Livestock and global change: Emerging issues for sustainable food systems

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The global food system is experiencing profound changes as a result of anthropogenic pressures. The ever-increasing human population (more than 9 billion by 2050), together with changes in consumption patterns (i.e., increasing demand for livestock products) caused by urbanization, increasing incomes, and nutritional and environmental concerns, is shaping what we eat, who eats, and how much, more than ever. The double burdens of nutrition (overconsumption and undernutrition), together with the need to reduce the impacts of climate change, are defining research agendas, affecting policies, and modifying conceptions about food in different ways around the world (1, 2) and have been the topic of other recent Special Features in PNAS (3, 4).

Against this background, the global food system that will have to improve its resource use efficiency and environmental performance significantly to ensure the sustainability of global food production and consumption.

Livestock, the largest land use sector on Earth, is an important part of this puzzle. Many solutions to the challenges of feeding the world sustainably lie in how we manage this sector. The demand for livestock products is projected to grow substantially in the coming decades (5). This growth will be driven by increasing populations, economic growth, and rapid urbanization in many parts of the developing world. The main conclusions from such projections is that a shift to diets with more animal products and fats is likely to happen, mostly in the developing world, as a result of increased incomes and urbanization (6). Although the consumption per capita of cereals is likely to stabilize, population growth will increase the total quantities of both meat (almost doubling) and cereals (50%) needed to feed the world in 2050.

The supply response of the global agriculture and livestock sectors, if current trends continue, is likely to be able to accommodate these demand increases (5). Most recent projections have important common features:

- Local production under current yield trends in many parts of the world, like Sub-Saharan Africa (SSA) and parts of Asia, will not be able to meet local food demand. Hence, increases in food trade are projected to increase in the future in some parts of the world. This is a key aspect of balancing the food supply and demand equation.
- Although increases in the yields of crops and livestock have occurred in most regions of the world (apart from SSA), projections show a variable increase in cropland and grassland expansion to meet demand (7).
- Animal numbers will increase. However, monogastric production (pork and poultry) will grow at faster rates than ruminants (especially for meat and less so for milk).
- These factors lead to net increases in greenhouse gas emissions (GHGs) from the agricultural and livestock sectors but a diminishing trend in the emissions intensities across commodities (GHGs per unit of product).
- Projections of water use show increased pressure on total fresh water resources, notably on blue water (irrigation), and moderate increases in the efficiency of green water use (8). Other studies have also demonstrated large quantities of reactive nitrogen used and a potential disruption of phosphorus cycles in the future (9).

In summary, food production can be attained under current productivity and demand trends but not necessarily in ways that make progress in achieving environmental goals or social goals.

There is significant uncertainty about both how livestock systems might evolve to meet the increased the demand for livestock products and what the social and environmental consequences of these changes will be. In addition, the dynamics and patterns of agricultural production and the functioning of ecosystems will be significantly affected by climate change and increases in climate variability. Major changes can thus be anticipated in livestock systems, although the nature of these changes is not easy to foresee. Livestock and livestock systems are substantial users of natural resources; at the same time, they contribute very significantly to the livelihoods of at least 1.3 billion poor people in rural households (10, 11). Recent global assessments (12–16) have considered particular elements of livestock and livestock systems, but none addresses such systems and their considerable variations in a comprehensive, integrated way. This has led to inaccurate simplifications of the messages surrounding how to manage the livestock sector's growth in the future. The lack of a systems perspective has also curtailed explorations of more sustainable options for the sector's development. This needs to be rectified. Global change will have highly differentiated impacts on food, livelihoods, and ecosystem goods and services from livestock systems around the world. Opportunities may exist for some households to take advantage of more improved rangeland and cropping conditions. In some of the highland areas of SSA, for example, temperature limitations on crop growth may be relaxed in the coming decades due to gradual warming. These places may present smallholders with new opportunities for income generation. In contrast, other places may see substantial reductions in agricultural potential, and these reductions may be drastic in places. Human dietary preferences, along with many other factors, may change the current patterns of land use systems, but discussion of the implications of those changes needs to be more sophisticated than popular generalizations about reducing meat consumption.

Dealing with changes in livestock systems needs to be informed by consideration of

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the benefits and problems they create. The benefits associated with livestock are societal, economic, and environmental. Livestock contribute 17% to the global food balance, in terms of calorific intake per person per day, and 33% of the protein in human diets (10). They contribute substantially to the livelihoods of (especially) the poor in the developing world. Livestock provide traction mainly in irrigated, densely populated areas and allow cropping in these places. They provide nutrients, particularly in the mixed systems of SSA. They can promote biodiversity increases in some pastoral systems (17), and the rangelands could capture significant quantities of carbon (12). At the same time, livestock and livestock systems can have negative effects locally and globally, as well as directly and indirectly. Locally, these include land conversion and land degradation. Twenty percent of the world's pastures and rangelands have been degraded to some extent through overgrazing, compaction, and erosion caused by livestock action (18). The livestock sector may be responsible for 8–18% of GHGs, a significant share considering their projected growth. A contraction in meat consumption per person in high-income countries would benefit human health, mainly by reducing the risk of heart disease, obesity, and colorectal cancer (16, 19).

The benefits of livestock, the negative impacts they can have on the environment, and the effects of climate change on livestock and livestock systems are all heavily differentiated spatially. These effects need to be put into regional and local contexts both for designing suitable research agendas and for engaging in environmental debates. Livestock are not bad everywhere, any more than they are unequivocally good in all developing country situations. These regional variations in public "goods" and "bads" need to be understood for the appropriate targeting of technology and policy, whether they relate to contamination by manure of water resources from intensive production systems in Asia or to increasing market opportunities for resource-poor livestock keepers in agropastoral systems of SSA.

This Special Feature is organized around five papers that examine different facets of the future of livestock systems. The paper by Herrero et al. (20) provides a high-resolution baseline global dataset of livestock's main biophysical interactions, including biomass use, production, excretion, and emissions by production systems and livestock products. This information forms the basis on which to study environmental impacts, resource use efficiencies, and socioeconomic aspects of livestock product consumption. Past, present, and future impacts of livestock on the global nitrogen and phosphorus cycles are studied by Bouwman et al. (9). Golub et al. (21) examine the impacts of GHG abatement policies on food security, land use, leakage impacts, and the evolution of the livestock sector in both the developed world and the developing world. Alkemade et al. (22) explore the impacts of different growth trajectories and agricultural intensification on rangeland biodiversity. Perry et al. (23) provide an account of drivers of livestock disease dynamics and suggest ways of reducing the burden of diseases as the livestock sector grows. These are all aspects that have received little attention in assessments of the interactions between livestock and the future trajectories of change in the global food system.

These papers reveal many issues at the heart of sustainability science and environmental and development policy. Some of those most essential for managing the growth of the livestock sector in the future are presented below.

Exploiting the Diversity of Livestock Systems Is a Prerequisite for the Sustainable Growth of the Sector

It has been widely demonstrated that different types of livestock systems, in diverse agroecologies and regions and producing different kinds of animal products (e.g., meat, milk, eggs), have widely differing resource use efficiencies (20, 24–27). For example, the paper by Herrero et al. (20) shows that land use and GHG intensities between beef, milk, and monogastric production can differ in specific cases by a factor of 10 or more. This is in agreement with recent life cycle assessment estimates (24, 25) and with earlier, more aggregated studies (26, 27). The magnitude of the differences reveals a significant potential for improvement (28, 29). There is unequivocal evidence that technical improvements, like improving animal diets, often used as part of sustainable intensification strategies, are likely to lead to increases in productivity and efficiency (and potentially land sparing), with the effects being larger the lower the productivity is (29–31). Diminishing or very small effects are observed at high productivity levels. This partly explains why the potential for increasing productivity and efficiency in the developing world is far larger than in the developed world. Structural changes, like shifts in production systems from grazing to mixed crop/livestock systems (32) or changes in the types of livestock products consumed (from red to white meats), could also play a significant role in shaping the resource use footprint of livestock globally (33). Recent evidence also suggests that exploiting the increasingly decoupled interactions between crops and livestock could be beneficial for promoting structural changes in the livestock sector. Havlík et al. (32) demonstrated that exploiting yield gaps of crops could indirectly improve the efficiency of livestock production by favoring the growth of more intensive production systems with better quality animal feeding practices. Their results also show additional land sparing due to increased resource use efficiencies.

Managing the Indirect Effects of Livestock Systems Intensification Is Critical for the Sustainability of the Global Food System

Much has been said recently about the potentially positive impacts of sustainably intensifying global food systems, including the livestock sector (2, 34, 35). It is now widely acknowledged that sustainable intensification goes beyond improving productivity and efficiency, and that it encompasses other aspects, such as creating the necessary incentives and investments for systems to intensify, developing regulations and limits for intensifying systems (i.e., animal welfare standards), and others. A large body of work on livestock in this area has focused on improving productivity and the impacts on GHGs, emissions intensities, and their close link to land sparing, which leads to a reduction in CO_2 emissions (32, 33, 36). The paper by Alkemade et al. (22) also shows that these land-sparing effects could lead to reducing the impacts of livestock on biodiversity.

An additional positive impact, and simultaneously a perverse incentive, is that these increases in productivity and efficiency lead, in many cases, to increased profitability and cash flow in livestock farms. These could be major incentives in many parts of the world to increase operation size (more animals, more use of land, potentially more deforestation, and more diverted resources toward livestock), whereas an essential premise to reduce environmental impacts of livestock production is to produce more with fewer but more productive animals (29). This is certainly an aspect requiring regulation and incentives to ensure that growth occurs within environmental bounds (21).

In the global quest for intensifying livestock systems, an aspect often overlooked is the impact of intensification on the evolution of infectious and zoonotic diseases. The paper by Perry et al. (23) provides a discussion on how different types of diseases are likely to evolve. Seeking to meet the demand for livestock products through the additional growth of monogastric systems (they are already growing at rates higher than 3% per year in many places) for the sake of maximizing the efficiency of livestock production presents significant disease challenges. Potential problems include increased risk and severity of outbreaks of influenza and other zoonotic diseases, and increased likelihood of new pathogens developing if proper disease surveillance methods and appropriate regulations and policies for managing animal densities and their location, for example, are not well designed, especially in the developing world.

The paper by Bouwman et al. (9) also shows that the continuous intensification of livestock systems has led to a large appropriation and control of nutrient cycles by the livestock sector, which, in turn, has led to significant recycling and disruptions in the global nitrogen and phosphorus cycles.

These examples clearly illustrate why the "sustainable" in sustainable intensification matters, and why it merits significantly more research. Diversity in livestock systems is a necessity for meeting environmental objectives and for managing risks, and there is a case to be made for not maximizing production efficiency at all costs and everywhere.

Mechanisms for Effecting Behavioral Change in Livestock Systems Need to Be Better Understood

Change is often mediated by incentives and rewards or by regulations, taxes, and subsidies. In livestock systems, the large differences between the needs of developed and developing countries require that sophisticated differentiated mechanisms be designed. Such mechanisms are needed for promoting changes in livestock product consumption, for managing structural change, for improving farmers' livelihoods, for reducing transaction costs, for promoting increased resource use efficiency in the sector, and for managing pollution from livestock systems. These mechanisms have been implemented in the livestock sector with different degrees of success, but it is essential that new alternatives be developed. Change and adoption of improved practices and new production systems are not occurring at a fast enough pace for promoting economic growth, improved livelihoods, food security, and environmental protection simultaneously.

Golub et al. (21) demonstrate how different policy mechanisms can have impacts on the mitigation of GHGs from livestock systems. They show that different methods can be effective on their own but, more interestingly, demonstrate that implementing combinations of incentives and taxes simultaneously in different parts of the world may have the greatest mitigation impacts. In their study, a combination of land-based carbon taxes for annex 1 countries, together with an incentive for forest carbon sequestration in non-annex 1 countries, yielded large mitigation impacts with little leakage. Additional abatement was obtained by adding a subsidized GHG tax in non-annex 1 countries. These practices led to the highest mitigation potentials and differential income effects in different parts of the world, with non-annex 1 countries increasing incomes, mainly for agricultural households, without largely affecting food security. There is an urgent need to develop and test these and similar mechanisms to ensure livestock systems contribute to the sustainability of the food system.

What Is Next for the Global Integrated Assessment of Livestock Systems?

The study of sustainable livestock futures needs the recognition that the livestock sector cannot be studied in isolation. Developing trends and alternative growth scenarios of how the sector might accommodate the increases in livestock product demand need an integrated approach. At the same time, most concerned with the evolution of the global food system need to accept that the livestock sector needs a sophisticated treatment in future assessments due to its connectedness to other food and economic systems.

From our perspective, the research topics presented in this Special Feature advance our understanding of livestock systems. However, still needed is additional research on these topics and integration of the results in frameworks for the study of global food systems.

Additionally, we feel that the following livestock-related areas have not received enough attention in global integrated assessment of food systems.

Most attention has focused on the environmental impacts of livestock systems. This was a good starting point because most integrated assessment frameworks require adequate knowledge of the main interactions between livestock and natural resources. However, social and economic impacts have not received enough attention in these assessments, although they are crucial for building convincing cases for change in the livestock sector. For example, two areas that have received significant attention recently, land sparing as a mitigation option and reducing livestock product consumption, cannot be studied properly unless something can be said about impacts on people and product value chains, on the economic contribution of the sector, on which sectors are going to absorb the idle producers, on what will be the opportunity costs of other alternatives, and on how will nutrition be affected. Answers to all these questions need significant regional, sex, and income differentiation.

Another area that merits more attention is adaptation to climate change. There are still large gaps in knowledge of the impacts of climate change on livestock systems, on livestock productivity, on feeds and rangelands, and on mitigation potentials, particularly in the tropics and subtropics (37). These have still not been comprehensively studied, nor have the necessary incremental or transformational changes required to adapt these systems to counteract these impacts in the future been identified. Appropriate adaptation measures in different places will depend in part on how livestock systems develop into the future. There is much still to learn about the potential impacts of different pathways of economic development on food system outcomes and how these may affect the livestock sector.

Integrated assessments to date have tended to be preoccupied with global change over the long term (38). More comprehensive approaches for evaluating impacts and assessing alternatives that take on board changes in climate variability and climate extremes are urgently needed. Much is already known about the impacts of climate variability and climate extremes on food systems, but there are undeniable challenges in setting in place adequate and appropriate monitoring systems as well as in dealing with our current, somewhat limited ability to quantify changes in climate variability and extremes over short temporal and high spatial scales. These challenges affect all sectors, not just livestock, but improved understanding of the full range of both long- and short-term impacts of global change on food systems is critical for being able to address the challenges effectively.

The livestock sector, the largest land user on Earth, holds a large stake in how to achieve the balance between food production, livelihoods, and environmental objectives. It is essential that we continue researching it with the urgency, consistency, and rigor that it merits to ensure its contribution to the sustainability of global food systems in the future.

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