Land, irrigation water, greenhouse gas, and reactive nitrogen burdens of meat, eggs, and dairy production in the United States

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Livestock production impacts air and water quality, ocean health, and greenhouse gas (GHG) emissions on regional to global scales and it is the largest use of land globally. Quantifying the environmental impacts of the various livestock categories, mostly arising from feed production, is thus a grand challenge of sustainability science. Here, we quantify land, irrigation water, and reactive nitrogen (Nr) impacts due to feed production, and recast published full life cycle GHG emission estimates, for each of the major animal-based categories in the US diet. Our calculations reveal that the environmental costs per consumed calorie of dairy, poultry, pork, and eggs are mutually comparable (to within a factor of 2), but strikingly lower than the impacts of beef. Beef production requires 28, 11, 5, and 6 times more land, irrigation water, GHG, and Nr, respectively, than the average of the other livestock categories. Preliminary analysis of three staple plant foods shows two- to sixfold lower land, GHG, and Nr requirements than those of the nonbeef animal-derived calories, whereas irrigation requirements are comparable. Our analysis is based on the best data currently available, but follow-up studies are necessary to improve parameter estimates and fill remaining knowledge gaps. Data imperfections notwithstanding, the key conclusion—that beef production demands about 1 order of magnitude more resources than alternative livestock categories—is robust under existing uncertainties. The study thus elucidates the multiple environmental benefits of potential, easy-to-implement dietary changes, and highlights the uniquely high resource demands of beef.

food impact | foodprint | geophysics of agriculture | multimetric analysis

Appreciation of the environmental costs of food production has grown steadily in recent years (e.g., refs. 1–3), often emphasizing the disproportionate role of livestock (4–12). Although potentially societally important, to date the impacts of this research on environmental policies (7, 13, 14) and individual dietary choices have been modest. Although pioneering early environmental burden estimates have tended to address wide food classes (notably the animal-based portion of the diet; e.g., refs. 9 and 15), most policy objectives and individual dietary choices are item specific.

For example, a person may consider beef and chicken mutually interchangeable on dietary or culinary grounds. However, even if an individual estimate of the environmental cost of one item exists, it is often not accompanied by a directly comparable study of the considered alternative. Even in the unlikely event that both estimates are available, they are unlikely to consider the costs in terms of more than one metric, and often rely on disparate methodologies. Therefore, environmentally motivated dietary choices and farm policies stand to benefit from more finely resolved environutritional information. Although early work yielded a short list of item-specific environmental cost estimates (16), those estimates were often based on meager data, and addressed a single environmental metric (typically energy), thus requiring expansion, updating, and further analysis to enhance statistical robustness (8).

Current work in the rapidly burgeoning field of diet and agricultural sustainability falls mostly into two complementary approaches. The first is bottom–up, applying rigorous life cycle assessment (LCA) methods to food production chains (17–22). Whereas early LCAs focused primarily on greenhouse gas (GHG) emissions (23–26), or in some cases GHGs and energy use (5, 27), more recent LCAs often simultaneously address several additional key metrics (17, 19–21, 28, 29), notably land, water, and reactive nitrogen (Nr, nitrogen fertilizer) use. Some studies also include emissions of such undesirable gases (in addition to GHGs) as smog precursors or malodors (30, 31), or adverse contributions to stream turbidity or erosional topsoil loss (e.g., refs. 32–34). This bottom–up approach is extremely important, and is poised to eventually merge with the top–down national efforts described in the next paragraph. This merger is not imminent, however, because the bottom–up approach considers one or at most a handful of farms at a time. Because of wide differences due to geography (35), year-to-year fluctuations (36), and agrotechnological practice (17, 37), numerous LCAs are required before robust national statistics emerge. Eventually, when a large and diverse LCA sample is at hand, the picture at the national level will emerge. Currently, however, the results from an LCA conducted in Iowa, for example, are unlikely to represent Vermont or Colorado. Given the current volume and

Significance

Livestock-based food production is an important and pervasive way humans impact the environment. It causes about one-fifth of global greenhouse gas emissions, and is the key land user and source of water pollution by nutrient overabundance. It also competes with biodiversity, and promotes species extinctions. Empowering consumers to make choices that mitigate some of these impacts through devising and disseminating numerically sound information is thus a key socioenvironmental priority. Unfortunately, currently available knowledge is incomplete and hampered by reliance on divergent methodologies that afford no general comparison of relative impacts of animal-based products. To overcome these hurdles, we introduce a methodology that facilitates such a comparison. We show that minimizing beef consumption mitigates the environmental costs of diet most effectively.

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scope of LCA research, and the complexity and variability of the problem, LCAs are still too few and too local to adequately sample the multifaceted, diverse US food system, and thus to collectively become nationally scalable.

The second agricultural sustainability research thrust, into which this study broadly falls, is a top–down analysis of national (10, 16, 38) or global (8, 39–41) production statistics. The top–down approach we follow here is conceptually straightforward, as described schematically in Fig. 1. The environmental needs (land, irrigation water, etc.) of feed production are collected and distributed among the feed-consuming animal categories. This is termed the partitioning step, and is based on information about the number of animals raised or slaughtered mass in each category, as well as the characteristic feed ration in each category. The burdens attributed to each category are divided by the caloric or protein mass output of that animal category, yielding the final result, the environmental burden per consumed unit (e.g., agricultural land needed per ingested kilocalorie of poultry). This method is mainly appealing because it (*i*) circumvents the variability issues raised above by using national or global aggregations; and (*ii*) it is based on relatively solid data. For the United States in particular, US Department of Agriculture (USDA) data tend to be temporally consistent, nearly all-inclusive (e.g., records of the main crops are based on close to 100% of the production), and are reported after some (albeit modest) quality control. The key challenge with this approach is obtaining defensible numerical values and uncertainty ranges for the tens if not hundreds of parameters needed in the calculations, many of which are poorly constrained by available data. Such parameters include, for example, the average feed required per animal per day or per kilogram of weight gain, or the relative fraction of pasture in beef and dairy diets. The values vary as a function of, at least, season, geographical location, and agrotechnology used. One research effort, focused on a single location, is unlikely to yield definitive results. Significant progress in both approaches is primarily realized through the tenacious and painstaking amassing of many independent analyses over time; analyses from which robust, meaningful statistics can be derived. Because of the challenges associated with each of the research thrusts discussed above, quantitatively robust, multimetric estimates that are comparable across different categories and represent the average national environmental burdens have yet to be devised. Although estimates of total national energy use and GHG emissions by agriculture do exist (e.g., refs. 4, 5, 42, and 43), they require further statistical evaluation. The costs in terms of land, irrigation water, and Nr are even less certain.

Applying a top–down, uniform methodology throughout, here we present estimates of land, irrigation water, GHG, and Nr requirements of each of the five main animal-based categories in the US diet—dairy, beef, poultry, pork, and eggs—jointly providing 96% of the US animal-based calories. We do not analyze fish for two reasons. First, during the period 2000–2013, fish contributed ≈14 kcal per person per day, ≈0.5% of the total and 2% of the animal-based energy (750 kcal per person per day) in the mean American diet (44). In addition, data addressing feed use by fisheries and aquaculture are very limited and incomplete (relative to the five categories considered). We do not claim to cover all important environmental impacts of livestock production. Rather, we focus on key metrics that can be reliably defined and quantified at the national level with currently available data.

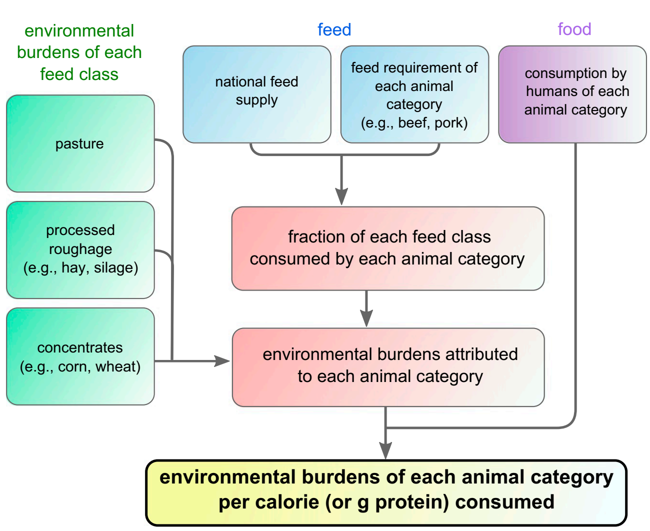

Fig. 1. A simplified schematic representation of the information flow in calculating environmental burdens per consumed calorie or gram of protein. Feed supply and requirements (blue boxes at top) previously yielded (38) the fraction of each feed class consumed by each animal category; e.g., pork requires 23 ± 9% of concentrated feed. Combined with the environmental burdens (green boxes at left; land, irrigation water, and nitrogen fertilizer for each of the three feed classes), these fractions yield the burdens attributed to each animal category. Finally, dividing those overall environmental burdens attributed to each of the five livestock categories by the number of calories (or grams of protein) nationally consumed by humans in the United States, we reach the final result of this paper (yellow box at bottom). Most input data (left and top boxes) is known with relative accuracy based on USDA data, whereas environmental burdens of pasture and average feed requirements are less certain.

Results

We base our calculations on annual 2000–2010 data for land, irrigation water, and fertilizer from the USDA, the Department of the Interior, and the Department of Energy (see *SI Text* and ref. 13 for details). We consider three feed classes: concentrates, which include crops (corn, soybean, wheat, and other minor crops) along with byproducts, processed roughage (mainly hay and silage), and pasture. Data used include land area required for feed production (9); Nr application rates for crops, hay, and pasture; crop-specific irrigation amounts; and category-specific animal GHG emissions (17, 19–23, 28, 45, 46). For GHG emissions we also use LCA data to cover not only feed production but also manure management and enteric fermentation.

We use these data to calculate the amount of resources (e.g., total land or irrigated water) required for the production of all feed consumed by each edible livestock. We then partition the resources needed for the production of these three feed classes among the five categories of edible livestock. These two steps (38) rely on numerical values of several parameters that current data constrain imperfectly. Key among those are the feed demands of individual animals—e.g., 1.8 kg dry matter (DM) feed per 1 kg of slaughtered broiler—for which we could not find a nationwide reputed long-term dataset. Although some of the poorly known parameters impact the overall results minimally, a few of those impact the results significantly. As such, these steps add uncertainty to our results for which our presented uncertainty estimates may account only partially. The partition of feed is performed according to the fraction of the national livestock feed consumption characterizing each category, using recently derived partition coefficients (see Table S1 and ref. 38). Finally, we divide the resource use of each category by the US national animal caloric consumption, obtaining a category-specific burden per unit of consumed energy. For clearer presentation, we report burdens per megacalorie, where a megacalorie is 10^3 kilocalories (also colloquially termed "10^3 calories" in popular US nutritional parlance), equivalent to roughly half of the recommended daily energy consumption for adults. That is, we focus on the environmental performance per unit of energy of each food category. This is by no means a unique or universally

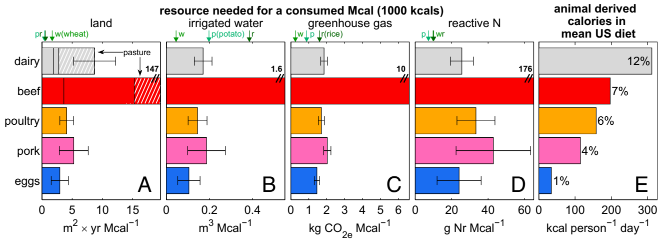

Fig. 2. (*A–D*) Environmental performance of the key livestock categories in the US diet, jointly accounting for >96% of animal-based calories. We report performance in resources required for producing a consumed Mcal (1 Mcal = 10^3 kcal, roughly half a person's mean daily caloric needs). For comparison, resource demands of staple plants potatoes (denoted p), rice (r), and wheat (w) are denoted by arrows above *A–D*. *E* displays actual US consumption of animal-based calories. Values to the right of the bars denote categories' percentages in the mean US diet. The demands of beef are larger than the figure scale and are thus written explicitly next to the red bars representing beef. Error (uncertainty) bars indicate SD. In *A*, for beef and dairy, demand for pastureland is marked with white hatching, and a vertical line separates demand for cropland (to the left), and processed roughage land (to the right).

superior choice. Other metrics, such as environmental costs per gram of protein (16), may be useful in other contexts or favored by some readers. We thus repeat our calculations using the protein metric, as shown in *SI Text*, section 6 and Fig. S1, conflating nutritional and environmental considerations (e.g., refs. 13 and 47).

We correct for feed consumption by other animals (goats, sheep, and horses) as well as export–import imbalances of individual animal categories. As pasture data coverage is poor, we derive the nitrogen fertilizer used for pasture as the residual between the overall agricultural use totals and the sums of crops and processed roughage totals, all well constrained by data. GHG emissions associated with the production of the various animal categories are derived from previous studies, considering CO_2, CH_4, and N_2O (17, 19–21, 28, 45, 46) from manure management, enteric fermentation, direct energy consumption, and fertilizer production inputs. An extended technical discussion of the methodology including data uncertainty and limitations is given in *SI Text*. Note however that using full life cycle GHG estimates (as we do here) renders the GHG approach distinct from those for the other metrics, which address only the feed production phase in total production.

The animal-based portion of the US diet uses ≈0.6 million km^2 for crops and processed roughage, equivalent to ≈40% of all US cropland or ≈2,000 m^2 per person. The total requirements, including pasture land, amount to ≈3.7 million km^2, equivalent to ≈40% of the total land area of the United States or ≈12,000 m^2 per person. Feed production requires ≈45 billion m^3 of irrigation water, equal to ≈27% of the total national irrigation use (48), or ≈150 m^3 per person per year, which is comparable to overall household consumption. It also uses ≈6 million metric tons of Nr fertilizer annually, about half of the national total. Finally, GHG emissions total 0.3×10^{12} kg CO_{2e} which is ≈5% of total US emissions (49), or 1.1 t per person per year, equivalent to about 20% of the transportation sector emissions.

We find that the five animal categories are markedly dichotomous in terms of the resources needed per consumed calories as shown in Fig. 2 *A–D*. Beef is consistently the least resource-efficient of the five animal categories in all four considered metrics. The resource requirements of the remaining four livestock categories are mutually similar. Producing 1 megacalorie of beef requires ≈28, 11, 5, and 6 times the average land, irrigation water, GHG, and Nr of the other animal categories. Fig. 2 thus achieves the main objective of this paper, enabling direct comparison of animal based food categories by their resource use. Its clearest message is that beef is by far the least environmentally efficient animal category in all four considered metrics, and that the other livestock categories are comparable (with the finer distinctions Fig. 2 presents).

A possible objection to the above conclusion is that beef production partly relies on pastureland in the arid west, land that is largely unfit for any other cultivation form. Whereas most western pastureland is indeed unfit for any other form of food production, the objection ignores other societal benefits those arid lands may provide, notably ecosystem services and biodiversity. It further ignores the ≈0.16 million km^2 of high-quality cropland used for grazing and the ≈0.46 million km^2 of grazing land east of longitude 100°W that enjoy ample precipitation (50) and that can thus be diverted to food production. Even when focusing only on agricultural land, beef still towers over the other categories. This can be seen by excluding pasture resources and summing only crops and processed roughage (mostly hay and silage, whose production claims prime agricultural land that can be hypothetically diverted to other crops). After this exclusion, 1 Mcal of beef still requires ≈15 m^2 land (Fig. 2*A*), about twofold higher than the second least-efficient category.

As a yardstick, in Fig. 2 we compare animal categories to three plant staples for which we were able to gather data on all four metrics analyzed. Results for potatoes, wheat, and rice (*SI Text*, section 9) are shown by three downward pointing arrows at the top of Fig. 2 *A–D* accompanied by their initial letters (e.g., "r" for rice). Compared with the average resource intensities of these plant items per megacalorie, beef requires 160, 8, 11, and 19 times as much land, irrigation water, GHG, and Nr, respectively, whereas the four nonbeef animal categories require on average 6, 0.5, 2, and 3 times as much, respectively (Fig. S2). Although potentially counterintuitive, the irrigation water requirements reflect the fact that the bulk of land supplying livestock feed is rainfed, i.e., not irrigated. For example, for the two key caloric contributors to the diet of US livestock, corn and soy,

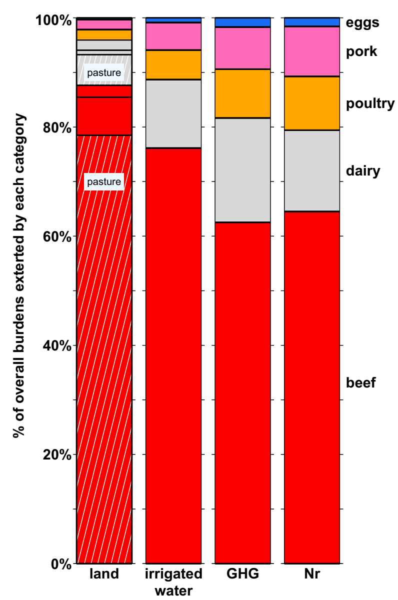

Fig. 3. Percentage of the overall national environmental burdens exerted by the individual animal categories. The results are obtained by multiplying the values of Fig. 2*E*, recast as annual overall national caloric consumption, by the resource per megacalorie of Fig. 2 *A–D*. Beef requires ≈88% of all US land allocated to producing animal-based calories, partitioned (from the bottom up) among pasture (≈79%), processed roughage (≈7%), and concentrated feed (≈2%). The land demands of dairy are displayed in the same format.

only 14% and 8% of the respective allocated lands are irrigated (≈44,000 km^2 and 25,000 km^2 of ≈300,000 km^2 each).

Our conclusions from the comparison among the five considered livestock categories are also valid, albeit slightly numerically modified, when analyzed per unit of protein consumed rather than on a caloric basis as shown in Fig. S1 and *SI Text*, section 6. For the analyzed plant items, whose protein content is lower, the differences are smaller by comparison with the livestock categories, as Fig. S1 shows. A detailed comparison of plant items calls for a dedicated future study. Such a study should also analyze high-protein plants such as soy and beans. We currently do not correct for differing protein digestibility whose relatively small quantitative effect (51) does not qualitatively change our results. We also do not account for differences in essential amino acid content. We note that the practical implications of protein sources in diverse diets are still vigorously debated (52) among nutritionists, and that the combined amino acid mass in current wheat, corn, rice, and soybean production exceeds the USDA recommended intake of these nutrients for the global human population.

Fig. 3 shows the partitioning of the total environmental burdens in the four metrics associated with feed production for the five livestock categories. We obtain these totals by multiplying the per calorie burdens depicted in Fig. 2 *A–D* by the caloric use shown in Fig. 2*E*. Fig. 3 thus identifies categories that dominate overall animal-based burdens, taking note of both resource efficiency and actual consumption patterns. Breaking down the total annual national burdens in each metric, Fig. 3 shows the dominance of beef over the environmental requirements of all other animal categories combined.

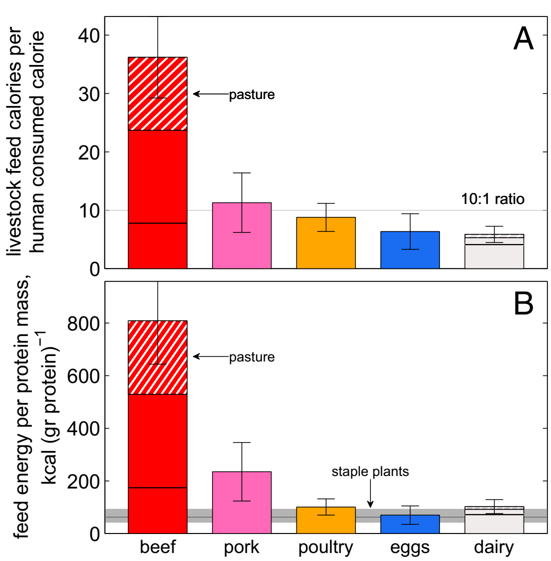

Fig. 4. Feed-to-food and feed-to-protein conversion factors of different livestock categories. The bar height of each category in *A* shows the total livestock feed calories used divided by the human-consumed calories they yield. For example, the value of ≈9 for poultry indicates that, on average, 9 feed calories fed to poultry yield 1 calorie consumed by humans. Note that this factor includes the approximately twofold loss reported by the USDA in the post-farm gate supply chain from primary production through retail to the consumer. The often-quoted 10:1 conversion factor per trophic level arising from studies in ecology is marked as a gray line. *B* depicts the conversion factors from livestock feed to human-consumed protein mass. For beef and dairy, the contribution of concentrates, processed roughage, and pasture is presented from the bottom to the top, respectively. The gray area marks the upper and lower bounds of the three staple plants. Error (uncertainty) bars indicate SD. See *SI Text* for calculation details.

The broad resource demand ranges of Fig. 2 *A–D* partly stem from differences in the basic biology-governed capacity of different farm animals to convert feed energy into calories consumed by humans. Fig. 4*A* quantifies these conversion factors from feed to consumed food for current US agricultural practices and exhibits a wide range, with beef three to six times less efficient than the other (largely mutually comparable) livestock categories. Modern, mostly intensive, US beef production is thus an energy conversion pathway about fourfold less efficient than other livestock. This value is in line with earlier analyses (53) and updates those analyses to reflect current data and practices. Comparing Figs. 2 and 4 suggests that biology does not explain all of the unusually high resource requirements of beef depicted in Fig. 2. Such results and methodology can also be used to quantify the tradeoffs associated with beef production relying primarily on grazing versus on processed roughage and concentrates; whereas grass-fed beef requires more pasture land, its irrigation water and Nr fertilizer needs are lower. In Fig. 4*B* we further show the conversion factor from feed calories to protein mass for each of the animal categories.

Discussion

How does the relative resource consumption calculated in this study compare with the caloric composition of the current mean US diet? In stark contrast with Fig. 2 *A–D*, Fig. 2*E* shows this composition and demonstrates the suboptimality of current US consumption patterns of animal-based foods with respect to the four environmental metrics considered. Beef, the least efficient against all four metrics, is the second most popular animal category in the mean US diet, accounting for 7% of all consumed calories. Interestingly, dairy, by far the most popular category, is not more efficient than pork, poultry, or eggs.

Because our results reflect current US farm policies and agrotechnology, the picture can change markedly in response to changes in agricultural technology and practice, national policies, and personal choice. By highlighting the categories that can most effectively reduce environmental resource burdens, our results can help illuminate directions corrective legislative measures should ideally take. Although our analysis is based on US data, and thus directly reflects current US practices, globalization-driven rapid diffusion of US customs, including dietary customs, into such large and burgeoning economies as those of China or India, lends a global significance to our analysis.

Corrective legislative measures are particularly important because, in addition to ethnic and cultural preferences, current consumption patterns of several food types partly track government policies (such as price floors, direct subsidies, or countercyclical measures). For example, at least historically, the caloric dominance of dairy in the US diet is tied to governmental promotion of dairy through marketing and monetary means (54), and meat ubiquity partly reflects governmental support for grain production, a dominant subsidy recipient in the agricultural sector. Our results thus offer policymakers a method for calculating some of the environmental consequences of food policies. Our results can also guide personal dietary choices that can collectively leverage market forces for environmental betterment. Given the broad, categorical disparities apparent in our results, it is clear that policy decisions designed to reduce animal-based food consumption stand to significantly reduce the environmental costs of food production (55) while sustaining a burgeoning populace.

Materials and Methods

Analysis Boundaries. For land, water, and Nr, we confine our analysis to resources used for feed production. First, on-farm use of these resources has been shown to be negligible by comparison. In addition, data addressing on-farm requirements are more geographically and temporally disparate, not

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always directly mutually comparable, and thus difficult to scale up into the national level our analysis requires.

We focus on irrigation water (i.e., blue water), neglecting direct precipitation on plants (i.e., green water) as the latter is not directly accessible for alternative human uses. Disregarding green water follows recent studies (10, 56, 57) that favor this approach and point out the large differences between results of studies that focus on irrigation water and those based on combining all water resources.

Beside feed-related costs, livestock production also involves non-CO_2 GHG emissions due to manure management and enteric emissions. These GHG burdens are included in the published LCAs we use in this study (refs. 17, 19–21, 23, 28, 29, and 58 and *SI Text*, section 7).

In analyzing the eutrophication potential of Nr, we address fertilizer use only, excluding manure and emissions of volatile nitrogenous compounds, which are considered in the GHG metric. The decision to focus the biogeochemistry portion of the work on nitrogen has several distinct motivations. First, N is by far the most widely applied nutrient, with application rates by nutrient mass approximately threefold higher than those of the other two agriculturally widely used nutrients, phosphate and potash. Second, because the geographical focus is North America, which has been glaciated recently, its soils and the fresh water systems that drain them are rarely P limited (59). Consequently, N dominates eutrophication and hypoxia in the estuaries and coastal ecosystems surrounding North America (60). Third, our focus on feed production implicitly focuses on the Midwest. This emphasizes the Gulf of Mexico Dead Zone, where N limitation dominates dissolved oxygen levels (61).

Correction for Export–Import. In evaluating national feed use, we take note of domestic consumption only, excluding and correcting for domestically produced exported feed. We similarly correct for net export–import of animal-based food items. To do so, we multiply the overall national resource use by a factor that reflects the export–import imbalance as a fraction of the total consumed calories of each animal category. For example, if 14% of the total pork produced is exported whereas imported pork is 5%, then we multiply each resource used domestically for pork production by 0.91. More details are given in *SI Text*.

Plant Staple Item Choice. We selected for analysis items for which we were able to gather information covering all four metrics, and that are a calorically significant part of the US diet. We note that low-caloric-content plant items, such as lettuce, have relatively high-resource burdens per calorie. As a result, these items do not lend themselves naturally to evaluation by either the per calorie or per gram protein metrics, and probably require a more nuanced, more revealing metric.

Feed Requirements and Fraction of Total Feed Supply of the Animal Categories. Our calculation of the total annual DM intake of each animal category begins with USDA data on livestock headcounts, slaughter weights, and feed requirements per head or slaughtered kilogram (ref. 38 and references therein). (See Dataset S1 for the raw data used and detailed analysis thereof.) We combine the intake requirements with USDA estimates of overall US feed production and availability by feed class (*SI Text*, section 2.1) (38), distinguishing and treating individually concentrated feed ("concentrates," meaning grains and byproducts), and roughage, subdivided into pasture and processed roughage (the latter combining hay, silage, haylage, and greenchop). Most used data are temporal averages over the years 2000–2010 of USDA reports. All data sources are referenced individually in *SI Text*, section 2.1, including USDA grain, oil, and wheat yearbooks; the 2011 Agriculture Statistics Yearbook; and, for pasture, an earlier study by Eshel et al. (38). The soy calculations are an exception to this pattern. They comprise soy feed and residual use plus 60% of crushed (i.e., the caloric and economic fraction of crushed soybean that goes into soybean meal feed). These data jointly yield our feed requirement estimates for each livestock category–feed class combination. The calculations presented take note of several issues. First, feed used by sheep and goats, whose meat jointly constitutes <1% of the American human diet's calories (44), and the more substantial amount of feed consumed by horses, is estimated. These feed values are subtracted from the national available feed totals, to arrive at the feed consumed by the five major edible livestock categories. A second issue is that pasture feed contributions are unknown, and are thus inferred by subtracting the known overall concentrates and processed roughage availability from the total livestock feed requirements. The concentrated feed requirements of poultry, pork, and eggs, which only consume concentrated feed, follow directly from their total feed requirements. From the fractions the three feed classes constitute in dairy rations reported in the cited literature, dairy's total requirements by feed class are obtained (38). Next, beef concentrated feed use is calculated as the total national supply of concentrates minus the combined use by poultry, pork, eggs, and dairy. Following a similar procedure, the processed roughage requirement of beef is inferred as the total available minus the fraction consumed by dairy. Finally, pasture needs of beef are inferred by subtracting from the known total beef feed needs the calculated contributions to these needs made by concentrates and processed roughage. More information is given in *SI Text* and in ref. 38.

We note that the USDA maintains records related to consumption of the main feed sources by the five livestock categories as part of the data yielding Animal Unit indices (62). In principle, this data can facilitate the sought partitioning. However, the underlying conversion factors used to translate headcounts into Animal Units have not changed since the late 1960s, when the USDA first introduced the indices. Because they are based on outdated farm practices markedly different from those used today, using them for environmental cost partitioning is questionable (63).

Byproducts in Beef Feed. One can suggest that beef should be credited in the environmental impact calculus for its ability to use as feed byproducts that would otherwise constitute waste in need of environmentally acceptable disposal. We do not follow this approach here for two reasons. First, such credits do not currently exist, and devising them in an environmentally and arithmetically sound manner is a major undertaking in its own right that we deem outside the current scope. On a more practical level, in addition, our preliminary analysis has established that the total mass of all byproducts (excluding soy meal) is less than 10% of the feed requirements of beef, and thus of small quantitative effect.

Aggregating and Allocating Environmental Burdens. We calculate and aggregate resources (land, irrigation water, and Nr) associated with individual feed types (various crops and hay types; *SI Text*, sections 2.2–2.4) into the three feed classes (concentrates, processed roughage, and pasture) by combining data on feed use, crop yields, irrigation, and nitrogen fertilizer application rates for each crop type and for pasture lands (*SI Text*, section 3). We then partition the overall resource use of each feed class among the five animal categories using the partition coefficients previously calculated (Table S1 and ref. 38) to determine the resources attributable to each animal category (*SI Text*, section 4).

Finally, we divide the total resource use of each animal category (mass GHG emitted and Nr applied, volume of water used for irrigation, and allocated land area for feed) by the contribution of that category to the total US caloric intake, obtaining the resource requirements per human-destined megacalorie. Replacing human destined calories with human-destined protein mass, we use a similar methodology to calculate resource requirements per unit of human-consumed protein (Fig. S1 and *SI Text*, section 6).

Derivation of Uncertainty Estimates. The uncertainty ranges for the raw data are based on variability among independent data sources or interannual variability. In the few cases where neither is available, we use as default an uncertainty of 10% of the parameter value.

We calculate uncertainty estimates using two distinct approaches. Dataset S1 contains traditional formal error propagation. We went to some length to properly handle cases with nonzero cross-covariance. A typical but by no means unique example of this involves feed requirements of, say, beef and the total feed requirement of all animal categories (which includes beef). In addition, we use Monte Carlo bootstrapping Matlab code (Mathworks) to perform 10,000 repeats, in each choosing at random subsets of the raw data, obtaining the end results, and deriving uncertainty ranges in the reported calculations from the distribution of end results thus obtained. Both methods yield similar but not identical uncertainty estimates. We believe the discrepancies, ≈10% on average, stem from imperfect account of all cross-correlations by the formal error propagation. We present the uncertainty estimates (SDs) based on the formal (parametric) error propagation, as we favor the method most easily available for future researchers.

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