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A Global Model Tracking Water, Nitrogen, and Land Inputs and Virtual Transfers from Industrialized Meat Production and Trade

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Abstract Rising populations and incomes throughout the world have boosted meat demand by over 75% in the last 20years, intensifying pressures on production systems and the natural resources to which they are linked. As a growing proportion of global meat production is traded, the environmental impacts of production become increasingly separated from where the meat is consumed. In this paper, we quantify the use of three important resources associated with industrial livestock production and trade—water, land, and nitrogen—using a country-specific model that combines trade, agronomic, biogeochemical, and hydrological data. Our model focuses on pigs and chickens, as these animals are raised predominantly in intensive systems using concentrated, compound feeds. The results describe the geographical patterns of environmental resource use due to meat production, trade, and consumption. We show that US feed, animal, and meat destined for export require almost as much nitrogen and land, and 20% more water, than products destined for domestic consumption. Model results also demonstrate that among various production factors, improvements in crop yields and animal feed conversion efficiencies result in the most significant reductions in environmental harm. By explicitly tracking the externalities of meat production, we hope to bolster suppliers' accountability and provide better information to meat consumers.

Keywords Industrial livestock production · Virtual transfers · Feed use · Water use · Nitrogen transport · Land use · Trade and environment · Environmental impact of meat

1 Introduction

The nature of global meat production is changing, with potentially serious consequences for the environment. An urbanizing population coupled with explosive growth in global demand for meat products has changed animal production fundamentally, from a system once closely linked to local feed inputs and nutrient cycles to one in which different stages of the production process are becoming increasingly separated in space [8, 20]. With projected growth in both world meat demand and meat trade expected to rise more than 50% over the next 25years [3], this decoupling of animals from the local resource base has far-reaching implications for both environmental and social systems. Although livestock production has long relied on the intensive use of environmental resources, rapid growth in meat and feed trade has increased the distance between most meat consumers and meat produc-

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tion's negative environmental impacts [13]. Given that the full costs of these impacts are rarely embodied in the input prices faced by producers, such as the price they pay for water, this distancing leads to a system in which many of the environmental costs of meat production are not reflected in the market price of meat—an underpricing that can lead to socially inefficient consumption decisions [13, 27].

Accounting for costs and benefits in this newly decoupled system is particularly difficult given the complicated landscape of trade and production that characterizes modern industrialized livestock systems. Grain can be grown in one country, shipped to a second country to feed animals, which are slaughtered and processed in a third country, and finally consumed in a fourth. Such trade is becoming increasingly important on the global scale, as both total traded volumes of meat and feed, and trade as a share of total production, continue to grow rapidly. International trade in maize and soy, two primary livestock feeds, has grown at annual rates of 2.8% and 7%, respectively, over the last decade, and trade in pig meat and chicken meat has grown annually at 5.6% and 6.8% over the same period [11]—equal to a doubling of trade flows every 10–12years. International meat trade as a share of total meat production has also doubled over the same period [11].

Trade is growing rapidly, and because each stage of the production process has particular resource inputs, emissions, and environmental costs associated with it, determining the magnitude of trade-related costs is crucial to designing appropriate policy instruments to address both domestic and international livestock issues. In this paper, we describe the MEAT model, which traces the use of various environmental resources through all stages of the industrialized meat production system and apply it to four case study countries and their trading partners. We concentrate on the production and consumption of pig meat and chicken meat, as these typically rely more heavily on concentrated feed inputs and are more often produced in intensive feeding operations than other widely consumed animals [14, 20]. Our focus is on environmental resources with a clear opportunity cost—that is, those resources with an alternative productive or environmental use.

The purpose of our model is to make numerically and spatially explicit both the decoupled nature of industrialized livestock production and the resulting environmental implications. We use the MEAT model to answer three questions: First, how large are the environmental impacts of traded livestock products relative to those which are produced and consumed domestically in our case study countries? Second, how do changes in livestock production practices or consumption decisions in one country affect environmental outcomes around the globe? Finally, which of several conservation measures in the livestock production process would have the largest overall effect on resource use?

This study departs from a traditional "footprint" analysis in that it focuses specifically on the components of nontraded inputs that are interesting from an environmental policy perspective. For example, in the case of water, we focus on irrigated water inputs to the exclusion of rainfall, which has fewer alternate uses. Appropriately pricing such inputs would provide economic incentives for allocating nitrogen, irrigation water, and land more efficiently within crop production and livestock rearing systems, as well as between agricultural and nonagricultural uses.

1.1 Industrialized Meat Production and Environmental Resources

In many regions around the world, industrialized livestock systems are quickly becoming the most common method of meat production. Industrialized meat production operations aim to increase output yields while decreasing input costs, which they achieve mainly by exploiting economies of scale. Industrialized systems are characterized by geographically concentrated production units with links to upstream feed suppliers and downstream processing plants. Already common in industrialized nations, production from these systems is growing rapidly throughout the developing world, while growth in extensive grazing systems is largely stagnant [27]. Pigs and chickens are two animals for which production is particularly industrialized; roughly 50% and 70% of global pig and chicken production, respectively, are industrialized, versus about 10% for beef and veal [27].

Industrialized production draws heavily on global land, water, and nutrient resources. The intensive use of fertilizer, water, and land in various stages of industrialized meat production pollutes air and water, destroys habitat, and reduces biodiversity [27]. The subsequent costs of this environmental damage include both the uncompensated costs to ecosystems and humans and the costs of cleanup actually undertaken. Such costs often are not included in the cost of production and, consequently, in the final price of meat. These downstream costs, or externalities, can be large. One study conservatively estimates that the external costs of all US agricultural production alone (including selected damages and government control and cleanup programs from crop and livestock production) total between \$9.4 and \$20.6 billion per year [28]. As long as meat prices do not reflect the full costs of inputs (e.g., irrigation water) and outputs (e.g., pollution), consumers and producers will continue to make decisions that are suboptimal from a social perspective.

To begin to quantify on a global scale the uncompensated environmental damage associated with industrialized livestock production and trade, we construct a model that traces three key inputs—water, nitrogen, and land—whose use (and misuse) have demonstrable consequences for the environment and social welfare. In the case of water, approximately one third of all freshwater withdrawals come from nonrenewable groundwater sources, a condition driven mainly by irrigation demand [19]. Farmers pay a fraction of the cost of water that urban users pay; as a result, irrigation is generally inefficient and wasteful [7, 15, 21, 28]. Surplus nitrogen's widespread effects on air and water quality include eutrophication, groundwater pollution, and greenhouse gas emissions [12, 18], yet cleanup costs are rarely borne by producers. Finally, agricultural land's price seldom reflects the value of the natural systems the land may support. Converting biologically diverse natural grasslands, wetlands, and native forests into less diverse crop production systems neglects these social benefits. Cultivated systems occupy approximately 24% of Earth's terrestrial surface [19], and any further expansion of cropped area to support intensive livestock production is likely to come at a significant environmental cost [18, 29–31, 33].

Increased trade in livestock products offers both environmental benefits and costs. A fundamental tenet of economics is that international trade can result in global gains in welfare, as countries specialize in producing those goods that they can make with relative efficiency, and trade for those they cannot. In the case of livestock products, countries with small land areas or few water resources are unlikely to be efficient producers of meat or feed, and both economics and intuition suggest they should trade for their meat. But if costs of production rarely reflect true environmental costs in the large meat- and feed-exporting nations, importers of livestock products can enjoy the benefits of meat consumption without having to suffer—or pay for—the environmental costs of that consumption. In the context of underpriced environmental resources, increasing trade can magnify the damage to the environment associated with industrialized livestock production. It is this damage that our model attempts to quantify.

1.2 Model Approach

In our model, we build on the concept of "virtual" transfers to trace the water, nitrogen, and land inputs into globally traded meat [1, 5, 22]. Virtual transfers refer to the resource inputs associated with the production of a commodity that are not actually embedded in the good—for example, the water used to grow a crop that is not contained in the grain itself. Monitoring virtual transfers provides an illustration of the environmental assets that exporting nations use in their production of resource-intensive exports.

We divide livestock production into three stages: feed production, production of live animals, and processing into final meat products. The model traces the virtual water, nitrogen, and land flows associated with each stage of production for a set of case study countries (Fig. 1). The three arrows entering the "Feed" box in Fig. 1, for example, correspond to the land, nitrogen, and water inputs into feed production for use as pig or chicken feed; the methodology for quantifying each arrow is discussed below.

We apply this framework to a set of case study countries and their trading partners. While nearly all countries in the world both enjoy the benefits and suffer the costs of meat production and consumption, we limit our study to the analysis of four countries—Brazil, the US, the Netherlands, and Japan—and their trading partners. Such a case study approach is warranted given the complexity of global production and trade relationships, the difficulty of obtaining necessary data for various model parameters in most countries, and the spatial nature of nutrient use and loss. The latter factor is important because a global analysis would not distinguish environmental "hotspots" associated with industrial meat production. And while in many cases *intra*national trade tends to be of much larger magnitude

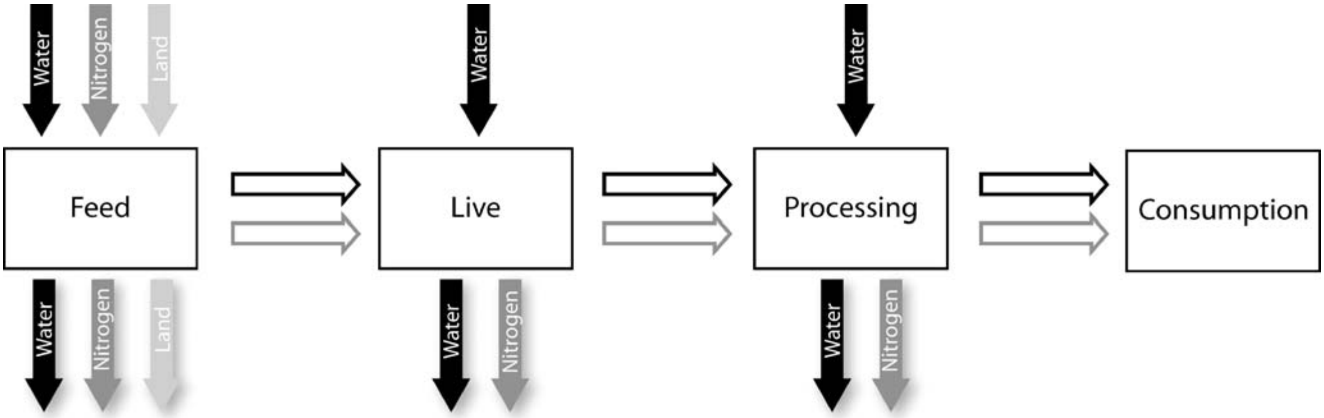

Fig. 1 Inputs, outputs, and flows of water, nitrogen, and land through the livestock production system

than *inter*national trade, the relative paucity of trade data on a subnational scale makes it difficult to illustrate the extent to which production and consumption are decoupled at this scale.

Our case study countries fulfill different roles with respect to production, trade, and consumption of industrialized meat products. Brazil and the US are two of the largest producers and exporters of industrialized animal products and animal feed in the world, together accounting for roughly 55% of chicken meat exports, 20% of pig meat exports, and 48% of feed exports [11]. On the receiving end is Japan, a country that depends almost entirely on imports to satisfy its high per capita consumption of meat products. In the middle is the Netherlands, which doubles as a large feed importer and primary meat exporter to much of Europe.

By treating each country and production stage explicitly, the MEAT model sets the stage for a more meaningful dialog about the hidden environmental costs of a highly distributed system of industrialized production and trade of animal products. Country-specific accounting makes use of country-specific production data, from irrigation and fertilizer use to components of animal feed and efficiency of feed conversion. Splitting up production stages permits us to quantify separately the environmental challenges posed by each stage of the production process. For example, as shown in Fig. 1, the model separates nonpoint source N waste associated with crop production (dark gray arrow coming out of Feed) from point source N waste associated with animal feeding operations (dark gray arrow coming out of Live). As inputs and waste have different consequences in each stage, the model allows for substantive analysis of the distribution of virtual resources used for animal production and trade.

Although the MEAT model does not include a dynamic component that could be used to predict how livestock production–consumption systems might respond to environmental taxes or other policy interventions, the model's framework could be applied on a national level to inform decision makers about the environmental impacts due to national livestock production and consumption.

2 Methods

This section summarizes the model's formulae, all of which are provided in the "Appendix".

2.1 Trade

Our overall objective is to quantify the trade flows between our case study countries and their trading partners and then to associate these flows with their related hydrologic and biogeochemical consequences in producing nations. Figure 2 illustrates the production and trade flows of interest for a given case study Country X. The left side of the figure represents the imports into Country X; the right side represents the exports from Country X. Because of empirical limitations, imports and exports are calculated slightly differently for feed trade, as described below.

2.1.1 Trade in Meat Products

Boxes A through I in Fig. 2 each represent a suite of countries with which Country X trades at a given stage of production, and arrows represent the traded quantity of feed, animals, or meat between these sets of countries. Quantities are derived from bilateral trade data as reported by the United Nations (UN) [32], averaged over the years 2000–2002 and corrected for reexports.[1] We assume all traded chicken and pig meat is from industrialized systems, and to manage the complexity of trade flows we only account for trade from and to the most significant trading partners, together comprising about 90% of a given case study country's imports and exports.

Data for processed meat imports and exports (arrows 6 and 12) are reported directly by the UN and require no manipulation beyond correction for reexports. Trade in live animals is accounted for through direct flows (arrow 3), also reported as tons of live animal directly by the UN. In addition to the direct import of live animals, we calculate the live weight equivalent of processed meat imports and their live animal origins (arrow 5). We do this by dividing by the share of a live animal that becomes a given processed product [6] and analyzing the trade data to locate where the original animals were produced prior to processing. Adding arrows 3+5 gives total direct and indirect live animal imports into country X. Similarly, live animal exports from Country X include direct exports (arrows 8 and 11) as well as the indirect feed inputs (from country X and elsewhere) used to raise animals in country X.

2.1.2 Feed Imports

Available trade data for grains and oilseeds unfortunately do not distinguish between end uses of these products in the importing country (e.g., feed, food, fuel, etc.). To determine the amount of shipped grain devoted to industrialized pig and chicken feed, we combine new country-specific data on

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[1] This "correction" is based on the ratio of imports to domestic production. If imports of a product into a given country equal 100 and domestic production of that product equals 50, we assume that exports from that country of the same product must be 2/3 "reexport" (100/(50+100)). Such corrections are particularly necessary for small, highly trading countries such as the Netherlands.

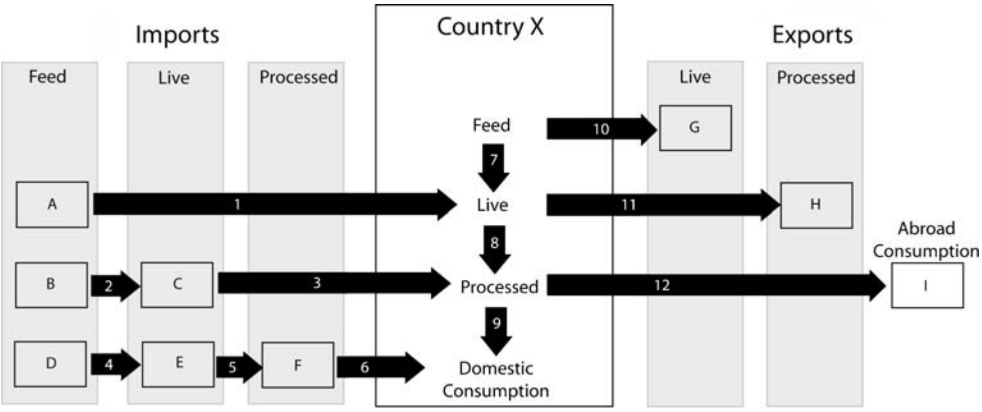

Fig. 2 Schematic of trade flows into and out of representative case study country. *Arrows* represent trade flows; *boxes* represent location of production or consumption

animal diets with manipulations of the available trade data. Country X's imports of feed for industrialized pig and chicken production are calculated "bottom-up" by taking the product of the total production of pig or chicken meat in the country (live weight), the feed conversion efficiency (kilogram feed per kilogram live weight) of each type of animal in the country, and the diet composition of each type of animal in the country. Finally, we "source" this feed total from other countries using the ratio of imports to total domestic supply for a given trade partner as reported in the trade and production data [11, 32]; for example, if 20% of the domestic supply of corn in country X is imported from country m, we assume that 20% of feed corn need in country X is supplied by country m. We repeat this process for each of our case study countries and their meat-producing trading partners.

To our knowledge, no prior systematic data existed on the feed conversion efficiency and diet composition of pigs and chickens by country. Collaborators at the Food and Agriculture Organization assembled this dataset for each of our case study countries and their primary meat trading partners through a combination of surveys and interviews with key informants in the public and private sector [27]. Data were collected to account for at least 90% of an animal's diet by volume.[2] Representative data from these surveys are shown in Fig. 3. These data reveal the wide diversity of animal diets across countries, even for a single species.

2.1.3 Feed Exports

The feed import methodology described above is a practical way to calculate end use of grain and oilseed shipments, if (as in our case) the number of trading countries involved is relatively small and livestock diets are known. On the export side, unfortunately, collecting data on diets, feed conversion efficiencies, and bilateral imports for each of these countries is unfeasible. Since two of our case study countries (the US and Brazil) are prolific feed exporters, shipping feed to over 150 countries, we alter our export methodology slightly to account for data deficiencies.

Country X's total feed exports destined for pig and chicken consumption abroad (arrow 10 in Fig. 2) are made up of direct exports (crop exports used as feed elsewhere) and implied exports (crops fed to animals exported from country X). Direct exports are calculated as the product of the total exports of crops from country X (extracted from UN [32] and adjusted for reexport), the specific feed import ratio (i.e., the percent of domestic supply of a given crop used as feed in importing nation m [11]), and the percent of each crop destined for consumption by a particular animal. The latter term is calculated by coupling global diet data for pigs, chickens, beef, and dairy animals with estimates of total industrial production of each animal by country to determine how feed imports are allocated within a given country.

Implied exports, or the feed required to produce animals domestically in country X that are then exported abroad as live animals or processed meat, are calculated by taking the product of the total live and processed animals produced in country X and exported, the feed conversion efficiency of animals in country X, the percent of the animal diet in that country made up by a particular crop, and the percentage of that crop grown domestically rather than imported.

To compare trade totals to what is produced and consumed domestically, we also calculate arrows 7, 8, and 9, which represent domestically produced feed, live animals, and processed pig or chicken meat that is consumed domestically. The next stage of the model associates the trade values calculated above with the virtual use and embedded flows of water, nitrogen, and land in producing countries.

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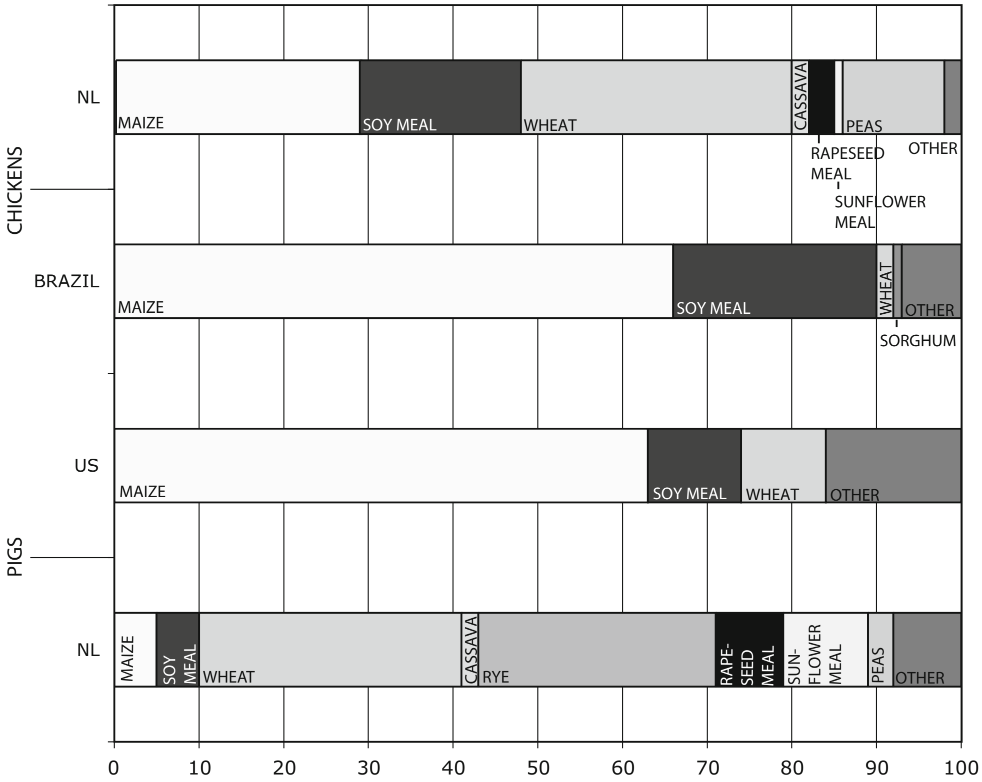
[2] This "90% rule" inevitably excludes some of the protein-rich feed additives such as blood meal or other plant meals and brans that make up a small percentage by volume of total pig or chicken diets but are important as inputs of nitrogen to the animal production stage. As a result, we likely underestimate the total nitrogen losses during animal production, as discussed in the "Nitrogen" section below.

Fig. 3 Sample diet compositions for chickens in the Netherlands and Brazil, and pigs in the US and the Netherlands. Data are crops as a percentage of diet by weight, extracted from [27]



2.2 Water

2.2.1 Feed Production Stage

To determine the virtual water associated with feed production, we first quantify the amount of water, specifically irrigation water, required to grow feed grains. We then deduct water embedded in the grain to determine the virtual water.[3]

We are most interested in irrigated systems because irrigation water, as opposed to rainwater, has alternate economic and environmental uses. Therefore, the virtual water calculation begins with estimates of crop water requirements to grow feed, by crop and country, in irrigated systems. Following the approach used in Allen et al. [2, 6], crop water requirement is defined as the total water needed for evapotranspiration from planting to harvest for a given crop in a given region.

Some of the crop water requirement is of course met by rainfall, and we assume that the entire deficit is provided by irrigation in irrigated systems. To estimate rainfall, we overlaid a precipitation map with a global map of cultivated areas [34]. We assumed that average annual rainfall on agricultural land falls uniformly throughout the year and then adjusted to account for the fraction of the year that constitutes each crop's growing season. For crops grown in countries with wet growing seasons, this will inevitably lead to an overestimation of irrigation water, but the reverse will also be true in other cases. Intraannual variation in rainfall is large for many tropical countries characterized by monsoon climates and smaller for others in temperate zones. In contrast, the spatial distribution of rainfall patterns within agricultural areas—another source of error and bias in our calculations when crops are grown in regions that suit them specifically—has a standard deviation of over 1,000mm in Ecuador and Bangladesh and less than 10mm in Egypt. An ideal crop–rainfall measure would be both spatially and temporally more precise than we have used in our model, but while climate data are readily obtainable at high levels of detail, management data that specify when and where individual crops are grown are not available with equal precision. One further assumption is that all rainfall is available for crop use, which means our water estimates are lower bounds for the amount of water needed for irrigation, since in practice some rainfall will run off or evaporate.

Whether or not farmers actually apply the entire water deficit in irrigated systems depends upon farmers' individual decisions. Our model cannot fully account for the many institutional, infrastructural, agronomic, and socioeconomic factors (including how much water costs, whether allocation rules are in place, historical use, and water scarcity)

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[3] While water embedded in the grain is rather insignificant, we still deduct it to be consistent with the methods for nitrogen.

affecting farmer decisions, so we assume irrigated crops receive 100% of their crop water requirement. This leads to an ambiguous bias since, in some systems, farmers supply far more than the crops need while, in others, they provide far less.

The last step in estimating total required irrigation water is to adjust for water use efficiencies. For crops requiring irrigation, the amount of water actually diverted exceeds the crop water requirement by some water use efficiency coefficient, which accounts for the losses incurred during storage, distribution, and field-level application of water. We define a national-level water use efficiency as the percent of water withdrawn that contributes to soil moisture in our feed crop systems [24]. Since a portion of this "lost" water may be available for future or downstream use, we choose conservative water use efficiency estimates of 60%, 75%, and 80%, depending upon the composition of irrigation systems in each country (surface, sprinkler, or micro; see, e.g., [23, 26]). Such estimates imply slightly higher efficiency than what is reported elsewhere [9]; thus, our calculations should once again underestimate feed water use.

In order to use consistent methodology across all inputs, we trace only the portion of water inputs that is "virtual", e.g., the water that is not contained in the grain. The virtual water content of a given animal's feed is thus the total irrigated water input minus the relatively small amount of water actually contained in the grain [6]. For a given crop, we assume the latter factor to be constant across countries, as feeds in international markets are typically sold at a fixed moisture content.

We use the information obtained in our trade and feed basket calculations to translate a given quantity of meat into the total volume of virtual water (used to grow the crop that is fed to an animal) by multiplying it by the volume of traded grain grown under irrigation in the producing country, which we obtained from unpublished data (based on personal communication with authors of [3]).

2.2.2 Animal Production Stage

Calculations for the animal production stage quantify the amount of water required to raise an animal, net of the water embedded in its carcass. The calculation of the virtual water content of live animals proceeds similarly to the feed calculation. Total water inputs include the water contained in the feed, the water the animal drinks, and any service water involved in the animal production system. We assume that the water contained in the animal after slaughter is constant across countries (extracted from [5]) and deduct that from the total water inputs to get the volume of virtual water associated with live animal production in a given country.

2.2.3 Animal Processing Stage

The final step in the virtual water calculation is to determine water inputs and losses during animal processing. Water inputs to this stage include the embedded water in the slaughtered animal and any other water used during processing and slaughter. We once again assume that the water embedded in the processed animal is constant across countries (extracted from [5]) and deduct that from the total water inputs to get the volume of virtual water associated with the processed animal.

Multiplying these virtual and embedded water totals from the animal production stages by the relevant trade flows yields the virtual and embedded water associated with production and trade of industrialized animals.

2.3 Nitrogen

2.3.1 Feed Production Stage

As with water, the virtual nitrogen calculation begins with estimates of crop nitrogen inputs, by crop and country. For each crop- and feed-producing country in our model, we set the total nitrogen input per hectare equal to the sum of farmer-applied nitrogen and biologically fixed nitrogen. Farmer-applied nitrogen is the sum of applied organic and Haber–Bosch-derived N, data for which are available by crop and country from the International Fertilizer Association [16]. We then divide by a country-level average yield [11] to translate total nitrogen applied on a per hectare basis to nitrogen applied per ton of crop produced.

The virtual nitrogen content of feed represents the portion of total nitrogen input that is not actually taken up in the grain. Unlike water, where the amount embedded in the grain is low, the quantity of nitrogen contained in transported grain is significant. We use National Research Council [29] data to determine nitrogen embedded in each crop, which we assume to be constant across all producing countries.

Given the complex field-level and even plant-level cycling of nitrogen, particularly the large indigenous sources of soil nitrogen available to plants, we cannot simply subtract embedded nitrogen from total nitrogen inputs to get the virtual total, as we did for water. Instead, we assume that, for all of our feed, 30% of the total nitrogen input ends up in the grain portion of the crop while 70% is taken up by the nongrain parts of the plant (most of which is eventually recycled to the soil), bound up in the soil directly, or lost to the surrounding air or water (Cassman K. et al. 2005, personal communication received by M. Burke); in other words, this 70% remains in the environment of the feed-producing nation and is thus the virtual nitrogen associated with feed. This estimate is broadly consistent with recent literature on the topic [4].

2.3.2 Animal Production Stage

For the animal production stage, we quantify the amount of nitrogen fed to pigs and chickens, net of any carcass nitrogen, so as to estimate the pollution burden from nitrogen-rich livestock wastes. The major difference between the nitrogen and water calculations for this stage is that feed grain is the only source of nitrogen for pigs and chickens throughout their production; that is, no additional nitrogen enters the animal production cycle in the second or third stage. As such, the nitrogen input into each finished live animal is simply a sum of the nitrogen content of the feeds it ate. The virtual nitrogen associated with those compound feeds, of course, depends upon where they were produced (determined in the feed production stage calculations). Again, to get the virtual nitrogen associated with live animal production, we then subtract out the nitrogen contained in the finished animal, assumed to be constant across all countries per unit weight, based on data from [5].

The ratio of the nitrogen contained in a live animal at the point of slaughter to total nitrogen consumed over its lifetime is called the nitrogen conversion efficiency. Our resulting estimates of N conversion efficiency for pigs (35%) and chickens (70%) are consistent with the empirical finding that broilers are roughly twice as efficient at converting protein as swine [25]. However, these estimates represent a higher bound of absolute efficiency for each animal, resulting in underestimation of the total N losses during animal production. We suspect that our high efficiency estimates are to some degree a function of our exclusion of certain protein-rich feed additives from the diet estimates.

2.3.3 Animal Processing Stage

The final step in our virtual nitrogen calculation is to quantify the nitrogen lost during animal processing. No nitrogen is added at the processing stage, so the only nitrogen inputs are those contained in the live animal. To get the virtual total, we subtract out the nitrogen contained in the processed product [5].

2.4 Land

Following the methodology used to calculate virtual water and virtual nitrogen, we estimate the amount of land required to produce the feed intended for animals in industrialized operations. Because the land area for feed dominates the land for the actual production and processing operations, we assume the operations themselves are landless.

For sink (importing) countries, the amount of land required to support their pig and chicken consumption is a worldwide aggregate of the land necessary to grow the animals' feed. Our MEAT model accounts for the fact that feed and animals are imported from all different nations, each with differing yields and animal diets. In addition to the land requirements for animals produced domestically, we calculate the land requirements associated with "indirect crop imports" or the crops fed to animals produced abroad which are imported. Total land is calculated by summing the direct (as feed) and indirect (as meat) imports of each crop, attributing them to an exporting nation, and dividing by the exporting nation's yield for a given crop.

For source countries, a similar calculation was required to capture both the land used for feed exports plus the land required to grow feed for exported animals.

3 Results and Scenarios

Three important conclusions emerge from our baseline model results. First, at the turn of the twenty-first century, the volumes of nitrogen, water, and land associated with traded pig meat, chicken meat, and related feed are large—both relative to volumes used for domestic production–consumption and relative to background fluxes in major producing countries. Figure 4 shows the virtual nitrogen associated with trade of pig and chicken products and associated feed in the US. We calculate that 922,000tons of N (0.92Tg N) are left behind in the US due to the production of pig and chicken meat and feed that are exported abroad (large dark gray bar). Exports to Mexico, Japan, and China make up almost half of this total, as shown on the left hand side of the figure. The 0.92Tg virtual N associated with export is about 75% of the 1.2 Tg N associated with production of feed and meat for domestic consumption, suggesting that the US's position as a large exporter is almost as important to nitrogen-related environmental outcomes in the US as domestic consumption decisions.

Figure 4 also shows that imports of meat and feed into the US are associated with the loss of roughly 100,000tons of N in other countries (mainly Canada), suggesting that even a large exporting country such as the US has significant impacts abroad through agricultural imports. The water story is similar: we calculate that the US uses 20km^3 of irrigation water for its feed exports, roughly 120% the amount used to grow feed for animals produced in the US. Likewise, land area used to grow feed exports is slightly higher than that used for domestic feed.

Figure 4 illustrates a second point: for nitrogen, "embedded" flows (arrows in the figure) are roughly as

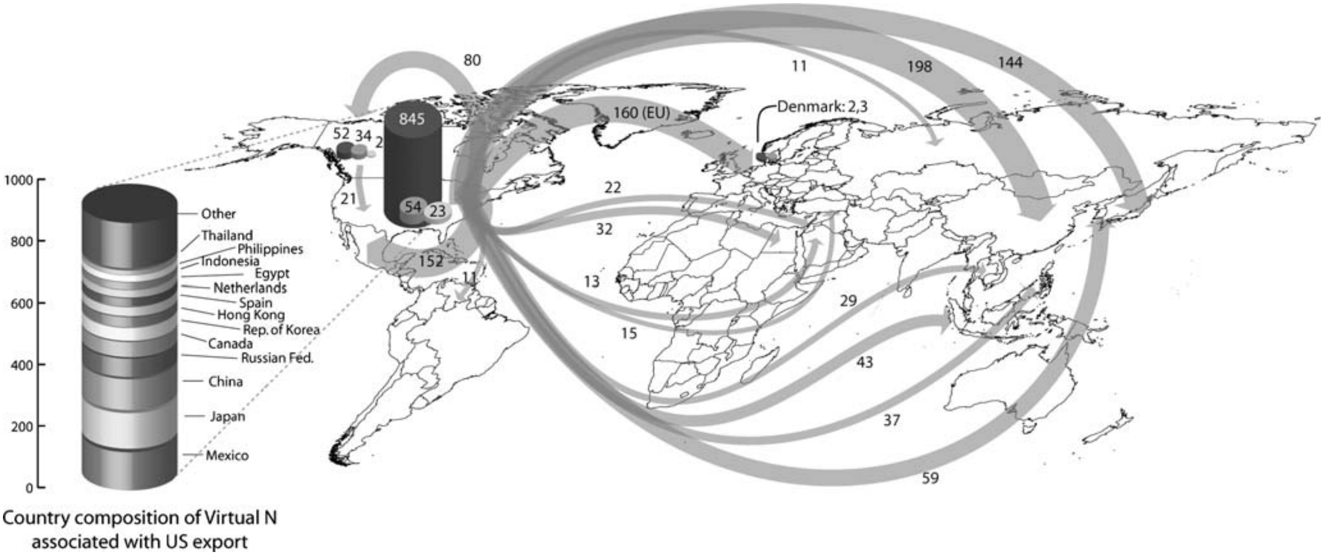

Fig. 4 Nitrogen association with US import and export of pigs and chickens. *Cylinders* refer to N left behind in the US, during different stages of production. *Dark gray* = feed; *medium gray* = live; *light gray* = processed. *Arrows* represent total transfer of N embedded in traded products. *Large cylinder* on *left* displays the countries to which exports are going. Data are in thousands of metric tons

large as the associated virtual flows. This is particularly true for large importers or exporters of soy products due to soy's relatively high N content. Exports of embedded N from the US total 1.1Tg, slightly more than what is lost to the environment locally; again, exports to China, Mexico, Japan, and the European Union account for well over half of the embedded N exports. This trend does not hold true for water, however. Because very little water is embedded in feed, animal, or meat products, the virtual flows (i.e., the water used in production that is not embedded in the traded product) swamp the embedded flows. Land, obviously, cannot be embedded in the shipped product, and thus all land transfers are virtual.

Baseline model results suggest that the feed production stage has the largest effect on resource impacts associated with the industrialized livestock sector. We calculate that roughly 70% of the nitrogen and 100% of the land and water associated with pig and chicken production result from concentrate feed production. This result is important in identifying spatially the hotspots and drivers of resource use and nutrient loss and in suggesting the stages of production where policy might focus most effectively. For example, expanding Brazil's soy plantations, which already devote approximately 5.5 million hectare to meeting export demand, will increasingly encroach on Brazil's already-threatened savannah and Amazon forest [17]. Policies aimed at curbing European demand for Brazilian soy grown in deforested areas could mitigate this trend.

To test the relative influence of key parameters on virtual resources, we develop multiple alternative scenarios, results for six of which are summarized for Japan (imports) and the US (exports) in Fig. 5. The scenarios provide insight into the sensitivity of resource use to plausible changes and improvements in the livestock production system.[4]

Our scenario analysis of feed production parameters suggests that small changes in crop production parameters have a large effect on environmental outcomes. Scenarios 1–3 in Fig. 5 show the change in total resource use under altered model assumptions about crop yield, nitrogen use efficiency (NUE), and irrigation efficiency. A 10% global increase in yield of all crops[5] reduces land and water use in the industrialized pig and chicken sectors by nearly 10%, with a much smaller effect on nitrogen totals due to the importance of soy in animal feed.[6] Other improvements in the crop production system, such as relatively modest increases in global NUE (defined as the amount of farmer-applied nitrogen removed in aboveground biomass) or in global irrigation efficiency (defined as the percent of applied irrigation water used in crop evapotranspiration), reduce substantially the amount of N loss and water use associated with pig and chicken production. An increase from 30% to 40% in global average NUE results in a 10–

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[4] The MEAT model is partial equilibrium. Therefore, unless otherwise indicated, each scenario assumes that changing model parameters do not have broad effects on production or consumption elsewhere in the system, e.g., we assume that improving feed conversion efficiencies does not change the price of feed or meat and thus does not alter consumption or production decisions.

[5] For purposes of the scenario, we assume yield growth to be "exogenous", i.e., caused by something other than increases in either fertilizer or water use, such as introduction of improved pest-resistant varieties.

[6] Little external N is applied to soy, so N loss per ton changes little as yields change.

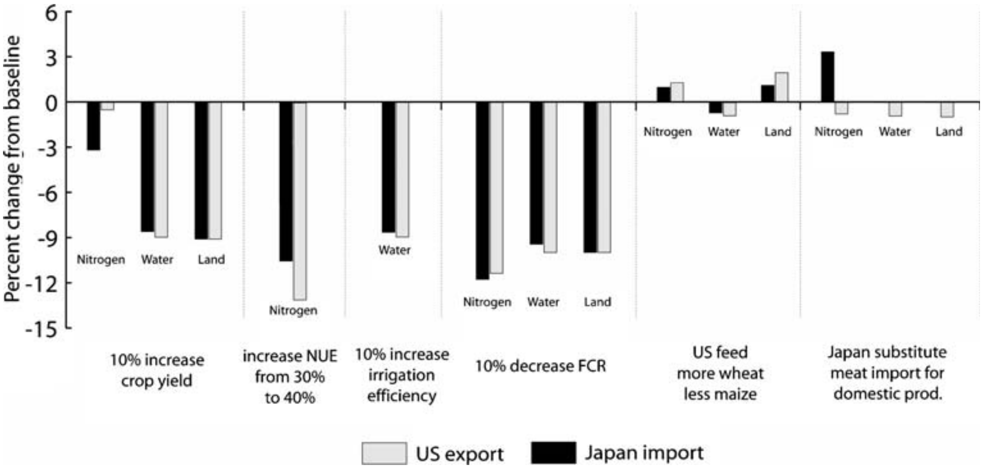

Fig. 5 Effect of various scenarios on model results, percent change from baseline, totaled across all production stages. *Black bars* are virtual totals associated with Japanese import of pig and chicken products and related feed; *gray bars* are totals associated with US export of the same

12% decrease in the amount of total N loss associated with pig and chicken production; a 10% increase in irrigation efficiency reduces total water use by almost 10%.

While improvements in feed production practices can substantially affect the "upstream" resource impacts of industrialized chicken and pig production, such changes have no effect on the markedly different impacts surrounding the actual growing and slaughter of animals. Changes in animal production can address both types of impact. Improving pig and chicken feed conversion ratios (FCR, kilogram feed per kilogram meat produced) by 10% eliminates one tenth of total feed use by the industrial livestock sector, which in turn shrinks by one tenth the nitrogen, water, and land used during feed production. Furthermore, in contrast to improvements limited to crop production, better FCRs result in lower losses of point source nitrogen that plague many pig- and chicken-producing areas of the world. Substantial changes in the composition of animal feed baskets will also change the landscape of environmental impact. We calculate that feeding US chickens and pigs 10% more wheat and less maize, a plausible scenario as US maize becomes increasingly devoted to biofuel production, increases the amount of land used and nitrogen lost during feed production in the US by about 2%, given lower wheat yields and higher N inputs per ton relative to maize. Total associated US water use drops under this scenario, however, since more wheat than maize is produced under rain-fed conditions in the US.

Finally, changes in the volume and pattern of trade could have large effects on the total amount and distribution of environmental impacts associated with industrialized livestock. If rising meat demand in a country is met entirely by growth in imports, all other things equal, countries that supply the imports will notice a 1:1 increase in N loss and water and land use (results not shown). With a projected global doubling of meat demand to 2030, much of it to be met by trade [3], the resource burden on exporting countries should be expected to grow substantially. Even with no net change in consumption, the further decoupling of meat consumption from production will also affect the distribution of environmental impacts. If Japan substitutes meat imports for 10% of its current domestic production (scenario 6), thereby importing more meat and less feed, domestic resource use declines 10% and the N loss in other countries associated with Japanese imports rises roughly 3%. While the pressure on environmental resources actually declines in the US under this scenario[7]—it exports primarily feed rather than meat to Japan—effects on other countries are large; concentrated N losses from pig-feeding operations in Denmark, for example, rise by over 2,000 tons.

4 Conclusions

Our MEAT model establishes a framework for measuring the magnitude and country-level spatial distribution of water, nitrogen, and land inputs into globally traded pig and chicken production for four case study nations. Even our highly conservative approach shows that current levels of consumption in industrialized meat production are indeed causing widespread and important environmental consequences. The virtual transfers associated with the trade of feed, live animals, and meat are significant for all three inputs when compared to their domestic consumption.

Distortions in production markets (due to underpriced water, nitrogen, and land) make it difficult to judge whether exporting nations are more efficient at producing livestock than importing nations. It might very well be the case that exporting nations should continue exporting, even once externalities are factored in, because they continue to have a comparative advantage. That said, exporters, by underestimating the true costs of production, are certainly not being fully compensated for their environmental and

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[7] We assume Japan's trading partners do not change.

resource costs. Environmental externalities would persist even if all meat was sold domestically but, through trade, domestic consumers do not get the benefit of the cheap prices yet they bear the costs. This implies that countries should consider carefully the domestic environmental consequences of their exports. Furthermore, increased production for exports could directly result in additional environmental impacts by triggering nonlinearities and density-dependent impacts which would not occur if production only had to meet domestic demand.

Many environmental consequences of inputs to meat production are excluded by our MEAT model, such as fuel use and pollution from shipping and energy consumed to produce nitrogen fertilizer or to pump groundwater. A full accounting could paint an even bleaker picture of the environmental impacts of meat trade at the national and international levels.

The scenario analysis underlines two main points. First, lessening the total environmental impact of industrialized livestock production is inextricably tied to the volume of feed use and the practices surrounding its production. Aside from changes in total meat consumption, the variable with the largest effect on resource use is the efficiency with which animals convert feed to meat. Second, changing the volume and pattern of meat consumption and trade affects both the size and location of environmental impacts. Substituting imported for domestically produced meat shifts environmental burdens abroad and is perhaps an economically rational strategy for nations concerned only with the domestic environmental consequences of meat production. Due to the decoupling of consumption from production, changes in meat consumption decisions in one country have demonstrable impacts on environmental outcomes in countries half a world away. Relinking the livestock production to the land, either physically or through the appropriate pricing of environmentally sensitive inputs to or outputs from production, might mitigate over consumption of nutrients and water, reduce stress on overloaded ecosystems, and change consumption decisions.

The model provides the foundation for future policy analysis. Because the most resource-intensive stage is feed production, policies should focus on controlling overapplication of nitrogen and water and conversion of fragile lands to feed production. Possible solutions would involve a combination of resource pricing, implementation of already existing best practices, scientific and technological advances in yield and uptake efficiencies, and consumer education. In addition to improved farm management practices, higher yields and feed conversion efficiencies would reduce meat production's environmental cost—two variables which have been well targeted in the past by public and private research. Improved feed conversion efficiencies would reduce waste at the production stage and reduce resource inputs at the feed stage, as less feed would be required to produce the same amount of animal protein.

The model also provides a tool to inform consumers about the global effect of their meat consumption decisions. In the absence of markets that internalize the environmental costs associated with livestock production, well-educated consumers who make conscientious decisions about the food they eat—the many countries it came from and the many resources used to produce it—will be the key to a sustainable food system.

This model, at the very least, sheds light on the previously hidden costs, in resource terms, of traded livestock products, providing the rationale both for regulation and intervention and for broad consumer education.

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Appendix. Model Equations

Trade

Meat Products

Meat trade includes trade in processed products and in live animals. Bilateral trade in live animals is reported in official databases in live weight terms, while trade in meat products is reported in processed weight. We converted meat products into their live animal equivalents to be comparable with animal production data, measured in per unit live animal weight. For representative importer X, to convert processed meat products into live weight equivalent and attribute them to their source of production, the calculation is:

$$L_{x,a} = \eta_a \times \sum_{m,g} \left(M_{a,x,m} \times \mu_{a,m,g} \right) \tag{1}$$

where:

$L_{x,a}$	Live weight equivalents of processed meat trade to country (x) of animal (a)

η_a	Conversion factor processed to live meat for animal (a)
$M_{a,x,m}$	Processed meat imports into country (x) from country (m)
$\mu_{a,m,g}$	Correction factor of live animal imports to country (m) from country (g)

μ is a factor which corrects for the portion of processed, imported meat that was sourced from live animals produced in a third country. It is equivalent to the portion of domestic supply in country m that was imported from elsewhere (country g).

Feed Imports

Representative country X's imports of feed for industrialized pig and chicken production are calculated as in Eq. 2:

$$F_{x,c,m} = O_x \times \gamma_{x,a} \times H_{x,c,a} \times I_{x,c,m} \tag{2}$$

where:

$\mathrm{F}_{x,c,m}$	Imports to country (x) of feed crop (c) from country (m)
O_x	Tons of live animal consumed domestically in country (x)
$\gamma_{x,a}$	Feed conversion ratio of animal (a) in country (x)
$\mathrm{H}_{x,c,a}$	Percentage of animal's (a) diet made up by crop (c) in country (x)
$\mathrm{I}_{x,c,m}$	Ratio of country's (x) imports of each crop (c) from country (m) to total feed supply

The quantity of live pigs or chickens produced and consumed domestically (O_x) is calculated as the difference between total pig or chicken production and live animal exports, which is then multiplied by the percentage of production in that country that is industrialized (the latter value is based on estimates from FAO [27]).

Feed Exports

Country X's total feed exports destined for pig and chicken consumption abroad are made up of direct exports (crop exports used as feed elsewhere, D) and implied exports (crops fed to animals exported from country X, E). Direct exports of feed ($D_{x,c}$) from country X describe the actual feed exported that is intended for industrialized pig or chicken consumption abroad; Eq. 3 describes these shipments into an importing country m:

$$D_{x,c,m} = C_{x,c} \times Rd_{m,c} \times Rf_{m,c,a} \tag{3}$$

where:

$D_{x,c,m}$	Direct export of feed crop (c) from country (x) to country (m)
$C_{x,c}$	Total exports of crop (c) from country (x)
$Rd_{m,c}$	Percent of domestic supply of crop (c) that goes to animal feed in country (m)
$Rf_{m,c,a}$	Percent of feed crop (c) that feeds animal (a) in country (m)

$Rf_{m,c}$ is determined as follows:

$$Rf_{m,c} = \frac{P_{m,a} \times \gamma_{m,a} \times H_{m,c,a}}{\sum_{\text{animal}} \left(P_{m,a} \times \gamma_{m,a} \times H_{m,c,a}\right)} \tag{4}$$

where:

$Rf_{m,c}$	Percent of feed crop (c) that feeds animal (a) in country (m)
$P_{m,a}$	Live animal (a) production in country (m)
$H_{m,c,a}$	Percent of crop (c) in animal's (a) diet in country (m)
$\gamma_{m,a}$	Feed conversion ratio of animal (a) in country (m)

Implied exports ($E_{x,c}$) describe the feed required to produce animals domestically in country X that are then exported abroad as live animals or processed meat. They are calculated as follows:

$$E_{x,c,m} = Q_{x,m} \times \gamma_{x,a} \times H_{x,c,a} \times Rf_{x,c} \tag{5}$$

where:

$E_{x,c,m}$	Implied export of crop (c) from meat produced in country (x) and exported to country (m)
$Q_{x,m}$	Total live and processed animal exports from country (x) to country (m)
$\gamma_{x,a}$	Feed conversion efficiency of animal (a) in country (x)
$H_{x,c,a}$	Percent of animal's (a) feed trough made up by crop (c) in country (x)
$Rf_{x,c}$	Percentage of crop (c) grown domestically

Water

Feed Production Stage

Equation 6 shows the calculation for crop water requirement ($\omega_{n,c}$). The approach uses estimates of the daily "reference evapotranspiration" for a given region (ρ_n in cubic meter per hectare), corrects this reference value for climate and crop-specific characteristics ($\mathrm{k_c}$), and integrates the crop-specific evapotranspiration value over the entire growing period. Our estimates of ρ_n and k_c are derived from

FAO's CROPWAT model and corresponding CLIMWAT data [10].

$$\omega_{n,c} = k_c \int_{\text{planting}}^{\text{harvest}} (\rho_n) \tag{6}$$

where:

$\omega_{n,c}$	Crop water requirement for crop (c) in feed-producing country (n)
ρ_n	Reference evapotranspiration in country (n)
k_c	Crop coefficient

For irrigated systems, the crop water requirement is met by a combination of rainfall ($S_{n,c}$) and irrigation ($t_{n,c}$), per Eq. 7.

$$\omega_{n,c} = Sn,c + tn,c \tag{7}$$

where:

$\omega_{n,c}$	Crop water requirement for crop (c) in country (n)
$S_{n,c}$	Rain that falls on crop (c) in country (n)
$t_{n,c}$	Irrigation supplied to crop (c) in country (n)

Total irrigation water required ($T_{n,c}$) is the amount of crop water requirement supplied by irrigation (t), adjusted by water use efficiency (ε_n), and transformed by yield ($\alpha_{n,c}$, in tons per hectare). We define national-level water use efficiency as the percent of water withdrawn that contributes soil moisture to the feed crops. We transform irrigation water requirement on a per hectare basis to water required per ton of crop produced by dividing by the yield of irrigated systems. Yield data are obtained from FAO [11].

$$T_{n,c} = t^{Irr}_{n,c} \times \frac{1}{\varepsilon_n} \times \frac{1}{\alpha_{n,c}} \tag{8}$$

where:

$T_{n,c}$	Total irrigation water for crop (c) in country (n)
$t^{Irr}_{n,c}$	Crop water requirement supplied by irrigation to crop (c) in country (n)
ε_n	Water use efficiency in country (n)
$\alpha_{n,c}$	Yield of irrigated crop (c) in country (n)

The virtual water content of a given animal's feed $\left(V^{\text{feed}}_{n,c,a}\right)$ is thus the total irrigated water input ($T_{n,c,a}$) minus the embedded water ($U_{c,a}$) all expressed as cubic meters of water per ton of grain (Eq. 9).

$$V^{\text{feed}}_{n,c,a} = T_{n,c,a} - U_{c,a} \tag{9}$$

where:

$V^{\text{feed}}_{n,c,a}$	Virtual water in animal's (a) feed crop (c) in country (n)
$T_{n,c,a}$	Total irrigation water applied to crop (c) fed to animal (a) in country (n)
$U_{c,a}$	Embedded water in grain in crop (c) fed to animal (a)

Animal Production Stage

In Eq. 10, we estimate total water inputs to animal production for any animal-producing country m ($X_{m,a}$), which include the water contained in the feed ($U_{m,a}$), the water the animal drinks ($Y_{m,a}$), and the "service water" involved in animal production systems (e.g., water used to clean the animals' housing, $y_{m,a}$). Both $Y^{\text{drinking}}_{m,a}$ and $Y^{\text{service}}_{m,a}$ are extracted from [5].

Per Eq. 11, $U_{m,a}$ is the sum of the water content of all imported and domestically produced feed fed to animal a ($G_{n,m,c,a}$ is the total imported and domestically produced feed). We then subtract from the total water input the water contained in the animal after slaughter (u_a, assumed to be constant across countries, extracted from [5]) to get the volume of virtual water associated with live animal production in a given country $\left(V^{\text{live}}_{m,a}\right)$. The output of the calculations is V^{live} in Eq. 12, which quantifies the virtual water associated with live animal production, expressed as cubic meters per ton of animal produced.

$$X^{live}_{m,a} = \int_{birth}^{slaughter} \left(U_{m,a} + Y^{drinking}_{m,a} + Y^{service}_{m,a}\right) \tag{10}$$

$$U_{m,a} = \sum_{n,c} \left(U_c \times G_{n,m,c,a}\right) \tag{11}$$

$$V^{live}_{m,a} = X_{m,a} - u_a \tag{12}$$

where:

$X^{\text{live}}_{m,a}$	Water needed to produce animal (a) in country (m)
$U_{m,a\ (or\ c)}$	Total embedded water in feed fed to animal (a) in country (m) or in crop (c)
$\mathrm{u_a}$	Water embedded in carcass of animal (a)
$Y_{m,a}$	Drinking or service water given to animal (a) in country (m)
$G_{n,m,c,a}$	Total imported (n) and domestic (m) feed crop (c) fed to animal (a)
$V^{\text{live}}_{m,a}$	Virtual water associated with production of animal (a) in country (m)

Animal Processing Stage

For any processing country p, total water inputs include the embedded water in the slaughtered animal $\left(u_a^{'}\right)$ and any other water used during processing and slaughter ($Y_{p,a}^{\text{slaughter}}$, obtained from [5]). Once again, we subtract from this total the water embedded in the processed animal ($u_a^{'}$, assumed to be constant across countries, obtained from [5]) to arrive at the virtual water content of the processed animal $\left(V_{p,a}^{\text{product}}\right)$.

$$X_{p,a}^{\text{slaughter}} = u_a + Y_{p,a}^{\text{slaughter}} \tag{13}$$

$$V_{p,a}^{\text{product}} = X_{p,a}^{\text{slaughter}} - u_a^{'} \tag{14}$$

where:

$X_{p,a}^{\text{slaughter}}$	Water needed to slaughter animal (a) in country (p)
$Y_{p,a}$	Service or processing water for animal (a) in country (p)
u_a	Embedded water in animal (a)
$u_a^{'}$	Embedded water in the processed animal (a)
$V_{p,a}^{\text{product}}$	Virtual processing water for animal (a) in country (p)

Nitrogen

Feed Production Stage

Virtual nitrogen for feed (A) represents the portion of total nitrogen input (B) that is not actually taken up in the grain (b_c). The virtual nitrogen content of a given feed in a given country ($A_{n,c}$) is a fixed proportion of each crop's total nitrogen input (Eq. 15). Note that we transform total nitrogen input ($B_{n,c}$) on a per hectare basis to nitrogen per ton of crop produced by dividing by the yield of irrigated systems ($\alpha_{n,c}$, in tons per hectare).

$$A_{n,a}^{\text{feed}} = 0.7 \times B_{n,c} \tag{15}$$

where:

$A_{n,c}^{\text{feed}}$	Virtual nitrogen of feed crop (c) in country (n)
$B_{n,c}$	Total nitrogen input per hectare of crop (c) in country (n)

Animal Production Stage

We can equate the nitrogen input into each finished live animal, a, produced in country m ($J_{m,a}$) to the nitrogen content of the feed shipment from country n to country m to feed animal a ($G_{n,m,c,a}$). We then subtract out the nitrogen contained in the finished live animal ($b_a^{'}$, assumed to be constant across all countries per unit weight, based on data from [5]) to get the volume of virtual nitrogen associated with live animal production in a given country $\left(A_{m,a}^{\text{live}}\right)$, as shown in Eq. 16.

$$J_{m,a} = \sum_{n,c} \left(b_{n,c} \times G_{n,m,c,a}\right) \tag{16}$$

$$A_{m,a}^{animal} = J_{m,a} - b_{m,a}^{'} \tag{17}$$

where:

$J_{m,a}$	Nitrogen input to animal (a) produced in country (m)
$b_{n,c}$	Nitrogen embedded in the grain of crop (c) imported from country (n)
$b_{m,a}^{'}$	Nitrogen embedded in finished animal (a) produced in country (m)
$G_{n,m,c,a}$	Total feed of crop (c), imported from country (n), fed to animal (a) produced in country (m)
$A_{m,a}^{\text{animal}}$	Virtual nitrogen associated with animal (a) in country (m)

Animal Processing Stage

For any processing country p, the nitrogen inputs are equal to the nitrogen embedded in the slaughtered animal $\left(b_a^{'}\right)$. We subtract from this the nitrogen in the processed product ($b_a^{''}$, obtained from [5]) to arrive at the virtual nitrogen content of the processed animal $\left(V_{p,a}^{\text{product}}\right)$.

$$A_{p,a}^{\text{product}} = b_a^{'} - b_a^{''} \tag{18}$$

Where:

$A_{p,a}^{\text{product}}$	Virtual nitrogen of processed product from animal (a) in country (p)
$b_a^{'}$	Embedded nitrogen in slaughtered animal (a)
$b_a^{''}$	Nitrogen in processed product from animal (a)

Land

For sink (importing) countries, total land required to support pig and chicken consumption ($K_{n,c}$, see Eq. 19) was calculated as an aggregate of the land required to produce the feed, specific to yield and feed basket parameters in each grain- or animal-exporting country. Total land (K) is calculated by dividing the imports of crop c from country n ($F_{n,c}$) by the yield of crop c in country n ($\alpha_{n,c}$). Crop imports include both direct imports of feed to produce pigs and chickens domestically, and "indirect" imports of feed that were used to produce meat abroad that was then imported. Yield data, by county and crop, were obtained from FAO [11].

$$K_{n,c} = \sum_{n,c} \left(\alpha_{n,c}^{-1} \times F_{n,c} \right) \tag{19}$$

where:

$K_{n,c}$ Total land required to grow crop (c) in country (n)
$\alpha_{n,c}$ Yield of crop (c) in country (n)
$F_{n,c}$ Total imports of crop (c) from country (n)

For source countries, a similar calculation was required to capture both the land used for feed exports, plus the land required to grow feed for exported animals. Equation 20 mimics the calculation above but replaces total imports with total exports ($D_{n,c}$ and $E_{n,c}$).

$$K_{n,c} = \sum_{n,c} \left(\alpha_{n,c}^{-1} \times \left(D_{n,c} + E_{n,c} \right) \right) \tag{20}$$

where:

$K_{n,c}$ Total land required to grow crop (c) in country (n)
$\alpha_{n,c}$ Yield of crop (c) in country (n)
$D_{n,c}$ Direct exports of crop (c) from country (n)
$E_{n,c}$ Indirect exports of crop (c) from country (n)

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