Forecasting potential global environmental costs of livestock production 2000–2050

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Food systems—in particular, livestock production—are key drivers of environmental change. Here, we compare the contributions of the global livestock sector in 2000 with estimated contributions of this sector in 2050 to three important environmental concerns: climate change, reactive nitrogen mobilization, and appropriation of plant biomass at planetary scales. Because environmental sustainability ultimately requires that human activities as a whole respect critical thresholds in each of these domains, we quantify the extent to which current and future livestock production contributes to published estimates of sustainability thresholds at projected production levels and under several alternative endpoint scenarios intended to illustrate the potential range of impacts associated with dietary choice. We suggest that, by 2050, the livestock sector alone may either occupy the majority of, or significantly overshoot, recently published estimates of humanity's "safe operating space" in each of these domains. In light of the magnitude of estimated impacts relative to these proposed (albeit uncertain) sustainability boundary conditions, we suggest that reining in growth of this sector should be prioritized in environmental governance.

Global food systems play a pivotal role in anthropogenic environmental change (1–4). In particular, the livestock sector is a key contributor to a range of critical environmental problems (2, 5). Substantial projected growth in this sector from 2000–2050 due to increasing population and per capita demand will effectively double production volumes (6, 7), exacerbating pressures on ecological systems. Although considerable research has been advanced to further our understanding of contemporary livestock/environment interactions, the implications of these trends for sustainability objectives is not sufficiently resolved.

On current trajectories, it is estimated that anthropogenic climate change may increase global mean temperatures by 3 °C by 2100 (8). Given that a rise of 2 °C above preindustrial levels may result in 'dangerous climate change,' with serious negative impacts to ecosystems and human welfare, this issue has necessarily moved to the fore of global environmental governance discourse (8, 9). To date, no full cradle-to-plate estimates of global food system greenhouse gas emissions are available (10). However, the Intergovernmental Panel on Climate Change (8) estimates the direct contribution from agriculture at 10–12%, not accounting for land conversion effects. If the latter is included, one recent study (11) estimates agriculture's contribution at 17–32% of anthropogenic emissions. Estimates of full supply chain emissions are available for the European Union (EU)-25, which suggest that the food system contributes 31% to total emissions (12). A large fraction of these emissions are attributable to the livestock sector (5).

Nitrogen is essential to all life forms and is also the most abundant element in the Earth's atmosphere. Atmospheric N, however, exists in a stable form (N_2) inaccessible to most organisms until fixed in a reactive form (N-). The supply of reactive nitrogen plays a pivotal role in controlling the productivity, carbon storage, and species composition of ecosystems (13). Since the industrial revolution, annual anthropogenic reactive nitrogen emissions have increased to the extent that human activities now contribute more fixed N to terrestrial ecosystems than do all natural sources combined. Background levels have effectively doubled since 1970 and continue to rise rapidly (2, 14). Alteration of the nitrogen cycle has numerous consequences, including increased radiative forcing, photochemical smog and acid deposition, and productivity increases leading to ecosystem simplification and biodiversity loss (13–17). Moreover, reactive nitrogen is known to cascade through ecosystems (16), sequentially contributing to these impacts as it cycles from one form to another. Global food systems dominate anthropogenic disruption of the nitrogen cycle by generating excess fixed nitrogen either through industrial fertilizer production or biological nitrogen fixation (17). Half of the synthetic nitrogen fertilizer ever used on Earth has been applied in just the last 15–20 y (18, 19). Of this fraction, it is estimated that only 10–20% was actually consumed by humans, 95% of which was subsequently lost to the environment (18, 19). Under status quo technological and consumption norms, the substantial increases in global food production volumes by 2050 (6) will strongly exacerbate reactive nitrogen pollution issues. Due to the large fraction of cereal and fodder crops directed toward livestock production, this sector will play a particularly important role.

Global estimates of biotic resource use have been reported by several researchers (3, 20). At present, it is estimated that humans appropriate 24% of potential net primary productivity (NPP), with the food system consuming 12% (20). Krausmann et al. (3) suggest that 58% of directly used human-appropriated biomass was utilized by the livestock sector in 2000. In light of the inefficiencies inherent to biological feed conversion, the projected expansion of animal husbandry will likely figure large in future anthropogenic biomass consumption. It is difficult to predict the precise implications of increasing NPP appropriation. However, as pointed out by Imhoff et al. (21), this level of appropriation is remarkable for a species representing only 0.5% of planetary heterotroph biomass. It also has notable consequences for energy flows within food webs, the biodiversity that ecosystems can support, the composition of the atmosphere, and the provision of important ecosystem services (21).

Environmental boundary conditions are biophysical limits which define a safe operating space for economic activities at a global scale (22). Building on the earlier work of ecological economists, who have long stressed the importance of scale (i.e., relative to biocapacity) in sustainability concerns (23–25), several authors have recently proposed sustainability boundary conditions for human activities in a suite of domains, including climate change (9), reactive nitrogen mobilization (22), and appropriation of net primary productivity (26). Clearly, there is considerable uncertainty associated with any such estimates—even in the case of climate change, which has stimulated the most concerted

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scientific effort in human history (27). From a thermodynamic perspective, however, the concept itself is unassailable. Moreover, in light of the high stakes associated with overshooting the tipping points of biogeochemical cycles that mutually constitute biospheric life support systems, it must certainly figure strongly in efforts to more effectively manage the global environmental commons for sustainability objectives.

Here, we use simplified but robust models to conservatively estimate the aggregate greenhouse gas emissions, reactive nitrogen mobilization, and biomass appropriation potentially associated with producing edible livestock products in 2050. Specifically, we evaluate four endpoint scenarios based on projected and alternative production and consumption patterns intended to illustrate the range of impacts associated with dietary choice at a global scale. Results are compared with published estimates of contributions of the livestock sector as of 2000 and with the recently estimated sustainability boundary conditions proposed by several authors for human activities as a whole (9, 22, 26). Although embodying considerable uncertainty, our models indicate that, by 2050, the livestock sector alone may either occupy the majority of, or considerably overshoot, current best estimates of humanity's safe operating space in each of these domains. On this basis, we suggest that potential contributions of livestock production to global environmental change relative to these proposed sustainability boundary conditions indicate that reining in growth of this sector should be a policy priority.

Results and Discussion

Estimating Livestock's Global Environmental Costs. As of 2000, the livestock sector is estimated to have contributed 14% of anthropogenic greenhouse gas emissions (18% taking into account land use, land use change, and forestry) (5), 63% of reactive nitrogen mobilization*, and consumed 58% of directly used human-appropriated biomass globally (3). Using simplified and (we believe) conservative models, we estimate that production of livestock in 2050 at levels projected by the United Nations Food and Agriculture Organization (FAO projections scenario) (6) may increase direct livestock-related greenhouse gas (GHG) emissions from meat, milk, and egg production on the order of 39%, biomass appropriation by 21%, and reactive nitrogen mobilization by 36% above reported year 2000 levels (Fig. 1). However, there is a wide range in resource and emissions intensities between different livestock products. Accordingly, under the same conditions, we estimate that substituting poultry (more resource efficient) for all marginal beef (less resource efficient) production above year 2000 levels (substitution scenario) could reduce these anticipated impacts by a modest 5–13%. Similarly, human protein needs may be satisfied in numerous ways and with differing contributions from livestock products. To capture this spectrum of impacts, we modeled two additional illustrative "endpoint scenarios" where dietary protein needs are satisfied completely from either livestock or legume (here, we employ soybeans) sources. The range of impacts associated with achieving United States Department of Agriculture (USDA) recommendations for kilogram per capita/year protein consumption levels when derived in entirety from either meat/eggs and dairy (livestock scenario), or from soybeans (soy protein scenario), for global populations in 2050, spans almost two orders of magnitude (Fig. 1). Although neither extreme is realistic, this range nonetheless underscores the considerable role of dietary patterns in determining environmental outcomes.

Based on the suggestion by Allison et al. (9) that per capita GHG emissions must fall below one metric ton per year by 2050 to prevent a potentially dangerously destabilizing increase in mean surface temperatures above 2 °C, as of 2000 we estimate that the livestock sector alone occupied 52% of humanity's suggested safe operating space for anthropogenic greenhouse gas emissions (Fig. 1). Similarly, relative to Bishop et al.'s (26) proposed sustainable scale for human-appropriated net primary productivity (which represents a more inclusive measure of NPP appropriation than does biomass use) in terms of biodiversity preservation, we suggest that the direct appropriation of biomass by the livestock sector accounted for 72% of our safe operating space in this domain (Fig. 1). The sustainability boundary condition for reactive nitrogen mobilization proposed by Rockstrom et al. (22) was exceeded by 117%. We further estimate that, by 2050, meeting projected demands for edible livestock products may increase these shares to 70%, 88%, and 294% of the proposed sustainability boundaries, respectively (Fig. 1). Our results also suggest that, if the livestock sector is to grow as forecasted but maintain its current proportional share of contributions to these issue areas and human activities are to be constrained to respect the proposed sustainability boundary conditions, it will be necessary to reduce greenhouse gas emissions per unit livestock protein produced to roughly 13% of year 2000 levels, biomass appropriation to 25%, and reactive nitrogen mobilization to 14%.

Modeling the future is fraught with uncertainties, and we would be remiss to present our estimates as definitive. We have endeavored to err on the side of caution in developing what we believe to be conservative forecasts of some of the potential future environmental impacts of livestock production. For example, it would be impressive, indeed, were all livestock production globally to achieve resource efficiencies comparable to those reported for the least impactful contemporary systems in industrialized countries, effectively reducing global impacts per unit protein produced by 35% in 2050 relative to 2000—as we have assumed here. We recognize, however, that we have failed to directly accommodate a number of important variables that may strongly influence outcomes, such as forecasted continued increases in productivity associated with agricultural intensification and greater cycling of animal manures in place of fertilizer production in developing countries (6). The former might serve to partially offset the scale of human-appropriated net primary productivity despite increases in biomass use, as has been reported for historical trends in several regions (as reviewed in ref. 28). It is possible that, in combination, such trends could surpass our assumed efficiency gains. We also recognize that the published estimates of sustainability boundary conditions we have used are themselves preliminary and highly uncertain. For example, Schlesinger (27) suggests that the sustainable boundary condition for reactive nitrogen emissions proposed by Rockstrom et al. (22) (25% of current rates) is arbitrary.

While providing only a coarse-grained indication of the role that the livestock sector might play, we nonetheless posit a profound disconnect between the anticipated scale of potential environmental impacts associated with projected livestock production levels and even the most optimistic mitigation strategies relative to these current, published estimates of sustainable biocapacity. As such, these observations merit serious consideration in food policy and environmental governance discourse.

Implications for Food and Environmental Policy. Due to the biological inefficiencies inherent to feed conversion, animal products have been described as the electricity of food (29). Certainly, substantial efficiency gains in recent decades and the range of existing regional efficiencies of livestock production suggest additional opportunities for improvements both at the level of feed crop production and animal husbandry (5, 30, 31)—all of which should be vigorously pursued (32). However, from our analysis (which includes generous assumptions regarding efficiency gains over time), it would seem that such objectives are unlikely to be met by technological means alone. Instead, all feasible options for reducing impacts in this sector must be considered (33) if

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*We have calculated this amount using information provided in ref. 5.

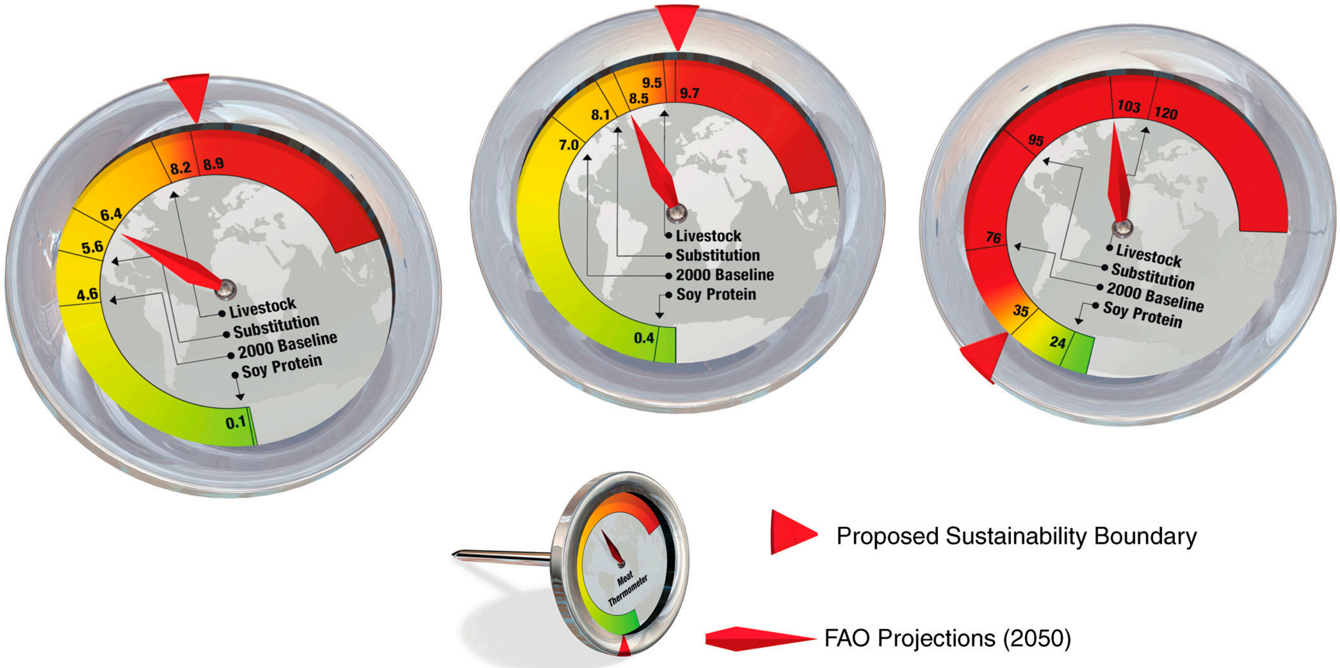

Fig. 1. Potential global environmental costs of livestock 2000–2050: Estimated greenhouse gas emissions (Gt CO_2-e) (*Left*), biomass appropriation (Gt C) (*Center*), and reactive nitrogen mobilization (Mt N_r) (*Right*) associated with the global livestock sector in 2000 versus 2050 under FAO production estimates (FAO projections scenario) as well as three alternative scenarios (substitution, livestock, and soy protein) relative to proposed sustainability boundary conditions for human activities in aggregate.

its relative and absolute contributions to achieving sustainability objectives are to be met.

Included here would be policies aimed at a shift in production away from ruminants (34) and toward lower impact species such as poultry (35, 36) through targeted taxes, subsidies, and regulation. Any such policies, however, must necessarily be attentive to probable tradeoffs across the spectrum of relevant social and ecological variables associated with specific species and production technologies. In some cases, extant systems may be preferable. Well-managed fisheries and aquaculture might similarly stand to displace a share of terrestrial animal protein production, also with careful attention to tradeoffs (37). Across the board reductions in per capita consumption of livestock products should similarly be a policy priority. To meet sustainability boundary conditions whilst maintaining year 2000 proportional contributions to total anthropogenic impacts for GHG emissions, biomass appropriation, and reactive nitrogen mobilization may require reductions in anticipated per capita consumption in 2050 to the order of 19%, 42%, and 21% of projected levels, respectively. Such reductions may be particularly feasible and advantageous in developed countries where consumption of meat products is currently twice USDA-recommended levels.

Certainly, a redistribution of livestock consumption from food surplus to food deficit regions would have coupled health and environmental benefits (36, 41). However, curbing growth in anticipated consumption in developing countries, where the majority of increase in production is projected to occur (5), will also be critical. Although neither of the extreme scenarios we modeled for global protein consumption are realistic (either entirely livestock- or soy-derived), a variety of authors have previously called attention to the environmental gains associated with diets lower in livestock products (38–41). Given the large differences in impacts associated with plant versus livestock protein-based diets, satisfying nutritional requirements through largely plant-based, regionally appropriate diets must be emphasized, while remaining sensitive to the developmental status and aspirations of the less advantaged, as well as the environmental implications of specific plant protein production strategies—for example, soybean agriculture in Amazonia (34, 42, 43).

Despite the uncertainty associated with both our simplified models and the sustainability thresholds we have adopted, we stress that the estimates reported here may equally be conservative and that, as with climate science, improved understanding of sustainable boundary conditions may continue to shift thresholds downward (44, 45). Moreover, increased competition for limited resources including energy for fertilizers, pesticides, and fuels, arable land for crops destined for direct human consumption, and political pressures for expanded biofuel production, will require difficult tradeoffs (31, 40). Given the limited consideration of the livestock sector in environmental governance regimes to date and the scale of the issues to be addressed, mobilizing the necessary political will to implement such policies is a daunting but necessary prospect. As the human species runs the final course of rapid population growth before beginning to level off midcentury, and food systems expand at commensurate pace, reining in the global livestock sector should be considered a key leverage point for averting irreversible ecological change and moving humanity toward a safe and sustainable operating space.

Methods

We coupled previously published estimates of aggregate greenhouse gas emissions (5), biomass appropriation (3), and reactive nitrogen mobilization (calculated from 5) for the global livestock sector in 2000 with United Nations FAO projections for the production of edible livestock products from 2000–2050 (6). Also in line with FAO projections, we conservatively assumed that all predicted increases in livestock production will occur in intensive, arable crop-based as opposed to extensive fodder-based animal husbandry systems (5, 46). We further assumed that impacts per unit production above year 2000 levels are equivalent to those reported for the most efficient contemporary intensive animal husbandry sectors. This assumption generously implies an average global decrease in impacts per unit livestock protein produced of 35% from year 2000 levels by 2050. (For a detailed methods and results description, see *SI Text*.) We subsequently predicted changes in the scale of absolute impacts over time associated with projected production levels (FAO projections scenario) and under three additional endpoint scenarios where we assumed that (*i*) all marginal production of beef is substituted with poultry production (substitution scenario); (*ii*) kilogram per capita/year consumption of protein from meat/legume sources matches USDA Food Pyramid recommendations and is satisfied entirely by livestock products at projected production ratios (livestock scenario); and (*iii*) USDA Food-Pyramid-recommended kilogram per capita/year protein consumption is satisfied entirely by soy beans (soy protein scenario). We then contrasted anticipated 2050 impact levels between scenarios relative to year 2000 levels (*SI Text*). We further estimated the distance to threshold for each of these scenarios relative to published estimates of sustainability boundary conditions of 8.9 Gt of total anthropogenic CO_2-e/year for GHG emissions (necessary to stabilize atmospheric CO_2 at 350 ppm) (calculated from 9); 35 Mt of N_r removed from the atmosphere per year (22); and a biomass appropriation rate of 9.7 Gt of carbon (26).

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