Nutritional and greenhouse gas impacts of removing animals from US agriculture

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Edited by B. L. Turner, Arizona State University, Tempe, AZ, and approved September 25, 2017 (received for review May 5, 2017)

As a major contributor to agricultural greenhouse gas (GHG) emissions, it has been suggested that reducing animal agriculture or consumption of animal-derived foods may reduce GHGs and enhance food security. Because the total removal of animals provides the extreme boundary to potential mitigation options and requires the fewest assumptions to model, the yearly nutritional and GHG impacts of eliminating animals from US agriculture were quantified. Animal-derived foods currently provide energy (24% of total), protein (48%), essential fatty acids (23–100%), and essential amino acids (34–67%) available for human consumption in the United States. The US livestock industry employs 1.6×10^6 people and accounts for $31.8 billion in exports. Livestock recycle more than 43.2×10^9 kg of human-inedible food and fiber processing byproducts, converting them into human-edible food, pet food, industrial products, and 4×10^9 kg of N fertilizer. Although modeled plants-only agriculture produced 23% more food, it met fewer of the US population's requirements for essential nutrients. When nutritional adequacy was evaluated by using least-cost diets produced from foods available, more nutrient deficiencies, a greater excess of energy, and a need to consume a greater amount of food solids were encountered in plants-only diets. In the simulated system with no animals, estimated agricultural GHG decreased (28%), but did not fully counterbalance the animal contribution of GHG (49% in this model). This assessment suggests that removing animals from US agriculture would reduce agricultural GHG emissions, but would also create a food supply incapable of supporting the US population's nutritional requirements.

livestock | food | greenhouse gases | agriculture | food security

Human society exists within an integrated ecological system that includes animal- and plant-based agriculture (Fig. 1). US agriculture provides raw materials used for food, fiber, biofuels, and myriad components of nonfood products used domestically and sold internationally. As with any ecological system, changes made in one facet must be evaluated for the direct effects of the change and for collateral impact. A report by the Food and Agriculture Organization (FAO) of the United Nations designated livestock as a major worldwide contributor to greenhouse gas (GHG) emissions that affect global warming (1). More recently, the 2015 Dietary Guidelines Advisory Committee claimed that plant-based diets would promote health and improve long-term sustainability of the US food supply (2). Implicit in such reports is the idea that modification or elimination of animal agriculture would offer benefits to society with minimal and acceptable deleterious effects (3, 4). Testing for the outcomes of benefits and adverse effects with livestock removal is complicated by the number, accuracy, and complexity of assumptions that need to be made in representing changes in food production systems. The scenario that requires the fewest assumptions is the elimination of animal agriculture, which also represents the boundary of the potential impact of other intermediate measures (e.g., partial livestock removal, reduced red meat consumption).

Given the challenge of providing adequate nutrition for a growing global population, addressing the question of why we feed animals to feed human society is of principal interest. Specific to animal agriculture is the inherently energetically inefficient conversion of feed to usable products. Because animals (and humans) obey the laws of thermodynamics, energy that is converted to heat through metabolic processes is lost and not retained in tissues (5, 6). Acceptability of such inefficiencies depends upon the resources used in this conversion and the value of the resulting products. Livestock, particularly ruminants, consume substantial amounts of byproducts from food, biofuel, and fiber production that are not edible by humans, and they make use of untillable pasture and grazing lands that are not suitable to produce crops for human consumption (7, 8). When compared on a human-edible nutrient input to human-edible nutrient output basis, animal and plant foods can have similar efficiencies (9). Animals also provide more than food. A multitude of animal-derived products are used in adhesives, ceramics, cosmetics, fertilizer, germicides, glues, candies, refining sugar, textiles, upholstery, photographic films, ointments, paper, heart valves, and other products (10). Given these additional contributions, assessment of agricultural systems must consider that animals and crops affect more than GHG. Specifically, the impact of changes to US agriculture needs to be considered in the context of the overall effect on meeting the short- and long-term needs of human society. Evaluation of the most extreme alternative, an agricultural system that is solely plant-based, can illuminate the strengths and detriments of animal agriculture in our system. The objective of this study was to compare the current contribution of animals to the US food supply and agricultural GHG by comparing current food production to a

Significance

US agriculture was modeled to determine impacts of removing farmed animals on food supply adequacy and greenhouse gas (GHG) emissions. The modeled system without animals increased total food production (23%), altered foods available for domestic consumption, and decreased agricultural US GHGs (28%), but only reduced total US GHG by 2.6 percentage units. Compared with systems with animals, diets formulated for the US population in the plants-only systems had greater excess of dietary energy and resulted in a greater number of deficiencies in essential nutrients. The results give insights into why decisions on modifications to agricultural systems must be made based on a description of direct and indirect effects of change and on a dietary, rather than an individual nutrient, basis.

Author contributions: R.R.W. and M.B.H. designed research, performed research, analyzed data, and wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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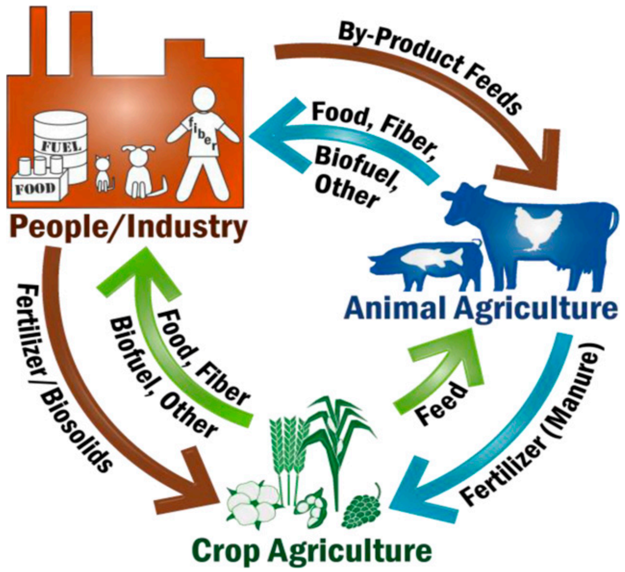
This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1707322114/-/DCSupplemental.



Yearly Contributions, kg

People/Industry	Animal Agriculture
To Animal Agriculture:	To People/Industry
By-product feed: 4.32×10^{10}	- Food: 1.20×10^{11}
Crop Agriculture	- Non-food: 1.22×10^{10}
To People/Industry:	To Crop Agriculture
- Food: 1.72×10^{11}	- Manure N: 4.01×10^{9}
- Non-food: 1.28×10^{11}	- Manure P: 1.69×10^{9}
To Animal Agriculture:	- Manure K: 1.88×10^{9}
- Crops: 1.12×10^{11}	- Manure S: 2.84×10^{8}

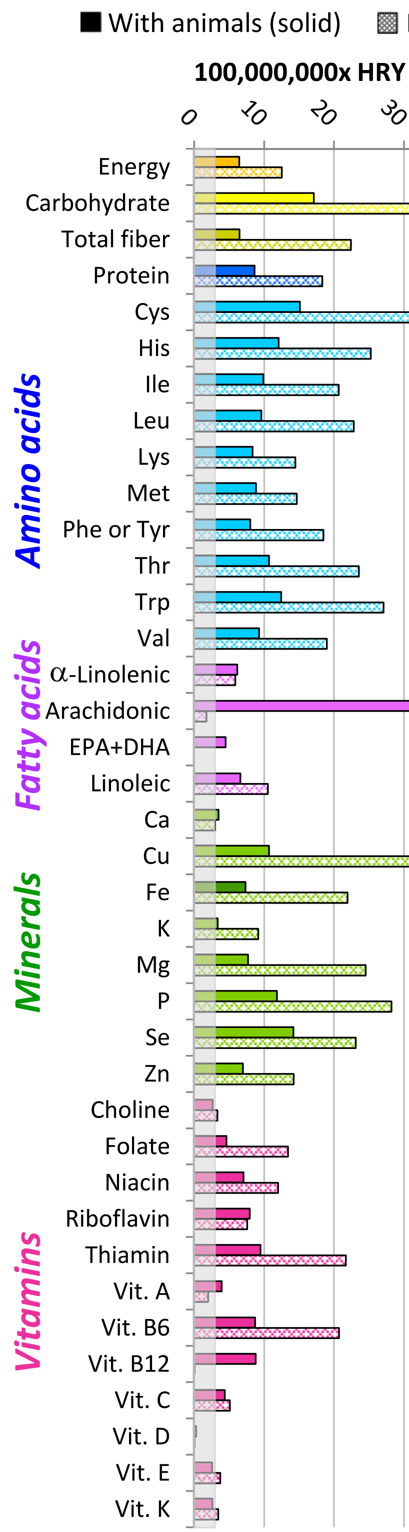
Fig. 1. United States food production as an ecosystem with transactions between components as identified in this study. Crops are processed or consumed directly by animals. Processing products and byproducts are shuttled to industrial applications or to animals and humans for consumption. Animals provide manure used to produce crops, byproducts used in a variety of industrial applications, and human food. Values are those calculated for the present study. Adapted with permission from ref. 63, copyright (1997) American Chemical Society.

modeled system in which animal agriculture and animal-derived foods are eliminated.

Results and Discussion

Contributions of Animals to the Current US Food Production System. Contributions of agricultural systems to the human food supply were evaluated in the context of specific nutrients required by humans. Total plant- and animal-derived nutrients produced and used in the United States tended to greatly exceed the US population's requirement, but this varied by nutrient. In the present system, domestically produced, animal-derived foods provided 24% of the energy, 48% of the protein, 23–100% of the essential fatty acids, and 34–67% of essential amino acids available for human consumption in the United States (Fig. 2). More than 50% of the food-derived Ca; vitamins A, B_{12}, and D; choline; and riboflavin were from animal products. Total amounts of nutrients produced in systems with animals were adequate to meet the requirements of the US population with the exception of vitamins D, E, and K and choline.

Although often a secondary consideration in comparison with humans, companion animals are part of human society. Assuming that people would keep their companion animals in a system without livestock production, the nutrient requirements of 69.9×10^6 dogs, 74.1×10^6 cats, 8.3×10^6 birds, and 89.4×10^6 other pets



Nutrient	Present system From Animals %	Present system HRY	Plants-only HRY
Energy	24%	6.46	12.51
Carbohydrate	5%	17.12	40.78
Total fiber	0%	6.51	22.38
Protein	48%	8.65	18.31
Cys	34%	15.13	39.22
His	51%	12.07	25.22
Ile	55%	9.88	20.67
Leu	48%	9.63	22.81
Lys	67%	8.36	14.47
Met	58%	8.84	14.66
Phe or Tyr	45%	8.04	18.46
Thr	53%	10.73	23.55
Trp	49%	12.47	27.08
Val	53%	9.31	18.97
α-Linolenic	39%	6.16	5.86
Arachidonic	97%	64.68	1.72
EPA+DHA	100%	4.50	0.00
Linoleic	23%	6.64	10.54
Ca	76%	3.50	2.97
Cu	12%	10.72	58.94
Fe	12%	7.34	21.90
K	31%	3.38	9.17
Mg	14%	7.73	24.52
P	35%	11.83	28.21
Se	31%	14.19	23.08
Zn	35%	6.97	14.21
Choline	51%	2.66	3.30
Folate	16%	4.64	13.42
Niacin	34%	7.08	11.99
Riboflavin	65%	7.94	7.57
Thiamin	25%	9.51	21.66
Vit. A	68%	3.94	1.99
Vit. B6	26%	8.72	20.70
Vit. B12	100%	8.82	0.00
Vit. C	3%	4.39	5.09
Vit. D	99%	0.30	0.00
Vit. E	9%	2.55	3.73
Vit. K	3%	2.61	3.44

Fig. 2. Total HRYs produced in 2013-based US food production systems with actual animal-derived food inputs or modeled without animal-derived food inputs (plants-only). The gray vertical rectangle indicates the number of HRYs needed to meet requirements of the US population. Grayed boxes indicate HRY production inadequate to meet US population requirements. Energy and protein HRYs required for pets were subtracted from the plants-only diet.

(11) and a population of 10.2×10^6 horses (12) would need to be satisfied. In 2010, rendered products from livestock provided 0.66×10^9 kg of protein products and 0.13×10^9 kg of fats used for pet foods (13). This consumption of animal food processing coproducts is equal to 37.4×10^6 protein human nutrient requirement years (HRYs; i.e., the amount of a nutrient required to support the average person for 1 y) and 12.3×10^6 energy HRYs (14), which would need to be provided from other nutritionally adequate sources in the absence of animal products.

An additional and noteworthy contribution of animals to US society is economic. Animal agriculture employs more than 1.6×10^6 Americans (15), and annual US exports of animal products have a value of $\$31.8 \times 10^9$, equivalent to 22% of the income from all agricultural exports (16). From a global standpoint, export of nutrient-dense livestock products from developed countries has been identified as a critical priority for promoting global food security in the face of a changing climate (17). Albeit to a lesser degree in developed countries, livestock also represent an important source of capital for farmers (18), and this contribution to livelihoods should not be overlooked.

One of the critical motivations for evaluating the role of livestock in the current US food production system is to evaluate how livestock contribute to food security. Although many targeted studies on underserved populations have evaluated food security challenges in the United States (19, 20), few studies domestically or abroad have evaluated nutrient provision by the current agricultural system on the scale of the entire population. An analysis of US energy and protein provision identified that switching to a more feed-efficient food production system (from beef to poultry) enhanced opportunities to meet US energy and protein demands by 120 and 140 million people, respectively (21); however, this study failed to consider nutrients other than energy and protein. Given the number of micronutrients identified as deficient in the present study, future work evaluating food security should likely focus on both macro and micronutrients. For example, Herrero et al. (22) evaluated global production of Ca, folate, iron, protein, vitamin D, vitamin B_{12}, and zinc, and identified the United States and Europe as hotspots of nutrient production. Given the intensity of animal agriculture in those areas, it is possible that the high production is associated with nutrient-dense animal food products. Both the present study and the work of Herrero et al. (22) suggest that micronutrients like Ca, which are provided in high concentrations in livestock-based foods, will be limiting as the global population continues to grow.

US Food and Nutrient Production With and Without Animals. Removal of farmed animals from the US agricultural system resulted in a 23% increase in total amount of food available exclusive of current exports (Fig. 3). Grain comprised the majority of the increase, of which corn grain accounted for 77%; 92% of the legumes were comprised of soybeans and soy flour. The dramatic increases in grain and legume production rather than in other crops reflect the allocation of tillable land based on current proportions of crops grown. Proportional allocation of land, rather than greater allocation to growing vegetables and fruits in a plants-only system, is indirectly supported by the current domestic fruit and vegetable consumption (23, 24), which are 203% and 164% of domestic production. Given the tremendous domestic demand for fruits and vegetables, if it was viable to produce more of these high-value crops in the current system, this would already be occurring. Limitations on increased fruit and vegetable production may reflect suitability of land, climate, and infrastructure to grow these crops.

The total domestic nutrient supply changes substantially when animal-derived foods are removed from the system; human-edible feeds that were previously used by livestock (25) are routed for human consumption, and tillable land is converted to

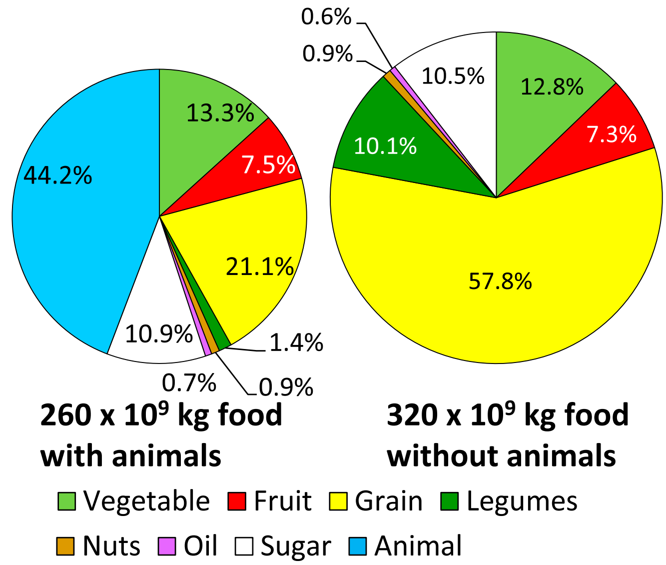


Fig. 3. Amounts and proportions of foods available in systems with and without animal inputs. Graphs are sized proportionally to the amounts of food available.

producing food for people, excepting the 1.8×10^6 ha used to produce hay for horses (Fig. 2). When animals were removed, gross supplies of many nutrients increased markedly and were in excess of domestic requirements. However, without animal-derived foods, domestic supplies of Ca; arachidonic, eicosapentaenoic, and docosahexaenoic fatty acids; and vitamins A and B_{12} were insufficient to meet the requirements of the US population. For the deficient fatty acids and vitamin B_{12}, animal products are the only nonsupplemental sources commonly found in human diets. The US Department of Agriculture (USDA) and FAO/World Health Organization (26, 27) recommend the consumption of eicosapentaenoic acid (EPA) plus docosahexaenoic acid (DHA) for the health benefit of reduced cardiovascular disease and for the positive effects on visual and cognitive development of infants. Arachidonic acid supplementation has been recommended for infants (27); its supplementation with DHA has been shown to improve visual acuity (28).

Nutritional Adequacy of Human Diets With and Without Animals. Although a useful metric, total domestic nutrient supply does not adequately describe the impact of changes in an agricultural system on the adequacy of diets for meeting a population's nutrient requirements. Nutrients are found in unique combinations in different foods. The impact of changes to the food production system needs to be considered in terms of how diets composed of available foods can meet human nutrient requirements.

The current US diet includes substantial proportions of fruits, vegetables, and animal-derived foods (Fig. 4). Nonanimal fats and sweeteners such as sugar comprised 2% and 7%, respectively, of the diet. Compared with the average requirements of the population, protein, many microminerals, vitamins, and amino acids consumed in unsupplemented foodstuffs are in excess in the average US diet; however, minerals and vitamins (Ca, 60% of requirement; vitamin K, 75%; vitamin D, 15%; choline, 73%), and essential fatty acids (linoleic, 90%; α-linolenic, 71%) were deficient. In contrast, dietary protein provided 171% of requirements, and energy consumed equated to a 12% excess for moderately active humans.

Simulated least-cost diets based on available foods differed markedly in food composition from the current US diet in scenarios in which the available food supply consisted of (*i*) currently

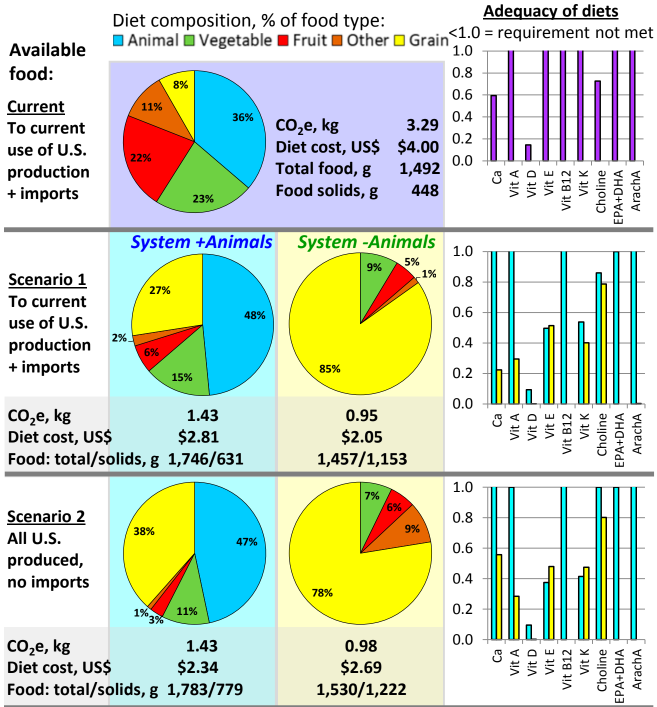


Fig. 4. Comparison of the daily diet composition, CO_2e emissions, intake, cost, and nutrient adequacy of the current US diet compared with a series of optimized diets with and without (modeled) animal-derived foods. Bar graphs indicate dietary adequacy of specific nutrients by scenario; purple indicates current diet, blue indicates diet with animals, yellow indicates plants-only diet. "Other" represents nuts, legumes, fats, and sweeteners. ArachA, arachidonic acid.

consumed domestic production plus imports or (*ii*) currently consumed and exported domestic production (Fig. 4). No diet contained refined sugars. Compared with the current consumption pattern, on a raw ingredient basis, when animal products were included, the proportions of animal-derived foods and grains increased, whereas those of vegetables and fruits decreased. In the plants-only system, the proportion of grain increased 10-fold and all other food types declined. Despite attempts to meet nutrient needs from foods alone within a daily intake of less than 2 kg of food, certain requirements could not be met from available foods. In all simulated diets, vitamins D, E, and K were deficient. Choline was deficient in all scenarios except the system with animals that used domestic currently consumed and exported production. In the plants-only diets, a greater number of nutrients were deficient, including Ca, vitamins A and B_{12}, and EPA, DHA, and arachidonic acid.

The challenges in meeting essential vitamin, mineral, and fatty acid requirements in plant-based diets are supported by previous works. It is entirely possible to meet the nutrient requirements of individual humans with carefully crafted, unsupplemented plant-based rations, but this can be a challenge to achieve in practice for an entire population. Based on data from the National Health and Nutrition Examination Survey (2007–2010), Cifelli et al. (29) found that plant-based rations were associated with greater deficiencies in Ca, protein, vitamin A, and vitamin D. In a review of the literature on environmental impacts of different diets, Payne et al. (30) also found that plant-based diets with reduced GHGs were also often high in sugar and low in essential micronutrients and concluded that plant-based diets with low GHGs may not result in improved nutritional quality or health outcomes. Although not accounted for in this study, it is also important to consider that animal-to-plant ratio is significantly correlated with bioavailability of many nutrients such as Fe, Zn, protein, and vitamin A (31). If bioavailability of minerals and vitamins were considered, it is possible that additional deficiencies of plant-based diets would be identified. It is important to note, however, that plant-based diets do have advantages. For example, McGirr et al. (32) suggested that vegetarian diets can contribute to reduced risk of coronary heart disease and obesity. Indeed, these health benefits are one reason why the 2015 Dietary Guidelines Advisory Committee claimed that plant-based diets would promote health (2). The challenge with plant-based diets comes when one considers the need to feed the entire growing population. Even though it is possible to balance plant-based diets for individual humans, it may be a challenge for these diets to scale well within the US food production system because of the types of crops that can be grown in the available climates and soils. When animals are allowed to convert some energy-dense, micronutrient-poor crops (e.g., grains) into more micronutrient dense foods (meat, milk, and eggs), the food production system has enhanced capacity to meet the micronutrient requirements of the population.

The simulated diets in the present paper support the idea that essential micronutrients, rather than macronutrients, are a critical challenge in scaling diets from individuals to a population. In this exercise, all diets exceeded protein and energy requirements as the formulation program attempted to balance for more limiting nutrients. The resulting diets provided more than 230% of the required protein, whereas average energy provision was 145% or 230% of requirements in systems with or without animals, respectively. Given the obesity rate in the United States (33), increased consumption of food energy is not desirable. Despite the production of a greater quantity of food in the plants-only system, the actual diets produced from the foods result in a greater number of deficient nutrients and an excess of energy. These changes in nutrient profile further support the role of farmed animals in generating foods with higher density of some micronutrients. The 2015 Dietary Guidelines Advisory Committee (2) and a systematic review of the literature (34) claimed that plant-based diets would promote health and improve long-term sustainability of the US food supply. However, considering the potential for plant-only diets to be deficient in key micronutrients (32, 35), particularly when they are implemented on a population scale, the role of animal-derived foods in meeting the macro- and micronutrient needs of a growing global population needs to be considered. In a simulation of possible land use options to meet global food demand, multiple scenarios were identified that met global caloric requirements and included animal-based foods (36). The data reported here suggest that diet evaluations need to assess essential micronutrients and the actual foods available to feed the population.

Another difference between plant-based and livestock-based food systems evidenced by the diets derived in the present work was the quantity of food solids that would need to be eaten to meet requirements with the foods available. These quantities differed among diets and could affect the feasibility of consuming the diets. Diet raw ingredient amounts discounted for water content brought the diets to a solids or dry matter basis for comparison; water can be added or removed from foods, but solids are the portion that contains the nutrients that must be digested or passed. Simulated diets contained between 183 and 774 g more food solids than the current US diet (Fig. 4). Within each food availability scenario, plants-only diets required 444–522 g more food solids than those with animal products to meet nutrient requirements. This lower solids intake is evidence of the higher essential nutrient density of animal-based food products, which has also been identified by research focusing on improving nutrient density of diets in developing nations and indigenous populations (37, 38).

Costs, GHGs and Exportable Nutrients for Human Diets With and Without Animals. The simulated diets substantially reduced daily per-person diet costs and GHGs compared with the current average diet, with those from plants-only systems giving lower values than those from systems with animals (Fig. 4). The GHG results are in agreement with a survey study of 13,000 American diets that reported that consumption of more plant protein foods and less animal protein foods produced diets with low GHGs based on current carbon footprints of food (39). This relationship is also supported by a survey of 10,723 Ontario residents (40) that found that minimizing household consumption of beef, eggs, and cheese had the potential to reduce the global warming potential of diets when global warming potential was calculated based on GHGs estimated from life cycle assessment (LCA). Based on meta-analysis of 742 LCAs, Clark and Tilman (41) also concluded that plant-based foods have reduced environmental impacts compared with animal-based foods, and that switching to a plant-based diet confers environmental benefits. However, each of these studies rely on LCAs estimated in the current food production system. Indeed, it is also assumed in the present study that the current LCA of food products would be valid in a dramatically shifted system in which humans no longer consume livestock products, an assumption that may be unlikely. Horton et al. (42) advocated for a system-wide approach to evaluating the food supply chain that integrates separate domains and multiple disciplines, importantly suggesting that food systems must be evaluated in their totality, which will allow tractable quantitative analysis by using LCA and related methods. Although we have taken steps toward a more inclusive analysis by accounting for fertilizer and coproduct changes in this exercise, a more complete LCA of the US food production system accounting for the diversity of foods and nutrients presented herein would be a logical next step toward evaluating opportunities to leverage the benefits of livestock production for human society.

It is widely acknowledged that food trade will have important implications for future global food security (43), and, for this reason, we evaluated exportable nutrient quantities available under each scenario. The quantity of HRYs available for export was greater for protein and Lys in the plants-only systems, but changed by scenario for energy. With available domestic and imported foods at the current level of consumption, the exportable HRYs × 10^6 for plants-only or with-animals systems, respectively, were energy (574 vs. 386), protein (746 vs. 546), and Lys (473 vs. 445). These represent increases over potential exports in the current US agricultural system of 354, 457, and 308 HRY × 10^6 for energy, protein, and Lys, respectively. When relying on US-grown foods alone, most of the amounts of exportable nutrients declined, with respective exportable HRY × 10^6 values for plants-only and with-animal systems as energy (125 vs. 283), protein (525 vs. 451), and Lys (543 vs. 412). Increases in exportable energy HRY would be of use in developing countries where energy may be a first limiting nutrient. Increases in exportable protein HRY could improve the global nutrient supply, if specific amino acid needs are also met. The changes in HRY values among scenarios suggests that consideration of specific nutrient needs and international nutrient/food routing is essential to determine the balance of agriculture needed to feed the global population.

The increased protein and Lys HRY available for export in the plants-only system are driven largely by the availability of soybean flour for human consumption. As detailed by Zaheer and Humayoun Akhtar (44), humans have been consuming moderate amounts of soy protein for centuries without deleterious health effects; however, there is serious concern about whether high consumption of soy products will lead to elevated plasma isoflavone levels, which may promote hormone-related health disorders. At present, we lack data to determine a maximum recommended daily consumption of soy products, which would be of benefit in further evaluating the health implications of the diets developed in the present study.

Given the fixed land mass, increasing the number of people fed from a given food production system is crucial, with total and essential nutrients considered. Perhaps most critically, future work needs to account for land quality, land availability, and maximization of nutrient production per unit of total land for whatever purpose the land is used. Removal of animals from the agricultural system removed 168 × 10^6 ha of nontillable pasture and rangeland from food production (45). Given that there is only 158 × 10^6 ha of tillable land in the United States, leveraging this additional land resource for food production may be a critical component of increasing domestic food supply and potentially exportable nutrients. It is important to consider, however, that only ruminant animals can make use of this nontillable land, and ruminant livestock production systems are significant contributors to GHGs. Future work should consider tradeoffs associated with the use of ruminant animals on this marginal land in terms of optimizing food availability and land use efficiency while concurrently attempting to minimize GHGs.

Livestock GHG Impacts. A primary environmental impact associated with food production is GHG. The modeled GHG here attributed 49% of agricultural emissions to animals, demonstrating excellent agreement with national inventories, which allocate 51% of agricultural emissions (and 3% of national emissions) to animals (46). By comparison, for human-used crops, 40% of agricultural emissions were accounted to grain production, 0.3% to legumes, 5% to vegetables, and 2% to fruits and nuts. GHGs produced from the US agricultural system declined by 28% with elimination of farmed animals (Fig. 5). A decrease equivalent to the full 49% of GHG attributed to animals was not realized because of the need to synthesize fertilizers to replace animal manures [23.2 × 10^9 kg CO_2 equivalents (CO_2e)], dispose of human-inedible byproduct feeds that had been used as feed for animals (1.7 × 10^9 kg CO_2e), and produce additional crops on land previously used by animals (32% increase over plant contributions in the system with animals). Assuming agricultural emissions account for 9% of total US emissions (47), and assuming that emission estimates here are

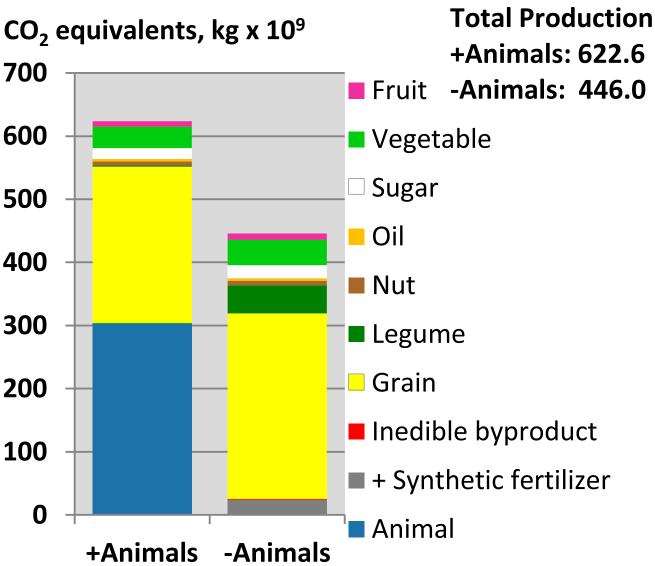


Fig. 5. GHG emissions associated with food production in a system representative of the current United States and a modeled system in which animal-derived food inputs are eliminated.

representative of national emissions, eliminating animal agriculture would decrease total US emissions by an estimated 2.6 percentage units. The finding of reduced GHG with elimination of animal agriculture agrees with the work of Clark and Tilman (41), who concluded that plant-based foods have reduced environmental impacts compared with animal-based foods.

Sensitivity Analysis of Results. To evaluate how robust the observations are over a range of production inputs, a sensitivity analysis was conducted by using production data from 2010 to 2016. These years were selected to represent technologically similar production with induced demand- or climate-based variation in yields of plant and animal-based foods. In each year, the domestic production of the crop and livestock products considered in this analysis were updated, and the resulting changes in HRY provided and GHG estimated were recorded. The variations in these outputs are provided in *SI Appendix*, Figs. S1–S5. With the exception of a few nutrients (α-linolenic acid, riboflavin) the delineations identified by the reference year (2013) are reflective of the population of years used in this sensitivity analysis. Interestingly, the difference in the mean GHG within production system (172×10^9 kg CO_2e without animals, 109×10^9 kg CO_2e with animals) are similar to the average cross-system differences in GHG (175×10^9 kg CO_2e). Although GHGs are consistently lower in systems without animals, the considerable variation within each system type suggests that adjustment of the profile of US agriculture beyond reduction of livestock production has substantial potential to shift domestic agricultural GHG.

Another sensitivity test was employed to assess how changes in efficiency of fertilizer production and byproduct disposal influenced GHG in the plants-only system. In this analysis, emission factors for N, P, K, and S synthesis and for non-CO_2 emission from byproduct feed disposal were varied incrementally and individually. Changes in total agricultural GHG were evaluated. Each incremental (1%) improvement in efficiency of N, P, K or S fertilizer synthesis would reduce total fertilizer synthesis emissions 0.69%, 0.24%, 0.047%, and 0.048%. Reducing the emission of CH_4 from combustion of byproduct waste would reduce total emissions by 0.45% for each 1% reduction in CH_4 emitted per terajoule waste combusted. Similarly, each 1% reduction in N_2O per terajoule waste combusted reduced total emissions by 0.69%. If greater efficiencies in fertilizer production and byproduct disposal could be achieved, GHGs in the plants-only system could be further reduced.

Strengths, Limitations, and Future Work. The present study differs from the previous body of literature in the breadth of consideration of food products (89 plant-based and 26 animal-based) and nutrients (39 accounted, 36 identified as vital) and provides an important look at how availability of nutrients within a food production system vs. a diet comprised of available foods differ. A principle limitation of this work is incomplete data availability that required many assumptions to be made. As such, the findings must be considered in the context of these assumptions. Assumptions when animals are removed from US agriculture included: (*i*) grain previously consumed by animals will be available for human consumption; (*ii*) tillable land previously used for hay, green chop, and silage production, and tillable pasture and grazing land will be used for human food production directly; (*iii*) the nutrients from animal products previously provided to humans will no longer be available for human consumption; (*iv*) GHGs from livestock production will no longer occur; (*v*) a large amount of feed processing byproducts previously consumed by animals will need to be disposed of; (*vi*) N, P, K, and S fertilizer previously sourced from manure will need to be synthesized; (*vii*) animal production byproducts previously available for pet food production will need to be replaced with plant nutrients; and (*viii*) humans can and will consume soy flour with no negative health impacts. Future work should focus on a more systems-oriented approach to use socioeconomic modeling to evaluate likely land-use changes associated with livestock removal and, concurrently, the different fertilizer opportunities and their impacts on crop yield. Similarly, enhanced integration of the human nutrition literature could enable evaluation of diets for their feasibility of consumption, nutritional adequacy beyond gross nutrient amounts, and identification of health indicators related to overconsumption of potentially harmful factors like energy or phytoestrogens.

Conclusions. The modeled removal of animals from the US agricultural system resulted in predictions of a greater total production of food, increases in deficient essential nutrients and excess of energy in the US population's diet, a potential increase in foods/nutrients that can be exported to other countries, and a decrease of 2.6 percentage units in US GHG emissions. Overall, the removal of animals resulted in diets that are nonviable in the long or short term to support the nutritional needs of the US population without nutrient supplementation. The mixed impact of eliminating animals from US agriculture illustrates the need for food system evaluations and decisions to be made based on a description of the system and on direct and indirect effects of a change that are as encompassing as possible.

Methods

US Population Nutrient Requirements. Contributions of agricultural systems to the human food supply were evaluated in the context of specific nutrients required by humans. Of 39 nutrients (energy, protein, carbohydrates, vitamins, minerals, amino acids, and fatty acids), 36 were identified as required to maintain life and health for humans (48, 49), with variation based on age and sex (*SI Appendix*, Tables S8–S11). Distribution of the US population by analogous age and sex groups (50) (*SI Appendix*, Table S12) was used to identify a weighted average nutrient requirement of the US population (*SI Appendix*, Table S13). Energy requirements for moderate activity were used. Mineral requirements were not adjusted for bioavailability of sources. Nutrient amounts required for an average human for 1 y were calculated as the daily requirement for each nutrient multiplied by 365 d to yield the primary functional unit used in the study: an HRY. This functional unit is referred to with the name refined by nutrient (e.g., energy HRY, protein HRY). Requirements of the US population were calculated by multiplying the 2013 US population of 316 million (51) by the HRY values.

US Food Supply. Data from ref. 23 were used to identify domestic production of 89 nonanimal and 26 animal-derived food products (*SI Appendix*, Tables S1 and S2). The 2013 data were chosen as representing a "normal" crop year, and avoiding extreme weather events such as drought that depress yields (23). Data from ref. 25 were sourced to identify the chemical composition of each food product (*SI Appendix*, Tables S3–S7). Production of 39 nutrients was calculated for each food product included in the study. Available food and food-derived nutrients from crops were calculated based on the proportion of unprocessed product that was human-edible food. These proportions of human edible food represented previously published product-specific milling or processing efficiencies or edible portions.

For grains and legumes with data available (52), the weight of product used for alternative outlets, including biofuel production, seed, and livestock feed, was subtracted from total production before adjusting for human-edible yield. For some grains, a substantial portion of the annual crop harvested goes to avenues other than human food consumption. Yearly grain summaries (53) partition grain and seed harvest into feed and residual use (feed use is assumed to be available for consumption by humans if animals are depopulated), seed use (assumed never to be consumed by humans), export, and use for crushings (*SI Appendix*, Table S14). Grain partitioned into "food, alcohol, and industrial" use was assumed to be entirely consumed by humans except in the case of corn, for which specific data were available on the amount of corn going to consumables compared with industrial use (*SI Appendix*, Table S15). In the plants-only system, all grains that had been used as animal feed were assumed to be consumable by people because reliable estimates were rare for the amounts of grains that are unsuitable as a result of contamination, spoilage, insect damage, or toxins. An exception was the proportion of corn grain intended for animal feed that is contaminated with ≥20 ppb of aflatoxin (median, 6.56%; 0–17.76% range over 10 y; data from the US Food and Drug Administration Center for Veterinary Medicine). Therefore, aflatoxin contamination removed 6.55×10^9 kg of corn grain from use as food in the absence of livestock.

Oilseed production in the United States is also complicated by end uses other than human food consumption. Quantities of oil crops produced, exported, and crushed were identified (54), and crops available for human consumption were assumed to be the difference between produced crop and exported and crushed crop. Total oil crop production was scaled from native reporting units to kilograms and adjusted for the proportion of oil crop going to crushings and the proportion of oil going to human food, rather than for export or manufacturing. In some cases (e.g., cottonseed, flaxseed), crushing demand exceeded domestic production, and it was therefore assumed that the domestically produced crop available for direct human consumption was 0%. Oil use data were also identified (54), and oil produced for human consumption was calculated as the total domestic oil production less exported oil and manufacturing oil demand. In some cases (e.g., canola, cottonseed), manufacturing and export demand greatly exceeded domestic oil production, and it was assumed that no domestically produced oil crop was available for human consumption.

Energy and protein HRYs required by pets were subtracted from calculated available HRYs in the plants-only system. Yearly forage, but no grain, required for the US population of horses was estimated as 2% of a mean body weight of 500 kg (55) multiplied by the population and the 122 d per year that animals would not be pastured. Providing hay for 4 mo not on pasture rather than for the entire year gives a conservative estimate of hay required to maintain the horse population. Grain previously fed to livestock (56) was sourced for major grain crops; when animals were removed from the system, the HRYs from these foods was calculated and included in estimates of total HRYs available for human use. Land used for hay, haylage, and silage production (57) was assumed to be repurposed for human food production. It was assumed that land use for foods would reflect the current proportions of land use. As such, the expansion in land available resulted in a net increase in food available, rather than a structure shift in the quantities of land used to produce certain food crops. The current yield of HRYs per hectare was used to project the increase in HRYs available from the new cropland. Land required to produce the needed forage (1.8×10^6 ha) was estimated as hay required divided by the 10-y average harvest of hay dry matter, excluding the drought year of 2012, of 6191.68 kg/ha (23) divided by a dry matter percentage of 88% for hay. When farmed animals were removed from the system, land cropped for forages (21×10^6 ha of silage, hay, and green chopped forage land) was converted to other food crops, assuming that land use would be proportional to the tillable acreage a food crop accounted for in the current system. Basal cropland accounted for in this analysis was 132×10^6 ha, and the addition of land when animals were removed represented a 19% increase. Gross changes in proportions of crops produced were not explored.

Total plant-based food production (*SI Appendix*, Table S1) was divided based on use for animal consumption, seed and nonfood use, export, or food use (*SI Appendix*, Table S16). The farmed, animal-derived foods included in this study encompassed poultry, livestock, fish, and shellfish. Total US animal production data (23), conversion rates of live weight to retail weight (23, 58–60), and nutritional value (25) were used to determine the total nutrients provided from US animal agriculture. Conversion rates to transfer from harvested product to human consumable product were sourced and used to estimate total consumable product for each plant-based food (*SI Appendix*, Table S17). The food production and human nutrient requirement data were compared with identify the number of HRYs satisfied for each nutrient by food item tracked (*SI Appendix*, Tables S18–S22).

The contributions of livestock to the US job market and to US export market were determined based on data from Bureau of Labor Statistics (15) and USDA Economic Research Service (16), respectively. Jobs associated with livestock production included farmers; ranchers; animal scientists; animal breeders; farm workers; farm, ranch, and aquaculture managers; butchers; meat cutters; veterinarians; veterinary technologists; and veterinary assistants. Export income from livestock included income from aquaculture, live animal exports, red meats and products, poultry meats and products, dairy products, hides and skins, eggs, and egg products. Total export income and export income as a proportion of total agricultural export income were estimated.

GHG Emissions. The carbon emissions associated with food production in systems with or without animals were evaluated by using published LCAs from peer-reviewed journals or publically available databases. Total area of cropping land was identified (23). Currently, animal manures provide 4×10^9 kg of N, 1.7×10^9 kg of P, 1.9×10^9 kg of K, and 0.28×10^9 kg of S for fertilizer (53). When livestock are removed, this fertilizer must be produced synthetically; associated GHGs from fertilizer production were calculated based on estimates of CO_2 production from US fertilizer manufacturing assuming replacement on an equal N, P, K, or S basis (61). By conservative estimates, livestock consume more than 43.2×10^9 kg of human-inedible byproducts per year in the United States (52). If livestock were depopulated, byproduct feeds were assumed to be incinerated. Non-CO_2 emissions from combustion were estimated based on feed nutrient content and Intergovernmental Panel on Climate Change tier II emissions factors. To account for potential recycling of feed byproduct nutrients for fertilizer, residual P and K produced during byproduct feed incineration were deducted from the amount of fertilizer to be synthesized.

Diet Comparisons Based on Food Supply Scenarios. Foods consumed and nutrients provided by the average US diet were calculated by using data on current US food consumption patterns (24); the average consumption of food products is included in *SI Appendix*, Table S51. When broad categories of food intake were reported (e.g., other grain), the value was equally divided over any remaining feeds within the food category.

To objectively compare diet options in different food supply scenarios with inclusion or exclusion of animals, a least-cost optimization approach was taken. Although linear programming produces a diet that lacks the variety and novelty sought by humans, it allows for objective comparison of different dietary strategies. A series of diets were optimized in GAMS version 23.8.2 to compare the economic, GHG, and nutritional implications of removing animals from food production; the code for this optimization is included in the *SI Appendix*. The objective and constraint specifications for these scenarios are listed in Fig. 5. Briefly, nutritionally adequate, least-cost diets were optimized, one with and one without animal products, within two scenarios: available food supply up to the current level of consumption of domestically produced and imported foods (scenario 1) or with only domestically produced foods including those currently exported, and no imports (scenario 2). Diets were initially constrained to meet all nutrient requirements of the US population. When a nutrient requirement could not be met, that specific nutrient was removed as a constraint and the diet was rerun. The assumed changes in food availability occurring with removal of animals from the system were used to estimate the total quantity of human-edible food (*SI Appendix*, Table S53), and human-edible nutrient requirement years for all evaluated nutrients (*SI Appendix*, Tables S54–S58) available in a system without animals.

For all diets, average daily cost was calculated by using current retail prices (62). When retail prices were not available for a specific food, the average price of that food class was used. The average cost of each product is included in *SI Appendix*, Table S51. The individual food carbon footprints identified from International Standards Organization-compliant LCAs were used to calculate the carbon footprint of the diet. Food intake on a solids or dry-matter basis was calculated as total weight of diet consumed minus water content of the diet.

Exportable nutrient supply in the four scenario diets were calculated as 1 minus the result of the projected consumed weight divided by the produced weight. This net value was used as an estimate of the importable/exportable proportion of the food. Food weights were converted to human energy and protein HRYs. This was done to estimate the number of yearly human energy and protein requirements that are exported from the United States today. The current exportable energy and protein requirement years are listed in *SI Appendix*, Table S52.

Sensitivity Analysis. Two types of sensitivity analysis were performed to evaluate the consistency of the results. First, a change/response analysis was performed by varying the emissions factors for producing N (1–4 kg CO_2e/kg N), P (1–4 kg CO_2e/kg P), K (0.25–1 kg CO_2e/kg K), and S (1–4 kg CO_2e/kg S) to evaluate how shifting efficiency of synthesizing fertilizer nutrients impacted projected GHGs. Linear regression of the resulting system GHGs against the emission factors were converted to percentage bases to generate an estimate of how a percent reduction in GHGs from fertilizer nutrient production changed agricultural GHGs in the system without animals. The same analysis was also done for byproduct disposal emissions by changing the factors used to estimate non-CO_2 emissions from combustion. A second analysis was done to evaluate consistency of the results across different production years. Food production data were updated by using domestic production data from 2010 until 2016. The resulting quantity of nutrients produced and estimated agricultural GHGs were tracked by using each year's inputs. Density plots were developed to show distribution in nutrient supply and agricultural GHGs across this range of years.

ACKNOWLEDGMENTS. The authors acknowledge the assistance of Lori Bocher (US Department of Agriculture/Agricultural Research Service) for assistance with graphics and Dr. Laurie Lawrence (University of Kentucky) for discussions on horse feed requirements.

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