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.

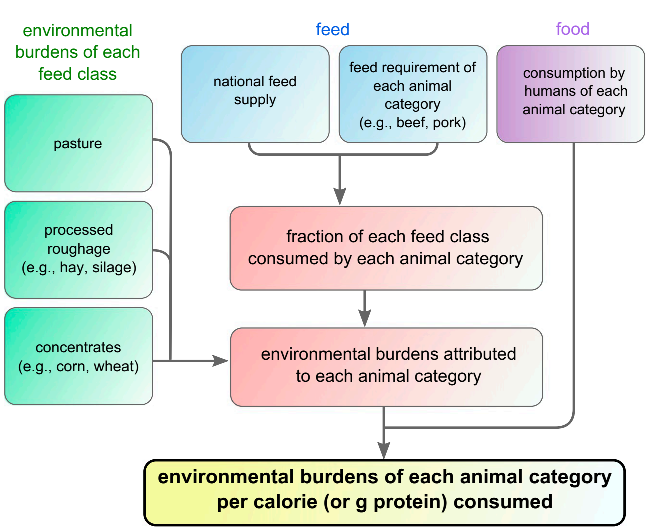

Fig. 1. A simplified schematic representation of the information flow in calculating environmental burdens per consumed calorie or gram of protein. Feed supply and requirements (blue boxes at top) previously yielded (38) the fraction of each feed class consumed by each animal category; e.g., pork requires 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.

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.

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

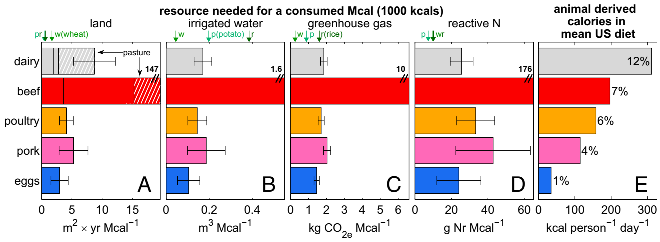

Fig. 2. (*A–D*) Environmental performance of the key livestock categories in the US diet, jointly accounting for >96% of animal-based calories. We report performance in resources required for producing a consumed Mcal (1 Mcal = 10^3 kcal, roughly half a person's mean daily caloric needs). For comparison, 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,

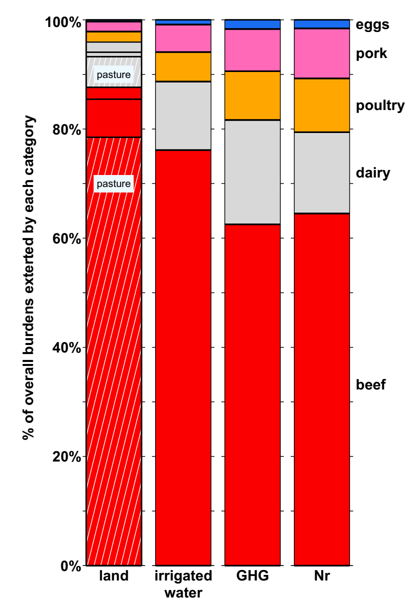

Fig. 3. Percentage of the overall national environmental burdens exerted by the individual animal categories. The results are obtained by multiplying the values of Fig. 2*E*, recast as annual overall national caloric consumption, by the resource per megacalorie of Fig. 2 *A–D*. Beef requires ≈88% of 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.

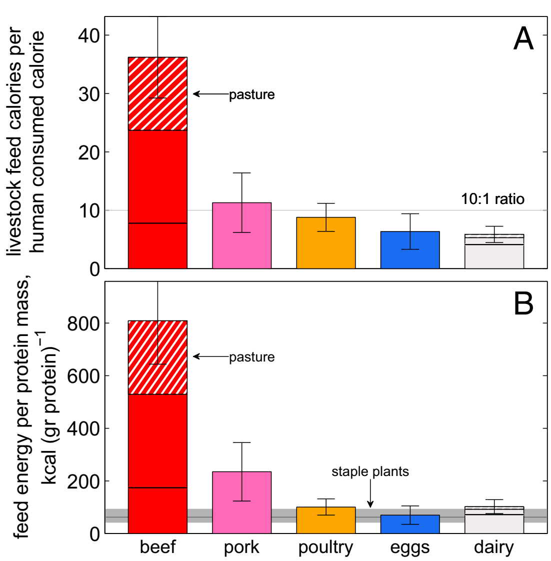

Fig. 4. Feed-to-food and feed-to-protein conversion factors of different livestock categories. The bar height of each category in *A* shows the total livestock feed calories used divided by the human-consumed calories they yield. For example, the value of ≈9 for poultry indicates that, on average, 9 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 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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Supporting Information

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SI Text

1. Overview

The method devised in this paper (depicted schematically in Fig. 1) permits partitioning of total resources used in and greenhouse gas (GHG) emissions associated with livestock production among the key edible animal categories: dairy, beef, poultry, pork, and eggs.

We begin by aggregating resources used [e.g., land, water, and reactive nitrogen (Nr)] by each individual feed type into the three feed classes: concentrated feed (i.e., concentrates), processed roughage (mostly hay and silage), and pasture (blue boxes in Fig. 1; and *SI Text*, sections 2 and 3). We then partition the resource aggregates for each feed class among the five animal categories using the partition coefficients devised by Eshel et al. in ref. 1 (upper red box in Fig. 1; and *SI Text*, sections 4 and 8) to determine total resources used in the production of each animal category (lower red box in Fig. 1; and *SI Text*, section 4). Finally, we divide total resources used per animal category by the US national caloric intake of that category, obtaining megacalorie resource efficiency per animal category for each of the three considered environmental metrics (yellow box in Fig. 1).

To derive the GHG burden of each animal category, we use published life cycle assessment (LCA) results of the production phase (including all relevant feed classes; *SI Text*, section 7). As a benchmark with which to compare the animal-based products' resource use, we devise the corresponding resource efficiency and GHG emissions of three common food plants (potato, wheat, and rice; *SI Text*, section 9).

All data and most supporting information calculations steps are fully documented and can be followed in Dataset S1, specific tabs and cells of which we reference in the text below. Dataset S1 also contains technical comments in specific cells, and specific reference points to data sources. [Dataset S1 comprises four main tabs that present the calculations' as the following key steps: (*i*) ResourceFeedMain, which is the starting point for all calculations, which summarizes the resources needed for feed production (land, water, and Nr), per feed type and class and the embodied calories of each feed type; (*ii*) PartitioningResource, which partitions all resource inputs among animal categories, e.g., total water or land needed for growing pork feed; (*iii*) PartitioningPerCal, which denotes resource use per human-consumed megacalorie in the United States by animal category; and (*iv*) PartitioningPerProtein, which denotes the resource use per human-consumed kilogram of protein in the United States by animal category.] Whereas the values in the main text appear in International System of Units format, the calculations presented here and in Dataset S1 are mostly in pounds (lb) or acres, conforming to US Department of Agriculture (USDA) nomenclature from which most data were derived.

2. Calculating the Resource Use of Individual Feeds

Our calculations are based on averaging the data available since 2000, typically (except for irrigation water) covering 2000–2011 or 2000–2012.

We summarize the resources used for each feed type included in the joint concentrates, processed roughage, and pasture feed classes in the ResourceFeedMain tab of Dataset S1. For simplicity we present a detailed, step-by-step numerical example of one feed or food category at the end of each subsection, along with the references from which the various data are derived.

Each feed class comprises several feed types (ResourceFeedMain tab in Dataset S1), where the two rightmost columns give the relevant national annual total and standard variation for that feed class (e.g., ResourceFeedMain tab columns Q and R for concentrates or Y and Z for processed roughage in the ResourceFeedMain tab in Dataset S1). This data are divided into feed (rows 4–9), needed land (rows 10–12), water (rows 16–17), fertilizer (rows 13–15), and feed calories produced (rows 18–19).

2.1. Feed Consumption by Feed Class. We start by presenting the feed consumed annually by all livestock (rows 4, 6, and 7 of the ResourceFeedMain tab in Dataset S1). The data presented are averages for the "feed and residual use" under the "domestic disappearance" category of the USDA. Data sources as indicated specifically for each dataset include USDA grain (2), oil (3) and wheat yearbooks (4), the 2011 Agriculture Statistics (5), and pasture (1) (see Dataset S1 for dynamic links to other tabs that present the raw data).

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).

For example, the mean value of corn used for feed and residual in 2000–2011 is 5,557 million bushels (cell C4), with the corn tab presenting the raw data and calculations (column W). Cells C6 and C7 represent the total feed in millions of pounds and short tons, respectively.

Because dry matter (DM) content varies among feed types, before aggregation into feed classes and partitioning among animal categories we convert all data to a DM basis. Mean DM content (row 8) is the DM average of various feed forms (in the case of corn, e.g., corn grains rolled, corn grains whole, high-lysine corn grains, etc.) based on feed nutrient composition tables (see dynamic links to the FeedNutrientComposition tab in Dataset S1, based on ref. 6).

For corn, this yields 0.87 DM pounds per fed pound (cell C8). Hay, haylage, and greenchop deviate from this because USDA data for these are reported in a DM content equivalent assuming 13% moisture content. We therefore used 87% DM, not the nutrient composition table's mean. We calculate the total feed DM (row 9) as average feed mass multiplied by DM content. For corn (cell C9), this value is

$$\text{Feed DM}_{\text{corn}} = 0.87 \times 311{,}195 \times 10^6 \text{ lb} = 271{,}432 \times 10^6 \text{ lb}. \quad \textbf{[S1]}$$

2.2. Land Use for the Various Feed Classes. We calculate feed land demands (feed needed land, row 12 of the ResourceFeedMain tab in Dataset S1) by dividing average consumed feed (in bushels, listed in the USDA nomenclature as "feed and residual use") by the average yield (bushel or mass) per planted acre (taking note of crop failures),

$$\text{Needed land} = \frac{\text{feed and residual use}}{\text{yield per planted acre}}. \quad \textbf{[S2]}$$

Because average yield is only available for harvested acreage, we calculate the yield per planted acre for each feed (row 10) using total production (in bushels or mass) and planted acres:

$$\text{Yield per planted acre} = \frac{\text{total production}}{\text{planted acres}}. \quad \textbf{[S3]}$$

The calculations are presented in the crop yields tab of Dataset S1 (for corn, sorghum, oats, and barely), soy table2 (for soy), and wheat (for wheat) (see dynamic links in the relevant cells of Dataset S1). Although in most cases the calculation is straightforward, to deduce corn's and sorghum's per planted acre yield for silage and grains, we must partition the planted acreage between the two products, and then divide the (known) production of each by its total planted acreage. This allocation is based on the harvested area of both products and is calculated in the following equation:

$$\text{Planted acreage}_{\text{grain}} = \frac{\text{harvested grain area} \times \text{planted acreage}}{\text{all-harvested area}}. \quad \textbf{[S4]}$$

A similar equation is used for silage. For corn, the mean total planted area is 83.3 million acres (crops yield tab, cell C20). The area harvested for grain is 75.9 million acres (cell I20) of a total of 81.6 million acres harvested (cell G20). The total corn grain planted area (cell H20) is therefore

$$\text{Planted acreage}_{\text{corn grain}} = 83.3 \times 10^6 \text{ acres} \times \frac{75.9}{81.6} \approx 76.6 \times 10^6 \text{ acres}. \quad \textbf{[S5]}$$

We then divide annual corn grain production (11, 271 million bushels, cell J20) by this result, obtaining corn grain's yield of 147 bushels per planted acre (cell K20).

Needed land for pastureland is the sum of the reported "cropland used for pasture," "grassland pasture," and "grazed forest" of the USDA categories (pasture tab and ref. 7).

A final note regarding land use addresses the ≈4% of cropland producing more than one crop annually (7). These acres are counted twice: once for each crop (8). Therefore, to avoid double counting, all land used for crops (everything other than pasture) is scaled by a factor of 0.96 (ResourceFeedMain tab, cell Q12).

2.3. Fertilization of the Various Feeds. Nitrogen fertilization data for corn, wheat, and soy are from the USDA Economic Research Service, Fertilizer Use and Price (9), whereas for barley, oats, and sorghum the source is USDA Economic Research Service, National Agriculture Statistics Service Quick Stats (10).

The mean Nr application rate per planted acre for each feed type (ResourceFeedMain tab, row 13 in Dataset S1) is calculated by dividing the feed type's total annual applied nitrogen (ConcentratesNr tab in Dataset S1) by its total planted acreage [the actual percentage of land fertilized also appears in the specified tab (e.g., for corn, in columns C–F of ConcentratesNr)]:

$$\text{Nr per planted acre} = \frac{\text{total Nr applied}}{\text{planted acreage}}. \quad \textbf{[S6]}$$

On average $4{,}956 \times 10^3$ (short) tons of Nr are applied on corn (grain) fields annually (cell C19), which, spread over the full 76.6 million planted acres of corn, yields a mean application rate of 129 lb $(\text{acres} \times \text{y})^{-1}$ (cell E21).

Based on the calculated needed land and mean Nr application rate, total applied Nr for each feed type is (ResourceFeedMain tab, row 15 in Dataset S1)

$$\text{Total Nr}_{\text{feed}} = \text{needed land}_{\text{feed}} \times \text{Nr per planted acre}_{\text{feed}}. \quad \textbf{[S7]}$$

Concentrated data on nitrogen use for pasture, hay, or silage are unavailable. We did however find data on total fertilized pastureland acreage (with no details as to fertilizer type; ref. (10) (in the ResourceFeedMain tab, cell AA14 in Dataset S1). Therefore, to estimate total pasture Nr use (ResourceFeedMain tab, cell AA15), we multiply the total area of pastureland fertilized by Nr application recommendations from the Natural Resources Conservation Service (cell AA13) (11).

To assess the amount of Nr used for all processed roughage (cell Y15) we subtract all known uses of Nr (grains, vegetable, fruit and nuts, and our result for pastureland) from the total Nr applied in the United States:

$$\text{Total Nr}_{\text{roughage}} = \text{total US Nr use} - \text{all known Nr use}. \quad \textbf{[S8]}$$

2.4. Irrigated Water Used for the Various Feed Types. Irrigation data were obtained from the 2008 Farm and Ranch Irrigation Survey, which reports average irrigation rates per harvested–irrigated acre in the years 2002–2003 and 2007–2008 (12).

To calculate mean irrigation rates per planted acre (irrigated and nonirrigated; ResourceFeedMain tab, row 16 in Dataset S1), we divide each crop's total water use (total irrigated acres × mean irrigation rate) by its planted acreage (water tab),

$$\text{Mean water irrigation rate} = \frac{\text{irrigated\&harvested acreage} \times \text{irrigation rate}}{\text{planted acres}}, \quad \textbf{[S9]}$$

and then obtain the crop's total water needs (ResourceFeedMain tab, row 17) using

$$\text{Total water}_{\text{feed}} = \text{mean water irrigation rate}_{\text{feed}} \times \text{needed land}_{\text{feed}}. \quad \textbf{[S10]}$$

For example, in 2007–2008, 12 million acres of corn grain were irrigated and harvested, with a reported average irrigation rate of 1 acre-foot, or 1,234 m^3 per harvested–irrigated acre (water tab, cell F18). That year, corn grain's total planted acreage (irrigated and nonirrigated) was 87.4 million acres (cell C18). Therefore, corn's 2007 irrigation rate per planted acre (cell H18) was

$$\frac{12 \times 10^6 \text{ acres} \times 1{,}234 \text{m}^3/(\text{acre} \times \text{y})}{87 \times 10^6 \text{ acres}} \approx 169 \frac{\text{m}^3}{\text{acre} \times \text{y}}. \quad \textbf{[S11]}$$

Averaged with 2003 data (the only other irrigation data point available since 2000), this becomes 185 $m^3/(acre \times y)$ (cell H24).

As no sorghum silage irrigation data exist, we assume sorghum's mean irrigation rate is that of corn silage.

We then proceed to multiply this average irrigation rate per planted acre by the total land required for corn grain feed production (37.9 million acres) to arrive at total annual water requirement for corn grain (7,022 million m^3/acre, ResourceFeedMain tab, cell C17).

2.5. Feed Calories Derived from Various Feeds. We calculate the energy content (kilocalories per pound) of the various feed types (ResourceFeedMain tab, row 18 in Dataset S1) based on feed composition tables (6) (see data presented in the FeedNutrientCompostion tab in Dataset S1), using

$$\text{DE} = \%\text{TDN} \times 0.02, \quad \textbf{[S12]}$$

where DE is the digestible energy in megacalories per pound (Mcal = 10^3 kcal), and % TDN is the mean percentage of total dry nutrient in the various forms of a given feed. We estimate pasture value as the average of wheat (6), grass, and legume forage pastures (13). (An online calculator with the grass and legume forage pasture values appears in ref. 13.) The total calories contributed by a specific feed type (row 19) is the total feed dry mass (row 9) times its energy content (row 18).

Corn is used in various forms (e.g., rolled grain, screenings) with an average TDN of 85%. Its mean energy content is therefore $85 \times 0.02 = 1.7$ Mcal/lb (cell C18).

With a total corn grain DM consumption of $271{,}432 \times 10^6$ lb (cell C9), livestock consume $271{,}432 \times 10^6 \text{ lb} \times 1.71 \text{ Mcal/lb} \approx 463{,}939 \times 10^6$ corn grain megacalories per year (cell C19).

3. Aggregating Individual Feed Type Results into Feed Classes

The next step is aggregating (summing) the various individual feed type resource use into the three feed classes: concentrates (ResourceFeedMain tab, column Q in Dataset S1), processed roughage (column Y), and pasture (column AA). The sums are feed DM intake (row 9), needed land (row 12), Nr fertilizer used (row 15), irrigated water (row 17), and calories produced (row 19).

4. Partitioning Environmental Burdens Among Animal Categories (Including Export–Import Correction)

To allocate the resource use to each animal category, we multiply each feed class sum by the portion of feed each individual animal category consumes from the total using coefficients derived by Eshel et al. (1) (see the Animal Partitioning tab, cells D7:J14 in Dataset S1 and *SI Text*, section 8 for coefficients). This step first requires two minor intermediate corrections, as follows.

First, we adjust total resources used to reflect only what is required for the animal categories which we analyze in this study (dairy, beef, poultry, pork, and eggs that we term the "edibles") which contribute substantially to the mean American diet. Because the presented resource use sums reflect requirements also for other livestock, including those whose contributions to the mean American diet is zero or minute (i.e., nonedibles: horses, sheep, goats), we multiply the results by a coefficient derived by Eshel et al. (1) that removes those feed requirements. The major edible coefficients are 98.07% (PartioningResources tab, cell B15) for concentrates, 95.21% (cell B16) for processed roughage, and 92.2% (cell B17) for pasture. The results for the edible animal categories' resource needs by feed class appear in the Partioning-Resources tab, cells A3:AF10 in Dataset S1. For example, beef's land needs for production of concentrates (abbreviated as "con."; cell C6) is

$$\begin{aligned} \text{Land con.}_{\text{beef}} &\equiv (\text{total needed land}_{\text{con.}}) \times (\text{beef's \% of con.}) \times \left(\frac{\text{edible con.}}{\text{total con.}}\right) \\ &= 78 \times 10^6 \ \frac{\text{acre}}{\text{y}} \times 24.1\% \times 0.9807 = 18 \times 10^6 \ \frac{\text{acre}}{\text{y}}. \end{aligned} \quad \textbf{[S13]}$$

Second, because there are export–import imbalances in livestock products, we adjust inputs to reflect only domestic consumption. To that end, we multiply the total resource needs of each animal category by the fraction of total production consumed domestically (cells B21–B25) (14, 15).

For example, the total land used by beef adjusted for domestic disappearance (cell K6) is then

$$\begin{aligned} \text{Total land}_{\text{beef}} &\equiv \text{total needed land}_{\text{beef}} \times \left(\frac{\text{domestic disappearance of beef}}{\text{total beef production}}\right) \\ &= 741 \times 10^6 \ \frac{\text{acre}}{\text{y}} \times 104\% = 770 \times 10^6 \ \frac{\text{acre}}{\text{y}}. \end{aligned} \quad \textbf{[S14]}$$

Where the value of 104% indicates that there is net import (minus export) of beef that amounts to 4% of the US national beef production and the total land resources need to be increased to account for that. To derive the resource use intensity per eaten kcal of each animal category, we divide the total resources used by each category by its national caloric de facto consumption,

$$\text{Resource use intensity} = \frac{\text{domestically adjusted annual resource use per animal category}}{\text{annual total US population caloric consumption of animal category}}. \quad \textbf{[S15]}$$

These final results, reported in cells A12:P18 of the PartitioningPerCal tab in Dataset S1, are the present paper's main results.

Annual national net caloric consumption (USA Cal-Protein Intake tab, cells E25:O25 in Dataset S1) are the products of mean daily loss adjusted per capita intakes (columns E, G, I, K, and M) (16), total US population (column P) (16), and 365.2 $d \cdot y^{-1}$.

For example, we obtain beef's water use in liters per eaten megacalorie (PartitioningPerCal tab, cell E14 in Dataset S1) by dividing beef's total water use (PartitioningResources tab, cell U6) by beef's national adjusted de facto caloric consumption (USA Cal-Protein Intake tab, cell F25),

$$\text{Water use}_{\text{beef}} = \frac{1{,}000\left(\text{L/m}^3\right) \times 34{,}924 \times 10^6 \text{ m}^3/\text{y}}{21{,}267 \times 10^6 \text{ Mcal/y}} = 1{,}642 \frac{\text{L}}{\text{Mcal}}. \quad \textbf{[S16]}$$

5. Allocation Issues

In calculating the burden per calorie for all of the categories we take into account that although slaughtered dairy cattle and laying hens have consumed during their lifetime feed from the dairy and egg categories, their slaughtered meat calories contribute to the beef and poultry categories, respectively. We thus partition their lifetime-consumed feed between the two relevant animal categories to faithfully reflect the feed related environmental costs each incurred.

The allocation procedure is based on calculating slaughtered dairy's feed consumption of each feed type and adding them to the beef category. We also apply a logically identical procedure to partition concentrated feed consumed by slaughtered laying hens between the egg and poultry categories. This procedure attributes the feed that would have been needed to produce the same mass of the corresponding meat types using the relevant meat categories' representative practices. Because the use of this feed was avoided, we refer to the cost reduction in the dairy and eggs categories as avoided costs. This partitioning of feed between the animal category pairs alters the partitioning coefficients of environmental costs among the animal categories (*SI Text*, section 8). We then use these new coefficients—now taking note of avoided feed costs—to carry out all subsequent calculations (Animal Partitioning tab, cells D7:J14 in Dataset S1).

Data on beef calories consumed take into account slaughtered dairy cattle (8.5% by mass; USA Cal-Protein Intake tab, cells F36:G38 in Dataset S1, based on Eshel et al., ref. 1). We multiplied this percentage value with beef's total DM feed and derived culled dairies' feed requirement. This total feed requirement was then divided between the various feed types according to dairy's feed type fractions (i.e., 60% for concentrates, 28% for processed roughage, and 12% for pasture). With the absolute amount of feed per feed type established, we then credited (subtracted) the dairy category and added these same values to beef's three feed types accordingly.

We use the same rationale as described above to credit the egg category's resources use by subtracting slaughtered layers' DM feed contribution per feed type from the egg category and adding them to the poultry category. First, we calculate the mass of slaughtered hens (layers) (≈1.7% from total poultry slaughtered; USA Cal-Protein Intake tab, cell G41) and multiplied it by poultry's feed intake per slaughtered pound. Normally, this feed requirement should be credited from the egg category and added to the poultry category. However, because only about 35% of these slaughtered hens (termed spent hens) are actually consumed by humans (17), the total feed requirement should be additionally multiplied by this value. Consequently, this resulted in crediting egg total feed intake by less than 3%; thus we neglected this allocation.

6. Protein-Based Partitioning of Environmental Burdens

As discussed in the *Results* section of the main text, for some applications the environmental costs per unit protein consumed is a more illuminating metric. In all cases, it is an important complement to the results per ingested megacalorie reported in Fig. 2. In Fig. S1 we therefore recast Fig. 2 (this paper's key result) in terms of environmental costs per kilogram of protein (see also the PartitioningPerProtein tab in Dataset S1). We derive national consumption of animal protein (against which the environmental burdens are compared; USA Cal-Protein Intake tab, cells R25:AB25 in Dataset S1) by dividing national caloric intakes by the corresponding $\text{Mcal} \cdot \text{kg}^{-1}$ of the various animal categories (USA Cal-Protein Intake tab, cells R23:AA23), and multiplying them by the categories mass protein percentages (18) (done in USA Cal-Protein Intake tab, cells R24:AB24).

7. GHG Emissions of the Various Animal Categories

We obtain GHG use intensity in kilograms of CO_{2e} emissions per edible megacalorie from LCA studies that quantify the GHG emissions associated with the production of animal-based products, taking note of all production aspects up to farm gate (from "cradle to farm gate"). These include feed production (carbon dioxide and nitrous oxide), enteric fermentation for beef, dairy and pig (methane), and manure excretion (methane and nitrous oxide) with the relative contribution of each constituent and its absolute value varying according to animal type, location (climate), and agrotechnological practice. To be consistent with the other data sources, we favored US studies, but also incorporated non-US values which presented a wide range of results (meta-analysis) for statistical robustness. The calculations and refs. 19–27 are reported in the GHG Animals tab in Dataset S1. The results also appear in the PartitioningPerCal tab, cells H13:J18 in Dataset S1.

Beef's GHG use per megacalorie values are based on the average of four studies (GHG Animals tab, cells B14:C21 in Dataset S1), three (19–21) reporting emissions per live weight (cells C16–C18), and one (22) per edible kilogram (cell C19). To recast the former three values as emissions per edible kilogram, we divide them by the boneless edible fraction of total beef mass, 43% (19, 22),

$$\text{GHG emission per edible kg}_{\text{beef}} = \frac{\text{kg CO}_{2\text{e}}/(\text{live weight kg})}{\text{boneless fraction from total mass}}. \quad \textbf{[S17]}$$

We then average the four derived and directly reported values, yielding cell's C20 result, 32 kg CO_{2e}/(edible kg). To convert edible kilograms to megacalories we use 1.52 Mcal/lb (cell H9), obtained by dividing national total caloric intake of beef with boneless weight national consumption, yielding

$$\text{GHG intensity}_{\text{beef}} = \frac{32.15 \text{ kg CO}_{2e}/(\text{edible kg})}{(1.52 \text{ Mcal/lb}) \times (2.204 \text{ lb/kg})} = 9.6 \frac{\text{kg CO}_{2e}}{\text{Mcal}} \quad \textbf{[S18]}$$

in the GHG Animals tab, cell C21 and PartitioningPerCal tab, cell H14 in Dataset S1.

8. Partitioning Coefficients

Motivated by the disproportionate environmental costs of animal-based categories mentioned above, we devise such a method expressly for US livestock. Because costs incurred downstream of the farm gate (processing, packaging, retail, and household) exhibit modest variations among the various livestock products (22), we base our method on partitioning feed consumption. We devise a method to partition a given food-related total environmental burden—say water or land use—into the fractions attributable to specific food categories (1). First, we calculate overall feed requirements of each livestock category by combining extensive data on headcounts, slaughter weights, and per head and per slaughtered weight feed requirements. We then combine these requirements with the USDA estimates of overall US feed production and availability by type considering concentrates and roughage subdivided into pasture and processed roughage: hay, silage, haylage, and greenchop. Taken together, these data yield our feed requirement estimates for each category and feed class, which constitute the required partitioning (1). These results (following the allocation procedure described in *SI Text*, section 5) together with their SD appear in both the Animal Partitioning tab, cells D6:J14 in Dataset S1 and in Table S1.

9. Plant Resource Use and GHG Emission Calculations

Resource use and GHG emissions by plant items per megacalorie and kilogram of protein are summarized in the PartitioningPerCal tab, cells A38:E44 and PartitioningPerProtein tab, cells I36:M42, respectively, in Dataset S1. The per megacalorie values are based on comparing plants' per acre planted yield (4, 5, 28), water use (12), and nitrogen application (10) with their energy content (megacalories per pound), derived from the National Nutrient Database for Standard References (29). For instance, we calculate potatoes' average annual yield by dividing total production, ≈44 billion lb per y, by total acreage of 1.2 million acres resulting in 37,950 lb/(acre × y) (5). Potatoes' loss adjustment factor (the ratio of ingested to produced, in the USDA's Loss-Adjusted Food Availability Documentation) (30) and energy content (29) are 0.75 and 350 kcal/lb, respectively. Therefore, potatoes' land use intensity is (PartitioningPerCal tab, cell B42 in Dataset S1)

$$\text{Land use}_{\text{potato}} = \frac{4{,}046{,}860 \times 10^{-3} \text{ m}^2/\text{acre}}{[37{,}950 \text{ lb}/(\text{acre} \times \text{y})] \times 0.75 \times (350 \text{ kcal/lb})} = 0.41 \frac{\text{m}^2 \times \text{y}}{\text{loss-adjusted Mcal}}. \quad \textbf{[S19]}$$

The average irrigation of harvested potatoes is 1.8 acre-foot/(acre × y) (12). Multiplying this value by the total harvested area and then dividing by the total planted area results in a water use per planted acreage of 1,971 m^3/(acre × y) (this calculation is not shown in Dataset S1).

Subsequently, the potato's water use intensity per loss-adjusted megacalorie is (PartitioningPerCal tab, cell C42 in Dataset S1)

$$\text{Water use}_{\text{potato}} = \frac{1{,}000 \text{ kcal/mcal}}{\{[37{,}950 \text{ lb}/(\text{acre} \times \text{y})] \times 0.75 \times (350 \text{ kcal/lb})\}/[1{,}971 \text{ m}^3/\text{acre} \times \text{y}]} = 0.20 \frac{\text{m}^3}{\text{loss-adjusted Mcal}}. \quad \textbf{[S20]}$$

Potatoes' mean annual Nr fertilization rates are obtained by dividing total application amounts for 2001, 2003, 2005, and 2010 (10) (the only available data since 2000) by the planted acreage resulting in 160 lb/(acre × y). Therefore, potato's nitrogen use intensity is (PartitioningPerCal tab, cell E42)

$$\text{Nitrogen use}_{\text{potato}} = \frac{453{,}592 \times 10^{-3} \text{ g/lb}}{\{[37{,}950 \text{ lb}/(\text{acre} \times \text{y})] \times 0.75 \times (350 \text{ kcal/lb})\}/[160 \text{ lb Nr}/(\text{acre} \times \text{y})]} = 7.30 \frac{\text{g Nr}}{\text{loss-adjusted Mcal}}. \quad \textbf{[S21]}$$

With no data on GHG emissions of US plants, we use data from a UK-based study (31) that evaluated the GHG emissions of food production in the United Kingdom, the "European Union (EU) for UK consumption," and "the rest of the world for UK consumption." Our first choice was to use EU values as they average over various countries and climates, not unlike the United States. When such values were not available (e.g., for rice), we used the rest-of-the-world value. Unlike the animal-based GHG emissions values, which address emissions up to farm gate, plant GHG emissions also consider emissions up until the regional distribution center.

Using a GHG emission value of 0.51kg CO_{2e} per kilogram of potato, a loss adjustment factor of 0.75, an energy content of 350 kcal/lb (as above), and with the appropriate unit conversion ratios reveal the potato's GHG emission intensity (PartitioningPerCal tab, cell D42)

$$\text{GHG intensity}_{\text{potato}} = \frac{(0.51 \text{ kg CO}_{2e}/\text{kg commodity}) \times (1{,}000 \text{ kcal/Mcal})}{(2.2 \text{ lb/kg}) \times 0.75 \times (350 \text{ kcal/lb})} = 0.88 \frac{\text{kg CO}_{2e}}{\text{loss-adjusted Mcal}}. \quad \textbf{[S22]}$$

In conclusion, we present the resource intensity uses and GHG emission burdens of the animal-based categories relative to three plant-based staple crops (including potatoes) in Fig. S2.

10. Uncertainty Estimates

We use SD as our uncertainty measure. Typical uncertainty estimates combine, additively or multiplicatively, several more basic terms. Consequently, full uncertainty estimates typically involve (*i*) determination of the individual uncertainty characteristic of each participating term; and (*ii*) propagating those individual uncertainties into a single final uncertainty measure using traditional uncertainty propagation rules for sums and products.

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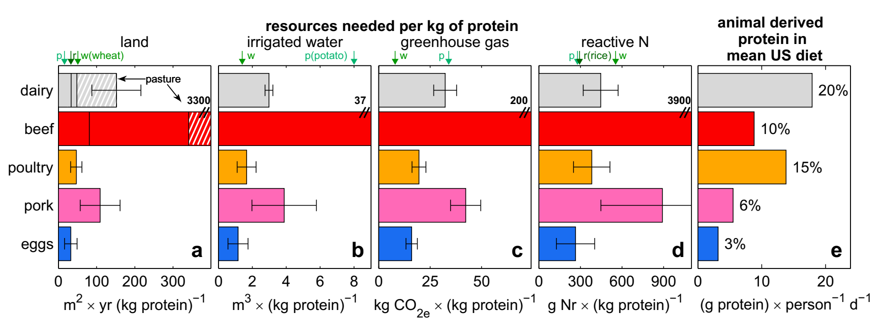

Fig. S1. The main results of this paper are plotted as resource use (land, irrigated water, and Nr) and emission (GHG) per animal kilogram of protein consumed (*A*–*D*). *E* details the national daily average per capita of animal protein intake and the relative contribution (percentage) of each animal category to mean US total protein intake of an adult. In *B*, the arrow denoting rice's water requirement per kilogram of protein is missing from the top of the panel [similar to wheat (w) and potato (p)] because its value of 21 m^3/kg of protein is above the indicated scale (0–9). The same is true for rice's GHG intensity (*C*) of 87 kg CO_2e/kg protein exceeding the indicated scale (0–75).

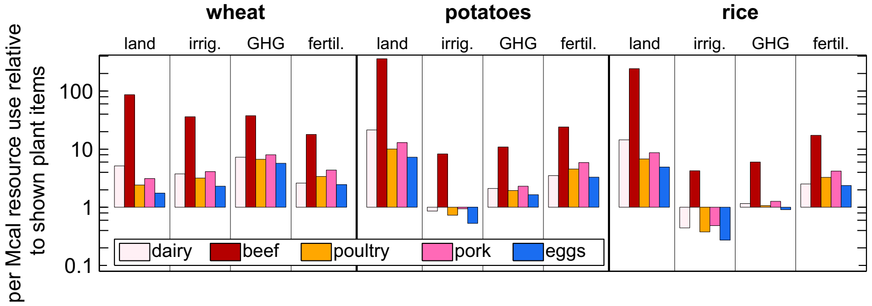

Fig. S2. Per megacalorie resource intensity uses and GHG emission burdens of the animal-based food categories relative to the three different crop plants. irrig, irrigation; fertil., nitrogen fertilization.

Table S1. The partition coefficients (%) of feed classes derived by Eshel et al. (1)

	Pasture		Processed roughage		Concentrates	
Feed class	Mean	SD	Mean	SD	Mean	SD
Dairy	8	3	13	3	24	4
Beef	92	3	87	3	21	11
Poultry	0	0	0	0	27	5
Pork	0	0	0	0	23	9
Eggs	0	0	0	0	4	2

SD, standard deviation.

Other Supporting Information Files

Dataset S1 (XLSX)