*a*) higher overall consumption of food per capita in the developed world; (*b*) large consumption gaps in meat and milk between the developed and the developing world; (*c*) significant increases in meat and milk consumption, mostly in the developing world, which although growing at a faster rate, will not reach even half of the consumption levels of the developed world by 2050; and (*d*) a stagnation in consumption of cereals and tubers both regionally and globally. These per capita consumption transitions toward higher ASF are rapidly continuing due to increased incomes, urbanization, and changes in the retail structure serving urban markets such as more supermarkets and more processed foods as indicated by increases in sugar consumption and oils, for example.

If we consider these numbers together with projected increases in human population to 2050, we can estimate gross increases in meat and milk demand in the order of 70 to 80% of current levels. This is consistent across several forward-looking assessments (8, 9).

What is the structure of the supply of livestock products? The demand for livestock products is met by very heterogeneous productions systems, with different levels of intensification, in varied agroecological zones and in many cases with different production objectives. Recent global data (10) suggest that most poultry products and pig meat are produced in industrial systems (more than 75% of global production), but with smallholders still contributing large shares in places such as Africa, South Asia, and parts of Southeast Asia, where the shares can be between 40% and 55%. Mixed crop-livestock systems produce the bulk of ruminant products globally (69% of milk and 61% of meat, respectively), and grazing systems contribute significantly to the production of cattle meat (Latin America, Oceania) and small ruminant meat (1, 10).

3. RESOURCE USE AND EFFICIENCY

3.1. Use of Land and Other Physical Resources in Livestock Systems: An Overview

Table 2 presents aggregate numbers on some of the most important physical resources used in livestock production; **Figure 1** places the livestock sector in the broader context of the land use and

Table 1 Per capita food demand: historical and projected values to 2050 (8)

Kg/person/year	1969/1971	1979/1981	1989/1991	2005/2007	2030	2050
World						
Cereals, food	144	153	161	158	160	160
Cereals, all uses	304	325	321	314	329	330
Roots and tubers	84	74	66	68	73	77
Sugar and sugar crops (raw sugar eq.)	22	23	22	22	24	25
Pulses, dry	7.6	6.5	6.2	6.1	6.6	7.0
Vegetable oils, oilseeds and products (oil eq.)	7	8	10	12	14	16
Meat (carcass weight)	26	30	33	39	45	49
Milk and dairy, excl. butter (fresh milk eq.)	76	77	77	83	92	99
Other food (kcal/person/day)	194	206	239	294	313	325
Total food (kcal/person/day)	**2,373**	**2,497**	**2,633**	**2,772**	**2,960**	**3,070**
Developing Countries						
Cereals, food	140	152	160	155	159	158
Cereals, all uses	193	219	229	242	254	262
Roots and tubers	79	70	62	66	73	78
(Developing minus China)	62	59	58	64	74	81
Sugar and sugar crops (raw sugar eq.)	15	17	18	19	22	24
Pulses, dry	9.3	7.8	7.3	7.0	7.4	7.7
Vegetable oils, oilseeds and products (oil eq.)	4.9	6.4	8.4	10.1	13.1	15.4
Meat (carcass weight)	11	14	18	28	36	42
(Developing minus China and Brazil)	11	12	13	17	23	30
Milk and dairy, excl. butter (fresh milk eq.)	29	34	38	52	66	76
Other food (kcal/person/day)	115	130	177	253	279	293
Total food (kcal/person/day)	**2,056**	**2,236**	**2,429**	**2,619**	**2,860**	**3,000**
Developed Countries						
Cereals, food	155	156	162	167	166	166
Cereals, all uses	571	620	618	591	682	695
Roots and tubers	96	84	78	77	73	72
Sugar and sugar crops (raw sugar eq.)	41	40	36	34	33	33
Pulses, dry	3.6	2.9	2.9	2.9	3.0	3.1
Vegetable oils, oilseeds and products (oil eq.)	11	14	16	19	20	21
Meat (carcass weight)	63	74	80	80	87	91
Milk and dairy, excl. butter (fresh milk eq.)	189	195	201	202	215	222
Other food (kcal/person/day)	492	508	498	458	488	509
Total food (kcal/person/day)	**3,138**	**3,222**	**3,288**	**3,360**	**3,430**	**3,490**

biomass flows of the entire food system. Globally, livestock uses ∼3,900 million ha of land, which is ∼80% of all agricultural land combined. The quality of this land and the intensity in which it is used vary enormously, with most of it being used by extensive, grazing-based ruminant systems.

With the exception of land, these grazing-based systems appropriate relatively little of most other crucial resources such as nitrogen and water. Grazing-based systems contribute very little to the human food supply globally, accounting for less than 1% of its edible energy; however, these systems do make critically important contributions to livelihoods and sociocultural interactions.

Table 2 Use of key physical resources and production in global livestock sectors (circa 2000)[a,b]

	Ruminant meat			Dairy			Pigs and poultry	
	Grazing	Mixed[c]	All	Grazing	Mixed[c]	All	All	All
	Total	Total	Per protein	Total	Total	Per protein	Total	Per protein
Land (million ha, ha/Mg protein)[d]								
Cropland (arable land)	8.0	80	9	2.0	130	6	280	10
Permanent grassland	1 600	800	240	560	400	50	NA	NA
Biomass (Tg DM year^{-1}, kg DM/kg protein)[d]								
All feed	610	2,200	280	180	1,200	60	880	30
Grains	24	130	NA	4.6	170	NA	880	NA
Grasses and legumes	500	1,200	NA	170	620	NA	NA	NA
Straw and stover	6.9	400	NA	1.6	230	NA	NA	NA
Other	81	410	NA	12	140	NA	NA	NA
Nitrogen (Tg N year^{-1}, kg N/kg protein)[e]								
Nitrogen in feed	12	38	5	3.6	21	1	26	1
Water (Pg year^{-1}, Mg/kg protein)[f]								
Blue water	5.1	33	4	2.3	51	3	65	2
Green water	220	620	80	45	460	20	590	20
Meat, dairy, and egg production[g]								
Energy (PJ ME year^{-1})	90	440	NA	120	1 600	NA	1 600	NA
Edible protein (Tg year^{-1})	1.7	8.4	NA	1.5	19	NA	28	NA

Abbreviations: ME, metabolizable energy; N, nitrogen; NA, not available; PJ, petajoule.
[a]Use per unit of edible-protein output is shown as an indicator of resource-use efficiency.
[b]The numbers are rounded to two significant digits (one digit for most numbers on resource use per protein); resource use by predominantly draft-work livestock (horses, mules, camels) is insignificant at the global scale and is, as such, ignored here.
[c]These numbers include landless systems, as well.
[d]Estimates are provided by References 10, 15, and 16.
[e]The data represent estimated levels of nitrogen in feed intake.
[f]This is the water "footprint" estimated from Reference 101.
[g]The data are provided by Reference 10.

Most of the global ruminant (beef, lamb, goat, and dairy) output comes from mixed systems in which there is a significant use of cropland-produced feeds such as grains, hay, and silage. Although these feed types amount to small fractions of average rations, the overall lower feed conversion efficiencies of ruminant systems (see below) make them substantial when compared to the systems' output. On average globally, cropland use per unit of protein output in mixed ruminant meat (beef, lamb, etc.) systems is similar to that of pork and poultry (**Table 2**). In regions dominated by intensive systems such as Europe, beef systems' cropland use per amount of protein produced is several times higher than even that of pork and poultry (11). This contrasts with the commonly held notion (12, 13) that beef does not subtract from global food supply because it uses only inedible feed and/or land with no or little alternative value for food production. As is evident from **Table 2**, ruminant meat supply relies on cropland, nitrogen, and water resources to approximately the same extent as pork and poultry, per unit of output globally, and thus places equivalent pressure on edible plant production resources.

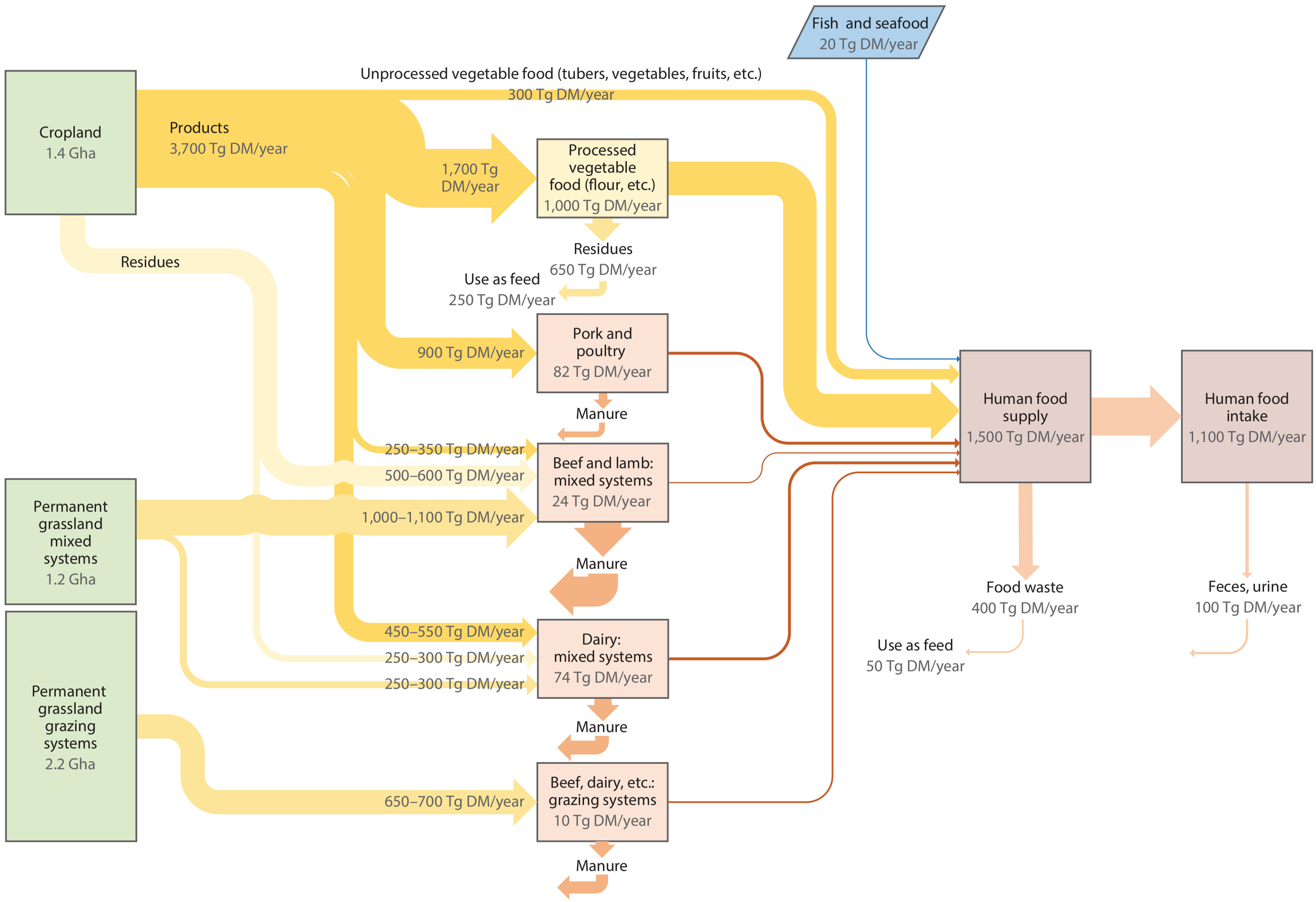

Figure 1

Land use and major flows of biomass and its derivatives in the global food and agriculture system (circa 2000). For simplicity, minor feed use flows and manure recycling to fields are not shown; excluded also are all gaseous flows (CO_2, CH_4, etc.). Figure adapted from Refs. 11, 16, and 17. Abbreviations: DM, dry matter; Gha, giga hectares; Tg, teragrams.

3.2. Resource-Use Efficiency in Livestock Systems: A Key Dimension

Assessing the efficiency with which livestock systems transform physical resources into food and other products is essential, not only from a productivity measurement perspective but also because low resource-use efficiency is often linked to high environmental impacts. For example, low efficiency in the utilization of nitrogen is closely correlated with high emissions of nitrous oxide, ammonia, and nitrate (14).

Due to the nature of the resource use, several efficiency concepts are needed to realistically portray the multifaceted nature of the physical efficiency of livestock systems. Feed conversion efficiency is a key concept, given that it directly relates to the principal process of livestock production: the conversion of plant mass into animal mass. Also, given feed is by far the dominating physical flow (in energy terms) in livestock systems, feed conversion efficiencies correlate fairly well to a system's overall efficiency in the use of the often-scarce photosynthetic resources, land, plant nutrients, and water. This is evident from the aggregated efficiencies given in **Table 2** (expressed as use per kilograms of protein produced), where differences between the three sectors in efficiency in the use of land, nitrogen, and water correlate relatively well with that of feed.

Because of variations in physical and economic conditions across regions and differences in species-specific lifecycle properties, feed conversion efficiencies vary widely. Measured as the amount of edible metabolizable energy in product per amount of total energy (gross energy) in feed, regional averages amount to 0.3–2% for beef and lamb, 2–15% for dairy, and 5–15% for pork and poultry (10, 15, 16). Current global averages are roughly 1% for ruminant meat, 7% for dairy, and 10% for pork and poultry (10).

In addition to large differences in site-specific conditions, methodological challenges and lack of detailed data add substantial noise to any estimates of feed efficiency at regional and global levels. One example of this is given in **Figure 2**, which shows beef efficiency estimates from three separate global analyses. From the relatively small differences in global averages, it is obvious that part of the variance at regional levels is due to differences between the studies in regional definitions and in the definition of production systems. Some variation is also due to differences in model types, modeling design, and data sets. This is an area that requires better and more disaggregated data to reduce the uncertainty of the estimates.

The inherent low feed efficiency of ruminant meat is mainly due to the comparatively low reproductive rates of cattle, sheep, and goats. A healthy cow gives birth to one calf per year (a female sheep/goat, two offspring), whereas a sow typically produces 20–25 piglets per year and a hen 100+ chicks per year. For ruminant meat, many more adult females are therefore needed per meat output compared to pork and chicken, which means that the overhead of feed required for adult, nongrowing animals is far higher for beef and lamb. In addition, potential animal growth rates relative to liveweight are lower for cattle and sheep than for pork and poultry. In feed efficiency terms, this is a disadvantage because the lower the growth rate, the larger the fraction of feed energy that is expended on maintenance metabolism instead of growth (17).

Although feed efficiencies correlate with efficiencies in the use of photosynthetic resources, large spatial heterogeneity (for example, in land use intensity and the opportunity cost of land for ecosystem and human services) limits their relevance for more detailed analysis. More detailed efficiency concepts are needed that specifically address the photosynthetic resources and, ideally, their ecological and economic opportunity costs.

Van Zanten et al. (18), for example, developed a new land use ratio (LUR) concept, defined as the maximum amount of human digestible protein (HDP) derived from food crops on all land used to cultivate feed required to produce 1 kg ASF over the amount of HDP in that 1 kg ASF. They illustrated this new concept for three case systems: laying hens, dairy farming on peat soils

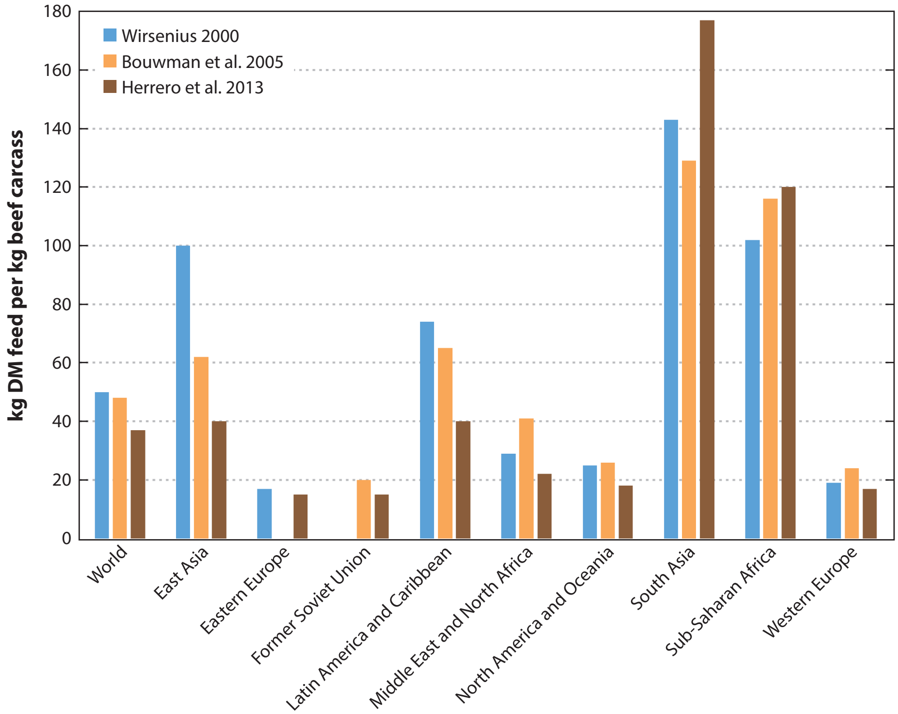

Figure 2

Comparison of feed efficiency estimates for beef [in kilograms of dry matter (DM) of feed per kilogram of fresh carcass] in studies by Wirsenius (16), Bouwman et al. (15), and Herrero et al. (10). Numbers refer to the efficiency of aggregate beef output from single-purpose beef cattle systems and dairy cattle bulls.

(i.e., low opportunity costs for food crops) and dairy farming on sandy soils. For dairy cows, the LUR was 2.10 when kept on sandy soils, and 0.67 when kept on peat soils. A value of 2 implies that all land required to produce 1 kg HDP from dairy cows on sand would yield approximately twice as much HDP if used directly to cultivate human food crops. In terms of food security, therefore, dairy cows on peat have a higher land efficiency than dairy cows on sand, whereas the feed conversion ratio (i.e., kilogram of dry matter in feed per kilogram of product) appeared higher for cows on peat (0.91) than for cows on sand (0.77).

Another example is new-fixed nitrogen and how its efficiency is linked to that of land (**Figure 3**). New-fixed nitrogen represents the net input of reactive nitrogen to the system, mainly through fertilizer application and biological fixation. New-fixed nitrogen per unit of output is a better indicator of the nitrogen efficiency of livestock systems than most other concepts, given it factors in the efficiency by which nitrogen in manure and soil organic matter is utilized in feed production (19). Furthermore, any input of new-fixed nitrogen contributes to the downstream cascade of emissions of reactive nitrogen species (20), which means that new-fixed nitrogen efficiency is also an indicator of the potential environmental impact from nitrogen effluence.

The large differences between beef and other systems in **Figure 3** are mainly related to the patterns of feed conversion efficiencies described above. However, given beef systems rely largely on perennial grass crops, which in general have much lower nitrogen losses than most annual crops (see below), the inferiority of beef in terms of new-fixed-nitrogen efficiency is slightly less compared with that of feed conversion efficiency. Also, beef production tends to occur on land

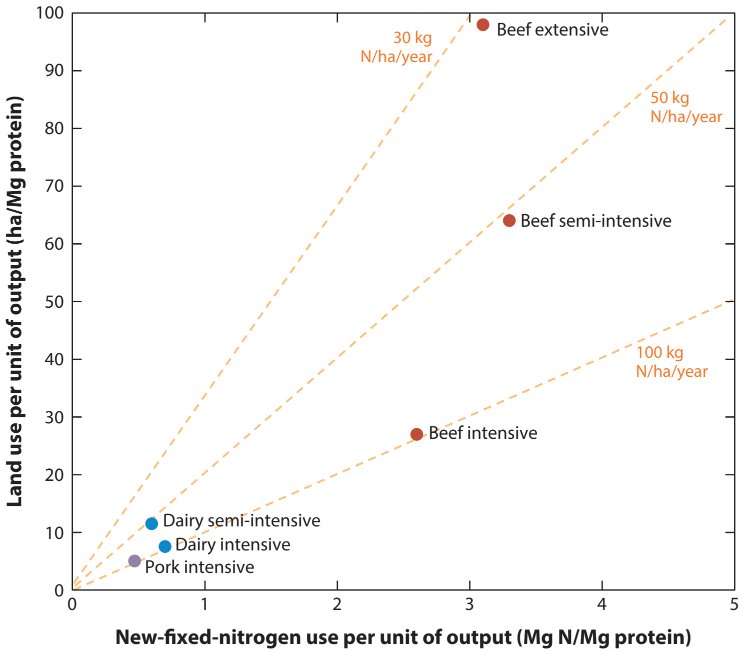

Figure 3

Efficiency of land and new-fixed-nitrogen (N) use in different livestock systems of varying intensity. These data refer to specific regions/farms, and under different conditions, numbers can deviate significantly from those presented here. Dashed lines represent the equivalent new-fixed-N flux on land at 30, 50, and 100 kg N/ha/year and correlate to the intensity in the plant subsystems (i.e., feed production). Author calculations based on data in Refs. 102–105.

with lower opportunity costs, which means that often the economic and ecological cost of land use for beef is typically not as high as its physical land area.

Differences between intensive dairy and pork systems are generally small in absolute terms and are likely to be within the range of influence of site-specific conditions and technology and management choices. However, under similar conditions, pork systems tend to be more land and nitrogen efficient because of the relatively high feed cost in dairy systems of producing the replacement heifer (i.e., the female calf that is reared for replacing the dairy cow).

In **Figure 3**, we plot land use efficiency against that of new-fixed nitrogen as a means of illustrating to what extent these two resources substitute for each other when moving between different levels of intensity. Although such substitution generally is characteristic of the feed-producing plant subsystem (because lower intensities and yields in plant production typically are associated with lower relative nitrogen losses), it is not necessarily so for the entire livestock system. **Figure 3** illustrates this with its examples for beef and dairy, where despite the lower land use efficiencies of the less intensive systems—owing largely to their lower intensity in plant production (compare the iso-nitrogen-flux lines)—the nitrogen efficiencies do not rise consistently. This is because in less intensive beef and dairy systems, some factors, in particular lower feed conversion efficiency in the animal subsystem, counteract the higher new-fixed-nitrogen efficiency related to low intensity in the plant subsystem.

An even more important feature, however, than low feed production intensity that contributes to high new-fixed-nitrogen efficiency of extensive ruminant systems is their greater reliance of perennial grass crops. Such crops have densely developed root systems, whereas the uptake efficiency of plant-available nitrogen is very high and, under normal conditions, little nitrogen is lost through leaching below the root zone (21). Furthermore, being permanent or semipermanent, these crop systems are more efficient than annual crops in the reuse of soil organic nitrogen that originates from the previous growing seasons (21).

However, perennial grass systems are not entirely closed with respect to nitrogen, and there are significant, inevitable gaseous losses, such as ammonia. Although these combined losses are small as a fraction of total nitrogen turnover in the soil-plant system (~5–10%), they are scaled up to a larger proportion relative to the systems' output because of their inferior performance relative to intensive systems in other respects. First, feed conversion efficiencies are generally lower in extensive systems because of poorer herd performance in terms of reproduction rates, milk yield, and weight gain rates. Second, utilization efficiency of produced plant mass as feed is lower in extensive systems because of their reliance on grazing, which under good conditions utilizes 50–60% of above-ground production, compared to ~80% in the case of (mechanized) cutting.

3.3. Water: Concepts and Usage in Livestock Systems

Fresh water is essential for livestock production; it is used for meeting the drinking and cooling needs of animals, for cleaning services (e.g., washing animals, cleaning housing facilities), for processing of livestock products and for the cultivation of feed (23).

To understand freshwater use along global livestock supply chains and their associated environmental impacts, we have to distinguish between so-called green and blue water. Green water refers to precipitation on land that does not run off or recharge an aquifer and is stored in the upper part of the rooted soil or temporarily stays on top of vegetation. This part of precipitation can eventually evaporate or transpire through soils and crops or can be embodied in crop material (23, 24). Blue water use is also referred to as consumptive water use. Water is considered consumptive if it is withdrawn from a watershed and not discharged into that same watershed, because it evaporates, is embodied in plant or animal product, or is discharged into another watershed (25). These definitions of green and blue water clearly demonstrate that green and blue water flows are not independent but interact spatially and geographically (22).

Fresh water used for drinking, cooling, cleaning, and processing is blue water, whereas fresh water used for cultivation of feed crops can include both green water (rainfall) and blue water (irrigation). At a global scale, livestock uses ~10% of the global annual rainfall (including green and blue water), which is ~25–32% of the total agricultural water use (3, 23, 26). Blue water used by livestock for drinking, servicing, and processing contributes only 0.2% to the total water use of livestock production. Almost all fresh water used in livestock production, therefore, is related to cultivation of feed. The majority of the fresh water currently used during the cultivation of feed crops, however, is green water (3, 22). Although exact estimates of the share of green and blue water used during the cultivation of feed crops are missing, irrigation of feed crops is currently assumed to be of minor importance at a global scale (3, 22).

The environmental impacts associated with the current production of ASF, therefore, are associated mainly with blue water use. Although it is relevant to quantify the green water use during cultivation of feed crops as it yields insight into the efficiency of using rainwater, it is not clear if there is an environmental impact associated with green water use. In cases in which green water would not have evaporated or transpired by grassland or cultivated maize land, the natural ecosystem might evapotranspire the same amount of green water (27). Green water use, therefore, does not generally have an impact on the environment. Only changes in land use or management (deforestation, ploughing grassland) or land degradation (such as from overgrazing) might affect the environment, because these processes affect the partitioning between green and blue water. At present, however, insights into changes in water partitioning from changes in land use or management and land degradation are missing. Insight into green water evapotranspired during feed cultivation, furthermore, might be valuable from the perspective of food security. In situations in which grassland is also suitable for cultivation of food crops production, the available green water may be used more efficiently for cultivation of food crops for humans (18).

Finally, the amount of blue water use in livestock production, especially irrigation water for cultivation of feed crops, is expected to rise, because of the increasing demand for ASF. Blue water use can have an impact on human health and ecosystem quality and can result in depletion of water resources. The environmental impact of blue water use, however, is very site specific and varies across seasons (28).

Studies that assess and compare water use in livestock production systems, therefore, should report both green and blue water use, distinguish between green water used on land suitable and unsuitable for cultivation of feed crops, and assess the site- and seasonal-specific impact of blue water use. At present, such assessments are lacking, which hinders a sound comparison of different livestock production systems and potential improvement options. In theory, however, ruminant systems have the potential to be highly water efficient in situations where they use efficiently land that is less suitable for crop production that is not irrigated, and where sustainable grazing management is applied. The use of irrigation water to increase grass or forage productivity is only sustainable in regions with low water scarcity. Water use efficiency in monogastric systems can be improved by increasing the proportion of by-products from human food production that are nonedible for humans, especially if these feed ingredients are cultivated with efficient use of rainwater or with additional irrigation in regions with low water scarcity.

4. LIVESTOCK AND CLIMATE CHANGE

4.1. Climate Impacts and Adaptation

The impacts of climate change on livestock systems have not received as much attention as those of crops. Thornton et al. (29) reviewed the major relevant biological impacts. Their documented impacts included (*a*) effects on the quantity and quality of feeds; (*b*) heat stress on animals; (*c*) water stress on animals and crops; (*d*) likely changes in distributions and increased prevalence and intensity of livestock diseases, e.g., the spread of bluetongue virus (sheep) across Europe (through increased seasonal activity of the Culicoides vector), the amplification of gastrointestinal parasites, and the spreading of ticks (responsible for Lyme disease and tickborne encephalitis) towards higher altitudes and latitudes (30; see **http://www.ipcc.ch/report/ar5/wg2/**); and (*e*) biodiversity losses. **Table 3** summarizes some of these impacts.

Adaptation options have been classified in several ways, such as the level at which each option operates and the pathway taken (31), and the time horizon that is being considered (32). Particularly, a classification has been proposed distinguishing between incremental, systemic, and transformational adaptations (**Table 3**). Incremental adaptations correspond to progressive technical improvements (feeding, grazing management, etc.). Systemic adaptations correspond to reconfigurations of farming systems. At the household level, four basic strategies in relation to incremental and systemic adaptation and mitigation options can be considered (33): (*a*) intensification of existing patterns of production; (*b*) diversification of production and processing; (*c*) extensification of existing or modified patterns of production; and (*d*) better risk management, that is, options designed expressly to address production and/or financial risk,

Table 3 Climate change impacts, adaptation options, and knowledge gaps in livestock systems

Climate change impacts		Adaptation options	Knowledge gaps
Specific impacts on crop, livestock and feed	**Quantity/quality of feed** (34):	**Incremental adaptation:**	**Rangelands:**
	Reduced grass or stover availability: Lower digestibility and N content of pastures and fodder crops	**Improved feeding:** Diet supplementation, improved grassland fodder species	Primary productivity impacts, species distribution, and change due to CO_2 and other competitive factors
		Grazing management: Adjust stocking densities to feed availability	Estimation of carrying capacities
	Lower grain consumption	Rotational grazing	**Mixed systems:** Localized impacts on primary productivity, harvest indexes, and stover production, and the extent of the problem, in a development context
	Heat stress on animals	**Change livestock breed:** Use of improved and/or stress-tolerant breeds	
		Change livestock species: Stress-tolerant species	
	Water stress on animals and crops	**Change crop varieties:** Higher-yielding, stress-tolerant, dual-purpose varieties	**Surface and groundwater supply, and impacts on livestock, particularly rangeland systems:** Effective ways to increase livestock water productivity
		Change crops: Increased use of dryland crops from cereals to tubers (i.e., cassava)	
		Use of perennial crops	
		Crop management: Modify planting dates, using multi-crop varieties with different times to maturity	
		Water-use efficiency and management: Irrigation to maximize water use	
		Modify cropping calendar	
Farm level	**Loss of income/household food security** (34, 52): Reductions in cash flows	**Incremental and Systemic:** **Weather-index insurance:** For crops and livestock	**Localized impacts on livelihoods and how systems will evolve in future**: Magnitude and effects of systems changes on ecosystem goods and services
		Use of weather information: To modify crops and for livestock management	

(*Continued*)

Table 3 (*Continued*)

Climate change impacts		Adaptation options	Knowledge gaps
	Less food available or for sale **Compromised children nutritional status**	**Alter integration within the system:** With the addition/deletion of enterprises within the farming system, changing the ratio of crops to livestock and/or the ratio of crops to pasture, or the addition of trees/shrubs	
Issues at regional level	**Four dimensions of regional food security: food availability, access, utilization, and their stability at the regional level** **Loss of biodiversity through habitat and landscape change (44):** Changes in distributions of livestock diseases Increased prevalence and intensity	**Systemic and transformational:** **Livestock farming system transition:** Place transformation and locations shift **Dietary shifts:** Substituting a proportion of maize meal in the diet for sorghum and/or millet meal **Food processing and storage:** More efficient to reduce postharvest losses and waste and added value at the farm gate **Change livestock breed and/or species:** Resistant breed and/or species **Change in farming systems:** From grazing systems to mixed systems **Increases in industrial systems** **More diversified production systems**	**Interactions between climate change, well-informed socioeconomic scenarios, and the evolution of farming systems at several scales:** Reconciling growing demand for food in the South and stagnating demand in the North from a nutritional security perspective **Ecological biodiversity:** The potential effects of a change in systems on the numbers of species **Animal breed biodiversity:** Specifying the genetic resources of an animal that could be useful in the future How the prevalence and intensity of key epizootic livestock diseases can change in the future How climate change can affect diseases as systems intensify

Table adapted from Reference 29, with updates from Reference 34.

through, e.g., using climatic or market-related information to help make crop and livestock management decisions. A great variety of possible adaptive responses related to one or more of these main farm strategies is available for different production systems globally (see Ref. 34 for options for mixed crop-livestock systems in developing countries). The list of available options is also continuously evolving and expanding (**Table 3**). Examples of emerging or growing research areas are the genetic selection of robust animals (35), and adaptive management of resource redundancies and diversity at farm level (36). To identify appropriate adaptation options, trade-offs with mitigation potential and food security need to be considered (34), together with institutional constraints and the three dimensions of sustainability (economic, environmental, and social).

An emerging challenge in recent years has been to move toward integrated frameworks considering timeframes and uncertainties associated with climate change, with the aim of better informing adaptation planning. Given that livestock systems are highly dynamic, the most appropriate options will change throughout time. In this area, a focus has progressively grown around transformational change as an adaptive response to climate change (37–39). In contrast with incremental and systemic adaptations, which have been described as extensions of "what is already being done," Kates et al. (36) identify at least three classes of adaptations as transformational: "(*a*) those that are adopted at a much larger scale or intensity, (*b*) those that are truly new to a particular region or resource system, (*c*) those that transform places and shift locations." As incremental adaptations, transformational changes can be autonomous or planned, responsive, or proactive (35). With the aim of supporting decision making, one major challenge is to study transformational changes in terms of the interaction with the dynamic evolution of farming systems and their socioeconomic context (40, 41), as indicated in knowledge gaps in **Table 3**. Scenario processes are being used as parts of frameworks to understand better transformational responses in the livestock sector (41). According to certain intensification theories (42), most transitions of livestock farming systems (LFS) can be described as dynamic evolutions from pastoral to mixed crop-livestock systems, and then from mixed crop-livestock to industrial systems. The main driver of this trend is human population growth, among other factors such as changes in consumption patterns and urbanization. Some empirical validation exists (43), confirming a particularly high dynamism of LFS transitions in countries with high population growth, where there are huge food security issues at stake. However, in general, there are many other factors that may radically modify these kinds of processes of intensification. Many challenges remain in assessing the impacts of climate change on such systems' transitions, as well as the impacts of ongoing transitions on mitigation potential and other dimensions of sustainable development. As an illustration of the complexity of these linkages, Searchinger et al. (44) found that converting Africa's wet savannahs to cropland would have high carbon and biodiversity costs, contrasting with previous influential studies that asserted that these lands provide a large, low-environmental-cost cropland reserve.

Major methodological advances have been achieved in integrated approaches (see, e.g., 45, 46), but to date these developments mainly have been focused on the environmental impacts of livestock systems (47), and more work on adaptation is needed. Building on previous studies, however, Leclère et al. (48) and Weindl (49) have developed integrated assessment frameworks linking combined general circulation models, global gridded crop models, and global economic models of the agricultural sector with a detailed and wide LFS database. On the basis of such a modeling chain, Weindl has been able to explore the effectiveness of two alternative livestock system transitions (shift to mixed crop-livestock systems or to rangeland systems) as an adaptation strategy with five different climate projections. The results of this study suggest that shifts toward mixed crop-livestock systems could reduce global agricultural adaptation costs from 3% to 0.5% of total production costs, because of higher feeding efficiencies in the mixed systems. Leclère et al. (48) found that transformational changes of agricultural systems would be required in most regions by the 2050s to cope with climate change, and that the nature and extent of the changes required vary across climate change scenarios. They also found that flexibility is the key to achieving cost effective solutions, as maladaptation can be very costly.

Finally, whereas climate change impact studies have tended to focus on progressive changes in climate, it is essential to include a focus on climate variability and climate extremes (47, 50, 51). Without this, the full impacts of climate change on livestock systems are probably being seriously underestimated (50). In a recent review, Thornton et al. (50) identified key knowledge and data gaps in this area. These include the timing and interactions of different climatic stresses on plant growth and development, particularly at higher temperatures, and the impacts of changes in climate variability and extreme events on pest-weed-disease complexes (50). At the farm scale, Van Wijk et al. (52) reviewed diverse modeling tools able to analyze the combined effects of climate variability and change on food production and economic performance. In addition to improving the sensitivity and robustness of crop and animal components of these farm models, three modeling research areas to better tackle the combined effects of climate variability and change are (*a*) decision making and adaptive management (53), (*b*) integration within integrated multiscale frameworks (34), and (*c*) participatory codesign of systemic adaptations (54, 55).

4.2. Greenhouse Gas Emissions and Mitigation

Livestock are a significant source of greenhouse gases globally. Accepted global greenhouse gas (GHG) emissions estimates from 17 billion domestic food-producing animals vary from 8 to 18% of global anthropogenic emissions (1, 56–59), with this range reflecting methodological differences (inventories versus life cycle analysis) and attribution of CO_2 from land use changes (livestock rearing, feed production). These numbers have been the subject of significant debate as regional differences and emissions sources have been contested (60–62). The main sources and types of GHGs from livestock systems include methane production from enteric fermentation and animal manure, CO_2 from land use and its changes, and N_2O from manure and slurry management (1). **Figure 4** shows the spatial distribution of GHG emissions and the associated emissions intensities.

The most important sources of emissions were enteric methane (1.6–2.7 Gt CO_2 eq); N_2O emissions associated with feed production (1.3–2.0 Gt CO_2 eq); and land use for animal feed and pastures, including change in land use ($\sim$1.6 Gt CO_2 eq). Cattle production dominates emissions (65–78%). The developing world contributes 70% of emissions from ruminants and 53% of emissions from monogastrics. Mixed crop-livestock systems dominate livestock emissions (58% of global livestock emissions), while grazing systems contribute 19% (10). Of all processes, feed production is the most important, accounting for 45% of global emissions (1).

In this section we review a range of field-tested and modeled management options for the mitigation of GHG emissions associated with livestock products. These mitigation options include animal-based measures, which target enteric methane as well as methane and nitrous oxide from manure; land-based mitigation measures, which are based on increasing carbon stocks through soil carbon sequestration in grazing lands and from intensification practices that avoid emissions from land use changes (e.g., conversion of forestland to pastureland); and reductions in the human consumption of livestock products.

4.2.1. Animal-based mitigation options.

A description of the various animal-based mitigation options can be found in Gerber et al.'s (63) comprehensive review. In aggregate, these options have the potential to mitigate 0.01–0.5 Gt CO_2 eq/year^{-1}. Owing to its dominant share of animal-based GHG emission sources, most of the mitigation research for livestock has focused on options for reducing enteric methane produced by ruminants (64–66).

4.2.1.1. Feed additives and feed improvements.

A range of feed additives have been assessed in experiments to reduce methane through the manipulation of rumen microbial processes. These additives include chemical compounds such as alternative electron receptors, ionophoric antibiotics, enzymes, and probiotic cultures (63). Although often effective in the short term, these compounds are generally less effective in the long term due to adaptation by the rumen microbial ecosystem. For some of these additives (e.g., ionophoric antibiotics), public acceptance and prohibitive regulations in some countries present additional obstacles for their application. Dietary lipids and nitrates (an electron receptor) appear to be the most promising feed additive options (63).

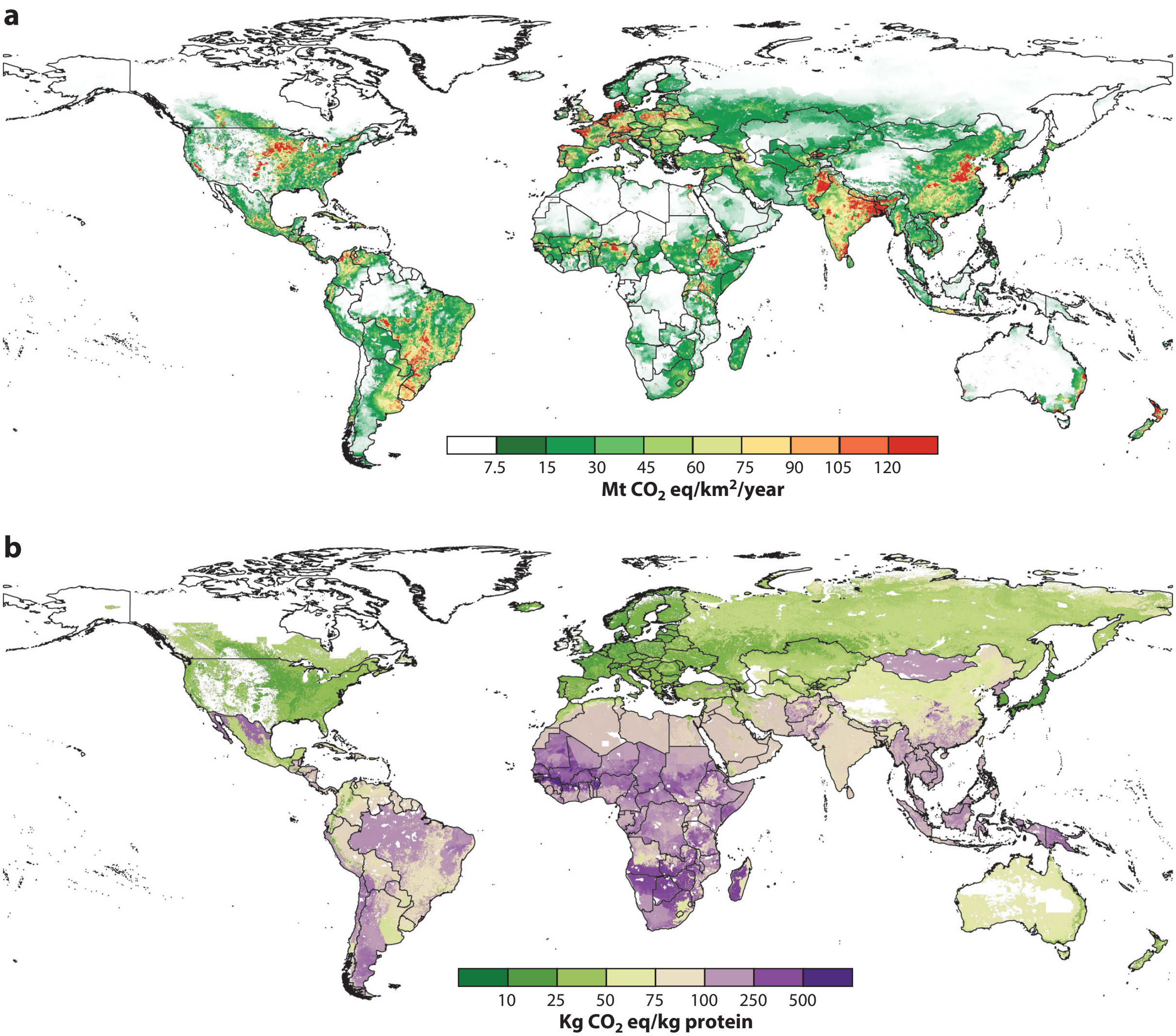

Figure 4

Greenhouse gas emissions (*a*) and emissions intensities (*b*) in global ruminant systems. Figure adapted from Reference 10.

Perhaps the most well-researched approach for mitigating enteric methane per unit of product emission intensity is the provision of higher quality, more digestible livestock feeds. This can lower emissions by improving animal productivity and, by lowering energy lost as methane, will be most effective in the developing countries where feed quality is a pervasive production constraint and productivity gains are needed to improve food security and economic growth in rural areas (67). The digestibility of feed rations can be improved by providing higher quality forages, the inclusion of energy-dense concentrates (e.g., cereal grains), and the processing and treatment of available low-quality feeds (e.g., urea treatment of straws) to improve their nutritional value (68). Because improved feed quality can significantly boost animal productivity, this approach may result in a net increase of emissions, despite substantial reduction in emission intensity. Although it is obviously possible for the sector to deliver the same level of output with fewer but more productive animals, feed improvement options can create incentives for farms to increase their herd sizes to extract higher investment returns (67). These incentives are, for instance, known to occur when farmers invest in pasture improvement (69). We estimate the technical mitigation potential of this option to be 0.68 Gt CO_2 eq year^{-1}, under the assumption of a 10% improvement in the digestibility of animal feed rations and widespread application among developing countries. However, considering economic constraints and the historically low adoption rates of improved feeding practices in developing countries (67, 70), we estimate this potential to fall to 0.12–0.15 Gt CO_2 eq year^{-1}.

4.2.1.2. Animal management. In addition to improved feed quality, there are several animal management options that can also improve animal and herd productivity. These include a combination of genetics, animal health, nutrition, and modern reproductive management to raise reproductive efficiency, reduce the burden of "unproductive" animals in herds, raise the productive lifespan of animals, and reduce mortality rates of calves and adult animals. These measures can reduce the breeding herd overhead and raise the production efficiency at the herd and animal levels, thereby reducing GHG emissions of per unit of product (63). We estimate that improved animal management could mitigate 0.2 Gt CO_2 eq year^{-1} by 2050. As with the feed improvement options, the productivity benefits associated with better animal management could, where profitable, create incentives for an expansion in animal numbers and thereby reduce their overall mitigation effectiveness.

4.2.1.3. Manure management. There are several manure management options available to mitigate emissions of CH_4 and N_2O associated with the handling, storage, and spreading of manures. In situations where manure can be collected and stored, N_2O emissions can be prevented by reducing nitrogen losses to the environment, by using manure storage practices that minimize losses from volatilization and leaching (71). These include simple approaches such as the covering and compacting of manure (72, 73), as well as more sophisticated approaches such as the anaerobic digestion of manure slurries prior to this application to soils. However, the evidence for the anaerobic digestion of manure reducing field-scale emissions is mixed (74, 75). In contrast, this measure has proven to be very effective for reducing manure CH_4 emissions. Nevertheless, this technology is only suitable for relatively confined production systems where wet manure is collected and stored. This is not typical for most of the world's livestock production, where excretion occurs in the field. The highest mitigation potential for manure (0.01–0.07 Gt CO_2 eq year^{-1}) comes from options to lower nitrogen losses to environment when manure applied to soils as a fertility amendment. These losses can be managed through method of application and timing, to better match plant requirements and to avoid heavy rains (76, 77). Nitrification inhibitors also have the potential to lower N_2O emissions in crop and grazing lands (78, 79).

4.2.2. Land-based mitigation options. Carbon sequestration in grazing lands. Improving grazing management, by adjusting grazing pressure to optimize forage production, can help to reverse historical soil carbon losses and build soil carbon stocks. This practice could sequester up to 148 Mt CO_2 eq year^{-1} in the world's grazing lands, with a significant share of this potential (81%) located in developing countries (80). The oversowing of grasses with legumes can also build grazing land carbon stocks. This practice has the potential to sequester up to 203 Mt CO_2 eq year^{-1} globally; however, associated increases in soil N_2O emissions of 57 Mt CO_2 eq year^{-1} are estimated to wipe out 28% of these sequestration benefits (80). The implementation of these practices could be economically attractive in many sites, given that these practices can substantially raise forage productivity (71). However, for many areas within the world's grazing lands, these offsets from nitrous oxide emissions can lead to a negative carbon balance. Therefore, their effectiveness depends fundamentally on being able to identify, a priori, areas that will be amenable to these practices, which would clearly be a great challenge for their large-scale application (80). Furthermore, because these practices generally result in increased forage consumption by ruminants, the implied additional animals and the offsetting impact of their associated emissions would also need to be accounted for.

4.2.2.1. Avoided land use changes due to sustainable intensification. There are a range of sustainable intensification options that can address widespread unsustainable practices within the global food system (81), including both the adoption of new technologies and improving the efficiency of current food production. High-tech options include cloning, genetic modification, and nanotechnology (7, 9, 82), although controversy surrounding some of these practices may continue to rouse resistance from regulators and consumers for some time. A growing number of studies (83, 84) have estimated yield gaps in crop production and the potential food supply benefits from closing these gaps. Such yield improvements could also help to reduce land requirements for both crop and livestock production (63).

Hertel et al. (85) showed that the substantial crop yield increase between 1961 and 2006, associated with the Green Revolution, led to more than a 200% increase in crop production, with only an 11% expansion in the global cropland area. The authors estimated that ~1.3 Gt CO_2 of emissions were avoided from land cover changes that would have otherwise occurred without the crop yield improvements of the Green Revolution. Looking at future land use changes, Havlík et al. (45) computed that maintaining past trends in crop yield growth would prevent the expansion of ~290 Mha of cropland and 120 Mha of grassland by 2030, compared to a baseline of stagnant yield growth. The authors estimate that these avoided land use changes would save more than 2 Gt CO_2 eq year^{-1}, with most of these savings coming from land use changes that would have been at least partly associated with livestock.

4.2.3. Mitigation packages. Introducing single mitigation practices is likely to generate relatively limited mitigation effect. There is growing recognition that significant and cost effective mitigation will require the development of mitigation packages that are adapted to local conditions, and that are adoptable and economically viable. Such packages have been estimated to generate emission intensity reduction ranging between 15 and 40% (1).

4.2.4. Mitigation through managing livestock consumption. Given that the resource-use efficiency of livestock production is low compared to crop production, and that livestock consume approximately one-third of global crop production (3), a shift away from livestock consumption to more crop-oriented human diets could substantially reduce global food resource requirements. For instance, although ~80% of the world's agricultural land is used for grazing or feed and fodder production for livestock (3), meat supplies only 15% of the total energy and 30% protein in the average global human diet. However, many extensively grazed areas would be unsuited to crop production. A handful of studies have explored the emissions and resource implications of lowering the human consumption of meat and other livestock products. Under the extreme case of eliminating the consumption of animal products entirely, Stehfest et al. (86) estimate that required food production in 2050 could be achieved with less agricultural land than is presently used, permitting a substantial increase in forest land and reducing emissions by 7.8 Gt CO_2 eq year^{-1}. More moderate scenarios, such as the removal of ruminant meat from diets and the adoption of a healthy diet (87), resulted in slightly lower mitigation benefits of 5.8 and 4.3 Gt CO_2 eq year^{-1}.

Smith et al. (81) also explored a range of scenarios demonstrating that a shift to more crop-oriented human diets could deliver large benefits, by sparing land for either bioenergy or carbon sequestration through afforestation, resulting in emission reductions of a similar magnitude. Although certainly promising, demand-side mitigation options need to be further investigated. Current studies capture only very imperfectly the indirect effects that massive consumption shifts would have, for example on elements such as land use, household expenditures, agricultural productivity, employment, and others.

5. FROM QUANTIFICATION TO ACTION: A RESEARCH AGENDA ON LIVESTOCK AND THE ENVIRONMENT

Undoubtedly, research on the issues surrounding livestock and the environment in the past decade has been prolific. It has produced vast amounts of information that was not available previously. We know a lot more about livestock now than ten years ago. The research has spanned not only multiple environmental dimensions but has also helped organize the livestock research community around critical issues. However, at the same time, it has in many cases polarized the views surrounding the roles of livestock in the food system.

Two features have dominated this research agenda: the focus on quantifying the impacts of livestock on the environment, and the evaluation of the technical potential of the improved strategies proposed. These have been important and foundational, as many of these impacts had not been robustly quantified before, nor did we have adequate baseline information globally for making decisions on the most appropriate strategies for increasing the sustainability of livestock production in different parts of the world.

Although it is important to refine some of these basic numbers, the agenda now needs to move forward. More effort needs to be focused on developing mechanisms that will create tangible changes and transformations in the livestock sector in a reasonably short timescale (the next 10 years). Most of these are heavily interconnected and are described below.

5.1. From Technical Potential to the Large-Scale Adoption of Key Practices

Many of the practices that could improve environmental performance look good on paper as in many cases they not only reduce environmental footprint, but also increase incomes and food security. The reality is, however, that farmers are not adopting these options at significant rates, and figures of 10–20% of farmers adopting new options over periods of a decade are not uncommon (67). Farmers may not adopt technologies for a host of reasons, which may be related to downside risk, unknown benefits, labor and cash constraints, costs of implementation, increased management needs, lack of fit with farmer objectives and sociocultural norms, and lack of incentives and markets, for example. More importantly, long-term environmental impacts may not be high on farmers' agendas in many cases, but are a cobenefit and not necessarily the key entry point for improving their systems. Studies on farmer behavior, decision-making and environmental and sociocultural perceptions (88) are desperately needed to address this challenge.

5.1.1. Getting the policy framework right. Policies at different levels have a massive role to play in making sure that the incentives and regulations exist for promoting growth of the livestock sector at a lower environmental cost. Most of the work done so far on supply-side policies has been on taxes and subsidies and their potential role in reducing land use changes and emissions (46, 89). It is essential that studies of this kind are taken a step forward toward pilot studies with real cases implementing these strategies to understand better how they work, and for identifying perverse incentives and unexpected impacts on different types of producers, for example.

Policy interventions are also needed on the demand side, in particular in affluent economies, for promoting the sustainable consumption of livestock products. Dietary changes hold a large theoretical potential for mitigating environmental impacts, which has been shown in numerous studies (86, 90–95). However, most of these analyses have been based on purely hypothetical changes in diets, with little consideration to existing constraints, such as consumer preferences, which tend to be conservative. Relatively little is known about the effectiveness of different policy options for guiding diets toward low-impact food, although knowledge may be drawn from health-oriented analyses (96, 97). Price-based policy instruments such as consumption taxes differentiated by impact levels are likely to be essential policy components, as they may be more effective and economically efficient than other options. However, hitherto, very few, and rather limited, studies have been carried out on such options (98, 99), and more comprehensive analyses of the potentials, administrative and social costs, and implementation hurdles of such interventions are needed.

5.1.2. Value chain/stakeholder harmonization. As the livestock sector increases in complexity and sophistication in terms of consumer demands, production methods, sectoral integration, and regulations, improved value chains and communication between stakeholders also become more critical. Understanding the perceptions, incentives, and the political economies of different actors involved in a particular location of the sector could determine whether desired sustainability outcomes are achieved. Public and private sector stakeholders, pressure groups, farmers associations, supermarkets and other retailers, support services, and consumers help shape the way in which we act (or not) with regard to livestock. Consensus and harmonization will be required to develop a viable, credible strategy and to implement an appropriate agenda of action, and multi-stakeholder platforms, such as the Global Agenda for Sustainable Livestock (**http://www.livestockdialogue.org**), have a significant role to play in this.

5.1.3. Multi-currency approaches, beyond single metrics. We know enough about impacts of livestock on individual environmental metrics such as GHG emissions, nitrogen balances, water productivity, etc. However, there is no single best indicator that describes the environmental performance of livestock systems, and there are always trade-offs between them (100); choice of indicator may compromise another key environmental dimension. With our current knowledge, the agenda is mature enough to move to multi-currency frameworks with indicators covering livelihoods, economics, human nutrition, sociocultural function, and a range of environmental metrics.

5.1.4. From single interventions to testing packages of options. Similarly to the above, there are many instances that require the study of packages of interventions, rather than studying them in isolation. It is essential that we quantify the constraints in implementing these potentially more complex practices and weigh them against the additive impacts they might have. Some notion of a household-level or systems-level framework for studying these seems essential, as well as methods for upscaling the potential impacts.

5.1.5. Data consolidation. There is a wealth of information on the environmental impacts of livestock systems. This information needs to be collated, consolidated, and expanded for the benefit of the research community. The study of environmental impacts in livestock systems can be expensive and time consuming, and any effort to share and compare data for subsequent studies would reduce significantly the costs in estimating these metrics and would advance the agendas of those interested in improving the environmental performance of livestock systems.

SUMMARY POINTS

1. The livestock sector is large and growing at an accelerated rate due to the increased demand of a fast-growing and affluent human population for animal products.
2. The contribution of different livestock systems to the supply of livestock products varies widely. Most meat and milk come from mixed crop-livestock production systems and industrial systems. Grazing systems contribute relatively little to food supply globally, but they occupy most of the land and play key social roles, especially in very extensive conditions.
3. Livestock systems emit 8–18% of GHGs and use 25–32% of global fresh water.
4. Livestock systems have vastly different resource-use efficiencies, which in large part drive their environmental performance per unit of product.
5. Mixed crop-livestock systems are the major source of GHGs, but their emissions intensities are usually lower than those of grazing systems. Monogastric systems have the lowest GHG intensities.
6. Large-scale adoption of many intensification technologies that could lead to improved environmental performance remain relatively slow, especially in large parts of the developing world.
7. The livestock and environment agenda of the past 10 years has been dominated by the assessment and quantification of the environmental impacts of livestock. A large body of novel information has been produced, but the design and adoption of practical sustainable solutions remain a considerable challenge.

FUTURE ISSUES

1. Research on the most efficient, equitable, and gender-sensitive pathways for transitioning to more sustainable livestock systems is urgently needed. We understand the current status reasonably well and have an idea of what might constitute a more sustainable system, but we do not know well how to get there.
2. Incentives and other policies for effecting consumption changes of livestock products are urgently needed to ensure that livestock contributes to the sustainable and nutritious diets of different age groups of the human population, and that they are regionally and culturally sensitive.
3. The costs and benefits associated with adopting more environmentally friendly practices, including land use changes, need considerable research. These need to be studied with multidimensional environmental, economic, and social indicators.
4. From a technical standpoint, the study of the impacts of livestock on biodiversity remains a large missing link. This needs to be rectified.
5. We must explore what the impacts are of climate variability and change on the environmental performance of livestock systems.

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