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Perspective

Toward a holistic and data-driven framework to evaluate livestock-derived protein systems

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SCIENCE FOR SOCIETY The ProNES framework advances a comprehensive view of emerging issues across global protein systems by analyzing data on environmental impacts, nutrient composition, and economic value for protein-rich food commodities. The framework can easily be expanded and modified to include different indicators of interest, geographical focus, and bespoke sets of protein-rich commodities. We used it to explore livestock-derived protein systems, where it provided insights into such issues as sustainable intensification, sustainable feed production, and demand optimization.
We found a lack of high-resolution data on the number and types of livelihoods that are tied to different forms of livestock-derived protein production systems. As the demand for animal-sourced foods increases, and as the need to shift toward more sustainable protein production becomes more urgent, such data are crucial to assess the effect that any "protein transition" will have on the people who rely on these systems for their livelihoods. In this way, using a transdisciplinary and holistic approach is necessary to ensure that transitions to truly sustainable food systems are fair and equitable for all.

SUMMARY

The environmental toll of protein production systems, such as greenhouse gas (GHG) emissions and land use associated with the production of livestock-derived foods, poses a substantial challenge for global agricultural sustainability. At the same time, livestock possess significant cultural and economic value for billions, while providing essential macro- and micronutrients. Such tensions fuel a debate on how to optimize livestock production systems, with implications for global nutrition, the environment, and society. Here, we introduce the Protein for Nutrition, Environment, and Society (ProNES) framework to address challenges related to the holistic evaluation of livestock-derived protein systems. ProNES uses publicly available data to comprehensively assess livestock-derived commodities in terms of their nutritional, social, economic, and environmental aspects. The exercise underscores areas where data gaps must be filled for more precise assessments, such as the contributions of livestock production systems to livelihoods across a range of geographic, economic, and sociocultural contexts.

INTRODUCTION

Whether the world will be able to produce enough protein to adequately feed a growing population, and whether it can do so without exceeding planetary boundaries, has emerged as a key set of questions for researchers, policymakers, and the private sector alike.[1] In particular, the environmental toll of current protein production and consumption systems has been cited as a reason to advance a global "protein transition" toward more sustainable approaches.[2] Adequately and responsibly meeting global protein demand is a complex and interdisciplinary challenge. It will require a deeper understanding of the biological value of different dietary proteins, as well as a nuanced grasp of the sociocultural and economic importance of protein-rich food commodities.[3,4] This is in addition to the challenge of advancing protein production systems that sit squarely within established global environmental limits and minimize greenhouse gas (GHG) emissions, land use, water use, and biodiversity loss, among other indicators of environmental performance.[5–9]

Given the sheer scale of livestock-derived protein production systems across the globe—such as an estimated 20%–47% of land area dedicated to livestock production, and an annual stock of chickens that reached over 26 billion in 2022—the environmental impacts of livestock-derived protein production systems must be strictly monitored and carefully evaluated.[10–12] In addition to their environmental performance, the nutritional contributions of livestock are central to any evaluation of protein systems, because livestock-derived foods are currently a vital source of nutrition for billions, and particularly important for the growth of children in certain regions where diets are often of low quality.[13] At the same time, the overconsumption of red and processed meat can contribute to an assortment of negative health outcomes in many dietary contexts.[14,15] To provide further nuance to the issue, a growing body of research highlights the importance of protein quality in addition to protein quantity to gauge the true nutritional utility of a range of protein-rich food commodities.[16] There are also substantial nutritional differences between processed and unprocessed forms of livestock-derived foods and high levels of variation with respect to the relative consumption levels of processed vs. unprocessed livestock-derived foods across contexts.[17]

Definitions of sustainable agriculture extend well beyond environmental performance and nutritional contributions, however, and often include considerations of the social, economic, and cultural value of the entire agricultural supply chain.[9,18] For example, for many smallholder farming communities, livestock can serve as important forms of transportation, labor, capital storage, risk reduction, and income diversification. They are also key indicators of cultural identity and social status, thus vitally contributing to the social, cultural, and economic sustainability of local food systems.[19–22] In addition, some definitions of agricultural sustainability emphasize impacts on animal welfare across production systems.[14,23] All agricultural production systems can be characterized by a series of tradeoffs and synergies across dimensions of sustainability— for example, benefits in animal welfare can come at the expense of increased land use for animal production.[24] Nevertheless, protein systems must strive to reduce negative externalities while amplifying co-benefits and synergies wherever possible.

In the case of protein production systems, there is a clear dearth of data on key dimensions of sustainability that are necessary to inform truly holistic assessments. For example, consistently derived country-level data on the socioeconomic value of different protein-rich food commodities are scarce. Data on the number and type of households whose livelihoods depend on the production and supply chain of individual protein-rich food commodities, as well as the level of household economic dependence on such commodities, are critically lacking. Such data are a crucial input into any effort that seeks to advance a "protein transition" and are necessary to inform responsible policymaking in agriculture and rural development. The expansion of this information through efforts such as the Food and Agriculture Organization of the United Nations (FAO) decadal agricultural census, which can capture important livelihood data for smallholder farmers across the globe, would be immensely beneficial. In addition, since diet is shaped by a confluence of social, cultural, economic, and environmental factors, better local-to-global data on dietary traditions and preferences is critical in any deliberation of how food system transitions should be designed and managed.[25,26]

Here, we put forward the Protein for Nutrition, Environment, and Society (ProNES) framework to demonstrate how transdisciplinary data on food commodities can be collected and presented in a more holistic fashion and use it to examine livestock-derived protein systems. We also incorporate an analysis on protein digestibility, which is often left out of assessments of the environmental performance of protein-rich food commodities. The application of the framework enables us to explore nuances related to sustainable intensification, feed production, and demand optimization. It also highlights key data gaps that are required for more precise assessments, such as the impact that protein system transitions will have on livelihoods across the globe. The goal of the framework is to enable a more nuanced and informed discussion surrounding the often-oversimplified concept of global protein transitions.

Presenting the ProNES framework

The ProNES framework echoes the conceptual groundwork of previous works, such as that put forth by recent FAO work called Progress Towards Sustainable Agriculture, which aims to combine a series of social, economic, and environmental indicators to monitor progress on Sustainable Development Goal 2.4.1.[27] In a similar vein, the ProNES framework attempts to bring nutrition, economic, and environmental data together to examine synergies and tradeoffs at the commodity level, with a special look at livestock production systems in different geographic contexts.

Specifically, the ProNES Framework uses data on environmental impacts, macro- and micronutrient composition, production, supply, and economic value for livestock-derived food commodities across regions, income levels, and production systems (e.g., industrial, mixed, pasture-based, backyard, intermediate). It applies a metric of protein quality called the digestible indispensable amino acid score to rank protein-rich food commodities in terms of their efficiency in producing high-quality protein. It also provides commodity-specific economic and nutritional data by country in various country sets, such as the most food-insecure countries or countries with highest share of employment in agriculture, as a lens to assess the importance of different livestock-derived food commodities in countries with specific food system challenges.

The data indicators and modes of analysis demonstrated in this paper are meant to be indicative of the added value that a more holistic evaluation can provide to improve the discourse on protein transitions. They are not meant to be exclusive to other sources of data or a broader set of potentially useful data indicators. Here, we have used the framework to explore specific issues related to livestock-derived protein systems, but any comprehensive analysis of global protein production systems would necessarily include a much greater degree of focus on the many nutrient-dense, economically important, and culturally vital plant-based sources of protein that are underrepresented in this paper. Aquatic sources of protein are also underemphasized in this paper, even though they have a hugely important and rapidly growing role in the provision of protein for a growing world population.[28]

Social and economic indicators

ProNES uses FAOSTAT data at the country level, such as on the prevalence of child stunting, child wasting, anemia in women of reproductive age, and moderate-to-severe food insecurity, to

Table 1. Digestible indispensable amino acid scores for food commodities

Food item	DIAAS, average	Limited indispensable amino acid, mode	Source
Barley	51	Lysine	Adhikari et al.[16]
Beans	74	SAA	Adhikari et al.,[16]; Herreman et al.[35]
Bovine meat	104	Valine	Adhikari et al.,[16]; Fanelli et al.[90]
Eggs	104	SAA	Adhikari et al.,[16]; Herreman et al.[35]
Fish	103	Histidine, leucine, valine	Shaheen et al.[37]
Hemp	54	Lysine	Herreman et al.[35]
Lentils	54	SAA	Shaheen et al.[37]
Maize	63	Lysine	Adhikari et al.,[16]; Herreman et al.[35]
Milk	102	Histidine	Herreman et al.[35]
Nuts	67	Lysine	Adhikari et al.[16]
Oats	81	Lysine	Adhikari et al.,[16]; Herreman et al.[35]
Peas	71	SAA, valine	Adhikari et al.,[16]; Herreman et al.[35]
Pigmeat	121	Valine	Adhikari et al.,[16]; Herreman et al.,[35]; Fanelli et al.[90]
Potatoes	54	NA	Herreman et al.[35]
Poultry meat	108	NA	Ertl et al.[36]
Rice	55	Lysine	Adhikari et al.,[16]; Herreman et al.,[35]; Shaheen et al.[37]
Rye	47	Lysine	Adhikari et al.[16]
Sorghum	29	Lysine	Adhikari et al.[16]
Soybeans	98	SAA	Adhikari et al.,[16]; Herreman et al.[35]
Wheat	47	Lysine	Adhikari et al.,[16]; Herreman et al.,[35]; Shaheen et al.[37]

Only protein reference patterns: >3 years old used. No isolates or protein powders considered. NA, not applicable; SAA, sulfur amino acid

create country sets that facilitate the analysis of protein systems in countries with specific food system challenges.[29] Such indicators are not purely diet dependent since they can be affected by nonfood factors that affect one's ability to use nutrients from food. However, in lieu of more detailed commodity-specific datasets on the links between socioeconomics and nutrition, this type of analytical lens can serve as a useful proxy to glean data from a subset of countries facing significant food system challenges. Here, we select the top quintile of countries with the highest prevalence of those indicators to examine the supply of individual commodities available in those country sets alongside their nutritional value and environmental performance. To examine the relative economic importance of protein-rich food commodities, we use gross production value data of individual commodities.[30] Commodity production value data were used for countries with the highest share of labor force in agriculture, as well as countries classified as low or lower-middle income by the World Bank.[31]

Production and supply data

Country-level production and supply data were obtained from FAO Food Balance Sheets data.[32] To disaggregate livestock across production systems, we used data from the Global Livestock Environmental Assessment Model (GLEAM), which contains data on the amount of protein produced from different livestock production systems at the subcontinental level. These relative proportions, which are regionally specific, were applied to Food Balance Sheet data in 2017 and used as a proxy to estimate the amount of production of each livestock-derived food commodity for countries in each region. Since Food Balance

Table 2. Livestock production system classification table

GLEAM commodity	GLEAM production system	ProNES commodity	ProNES production system
Cattle meat	Grassland, mixed, feedlots	Bovine meat	Pasture based,[a] mixed, industrial
Buffalo meat	Grassland, mixed	Bovine meat	Pasture based, mixed
Cattle milk	Grassland, mixed	Bovine milk	Pasture based, mixed
Buffalo milk	Grassland, mixed	Bovine milk	Pasture based, mixed
Sheep meat	Grassland, mixed	Mutton and goat meat	Pasture based, mixed
Goat meat	Grassland, mixed	Mutton and goat meat	Pasture based, mixed
Pigs	Backyard, intermediate, industrial	Pigmeat	Backyard, intermediate industrial
Chicken eggs	Layers, backyard	Eggs	Industrial, backyard
Chicken meat	Broilers, backyard	Poultry meat	Industrial, backyard

[a]Pasture based is defined by systems in which over 90% of animal feed source come from pasture (Gerssen-Gondelach et al.[40]).

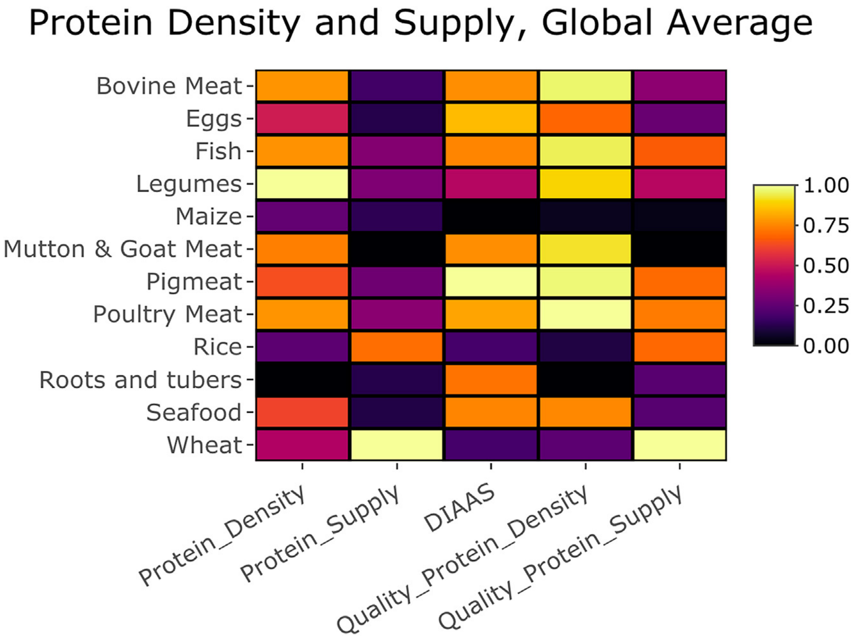

Figure 1. Protein density (grams per kilogram product) and supply (grams per capita per day), next to high-quality protein density and high-quality protein supply (protein density and supply are adjusted by the DIAAS)

Each indicator in this figure is scaled to reflect the specific subset of items being examined in the selected analytical context. Lighter colors indicate higher nutritional density, higher DIAAS, and higher supply. Source data, including commodity nutrition composition, are either country or region specific and are aggregated using a weighted mean. All of the data represent the year 2017.

Sheets only include a milk aggregate without specifying the milk source, the ratio of bovine milk to nonbovine milk in FAOSTAT commodity production data was used as a proxy for the supply of milk in each country that comes from either bovine or nonbovine sources.[33]

Nutrition composition data

Macro- and micronutrient profiles of all food commodities were taken from the Global Expanded Nutrient Supply Model (GENuS).[34] GENuS contains regionally specific estimates for nutrient profiles across food commodities, such as the concentration of calories, protein, fat, iron, zinc, calcium, and folate per mass of food product, among other nutrition indicators. Missing commodity data were imputed by calculating the average of items in smaller item groupings in a region, and, if still unavailable, by applying the global average for the item or item group. If data were still unavailable at this level, then regional means from larger item categories were applied and global means if regional data were unavailable. Item group and category means at both regional and global levels were weighted according to the production quantity of the food commodities in the group or category.

We also used the protein quality metric of the digestible indispensable amino acid score (DIAAS), which was recommended by the FAO in 2011 as a replacement for previous protein

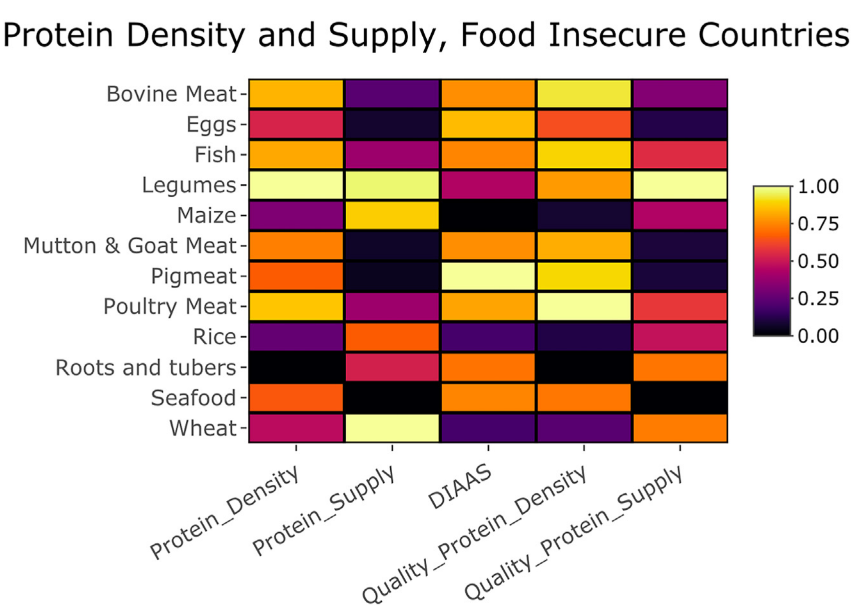

Figure 2. Protein density (grams per kilogram product) and supply (grams per capita per day), next to high-quality protein density and supply (protein density and supply adjusted by the DIAAS)

Top quintile of food-insecure countries. Each indicator in these figures is scaled to reflect the specific subset of items being examined in the selected analytical context. Lighter colors indicater higher protein density, higher DIAAS, and higher supply. Source data, including commodity nutrition composition, are either country or region specific and are aggregated using a weighted mean. All of the data represent the year 2017.

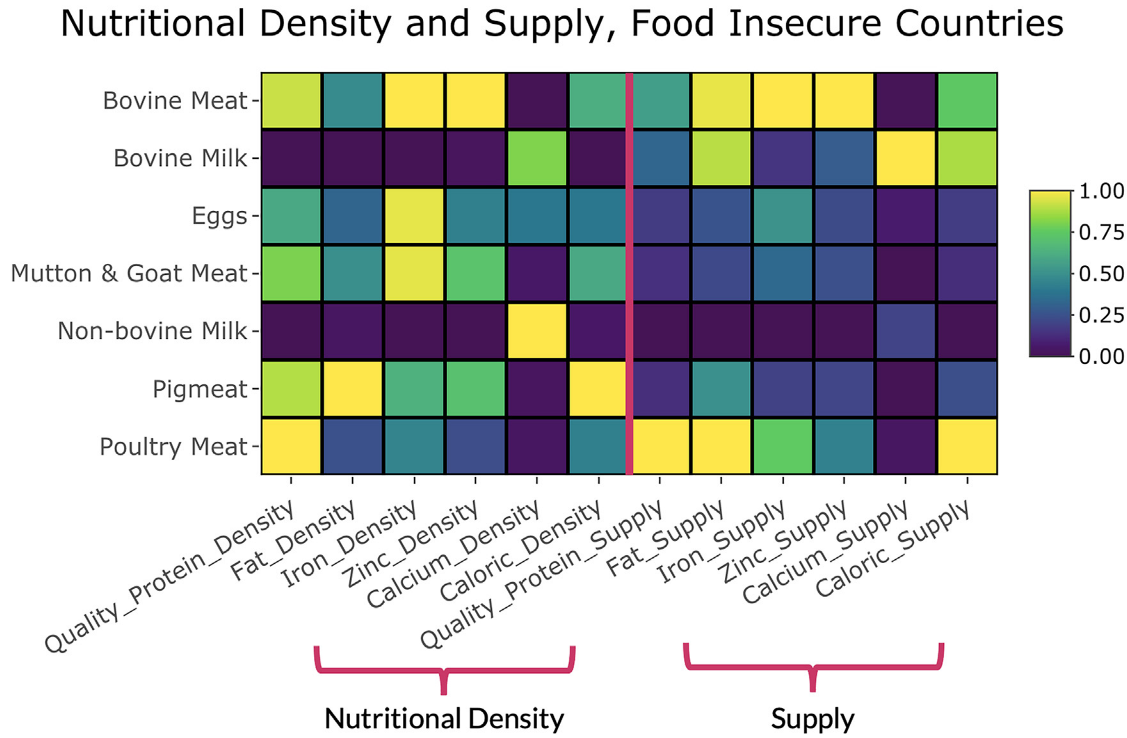

Figure 3. Nutritional profile and supply of livestock-derived foods in food-insecure countries
Each indicator in this figure is scaled to reflect the subset of items being examined in the selected context of analysis. Source data, including commodity nutrition composition, are either country or region specific and are aggregated using a weighted mean. Lighter colors indicate higher nutritional density and higher supply. All of the data represent the year 2017. Iron, zinc, and calcium densities are not adjusted for their bioavailability.

quality metrics.[16] The DIAAS represents an advancement over some previously used protein quality metrics for two main reasons: (1) they reflect the ileal digestibility of individual amino acids, which has been found to be more accurate on average than fecal digestibility, and (2) they focus on amino acids that the body cannot synthesize (i.e., "indispensable" amino acids). In addition to communicating the relative protein quality of different food commodities, the DIAAS can be used to modify our understanding of the environmental performance of different food commodities by including a measure of protein quality alongside protein quantity (Table 1). However, the DIAAS must be used with caution because there are relatively few studies that examine a comprehensive range of food items with a consistent methodology, and there is significant variation in the DIAAS across studies for the same food commodity.[22,35–37]

Finally, it is important to note that DIAASs are highly dependent on the cooking methods applied and do not reflect protein complementarity—that is, they do not account for the protein profile of foods that are eaten in combination, which would better reflect real-world eating situations. Nevertheless, by multiplying protein quantity by the DIAAS of a food item, we can develop some sense of the relative availability of high-quality protein stemming from different proteinaceous food commodities in each country and region.

Environmental indicators

GHG emissions from rice production were taken from the FAOSTAT emissions intensities dataset and are available at the country level.[38] For livestock-derived foods, GHG emissions factors are regionally specific and livestock production system specific and were taken from GLEAM 2.0. For all other foods, global average GHG emissions factors from Poore and Nemecek were applied.[7] Land use data for bovine meat and milk are taken from Herrero et al. and Gerssen-Gondelach et al. and contain regionally specific data disaggregated by livestock production system.[39,40] Land use data for all other food commodities are global means taken from Poore and Nemececk.[7] Data on freshwater use, eutrophying emissions, and acidifying emissions are also commodity-specific global means taken from Poore and Nemecek.[7] Missing commodity data were imputed in the same fashion as for the nutrition indicators. The livestock production systems of Gerssen-Gondelach et al. and GLEAM 2.0 are matched as shown in Table 2.

Data scaling and interpretation

The data used for all indicators in this work are for the year 2017 because it was the last year that data sources across all of the indicators were consistently available. All of the indicators are scaled between 0 and 1 for the purpose of visualizing them alongside one another in a consistent fashion, while maintaining the relative distance of the data. Where higher indicator values are positively associated with desirable attributes, such as high relative protein percentage or high relative economic value, the data are scaled naturally such that the highest value is set to 1 and the lowest value is set to 0. Where higher indicator values are negatively associated with desirable attributes, such as GHG emissions and land use, the data are scaled in reverse order, such

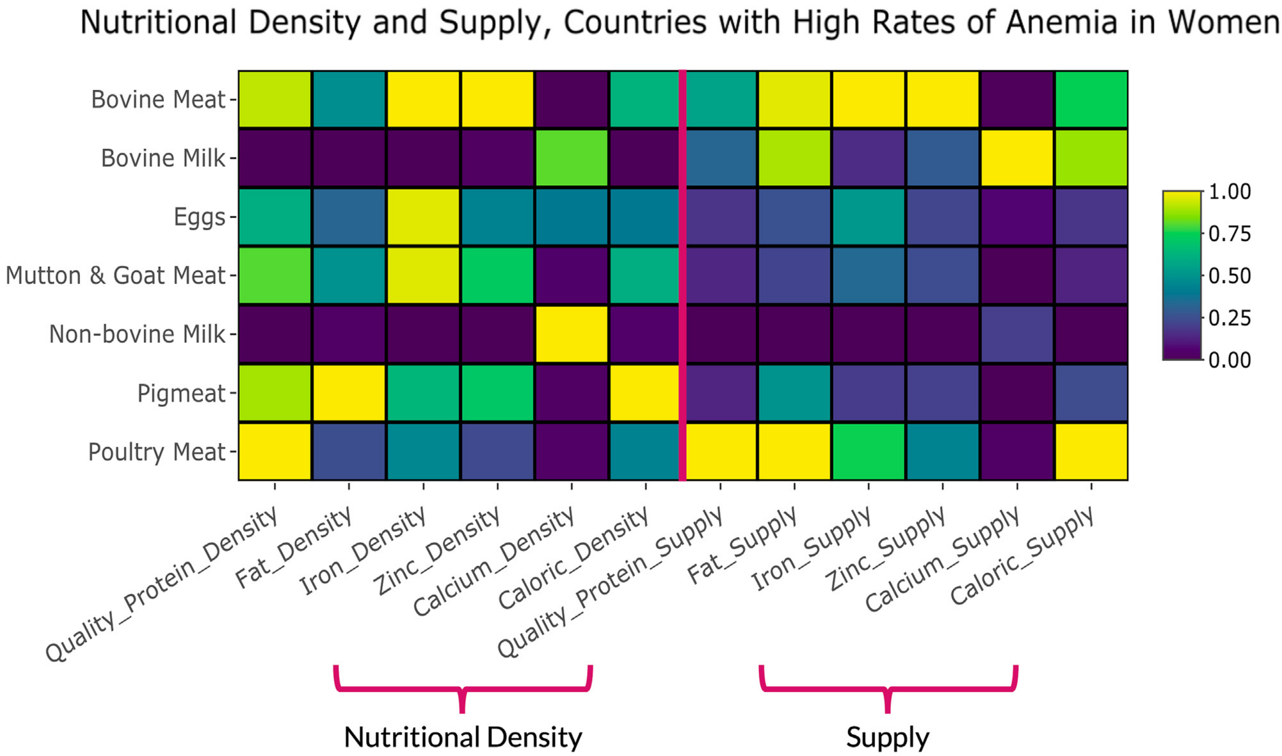

Figure 4. Nutritional densities and supply from livestock-derived foods in countries with a high prevalence of anemia in women

Each indicator is scaled to reflect the specific subset of items being examined in the selected context of analysis. Lighter colors indicate higher nutritional density and higher supply. Source data, including commodity nutrition composition, are either country or region specific and are aggregated using a weighted mean. All of the data represent the year 2017. Iron, zinc, and calcium densities are not adjusted for their bioavailability.

that the highest value is set to 0 and the lowest value is set to 1. This provides for an intuitive visual framework for comparing indicators alongside one another, as demonstrated in the results section below. Each indicator is scaled based on the list of items that is analyzed in that specific table, so that each table represents a purely relative ranking for each contextual analysis. Source data, including commodity nutrition composition, are either country or region specific and are aggregated in respective country sets using a weighted mean (weighted based on either production or consumption quantity, depending on the indicator).

Applications of the ProNES framework

Examples in nutritional analysis

Figures 1 and 2 present protein density and supply of protein-rich food commodities alongside their DIAAS and subsequent quality protein rankings. Protein densities are expressed as grams per kilogram of product, which is why milk products were excluded from the list, since they would have the lowest protein density per kilogram of product by a significant margin (expressing protein densities per 1,000 kcal of food product will provide for better standardization of milk and meat products in future iterations of this type of analysis). Protein supply is expressed in units of grams per capita per day and is a weighted average of the country sets displayed below.

At a high-level first glance, wheat, pigmeat, poultry, rice, and fish currently provide the highest relative amount of quality protein supply per capita globally (Figure 1), whereas legumes and roots and tubers currently supply more per capita high-quality protein in countries with the highest prevalence of food insecurity (Figure 2). In general, the supply of protein in food-insecure countries is weighted more heavily toward plant-based sources than livestock-derived foods, although this balance can shift significantly both within and across countries.

Adding micronutrient composition to the analysis (Figures 3 and 4) provides a fuller nutritional examination of protein-rich food commodities. Here, it is important to note that iron and zinc have markedly different bioavailability across food types, for which this version of the framework does not currently adjust. One key source of differentiation is that heme iron, which is available only from animal sources, is generally well absorbed by the body compared to nonheme iron.[41–43] Furthermore, phytate, polyphenols, and calcium are known to decrease iron absorption.[43] Zinc bioavailability is also negatively affected by the presence of phytate, which is present in plant-based foods, with the highest levels occurring in unrefined cereals, legumes, and oilseeds (animal-sourced foods have none).[44,45] However, phytate levels in plant-based foods can be significantly lowered through a variety of traditional and industrial food processing methods, as well as through modern approaches such as transgenic biofortification.[45–47] Calcium is generally absorbable in dairy products, and its bioavailability has been reported to be negatively affected by the presence of phytate and oxalate, the latter of which can

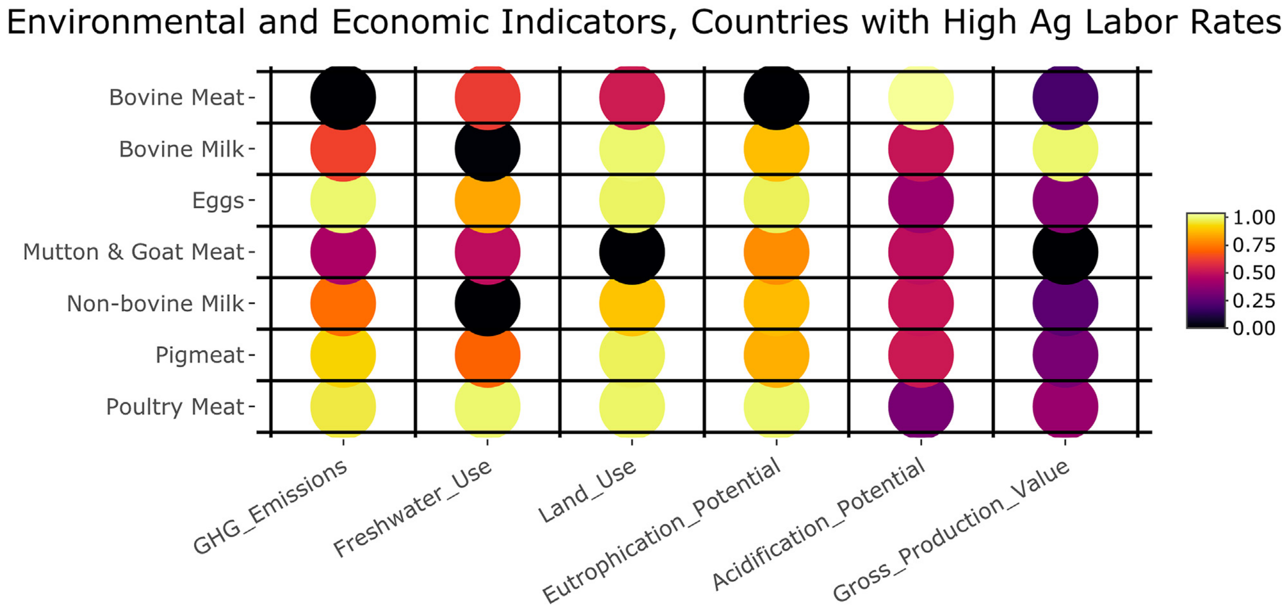

Figure 5. Environmental performance and economic production value of livestock-derived foods in the top quintile of countries with the highest labor force share in agriculture
All of the indicators are calculated per gram of high-quality protein (high-quality protein = protein concentration × DIAAS). Each indicator in this figure is scaled to reflect the specific subset of items being examined in the selected context of analysis. Lighter colors indicate more desirable features, such as fewer GHG emissions or higher gross production value. Source data, including commodity nutrition composition, are either country or region specific and are aggregated using a weighted mean. All of the data represent the year 2017.

be found in relatively high quantities in protein-rich commodities such as legumes and tree nuts.[48] Calcium from dairy products can act as an inhibitor of iron uptake, but such interactions are heavily mediated by the dose of each micronutrient.[44] The presence of micronutrients in food is also affected by many nondietary factors such as soil characteristics and agricultural management practices.[49,50] There are also potential differences in the nutritional composition of livestock-derived foods across production systems, such as pasture-based vs. industrial bovine meat production.[51]

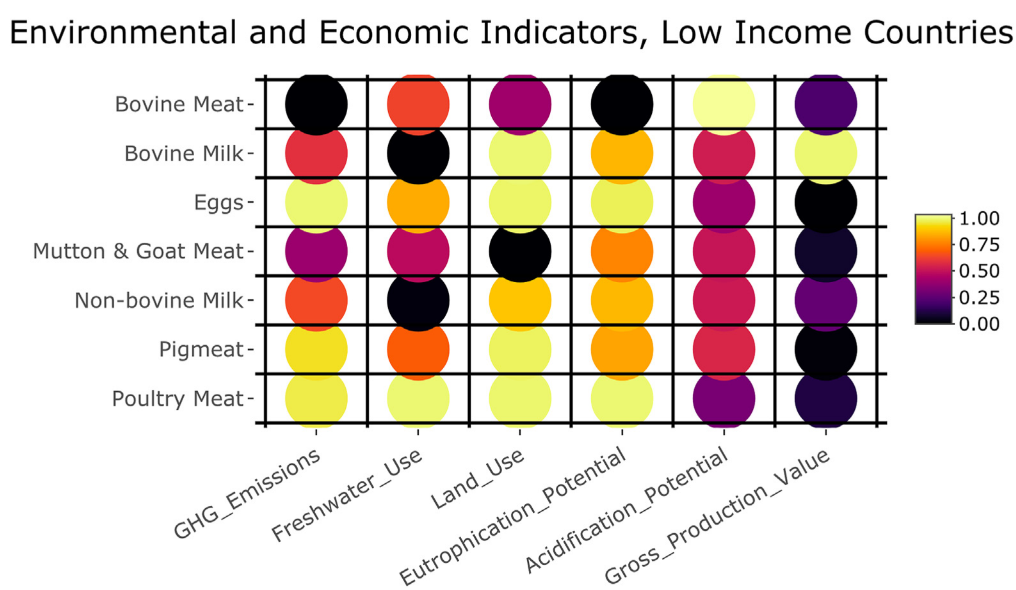

Figure 6. Environmental performance and production value of livestock-derived foods in the top quintile of countries with the highest labor force share in agriculture
All of the indicators are calculated per gram of high-quality protein (high-quality protein = protein concentration × DIAAS). Each indicator in this figure is scaled to reflect the specific subset of items being examined in the selected context of analysis. Lighter colors indicate more desirable features, such as fewer GHG emissions or higher gross production value. Source data, including commodity nutrition composition, are either country or region specific and are aggregated using a weighted mean. All of the data represent the year 2017.

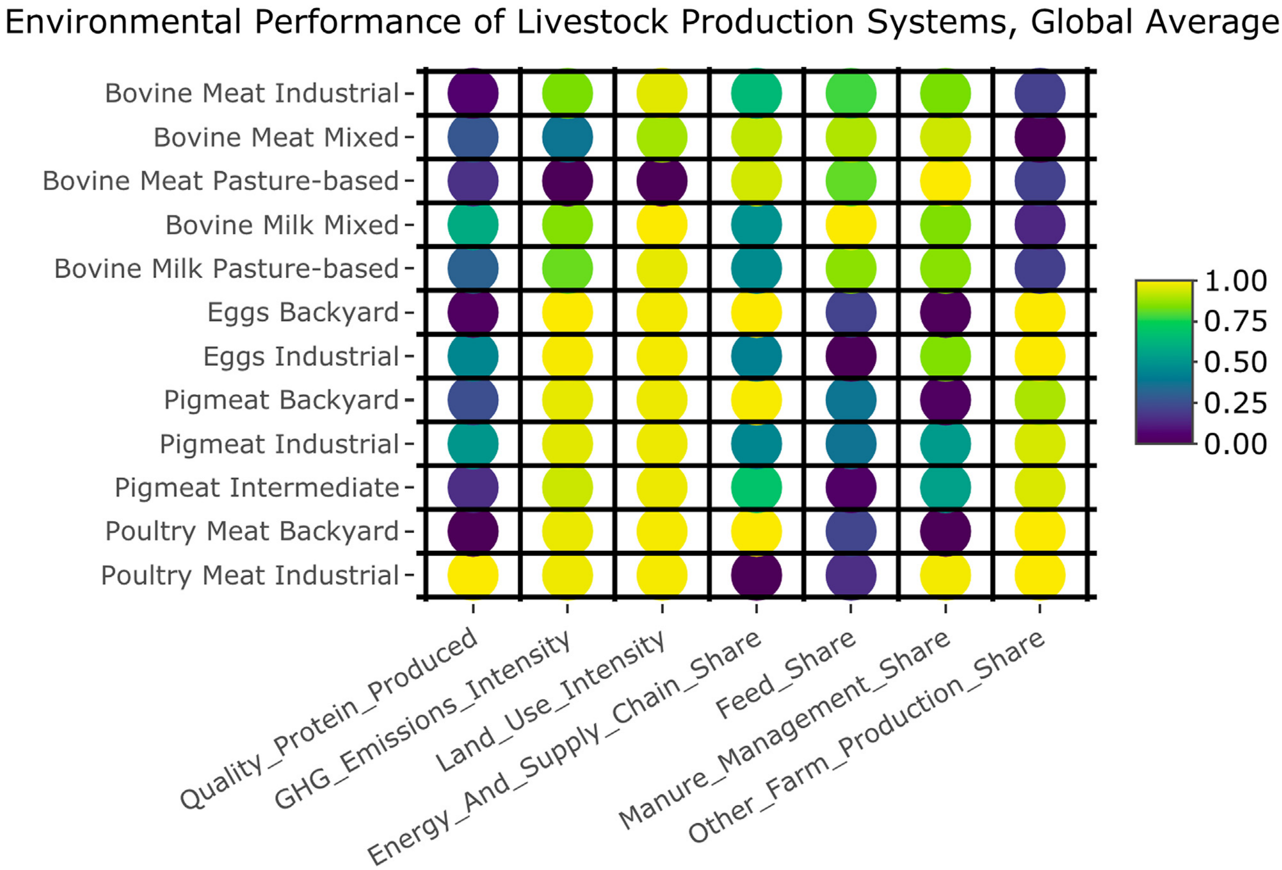

Figure 7. High-quality protein produced alongside GHG emissions intensity, land use intensity, and the GHG emissions profile of various livestock production systems: global average

GHG emissions and land use intensities are per unit of high-quality protein produced. GHG emissions shares are percentages of overall GHG emissions from specific elements of livestock production chains (red = high percentage). Enteric fermentation is included in "other farm production share." Each indicator in this figure is scaled to reflect the specific subset of items being examined in the selected context of analysis. Lighter colors indicate more desirable features, such as higher quality protein produced and lower GHG emissions intensity. They also indicate lower GHG emission shares for each source category. Source data are either country or region specific and are aggregated using a weighted mean. All of the data represent the year 2017.

Nevertheless, bovine meat contains relatively high quantities of high-quality protein, iron, and zinc compared to other livestock-derived products. Although poultry meat currently provides the largest amount of per capita livestock-derived high-quality protein in countries with the highest prevalence of food insecurity (Figure 3), as well as in countries with the highest prevalence of anemia in women of reproductive age (Figure 4), bovine meat provides the highest quantities of iron and zinc in those country sets relative to other livestock-derived foods. Bovine milk has the highest supply quantity in both country sets and is a relatively significant source of calcium, fat, and calories in both country sets. Eggs and mutton and goat meat have a high iron quantity but are low in supply in countries with a high incidence of anemia. Pigmeat contains relatively high densities of calories and fat but are in low supply in countries with a high prevalence of moderate or severe food insecurity (Figure 3).

Examples in environmental and economic analysis

For countries with the highest share of labor force in agriculture, bovine milk has the highest gross production value of all livestock-derived products, followed by poultry meat (Figure 5). Bovine meat and mutton and goat meat provide relatively minimal economic value in these countries, while possessing high GHG emissions intensities and land use intensities per unit of high-quality protein measured. In low-income countries, livestock-derived food products had similar environmental performance across commodities, and bovine milk was also found to be the most economically important commodity by gross production value (Figure 6). Unlike in the high agricultural labor country set, bovine meat was found to be the second most economically important item in low-income countries in terms of gross production value (Figure 6).

Examples in environmental analysis across production systems

There are wide variations in environmental performance of livestock-derived food commodities by production system (Figures 7, 8, 9, and 10). Industrial poultry meat production currently produces the most high-quality protein relative to other livestock production systems considered at various scales, including globally and in Sub-Saharan Africa, Latin America, and the Caribbean,

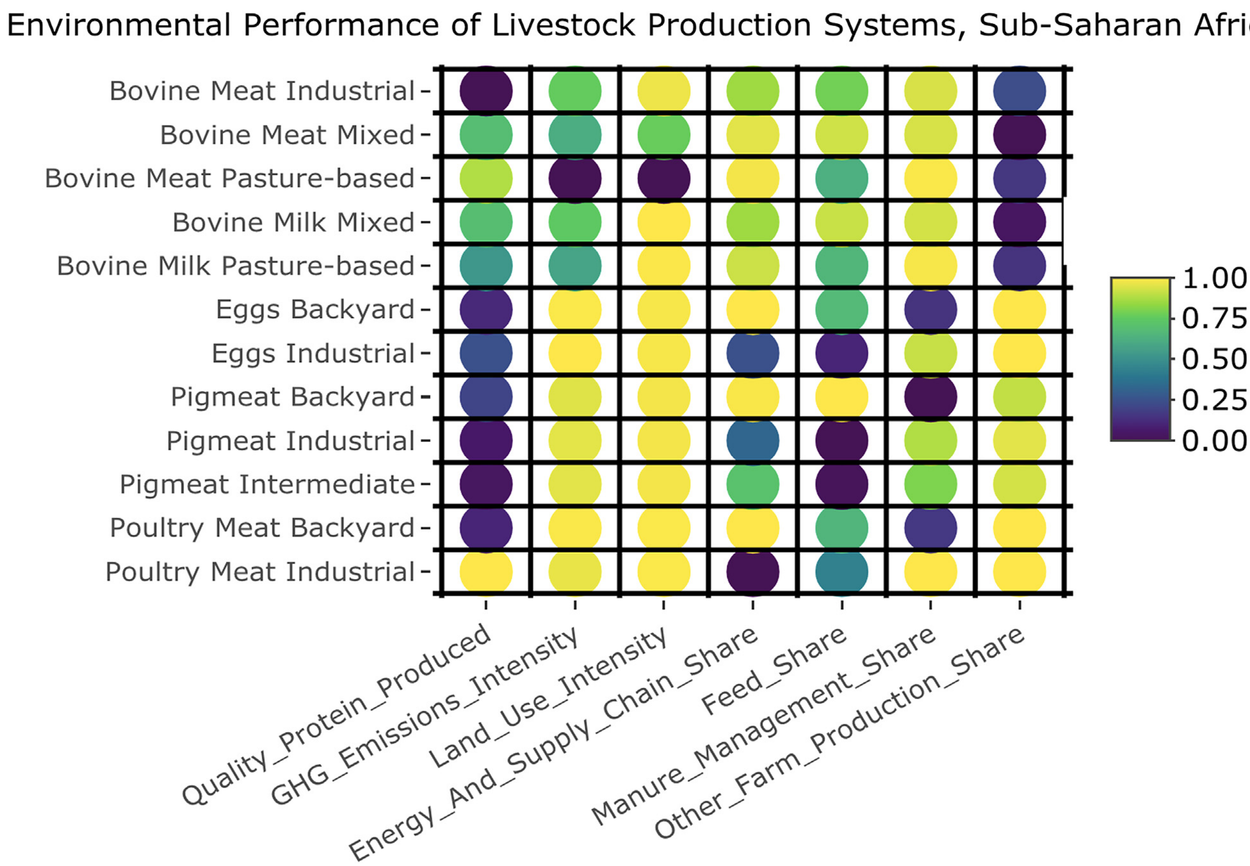

Figure 8. High-quality protein produced alongside GHG emissions intensity, land use intensity, and the GHG emissions profile of various livestock production systems: Sub-Saharan Africa

GHG emissions and land use intensities are per unit of high-quality protein produced. GHG emissions shares are percentages of overall GHG emissions from specific elements of livestock production chains (red = high percentage). Enteric fermentation is included in "other farm production share." Each indicator in this figure is scaled to reflect the specific subset of items being examined in the selected context of analysis. Lighter colors indicate higher quality protein produced, lower GHG emissions and land use intensities, and lower GHG emissions shares for each source category. Source data are either country or region specific and are aggregated using a weighted mean. All of the data represent the year 2017.

and in high-income countries (Figures 7, 8, 9, and 10). Poultry meat and pigmeat have the lowest GHG emissions intensity per measure of high-quality protein, with relatively higher shares of their GHG emissions stemming from feed production and manure management. This is as opposed to ruminant meat and milk, which have higher emissions intensities, land use requirements, and relatively low shares of their emissions deriving from feed production and manure management, instead deriving primarily from enteric fermentation, which falls into the "other agricultural production" category here. GHG emissions from bovine meat and mutton and goat meat consistently increase with more extensive production systems that occupy more land. The emissions intensity of pasture-based bovine meat is the highest among livestock-derived food products, especially in Sub-Saharan Africa and Latin America and the Caribbean. (Figures 8 and 9).

Finally, it is important to note the variance across regions in the environmental performance of production system categories. As Table 4 demonstrates, drawing on data from Table 3, the SD of the carbon and land footprint of pasture-based production systems is much larger than it is for mixed systems, which is in turn much larger than it is for industrial systems. Importantly, duplicative values were removed when calculating the variance so that redundant values (caused by gap-filling missing data with larger regional values) did not affect the variance calculation.

DISCUSSION

The ProNES framework aims to advance a more comprehensive view of emerging issues across global protein systems by analyzing data on environmental impacts, nutrient composition, and economic value for protein-rich food commodities for countries with unique food system challenges. The framework can be expanded and modified for different economic and geographic contexts and can easily include a broader set of indicators of interest, as well as a wider array of plant-based, aquatic, and alternative protein commodities. Here, we have used it to explore key issues and opportunity areas within and across livestock-derived protein production systems. The application of the framework exposed a few key themes worthy of discussion, such as nuances in sustainable intensification, sustainable feed production, and the optimization of demand for livestock-derived foods. We conclude with notes on the types of data

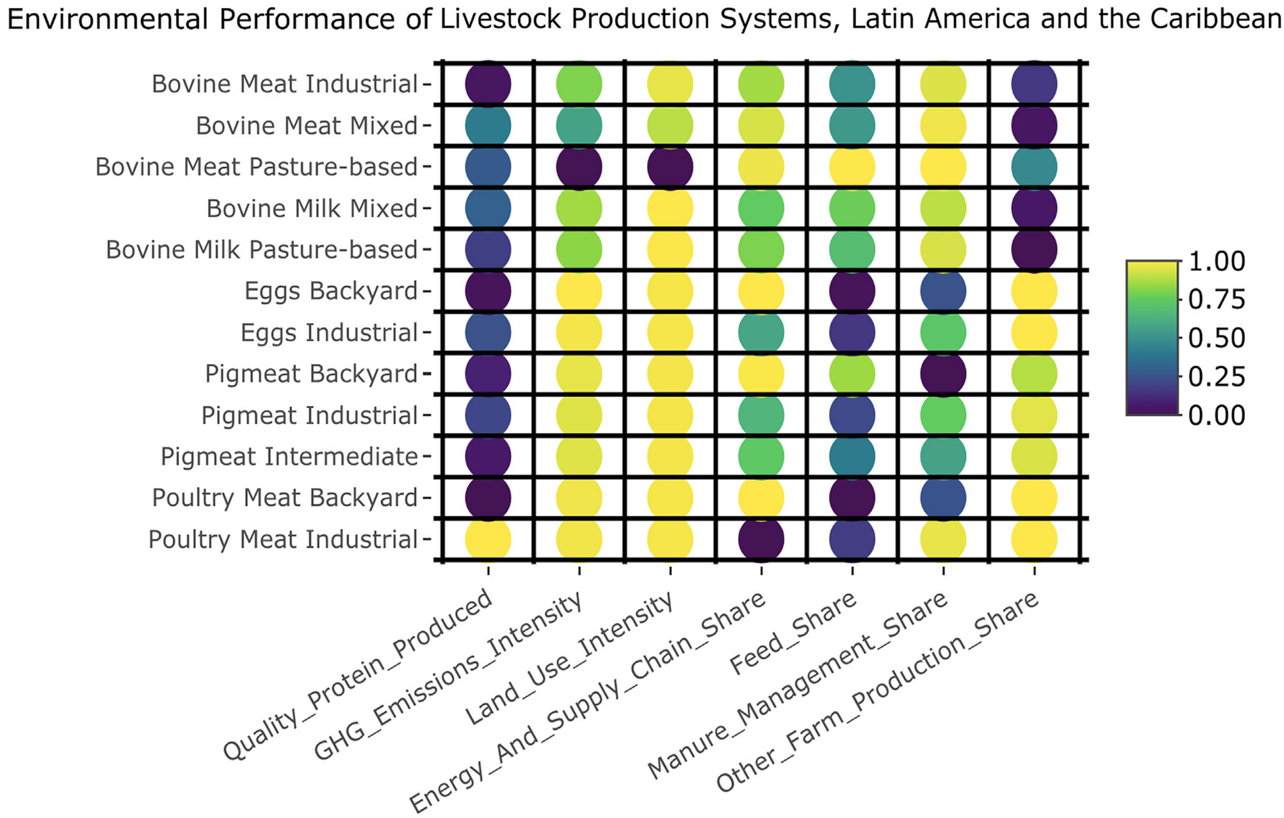

Figure 9. High-quality protein produced alongside GHG emissions intensity, land use intensity, and the GHG emissions profile of various livestock production systems: Latin American and the Caribbean

GHG emissions and land use intensities are per unit of high-quality protein produced. GHG emissions shares are percentages of overall GHG emissions from specific elements of livestock production chains (red = high percentage). Enteric fermentation is included in "other farm production share." Each indicator in this figure is scaled to reflect the specific subset of items being examined in the selected context of analysis. Lighter colors indicate higher quality protein produced, lower GHG emissions and land usee intensities, and lower GHG emissions shares for each source category. Source data are either country or region specific and are aggregated using a weighted mean. All of the data represent the year 2017.

that are most sorely needed to unlock much deeper evaluations of local-to-global protein systems.

Sustainable intensification of pasture-based bovine production

Bovine meat is among the highest sources of high-quality protein from livestock available in Sub-Saharan Africa, while contributing, on average, the highest GHG emissions intensity from all livestock production systems considered (Figures 7 and 8). However, this framework also clearly shows that sustainable intensification of beef production would make a significant impact on reducing both the land use and GHG emissions profile of beef production, particularly at the regional level in places such as South America or Sub-Saharan Africa.[52] Given the demonstrated nutritional importance of bovine meat in food-insecure countries (Figure 2), as well as the disproportionate average climate and land use impact of extensive, pasture-based bovine meat production systems in those countries (Table 3), sustainable intensification of bovine meat could be one focal area in efforts to advance sustainability. However, it is important to consider that the largest relative change in GHG emissions intensities, in general, were found to be within pasture-based systems, as opposed to differences between pasture-based and mixed systems or between mixed and industrial systems per se (Table 4). In other words, there is more variation in environmental performance across ruminant pasture-based systems in different parts of the world than there is between pasture-based, mixed, and industrial systems.

The suite of practices that often fall under "sustainable intensification" provide promising pathways to advance sustainable beef production systems[53–56] and diverge significantly from prevailing forms of industrial beef production. For many livestock producers, however, sustainable intensification practices, such as crop-livestock integration, higher stocking rates, rotational grazing, and pasture seeding, fertilization, and irrigation, entail a need for increased capital and labor costs that can either enhance or decrease profitability, depending on circumstance.[57,58] Nevertheless, the theoretical global potential for sustainable intensification is high even in grazed-only permanent pastures, and properly managed grazing intensification can improve biodiversity and ecosystem services even in a dryland context.[59,60]

Toward sustainable feed production

One of the main sources of variation across livestock production systems is the production and procurement of feed. The growth of the livestock sector, even in areas with highly productive native

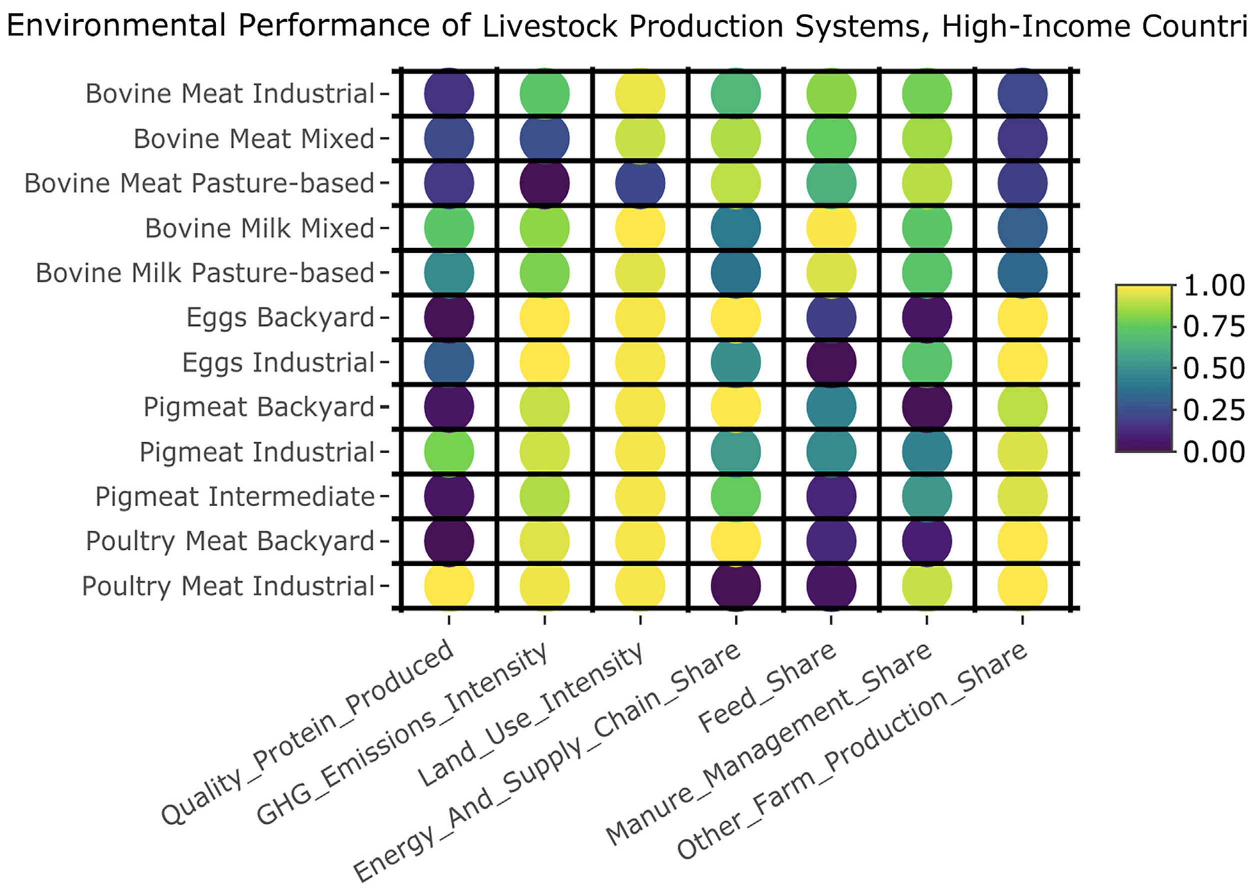

Figure 10. High-quality protein produced alongside GHG emissions intensity, land use intensity, and the GHG emissions profile of various livestock production systems: high-income countries.
GHG emissions and land use intensities are per unit of high-quality protein produced. GHG emissions shares are percentages of overall GHG emissions from specific elements of livestock production chains (red = high percentage). Enteric fermentation is included in "other farm production share." Each indicator in this figure is scaled to reflect the specific subset of items being examined in the selected context of analysis. Lighter colors represented higher quality protein produced, lower GHG emissions and land use intensities and lower GHG emissions shares for each source category. Source data are either country or region specific and are aggregated using a weighted mean. All of the data represent the year 2017.

grasslands, has been accompanied by tremendous increases in the amount of land used to produce feed, some of which is converted from natural ecosystems for agricultural purposes.[5,61] The amount of land currently used for livestock feed production at the global level is approximately 2.5 billion ha—nearly half of the global agricultural area—with the largest share in grasslands, comprising nearly 2 billion ha.[62] That equates to 500 million ha of land converted specifically to produce feed. Assuming that rates of sustainable intensification increase in the future, this will put even more pressure on feed production, since supplementing animal diets with feed from outside sources is one practice that is often associated with intensified livestock production.[63]

The ProNES framework shows that industrial livestock production systems, such as industrial poultry and pigmeat systems, have consistently lower land use and GHG emissions than land-based production systems, with a higher proportion of their GHG emissions stemming from feed production (Figures 7–10). Although these production systems may be more environmentally efficient from a land and climate standpoint relative to other livestock production systems, they are still less environmentally efficient than plant-based proteins such as legumes, even when considering protein quality. They have also been noted to be among the poorest-performing protein systems from an animal welfare perspective in a variety of contexts.[64,65] Furthermore, such productions systems are often responsible for a disproportionate negative impact on surface and groundwater quality due to the intense concentration of manure production and associated land application at rates that can exceed agronomic uptake of nutrients.[66,67] However, various management systems are available to minimize such effects through the circular utilization of available by-products (methane, nutrients, and solids), and associated deployment would benefit from support for broader geographic and sector application.[68,69]

Nevertheless, the production of monogastrics such as poultry meat and pigmeat requires less feed per kilogram of meat produced than ruminants, on average, although this comparison can be difficult to make given the variation in types of feed that these two classes of livestock primarily consume (e.g., grain vs. forage).[70,71] Still, given the current global importance of industrial pigmeat and poultry meat as a source of high-quality protein (Figure 1), and the significant projected increases in demand for poultry meat and pigmeat in the future,[72] it is imperative

Table 3. Regional environmental performance indicators for bovine meat production systems

Region name	Production system	Adjusted GHG intensity (kg CO_2equiv/kg high-quality protein)	Adjusted land intensity (ha/1,000 tonnes high-quality protein)
Australia and New Zealand	Industrial	143	9,485
Caribbean	Industrial	165	9,041
Eastern Africa	Industrial	171	9,133
Eastern Asia	Industrial	167	9,026
Middle Africa	Industrial	179	9,537
North America	Industrial	89	10,370
Northern Europe	Industrial	98	10,370
Southeast Asia	Industrial	167	9,271
Southern Europe	Industrial	105	10,370
Western Africa	Industrial	178	9,501
Australia and New Zealand	Mixed	229	21,613
Caribbean	Mixed	336	20,588
Central America	Mixed	336	20,588
Central Asia	Mixed	233	23,268
Eastern Africa	Mixed	265	61,696
Eastern Asia	Mixed	429	20,088
Eastern Europe	Mixed	120	23,268
Melanesia	Mixed	229	21,410
Middle Africa	Mixed	277	64,484
Northern Africa	Mixed	232	31,407
North America	Mixed	258	23,268
Northern Europe	Mixed	149	23,135
Southeast Asia	Mixed	429	20,630
Southern Asia	Mixed	560	18,631
Southern Europe	Mixed	148	23,268
Western Africa	Mixed	276	62,874
Western Asia	Mixed	235	22,070
Western Europe	Mixed	149	23,268
Australia and New Zealand	Pasture based	258	182,280
Caribbean	Pasture based	766	174,381
Central Asia	Pasture based	478	198,385
Eastern Africa	Pasture based	647	255,682
Eastern Asia	Pasture based	584	174,146
Eastern Europe	Pasture based	122	198,385
Melanesia	Pasture based	258	183,981
Middle Africa	Pasture based	676	267,030
Northern Africa	Pasture based	478	206,792
North America	Pasture based	283	198,385
Northern Europe	Pasture based	162	198,188
South America	Pasture based	766	173,583
Southeast Asia	Pasture based	584	180,362
Southern Asia	Pasture based	588	198,060
Southern Europe	Pasture based	161	198,385
Western Africa	Pasture based	674	263,559
Western Asia	Pasture based	484	192,347
Western Europe	Pasture based	162	198,385

Table 4. SD for environmental performance indicators across bovine meat production systems

Item	Adjusted GHG emissions: SD	Adjusted land use: SD
Bovine meat industrial	35	555
Bovine meat mixed	113	15,789
Bovine meat pasture based	224	29,343

to invest in the development of sustainable feed production systems, even in scenarios in which legume production and consumption are sufficiently scaled up to provide more environmentally responsible substitutes for significant segments of the poultry and pigmeat market.

There are a variety of promising pathways to improve feed systems, such as more sustainably produced inputs and enhancements in feed regimens that yield greater conversion efficiency. One that has gained attention in recent years is insect production for poultry feed.[73,74] Developing industrial systems to grow single-celled microbial proteins in aerobic fermentation reactors is another promising feed production system with the potential to significantly reduce land use.[75] Improvements in feed use efficiency, which can be accomplished in a number of ways, including but not limited to genetics, feed additives, and improvements in feed quality, can reduce GHG emissions both by increasing resource efficiency and by altering the microbial composition of ruminant digestive systems.[76,77]

Optimizing demand of livestock-derived foods

In addition to analyzing the relative environmental impacts of livestock-derived protein production systems, the ProNES framework highlights variances in the livestock-derived supply of micro- and macronutrients in different contexts (Figures 3 and 4). This represents a preliminary foray into a set of important questions related to consumer-facing issues, such as consumer access to and affordability of different protein-rich food commodities. Given the improved data on the access and affordability of different protein-rich food commodities at the local and country level, future iterations of this framework could easily be used to help optimize demand for livestock-derived foods in countries where consumption of those products are in excess of human dietary requirements, which could serve as one strategy to minimize the negative environmental impacts of protein production systems[78,79] However, in countries where protein consumption is relatively low, increasing the access, availability, and affordability of nutrient-dense livestock-derived foods could be one key lever to bolster the supply of key macro- and micronutrients. Such efforts should be paired with programs to increase the access, availability, and affordability of rich sources of plant-based protein, such as legumes, seeds, and nuts.

Promoting the consumption of more diverse, plant-rich diets through public education campaigns and increasing their availability in schools, hospitals, and other public institutions via public procurement policy are examples of interventions that could advance more environmentally optimized protein-rich food baskets.[80–82] In addition to reducing the environmental impact of

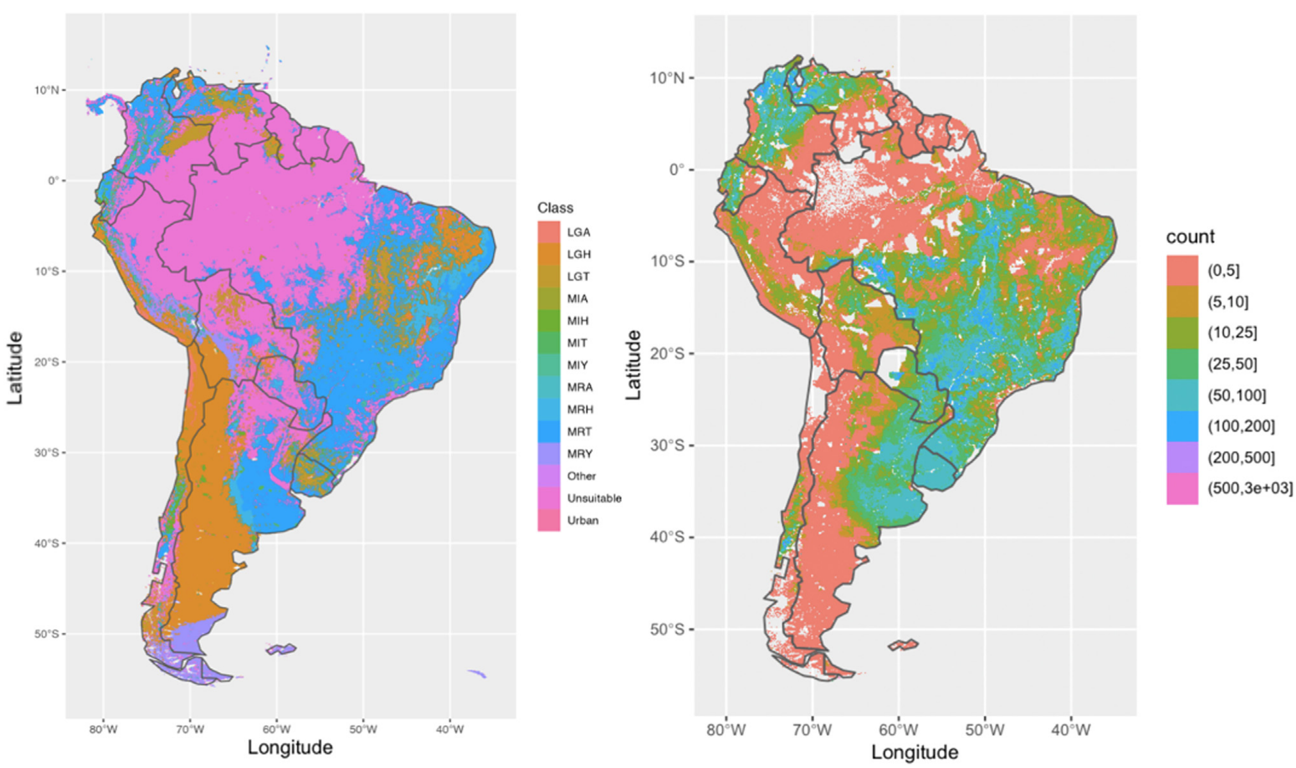

Figure 11. Livestock production systems and bovine count in South America

The classification system is as follows: livestock only, grassland based (LG), which may be arid/semiarid (LGA), humid/subhumid (LGH), or tropical highland/temperate (LGT); rainfed systems (MR) by the 3 agroecological zones, such as arid/semiarid (MRA) and mixed, irrigated systems (MI), and also by the 3 agroecological zones, such as arid/semiarid (MIA). (Left) Adapted from Robinson and FAO[84]; (right) adapted from Gridded Livestock of the World (version 2.01).[84]

protein production, shifting consumption toward plant-based protein sources can provide health benefits for many individuals. Such dietary transitions can be associated with a lower prevalence of chronic diseases, such as obesity and heart disease, for populations that rely excessively on livestock-derived sources of food (where such dietary choices are possible).[83] Although increasing the access and affordability of livestock-derived products in food-insecure countries, particularly in countries with high levels of child wasting and child stunting, could be one important food policy objective, decreasing the demand for livestock-derived foods in countries with more than an adequate supply could also be an important lever for minimizing the effect of protein production on the environment.

Limitations and data gaps

One detail that this framework currently lacks is a comparison of the performance of livestock production systems across agroecological zones. As demonstrated in Figure 11, cattle are distributed across a range of agroecological zones, including in unsuitable, arid, and semiarid regions, which are ecologically vulnerable and susceptible to overgrazing.[84,85] It is also apparent from this figure and from supporting literature that there is significant potential to more efficiently use the resources that are available in ecologically productive areas, which, from a regional perspective, could alleviate the land use change pressure stemming from the expansion of pasture for bovine meat production.[86] In particular, native grasslands that coevolved with large herbivores, such as in the Central Great Plains of the United States or the Pampas in South America, may have unique ecological advantages that support the sustainable production of bovine meat (although they too are susceptible to overgrazing if not managed properly).[87] In general, an agroecological approach would be a useful lens to analyze commodity-level data, since so much of the land being grazed by ruminants (roughly 1.3 billion ha) are not suitable for crop production, which is an important distinction to bear in mind when accounting for land use.[61]

Nonetheless, efforts to intensify production must also account for the cost of livelihood transitions in which culture and socioeconomics shape livestock and grazing management practices. One of the main limitations of the ProNES dataset framework is the lack of high-resolution data on the number and types of livelihoods that are tied to different forms of livestock-derived protein production systems, such as pastoralist societies. This reflects the paucity of such data globally, which are direly needed to inform a truly just transition to more sustainable food systems. As the demand for animal-sourced proteins increases, as it is poised to do, and as the need to shift toward more sustainable protein production becomes more urgent, it is imperative to consider the effect that any protein transition will have on the people who rely on these systems for their livelihoods. By collecting data on the number of people employed in different sectors within and across livestock production industries, as well as the types of jobs and the geographic distribution of these workers, policymakers and advocates can develop strategies to support and retrain workers as the industry shifts toward more sustainable practices. This will be critical for ensuring that the transition to sustainable food systems is fair and equitable for all.

Finally, it is also important to improve data collection on the heterogeneity that exists within and across production systems of a single livestock-derived commodities in a country. For example, within the beef industry, there is significant variation across industrial operations with respect to many management dimensions, such as manure management and animal welfare, among others.[88,89] It has also been estimated that livestock production systems based on circular economy principles, which rely in large part on human-inedible food such as crop residues and co-products from crop processing, could produce between 9 and 23 g of daily protein per capita from entirely circular systems. By collecting more nuanced data on a larger set of livestock production system classifications, rather than simply pasture-based, mixed, and industrial, policymakers can design targeted interventions to address specific challenges and opportunities faced by stakeholders across a range of protein production systems and their associated value chains.

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AUTHOR CONTRIBUTIONS

K.K. created the conceptual foundation, executed the data analysis, composed the figures, and wrote the manuscript. R.D., W.B., M.F., J.P., and C.R. provided crucial guidance, supervision, and input throughout the process. E.M.C. and E.M.L. provided important structural and textual editing and review.

DECLARATION OF INTERESTS

M.F. serves as an independent member of the Sustainability Committee of Marfrig Global Foods S.A. This funding did not have contracted deliverables.

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