Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems

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We present a unique, biologically consistent, spatially disaggregated global livestock dataset containing information on biomass use, production, feed efficiency, excretion, and greenhouse gas emissions for 28 regions, 8 livestock production systems, 4 animal species (cattle, small ruminants, pigs, and poultry), and 3 livestock products (milk, meat, and eggs). The dataset contains over 50 new global maps containing high-resolution information for understanding the multiple roles (biophysical, economic, social) that livestock can play in different parts of the world. The dataset highlights: (*i*) feed efficiency as a key driver of productivity, resource use, and greenhouse gas emission intensities, with vast differences between production systems and animal products; (*ii*) the importance of grasslands as a global resource, supplying almost 50% of biomass for animals while continuing to be at the epicentre of land conversion processes; and (*iii*) the importance of mixed crop–livestock systems, producing the greater part of animal production (over 60%) in both the developed and the developing world. These data provide critical information for developing targeted, sustainable solutions for the livestock sector and its widely ranging contribution to the global food system.

global change | sustainability | GHG emissions | land use

The importance of the livestock sector as a user of natural resources, as a source of livelihoods, and as an engine of economic growth has been the focus of significant attention in the last decade (1–5). As the largest land-use system on Earth, the livestock sector occupies 30% of the world's ice-free surface, contributes 40% of global agricultural gross domestic product, and provides income for more than 1.3 billion people and nourishment for at least 800 million food-insecure people, all the while using vast areas of rangelands, one-third of the freshwater, and one-third of global cropland as feed. In the process, livestock can both contribute valuable nutrients for crops and be responsible for nutrient pollution and land degradation, and they can both provide critically important protein and micronutrients to human diets and contribute to obesity. The sector has many dualities, and the roles played by livestock change depending on location and circumstances. However, there is growing recognition that improving the environmental performance of livestock systems as well as establishing sustainable levels of consumption of animal-sourced foods, are essential for the sustainability of the global food system (5–7).

Insufficient attention has been paid to the generation of livestock data at the level of detail required for elucidating their future role in attaining key global sustainability goals. Some of these goals are poverty reduction, food and nutritional security, ecosystem protection, mitigation of greenhouse gases (GHG), and adaptation to climate change, for example. To date, global integrated assessments have included incomplete representations, at best, of the livestock sector (8–11). Some global analyses exist (1, 12–16); although these have focused on specific topics, such as biomass use, GHG emissions, and water footprints, they have required methodological simplifications to achieve global coverage. Such analyses fail to do justice to the considerable heterogeneity that exists in livestock production systems, management practices, resource-use efficiencies, and mitigation potentials. Detailed, disaggregated global livestock data are essential for informing policy analyses of the choices facing humanity in feeding the world, managing ecosystems, promoting economic growth, and sustaining the livelihoods of the poor. If the problems are global, the solutions are generally local and highly situation-specific: high-resolution spatially explicit data are critical if targeting of technology and policy to achieve sustainability is to be efficient and effective.

Here we take one step toward filling a critical data gap for global change and sustainability research of the world's food and ecosystems. We are unique in developing and describing a global, biologically consistent, spatially disaggregated dataset on biomass use, productivity, GHG emissions, and key resource-use efficiencies for the livestock sector, broken down into 28 geographical regions, 8 production systems, 4 animal species (cattle, small ruminants, pigs, and poultry), and 3 animal products (milk, meat, and eggs). We analyze the biological consistency of the data and discuss the main drivers of resource-use efficiency in the global livestock sector. We discuss how these data can contribute to the unraveling of key sustainability issues for the sector and conclude with further data and research needs.

Results

We present results using a livestock classification system adapted from Robinson et al. (17). This classification aims to distinguish grazing from mixed crop–livestock systems in arid, humid, and temperate regions, and also account for periurban and other systems. Our results are aggregated to 9 global regions (from 28) to aid clarity: the more developed regions of Europe and Russia (EUR), Oceania (OCE), and North America (NAM), and the

Significance

This report is unique in presenting a high-resolution dataset of biomass use, production, feed efficiencies, and greenhouse gas emissions by global livestock. This information will allow the global-change research community in enhancing our understanding of the sustainability of livestock systems and their role in food security, livelihoods and environmental sustainability.

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developing regions of Southeast Asia (SEA), Eastern Asia (EAS), South Asia (SAS), Latin America and the Caribbean (LAM), sub-Saharan Africa (SSA), and the Middle East-North Africa (MNA). Animal numbers for each species, region, and production system were computed. Details of these procedures are described below and in the *SI Appendix*.

A summary of the spatial layers produced and other information produced are shown in the *SI Appendix*. This information can be obtained by contacting M.H. Below, key aspects of the dataset are summarized.

Global Livestock Production. In 2000 the global livestock sector produced 586 million tons of milk, and 59, 11, 91 and 124 million tons of beef, small ruminant meat, pork, and poultry, respectively (1, 9, 18). Production maps for these commodities are shown in the *SI Appendix*. Our spatially disaggregated estimates suggest that mixed crop–livestock systems produced 69% of the milk (407 million tons) and 61% of the meat (43 million tons) from ruminants, globally (Fig. 1). In both developed and developing regions, these are the most important production systems in terms of ruminant production. Grazing systems have localized importance for the production of beef in LAM (22%) and OCE (55%), small ruminant milk in SSA (56%) and MNA (31%), and small ruminant meat in most regions, where they account for 25–40% of production. The production from grazing systems in the developing world is modest, mostly because of low productivity, low feed availability, and poor quality of feed resources in these predominantly arid regions (with the exceptions of the humid rangelands of LAM). Although the quantities produced might seem small at global level, they play a vital importance in supporting the nutritional security and incomes in pastoral and other extensive livestock systems in these regions (19, 20).

We differentiated between industrial and smallholder systems in relation to the production of pork and poultry meat and eggs (see *SI Appendix* for details). Our estimates suggest that on a global level, industrial systems account for 76–79% of total production of these commodities. These statistics are dominated by the largest producers of these products. These regions include the developed countries of EUR, NAM, and OCE, and regions

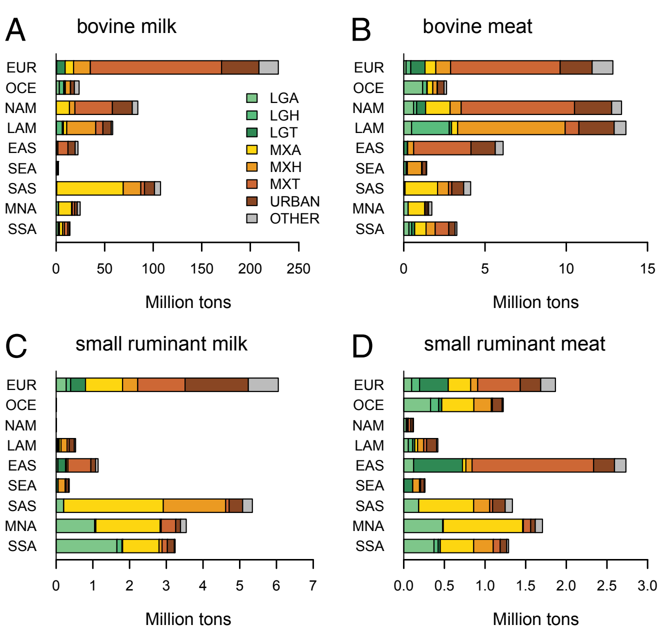

Fig. 1. Global production of meat and milk from ruminants by region and production system. LGA. livestock grazing arid; LGH, livestock grazing humid; LGT, livestock grazing temperate; MXA, mixed arid; MXH, mixed humid; MXT, mixed temperate; OTHER, other systems; URBAN, urban systems.

with significant economic growth, such as EAS (particularly China) and LAM, which account for over 80% of the production of these commodities. Intensification of production and the adoption of industrial practices have occurred in these latter regions, with industrial systems accounting for 70–98% of production. There is considerable heterogeneity between regions, however, with smallholders accounting for 45–80% of production in SEA, SAS, MNA, and SSA (see *SI Appendix* for details), where the majority of resource-poor livestock keepers live (17, 21). Although production levels are modest in these regions, these systems provide important sources of income and nutrition for smallholder producers.

Biomass Use by Livestock. Feed is what links livestock to land use, both directly via grazing and indirectly via traded grain or forage. Here we classify feed into four commonly observed types (22): (*i*) grain, usually fed as concentrates, (*ii*) grass for direct grazing and as silage; (*iii*) occasional feeds, such as cut-and-carry forages and legumes, and roadside grasses; and (*iv*) stovers (fibrous crop residues). We show the amount of these feeds consumed by livestock in different regions for different commodities in Fig. 2. Globally, livestock consumed ~4.7 billion tons of feed biomass in 2000, with ruminants consuming the bulk of feed (3.7 billion tons compared with 1 billion tons by pigs and poultry). Overall, grasses comprise some 48% (2.3 billion tons) of the biomass used by livestock, followed by grains (1.3 billion tons, 28%). Occasional feeds and stovers comprise the rest and are significant sources of feed in certain regions. Occasional feeds are of importance in SAS and LAM, where supplementation with fodder crops is common (23), whereas stovers are a key feed resource in most of the developing regions, comprising sometimes up to 50% of the diet of ruminants in these regions (22–24). Livestock in the developing regions are the main users of grasses, stovers, and occasional feeds (73%, 95%, and 90%, respectively, of the total global consumption of each feed), which is explained by higher ruminant livestock numbers in these regions and the need for obtaining feed from multiple sources. In terms of feed grain, the developing world uses 59% of total grain use, as a result of the significant increases in monogastric production in parts of the developing world over the last 20 y (1, 25).

Different feeds are used for the production of different livestock commodities. Most feed grain (78%) is fed to pigs and poultry in regions where industrial, intensive systems dominate production (EUR, NAM, LAM, and EAS). The rest is used for dairy production in mixed systems globally and for feedlot operations, notably in NAM. Cattle consume 83% of fibrous feeds (grass, occasional feeds, stovers), with over two-thirds of this biomass used for meat production. The remainder is used for dairy production and, in OCE and SSA, for small ruminant meat production.

Feed use differs considerably between livestock production systems (see *SI Appendix* for details). Apart from grains, which are used mostly for industrial monogastric systems, mixed crop-livestock systems—where the majority of ruminant livestock are located (56% of ruminants)—use 59% of all fibrous feeds (3.4 billion tons). There is significant regional heterogeneity in this figure, however, and the predominant mixed crop–livestock system in each region dominates total feed consumption independent of diet quality. At the global level, most feed is consumed in the mixed arid systems (926 million tons).

Grass is a key feed resource for both grazing and mixed crop–livestock systems. Even though the proportion of grass in the diet of ruminants is smaller in mixed crop–livestock systems than in grazing systems, total grass consumption in the mixed crop–livestock systems is higher than in grazing systems (1.097 million tons vs. 583 million tons), because of the larger numbers of animals in these systems. Occasional feeds and stovers are consumed in larger quantities in mixed crop–livestock systems, where stall-feeding is a common practice.

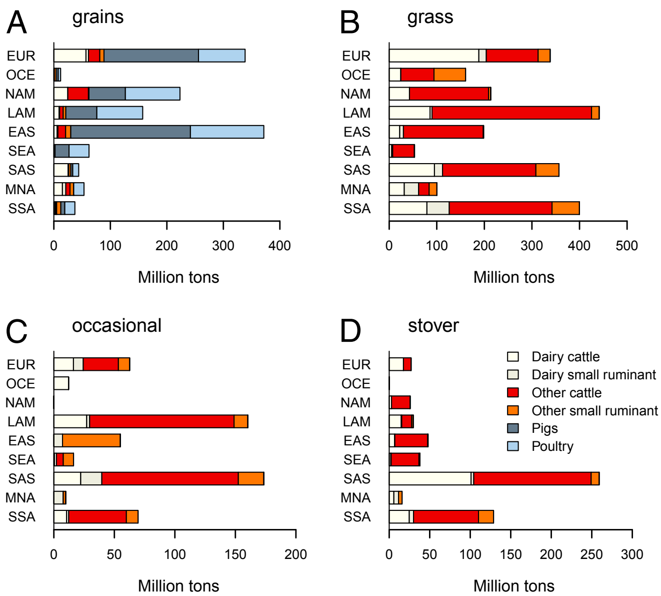

Fig. 2. Regional estimates of global feed consumption by livestock species: (*A*) grains, (*B*) grass, (*C*) occasional feeds, (*D*) stovers (all in million tons of DM). BOVDh, dairy cattle; BOVOh, beef cattle; PIGS and PTRY, poultry; SGTDh, small ruminant dairy; SGTOh, small ruminants for meat.

Diet Quality and Feed-Use Efficiency. Diet composition and quality are key determinants of the productivity and feed-use efficiency of farm animals (26, 27). Together with animal characteristics, such as body weight and physiological state, they largely regulate feed intake, animal productivity, methane emissions, and manure and urine output and composition. Diets for ruminants exhibit considerable variation in composition and quality, mainly explained by agroecology, type of production system, and intensity of production. In general terms, the higher the quality of the diet, the higher the feed efficiency. The amount of metabolizable energy (ME) consumed by ruminants is shown in Fig. 3. Two factors explain the sources of variation in the map. On the one hand, large numbers of animals with low productivity are responsible for hotspots of feed consumption (i.e., India, parts of LAM), whereas in parts of Europe and NAM, this is driven by lesser animals but with higher intakes and productivity. Feed-use efficiencies for meat and milk production by system by region are shown in Fig. 4 (see *SI Appendix* for a detailed description of the diets used). The main factors driving these variations are discussed in the following sections.

Agroecology. Diets in arid areas are typically of lower digestibility and crude protein concentration, and with slower fiber and nitrogen degradation rates than in humid or temperate regions. The result of this is lower ME concentrations [8–9.5 MJ/kg dry matter (DM)] than in humid or temperate areas (9.5–12.5 MJ/kg

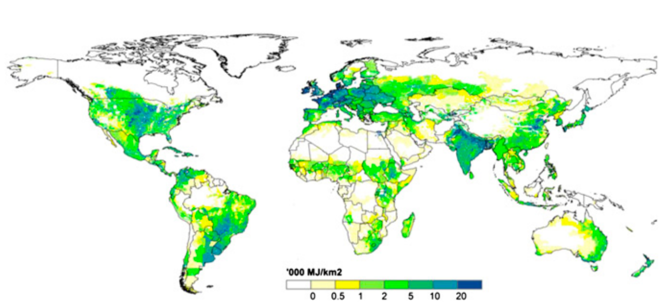

Fig. 3. Map of global ME intake by ruminants (thousands of megajoules per square kilometer).

DM). These lower energy densities led to lower intake and animal productivity, and result in lower feed-use efficiencies (Fig. 4).

Production systems. Livestock in grazing systems consume mostly grass (occasionally with small levels of supplementation), whereas those in mixed systems typically consume a wide array of feeds. In developing regions, most of the feeding practices in mixed systems revolve around grazing, the utilization of cereal stovers and straws, and occasional feeds, such as Napier grass, groundnut hay, and cowpea hay, with limited amounts of grain supplementation, mostly in highland regions. The combination of these feeds usually results in diets of higher quality than those in grazing systems, unless the diet has a high proportion of cereal stovers, which are of lower digestibility. Cereal stovers are not widely used in LAM or in the developed regions. Occasional feeds in LAM and the developed regions are often high quality and nutrient rich, feeds that can be used in small amounts (for example, agroforestry species such as *Calliandra* spp. and *Leucaena* spp., maize silage, lucerne hay, and other components of total mixed rations). The mixed systems in LAM and the developed world exhibit diets with consistently higher ME concentrations (9.5–12.5 MJ ME per kilogram DM) and higher feed efficiencies (Fig. 4) than in the rest of the developing world, with the exception of MNA, where diets in mixed systems are of higher quality because of the widespread use of cheap agroindustrial by-products that permit high levels of their inclusion in ruminant diets.

Intensity of production. The high production potential of livestock and a high level of intensification of production practices, such as increased grain use in the developed world and in some of the highland mixed systems, results in high-quality diets (>10.5 MJ ME per kilogram DM). This finding explains the higher feed-use efficiencies in these regions.

Type of product. The feed efficiency for producing different commodities ranges widely, both between commodities and within the same commodity produced in different circumstances. We find feed efficiencies for the production of animal edible protein from milk to be between 1.5- and 5-times higher than that of protein from ruminant meat for the same agroecological regions. The explanation lies in the efficiency of ME utilization, which is higher for ruminant milk than for meat (26, 27). We find differences within products to be at least as large as between products, when comparing across all systems. For milk and meat, the range of observed feed efficiencies is between 40–400 and 100–2,200 kg DM per kilogram of edible animal protein, respectively (Fig. 4). Smaller ranges were observed for monogastrics in industrial systems (25–140 and 15–60 kg DM per kilogram edible protein, for pigs and poultry, respectively).

Non-CO_2 GHG Emissions. We estimate that total non-CO_2 GHG emissions from the livestock sector in 2000 were 2.45 Gt CO_2 eq. Methane from enteric fermentation from ruminants, estimated using tier 3 methods, was by far the largest source of GHG emissions (1.6 Gt CO_2 eq). Methane and nitrous oxide (N_2O) from manure management, and N_2O from manure application to soils were 0.25, 0.21, and 0.49 Gt CO_2 eq, respectively. Cattle accounted for 77% of emissions. The contribution of monogastrics to GHG emissions was only 10% of total livestock emissions, and most of this is in the form of methane from manure management (56% of their total emissions).

The developing world contributes 75% of global GHG emissions from ruminants (Fig. 5*A*) and 56% of emissions from monogastrics. Mixed crop–livestock systems produce the bulk of emissions from ruminants (61%), and grazing systems account for 12% of emissions. Urban and other systems comprise the rest. Non-CO_2 emissions from different regions are largely driven by numbers of animals and the predominant production systems, with SAS, LAM, SSA, and EUR having the highest total emissions (Fig. 5*A*).

Non-CO_2 GHG Emission Intensities. Global average non-CO_2 emission intensity for all livestock commodities was 41 kg CO_2 eq per

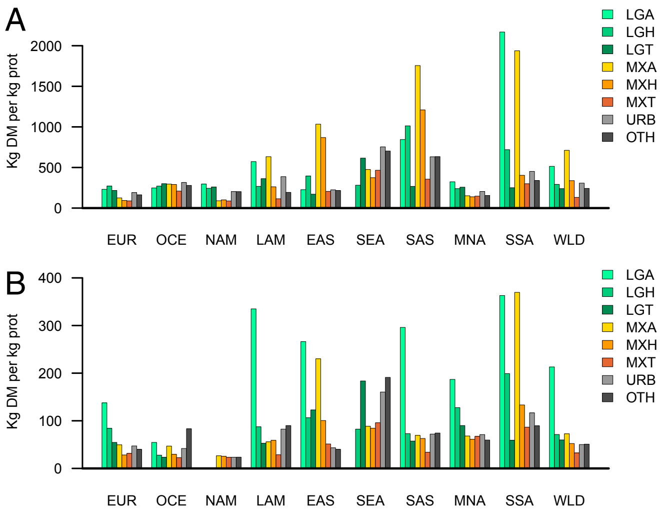

Fig. 4. Feed-use efficiencies per kilogram of protein from (*A*) cattle meat and (*B*) cattle milk by production system and region.

kilogram edible animal protein. This figure, although important for comparative purposes, hides enormous variability because of region, production system, and type of product (Fig. 5 *B–D*) (see *SI Appendix* for more detailed information). With regard to the spatial distribution of livestock-emission intensities (Fig. 5*B*), SSA is the global hotspot. These high GHG emission intensities are driven by low animal productivity across large areas of arid lands, the use of low-quality feeds, feed scarcity, and animals with low productive potential that are often used for draft power and to manage household risk, as well as for production. Nevertheless, most ruminants in SSA are raised for meat, and the production of meat is associated with lower feed efficiency and higher emission intensities in comparison with a product such as milk (Fig. 5 *C* and *D*). Other areas with moderate emission intensities occur throughout the developing world, in arid regions (Andean region, El Chaco in South America, Mongolia), in places with significant beef production (Amazonia), and in places where diet intensification in ruminants is low (large parts of South Asia). In most of the developed world emission intensities are low as a result of improved and more intensive feeding practices and temperate conditions, where feed quality is inherently higher.

Although the emission intensities of ruminant milk and meat differ considerably (12–140 compared with 58 ≥ 1,000 kg CO_2 eq per kg edible animal protein, respectively), these decline as the quality of the diet improves (Fig. 5 *C* and *D*), to the point at which the emission intensities of the two products are comparable. Although no obvious trend by production system is discernible, all systems in the developed world have lower emission intensities than those in the developing regions.

The production of meat and eggs from monogastrics has significantly lower emission intensities than milk and meat from ruminants. We estimate emission intensities for global pork production of 24 kg CO_2 eq per kilogram protein, and for poultry meat and eggs, 3.7 kg CO_2 eq per kilogram edible protein. These emission intensities are driven largely by the industrial pig and poultry sectors, which consume high quality, balanced concentrate diets, and which tend to use animals of high genetic potential.

Discussion

Value of Livestock Data Disaggregation for Global Change and Sustainability Research. We set out to construct a biologically consistent, spatially disaggregated global dataset of the main biophysical interactions between feed use, animal production, and emissions for different species and regions of the world. What did we gain in terms of our understanding of livestock systems and their sustainability? The dataset is consistent in that national and regional production figures of livestock commodities are matched to Food and Agriculture Organization (FAO) statistics for the year 2000, although they can be harmonized to other years if needed. This aspect is important for users who want to harmonize their analyses to a consistent baseline but to also get added disaggregation by production systems, livestock commodity, and agroecology. The information generated constitutes an important baseline for studying adaptation and mitigation options in livestock systems, as potential solutions vary depending on these factors (28). Some of the information generated can also be used to study additional biophysical processes in livestock systems, such as water productivity (29) and nutrient use (30). At the same time, this information can be used to integrate livestock knowledge with other dimensions of the world food system. Manure production data are an important component of this dataset for such purposes. Together with other data on cropland extent and productivity (31, 32) and crop models (33, 34), the dataset could be used to study key nutrient cycles (N, P) in terrestrial ecosystems and as inputs for parameterizing global or regional crop models for assessing the contribution of organic inputs to crop production, for example. Information on the spatial distribution of kilocalorie availability from livestock products globally could provide inputs into future-orientated studies on the impacts of changes in livestock systems on human nutrition, trade in livestock commodities, and more sustainable diets (6, 35).

The estimated regional feed use efficiencies for producing different livestock products are in close agreement with Wirsenius et al. (15) and Bouwman et al. (13) for beef, milk, pork, and poultry. The same trends in regional differences were observed, and the magnitude of the feed efficiencies was similar, with our numbers usually in between the slightly lower feed use efficiencies of Wirsenius et al. (15) and the higher figures from Bouwman et al. (13). Exceptions were beef in SAS, milk in SAS and SSA, and small ruminant meat production. Differences are likely the result of differences in the methods used to estimate animal productivity. Wirsenius et al. (15) and Bouwman et al. (13) used statistical approaches based on FAO data for estimating their feed efficiencies, whereas we used a mechanistic model of digestion in ruminants as the basis of our computations. Another source of variation is our more disaggregated production systems data. Wirsenius et al. (15) and Bouwman et al. (13) harmonize their statistics at national level, and Bouwman et al. (13) additionally differentiate between two types of production systems (mixed and grazing). We distinguish between eight types of production systems, thus adding additional resolution to the feed consumption and production data.

Our global estimates of GHG emissions are in broad agreement with the Environmental Protection Agency (EPA) (36) and the Emission Database for Global Atmospheric Research (EDGAR) (37). Our tier 3 estimates of global enteric methane (1.6 Gt CO_2 eq) are slightly lower than the EPA (36) and FAO (1) (range 1.8–2.0 Gt CO_2 eq), but these sources use more aggregated methods for their calculations [combinations of International Panel on Climate Change (IPCC) tier 1 and tier 2]. Non-CO_2 emissions from manure management and manure applied to pastures are in close agreement to published sources using IPCC source categories (36, 37). Larger discrepancies are found with studies applying life-cycle analysis methods, which are more complete inventories of sources of emissions (i.e., ref. 38) and beyond the scope of our study.

Resource-Use Efficiencies: The Key? Our study has shown that there are large differences in feed efficiency and emission intensities in livestock systems. These findings vary because of type of livestock product, the production of pork and poultry being most efficient, followed by milk production and red meat production from cattle and small ruminants. Similar findings were obtained by de Vries and de Boer (39) for Organization for Economic Cooperation and Development countries. Large differences in feed and GHG efficiencies were observed within products (i.e., milk, meat),

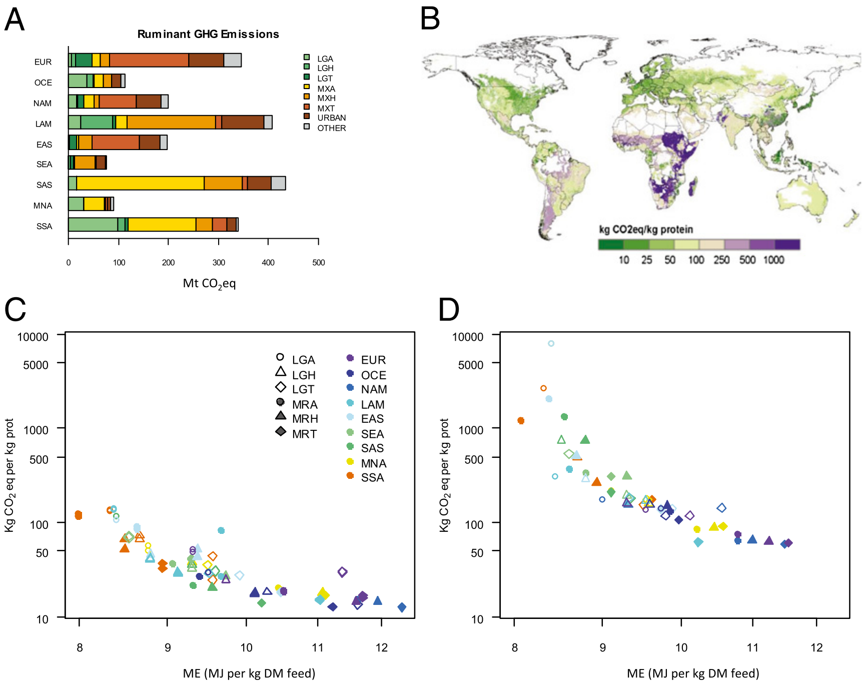

Fig. 5. (*A*) Non-CO_2 GHG emissions from global ruminant livestock (cattle, sheep, and goats) by production system and region. (*B*) Spatial distribution of non-CO_2 greenhouse emissions from ruminants (kg CO_2 eq kilogram edible animal protein). The relationship between the diet quality of ruminants [ME (MJ)/kg DM] and the non CO_2 greenhouse gas emission intensity for edible animal protein (kg CO_2 eq per kilogram edible animal protein) from ruminant milk (*C*) and meat (*D*).

especially those from ruminants, with the differences driven by agroecology and level of intensification of production. Similar observations were made by the FAO (38) for dairy production. These two factors control the quality of the diet of ruminants, with temperate areas having higher-quality grasses and feeds in general, and more intensive systems offering more concentrates and other supplements as part of their rations. These large differences suggest the following. First, in regions with low feed efficiencies and high emission intensities, such as SSA and parts of SAS and LAM, there is significant scope for improving the efficiency of livestock production through improved feeding and management, given the right production incentives, investment, and institutional support (3, 40). Second, structural change in the livestock sector could play a pivotal role in improving its efficiency; transformational change, including shifts between production systems, warrants further research as an option for increasing the sustainability of livestock production and for enhancing national and regional food security and self-sufficiency in countries where this is a policy priority (41). Third, the questions concerning which livestock product, how much of it we eat, and how it is raised, matter a great deal in a changing, resource-use hungry world: the large differences in the efficiency of production of livestock products warrant considerable attention in the search to define sustainable and culturally appropriate levels of consumption of livestock products as part of food-demand management strategies (42).

Grasslands Are Precious, but Improved Management Is Required. We estimate that grass accounts for close to 50% of feed use in livestock systems and that it is a crucial feed resource for both grazing and mixed production systems. At the same time, grasslands are sometimes considered either underused or seen as an ecosystem warranting judicious management because of their importance for protecting key regulating ecosystems services (carbon, biodiversity, water) (1, 5, 29). The importance of this finding lies in the impacts that the increasing demand for livestock products might have on grassland ecosystems. Grasslands are often at the epicentre of land-use change processes (43): conversion into grassland is a primary cause of deforestation; afforestation for carbon sequestration or biofuel production occurs in grassland areas that have previously been cleared; pasture intensification to increase productivity, incomes, and mitigate GHG is occurring in several parts of the world; at the same time, rangeland degradation because of overgrazing and land subdivision occurs in other parts of the world; yet grasslands sustain the livelihoods of large numbers of vulnerable people in many parts of the world. Detailed studies on the role and fate of grasslands as a multifunctional resource require urgent attention.

The information presented here constitutes an important step toward an improved understanding of the multiple roles of livestock, and for better assessing the synergies and trade-offs of our choices for sustainably managing the world's natural resources.

Methods

Detailed information on the methods used is presented in *SI Appendix*. To summarize, we used a livestock systems classification based on Seré and Steinfeld (44), first mapped by Kruska et al. (45), and recently updated by Robinson et al. (17). This classification system has been widely used for studying different aspects of livestock production, such as linkages with poverty (21), environmental impacts (1), systems evolution (3), and livestock demographics (17). The system has many useful features for studying biogeochemical aspects of livestock production; it distinguishes between grazing systems, mixed crop-livestock systems, and landless livestock systems. Systems are also broken down based on agroecological differentiations (arid-semiarid, humid-subhumid, and temperate/tropical highland areas), which help in establishing the composition of diets for animals in different regions and different agroecologies. We differentiated 8 different types of livestock systems in 28 geographical regions of the world for this study.

Numbers of animals for each of these systems and regions were estimated using the data of Wint and Robinson (46) for the year 2000. For ruminants (cattle, sheep, and goats), we disaggregated the dairy and beef cattle herds using livestock demographic data for total cattle, sheep, and goats, and the dairy females for each species, respectively, from FAOSTAT (the statistics division of the FAO). We used herd dynamics models (47) parameterized for each region and production system using reproduction and mortality rates, obtained from extensive literature reviews, to estimate the number of followers in the dairy herds. We then subtracted the number of total dairy animals from the total number for each species. This procedure enabled us to have distinct herds for the production of milk and beef.

For monogastrics (pigs and poultry), only two systems were differentiated: smallholder and industrial production systems. The allocation of poultry, eggs, and pork production was done on the basis of knowledge of the total product output from these two systems from national information from selected countries in the different regions, applied to the respective region. The numbers of animals contributing to the estimated production was computed using a herd dynamics models coupled with information on mortalities, reproduction, and productivity for these two main systems for each region.

Biomass consumption by different species in each region and system followed a three-stage process. First, feed availability of four main types of feeds (grass, crop residues, grains, occasional feeds) was estimated. Hybrid maps of grassland productivity were developed using rain-use efficiency concepts in drylands (48, 49) and EPIC model output (28) for humid and temperate regions of the world. Crop residue availability was estimated using the Spatial Production Allocation Model cropland layers (32) and applying coefficients of stover use for animal feeding and harvest indexes for different parts of the world (3, 50). Data on grain availability for animal production were taken from the FAO commodity balance sheets and the availability of occasional feeds was obtained from literature reviews. The second step consisted in developing feasible diets for each species in each region and production system. The proportion of each feed in the diet of each livestock species was obtained from extensive information available in the literature and from databases and feeding practice surveys at key research centers in the world (such as FAO and the International Livestock Research Institute). Data on feed quality were obtained from databases containing regional feed composition data for each feed (22). For ruminants, information on the quantity and quality of the different feeds was then used to parameterize an IPCC tier 3 digestion and metabolism model (RUMINANT), as described in Herrero et al. (22) and Thornton and Herrero (51). The model estimates production of milk and meat, manure production, N excretion, and methane emissions using stoichiometric calculations. A detailed description is provided in the *SI Appendix*. For monogastrics, information on feed quality was used to estimate feed intake, productivity, and feed-use efficiency, using standard nutrient requirements guidelines (52).

For the estimation of nitrous oxide emissions, the IPCC tier 2 approach was used with specific manure management practices for each species, system, and region. Further details are available in the *SI Appendix*. All information on animal production (bovine milk, bovine meat, sheep and goat milk, sheep and goat meat, pork, poultry, and eggs) and for grains as feed was harmonized with FAOSTAT's commodity balance sheets at national level following an iterative procedure that restricts deviations to ±20% from the statistical data in FAOSTAT. More information of this process is given in Havlík et al. (28).

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