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Article

Consumption-Based Accounting for Tracing Virtual Water Flows Associated with Beef Supply Chains in the United States

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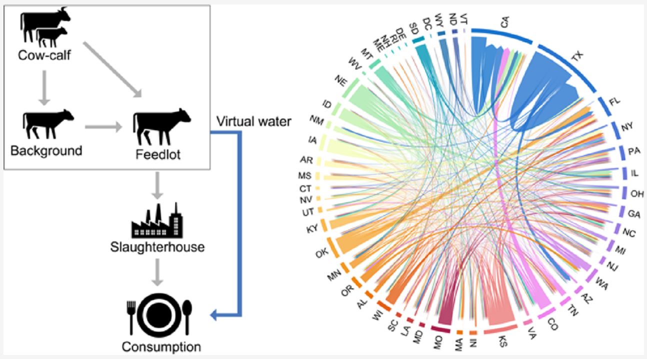
ABSTRACT: Enhancing the environmental sustainability of food systems requires an understanding of both production- and consumption-based impacts. As food supply chains become increasingly complex and connected, they also present a unique context in which to understand the environmental impacts of consumption. This is critical for understanding the disconnect between production- and consumption-based impacts of food systems and ultimately designing, evaluating, and implementing interventions for improving security, resilience, and sustainability of food systems. Using publicly available datasets and an optimization-based framework, we present a county-to-county level network model of beef supply chains in the United States. The model is used to connect and attribute the consumption-based impacts of beef consumption to production in distant locations, specifically focusing on water-based impacts. We specifically focus on the beef system because of its importance in the diet of U.S. consumers and in environmental sustainability discourse. The findings from this work show the spatial disconnect between the consumption and production counties with approximately 22 billion m^3 of blue virtual water being transferred for the year 2017, mainly from the northern and southern plains toward the coasts. These results highlight the importance of understanding environmental impacts from both production and consumption perspectives.



KEYWORDS: *beef production, virtual water, optimization, supply chain, network analysis*

■ INTRODUCTION

Food production and consumption are associated with significant resource consumption and associated environmental pressures. The production-based environmental impacts of diverse food crops and products have been widely studied and documented. Specifically, animal-based products have been shown to have disproportionate environmental impacts compared to other food categories.[1,2] Further, as food supply chains become increasingly complex and connected, the impacts of food consumption are often felt far from the point of consumption. This is challenging when attempting to connect consumption patterns to environmental impacts. The environmental impacts of food production and specifically the same food product can be highly dependent on the origin (production location), leading to very different impacts for the same consumption patterns. Linking consumption patterns to impacts in specific areas can create opportunities for targeted improvements from both production and consumption perspectives.[3,4] It also has the potential of complementing production-based accounting of environmental impacts, as the underlying drivers are uncovered and shared responsibility is assigned.

Among food items, animal-based products have received significant attention because of their high resource requirements and life cycle environmental impacts. Beef production in particular has the lowest water-use efficiency among livestock products.[5,6] The water-use performance of cattle production is highly dependent on abiotic factors, such as weather and soil, that determine the requirement for irrigation during feed production.[7] In sync with improvements in yield optimization, production practices, and supply chain management, reducing demand of animal-based products is one of the most impactful changes for sustainability purposes.[1,8,9] Thus, understanding beef demands and the spatial distribution of both feed and cattle production are key for evaluating the environmental sustainability of food systems and developing improvement strategies. In the absence of detailed information on the origin of food items, average values are often assigned to environmental impacts of food consumption. Specifically, there exists a knowledge gap in attributing environmental impacts of meat consumption in a systematic manner to production locations. Mubako[10] developed a framework to estimate virtual water flows

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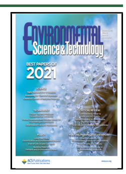

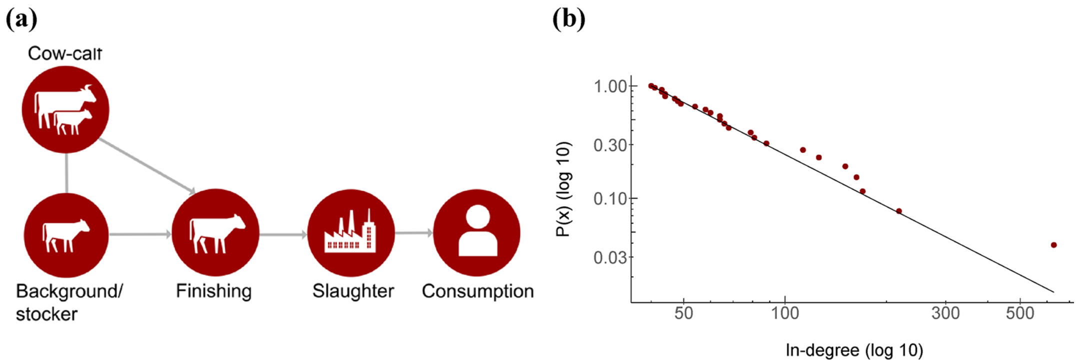

Figure 1. (a) Schematic of the beef network. The figure shows the beef network model scheme, from cow−calf to consumer. Background and cow−calf operations were collapsed into one category for analysis due to the lack of specific data from the USDA. (b) In-degree distribution of nodes in the beef network. The theoretical power-law cumulative distribution function (CDF) is shown as a straight line, while the empirical CDF is shown as red dots.

among states in the United States via water footprint and input−output tables and provided a solid overview of water use by the agricultural sector. However, the study was limited in scope because of availability of detailed trade data at fine spatial scales.

The challenge of linking consumption patterns to production impacts often referred to as "consumption-based accounting" has been recognized and received attention in the literature for food products. Recent studies have used network theory coupled with bilateral trade data to model and analyze food trade networks at national and international scales to trace the origin of products. Specifically, these studies have made important contributions to our understanding of water embodied in food production and trade (often referred to as "virtual water") and its evolution over time.[11−19] In addition, some studies have focused on the understanding of the dynamic between rural and urban settings and their virtual water dependencies and efficiencies.[20,21] However, the use of bilateral trade data to locate the origin of food products is problematic when the origin node is the re-exporting location or the distribution center. Similarly, the destination might actually represent the distribution center or processing location rather than the point of final consumption. Further, trade data at subnational scales is often aggregated by broad food categories (e.g., cereal grains, meat, and milled products). This challenge can be addressed by disaggregation but requires vast quantities of additional data.[22] Methods based on input−output analysis in conjunction with trade data have been used to address some of the limitations mentioned above, including an approach involving multilayered networks to include links between sectors (e.g., cereal grains and live animal flows), which is able to provide a clearer picture from a consumption perspective as well.[23] But these approaches still require disaggregated trade data, which is not readily available for studying specific commodities at a national scale.[3]

There also exists a decent body of work based on operations research techniques for designing and analyzing food supply chains.[24−27] This alternative allows the construction of food supply chains and networks by optimization of economic (costs) or environmental objectives (emissions reduction) based on production and demand constraints. Smith et al.[4] modeled the mobility of corn from farm to animal feed and ethanol fuel using optimization techniques, where consumption was defined as primary processing plants, to link companies to upstream corn production in the supply chain. Richter et al.[28] derived a beef flow network from commodity flows datasets and identified beef consumption as the driver of water scarcity mainly due to irrigation of feed crops. Brauman et al.[29] applied an optimization-based commodity flow model to link blue water resource impacts to meat and ethanol processing facilities.

The goal of our present work is to develop a county-to-county network model of beef supply chains to account for consumption-based impacts associated with beef consumption in the United States. Using available production and sales data and optimization techniques, a directed and weighted network model is created to link cattle movement between counties during the cattle production phase and further to meat packing plants and consumption counties. The model is combined with available information on blue water footprint of feed and cattle production, including irrigation and animal-related uses, to track and quantify virtual water movement associated with beef consumption. To the best of our knowledge, it is the first study to provide a consumption-based accounting of virtual water impacts of the domestic beef supply chain for the United States. The resulting optimization-based network model provides several important insights including (i) spatially explicit consumption-based accounting of blue virtual water impacts associated with beef consumption at the county level, (ii) location and magnitude of water requirements in beef production, and (iii) general patterns of cattle movements around the country as they are transported from ranch to feedlot and to slaughterhouse.

METHODS AND DATA

Beef Production System. A conceptual schematic of the beef network is shown in Figure 1a. There are a number of operations involved in the production of beef cattle, from cow−calf stage to slaughterhouses. In the cow−calf operation, calves are born and raised alongside their mothers (referred to as beef cows) until they are weaned at 3−7 months old.[30] Post this period, there are a few possible paths. Some animals might be retained for reproduction and expansion of the herd. Otherwise, the heifers (females that have not calved) and steers (castrated males) are either directly placed in feedlots with a finishing diet or moved to stock and background operations in the feedlots.[31] Thus, we reserve the word feedlot to refer to the location of both backgrounding and finishing. In stock and background operations, the cattle grow in muscle and frame until they are ready to start the finishing phase. These operations last approximately 3 to 4 months.[30] Finishing is the final growth stage in the feedlot where most of the cattle are produced.[32] The animals receive grain-based products and supplements for 3 to 9 months depending on the desired grade.[30] The industry is highly segmented as the animals are marketed between these

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operations.[32] In 2017, 32.2 million cattle were commercially slaughtered, where 80% were steers and heifers, 8.8% dairy cows, 9.5% other cows, and 1.7% bulls.[33] The system boundary in this study spans the cow−calf stage (origin county) to the point of final demand (beef consumption or final destination county) for the year 2017. The scope of this study is limited to the grain-fed animals raised for beef production and does not include dairy herds or culled cows and bulls.

Data Sources. *Cow−Calf, Background, and Finishing.* Cattle inventory and sales data from the United States Department of Agriculture (USDA) is used to map fed cattle at the county level. This data is made available annually by the National Agricultural Statistics Survey.[34,35] Since the data is disclosed partially due to privacy reasons, we employed statistical learning techniques to estimate missing values of cattle sales for slaughter. We use k-means clustering to classify states based on production practices, specifically the total number of cattle and percentage of fed cattle. Subsequently, machine learning models were fitted to each cluster with cattle sales and the number of operations from the USDA as predictors to infer the number of fed cattle sold to slaughterhouses. More details on the machine learning methodology can be found in the Data section in the Supporting Information (SI). State-level data of sales for slaughter from the USDA was used to ensure that estimated county totals in a state respected the reported values at the state level. In addition, information on the portion of cattle that are placed in background operations instead of starting finishing diets directly was adopted from Asem-Hiablie et al.[36−39]

Slaughterhouse Data. The location of slaughterhouses was obtained from the Food Safety and Inspection Service (FSIS) and the Meat, Poultry and Egg Product Inspection Directory.[40] A total of 672 federally inspected establishments perform livestock slaughter for beef production. We only considered establishments with capacity greater than 10,000 heads per year since these facilities are responsible for 98.7% of the cattle slaughtering.[33] Specific slaughter capacity was obtained from publicly available information, such as the companies' websites, press releases, and reports in addition to the Cattle Buyers Weekly meat packing ranking.[41] The establishments list was reduced to 48 facilities spread across 17 states that account for 96% of fed cattle slaughtering capacity.

Network Construction. In this study, it was assumed that backgrounding occurs in the same county as feedlot operations[31,42] due to the lack of available disaggregated data. As such, we trace the beef movement in four stages at the county level: cow−calf, feedlot, slaughterhouse, and consumption. Further, in the absence of information on distribution centers, we assumed and modeled direct links between slaughterhouses and consumption counties. Herein, we refer to the respective links between successive stages as *calf* (cow−calf to feedlot), *cattle* (feedlot to slaughter), and *consumption* (slaughterhouse to consumption) networks. The term *beef network* is reserved for the entire supply chain network including all stages and counties.

The beef network was constructed in two steps using an optimization-based framework. The first step involves minimizing the costs for slaughterhouses when procuring cattle from the feedlots and distributing the packed meat (P1). In the second step, the feedlot costs are minimized for procuring calves from cow−calf operations (P2). The optimization problems were formulated as mixed-integer linear programming (MILP) models.[43] We assume rational decision-making;[44] thus, all decision-makers have perfect information and are fully equipped to minimize their transportation costs. The network is modeled as a hierarchical network due to the assumption that nodes with the same function do not communicate with each other even when they are in the same county (e.g., a feedlot will not send cattle to another feedlot). Furthermore, although firm-level data is available for slaughterhouses, the supply chain is still said to be county level because data for animal operations are aggregated. Mathematical details of the two steps are described as follows.

The slaughterhouse MILP problem seeks to satisfy the county-level meat demand (consumption) by considering two major links: from cattle feedlots to slaughterhouses and from the latter to the consumption county. Intermediate links from and to retailers and restaurants are not considered. Relevant equations for the slaughterhouse MILP problem are provided below.

$$\mathbf{P1}: \min\ t^{(1)} \sum_i \sum_j d_{ij}^{(1)} f_{ij} + c \sum_j \sum_k d_{jk}^{(2)} g_{jk} \# \tag{1a}$$

$$\text{subject to} \sum_j f_{ij} \le F_i\ \forall\ i \in I \# \tag{1b}$$

$$\sum_j f_{ij} \le Q_j\ \forall\ i \in I \# \tag{1c}$$

$$\sum_k g_{jk} = \sum_i W_j f_{ij}\ \forall\ j \in J \tag{1d}$$

$$\sum_j g_{jk} \ge D_k^{(1)}\ \forall\ k \in K \tag{1e}$$

$$\sum_i f_i \ge M_j\ \forall\ j \in J \tag{1f}$$

$$g_{jk} \le D_k^{(1)}\ \forall\ j \in J, k \in K \tag{1g}$$

$$f_{ij} \le F_i y_{ij}\ \forall\ i \in I, j \in J \tag{1h}$$

$$f_{ij} \ge L y_{ij}\ \forall\ i \in I, j \in J \tag{1i}$$

$$f_{ij}, g_{jk} \ge 0\ \forall\ i \in I, j \in J \tag{1j}$$

$$y_{ij} \in \{0, 1\}\ \forall\ i \in I, j \in J \tag{1k}$$

Sets.

I: set of feedlot counties
J: set of slaughterhouses
K: set of consumption counties

Parameters.

$d_{ij}^{(1)}$: distance between feedlot county i and slaughterhouse j (km)
$d_{jk}^{(2)}$: distance between slaughterhouse j and consumption county k (km)
$t^{(1)}$: average transportation cost from feedlot county to slaughterhouse (U\$/km ton)
c: average cost of refrigerated transportation from slaughterhouse to the consumption county (U\$/km ton)
$D_k^{(1)}$: demand for county k (ton)
Q_j: capacity of slaughterhouse j (heads)
M_j: minimum demand of slaughterhouse j (number of animal heads)
F_i: total production by feedlot i (heads)

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W_j: average hot carcass weight at slaughterhouse j (ton/head)

L : the minimum number of animals to be transported between feedlot county and slaughterhouse, or "load lot", considered as equivalent to 50,000 pounds[45] or 37 animals with an average live weight of 1349 pounds[33]

Decision variables.

f_{ij}: cattle flow between feedlot county i and slaughterhouse j (heads)

g_{jk}: packed meat flow between slaughterhouse j and consumption county k (ton)

y_{ij}: binary variable indicating the existence of a link between feedlot county i and slaughterhouse j

Equation 1a represents the objective function seeking to minimize transportation costs for slaughterhouses when buying cattle and transporting packaged beef. Constraints 1b and 1c represent constraints on capacity limitations of feedlot and slaughterhouse counties, respectively. Constraint 1d ensures the balance between inflow of cattle and outflow of beef and the conversion from the number of heads to hot carcass weight. The average carcass weight W_j is based on the assumption that carcass is 63% of animal live weight[46] and the state-level weight at the time of slaughter obtained from a USDA livestock slaughter report.[33] Constraints 1e and 1f are constraints that ensure that the demand in consumption county and slaughterhouse is being met. Constraint 1g ensures the existence of the variable g_{jk} as being less than or equal to the final demand of county k. Constraints 1h and 1i ensure the maximum and minimum load lot for transporting cattle between feedlot and slaughter. Equation 1j ensures that decision variables are non-negative. Finally, constraint 1k refers to binary variable y_{ij}, where it is equal to 1 if a link between i and j exists, and 0 otherwise.

The results of the slaughterhouse MILP model are used to develop the county-to-county cow–calf operation to feedlot network. Specifically, it maps the incoming cattle flow from cow–calf to feedlots. Mathematical details are as follows.

$$\mathbf{P2}\text{: } \min \sum_n \sum_i (t^{(2)} d_{ni}^{(3)} h_{ni} + p_n h_{ni})\# \tag{2a}$$

$$\text{subject to } \sum_i h_{ni} \le C_n \ \forall\ n \in N\# \tag{2b}$$

$$\sum_n h_{ni} = D_i^{(2)} \ \forall\ i \in I \tag{2c}$$

$$h_{ni} \le C_n z_{ni} \ \forall\ n \in N,\ i \in I \tag{2d}$$

$$h_{ni} \ge 0 \ \forall\ n \in N,\ i \in I \tag{2e}$$

$$z_{ni} \in \{0, 1\} \ \forall\ n \in N,\ i \in I \tag{2f}$$

The sets, parameters, and decision variables are shown below.

Sets.

N: set of cow–calf counties

I: set of feedlot counties

Parameters.

$d_{ni}^{(3)}$: distance between cow–calf county n and feedlot county i (km)

$t^{(2)}$: average cost of cattle transportation to feedlot (U \$/km ton)

C_n: capacity of cow–calf county n (heads)

$D_i^{(2)}$: demand of feedlot county i (heads)

p_n: price of feeder cattle in county n

Decision variables.

h_{ni}: flow of cattle between cow–calf/background county n and feedlot county i (heads)

z_{ni}: binary variable indicating the existence of a link between cow–calf county n and feedlot county i

Equation 2a is the objective function to minimize transportation and purchase costs of cattle. Constraint 2b imposes the appropriate upper bound to respect the number of cattle sold by county n according to USDA cattle sales data, while constraint 2c ensures that each feedlot receives the total amount of cattle established previously in the slaughterhouse MILP model. Constraints 2d and 2e make sure that h_{ni} is lower than the maximum capacity of the receiving feedlot and above zero, respectively. Finally, constraint 2f ensures that the binary variable z_{ni} is equal to 1 if there is a link between n and i and 0 otherwise.

Linking Production to Consumption. Once the beef network is developed, the next step involves tracing and attributing environmental impacts of meat consumption to distant locations. For this work, this refers to water consumption impacts in cow–calf and feedlot counties. In doing so, we assumed that the amounts are passed proportionally throughout the network. For example, if one slaughterhouse receives 60% flow from feedlot 1 and 40% from feedlot 2, the consumption county receiving meat from this slaughterhouse is assumed to be ultimately obtaining meat in the same proportion from feedlots 1 and 2, respectively. In other words, the flows are "well mixed" at every node, which is an assumption consistent with prior modeling studies.[3]

The slaughterhouse optimization model generated two matrices. The first is $I \times J$ matrix Φ, where the coefficients represent the flow of cattle from feedlot county i to slaughterhouse j. The second is $J \times K$ matrix Ψ, where the coefficients represent the flow of meat from slaughterhouse j to county of consumption k. Here, I is the number of feedlots, J is the number of slaughterhouses, and K is the number of consumption counties. Using Φ and Ψ, we obtain $I \times K$ matrix P, with coefficients ρ_{ik}, representing the flow from the feedlot county to the meat consumption county.

$$\mathrm{P} = \Phi \times \Psi \tag{3}$$

Next, we introduced a new matrix S (with dimensions $I \times K$), whose coefficients s_{ik} represent the fraction of the amount of meat consumed in county k that comes from county i:

$$s_{ik} = \rho_{ik} \times \frac{1}{\sum_i \rho_{ik}} \tag{4}$$

And finally, matrix R (dimensions $I \times K$) is derived based on the percentage in matrix S and the total amount received by county k in matrix Ψ. Each element (r_{ik}) of R represents the amount of meat consumed in county k that comes from feedlot county I as

$$r_{ik} = s_{ik} \times \sum_j \psi_{jk} \tag{5}$$

The steps described above are repeated to obtain the cow–calf county to consumer county matrix. The networks used in this case are cow–calf to feedlot and feedlot to consumer networks developed previously using MILP models.

Water Footprint and Virtual Water. To calculate the water footprint of beef production, we adopted the methodology

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described in Mubako.[10] For the purpose of this study, we disaggregated and quantified water consumed throughout each phase of animal's life: cow−calf, background, and finishing. This is an important change because we are considering cattle movement across counties and hence the water consumption impacts of beef production are distributed in space. We utilized county-level blue water footprint of feed crops per unit of production from Marston et al.[47] as well as irrigated fractions determined based on information on the irrigated and total crop area from the agricultural census[48] and estimates of water withdrawals for livestock activities.[10] As such, the total water footprint for each state (m^3/animal) was estimated as below.

$$\mathrm{WF_{total}} = \sum_{n=1}^{N}\sum_{p=1}^{P} \mathrm{intake}_{n,p} \times \mathrm{irrigated}_n \times \mathrm{WF}_n \times \mathrm{length}_p + \sum_{p=1}^{P} \mathrm{withdrawal}_p \tag{6}$$

where $\mathrm{intake}_{n,p}$ is the intake of animal feed product n (ton/animal/year) during phase p, WF_n is the blue water footprint of feed product n (m^3/ton), $\mathrm{irrigated}_n$ is the irrigated fraction for feed n, and length_p is the length of phase p (year). The $\mathrm{withdrawal}_p$ represents the amount of water withdrawal (m^3/animal) in phase p and refers to the water used directly for drinking, feed mixing, and other animal-related activities, and was assumed to be consumptive. The state-level water withdrawal and the crop (animal feed) water footprint were extracted from the work of Mubako.[10,49] Phase p represents beef cow ($p = 1$), calves ($p = 2$), background ($p = 3$), and finishing ($p = 4$).

In the cow−calf phase, the consumption of water associated with both the cow and the calf was considered, from gestation to weaning. The length of each phase was adopted from Mekonnen et al.,[6] where they estimated the number of days based on the average weight gain. We assumed that the feed intake is similar to Canadian averages from the report published by Statistics Canada[50] due to the lack of specific data for the United States. This dataset was used for the phases of cow−calf and finishing, since the numbers are broken down by beef cows, calves, and steers/heifers in finishing. However, we noticed a discrepancy between the total feed intake by calves when comparing to Mekonnen et al.,[6] so for this category, the intake of each crop product was proportionally reduced to be consistent with the average daily gain of body mass. Feed rations for the backgrounding phase were obtained from a University of Missouri Extension report.[51]

To obtain the virtual water network associated with beef production and consumption, the water footprint of beef production in a given state and phase was multiplied by the respective link value based on the origin of the link. The water footprint originally expressed in m^3/animal was transformed to m^3/ton of carcass weight. The original dataset of carcass weight was obtained for the slaughterhouse node based on USDA data[33] and thus was traced back throughout the network. This step was essential, since the weight of the cattle in the different phases of the supply chain varies greatly. To ensure that there was no double-counting, the water footprint of the backgrounding and finishing phases was multiplied by the feedlot to consumption county network taking into consideration the proportion of cattle that are actually backgrounded, while the water footprints of the calves and beef cows were multiplied by the cow−calf to consumption county network. By grouping these datasets by origin and destination and summing over all links, we obtained the production to consumption virtual water network for beef.

■ RESULTS

Network Structure. The resulting beef network is a three-echelon network that, on a high level, is characterized by a series of star-like connections with no isolated components. For example, a given slaughterhouse is connected to several consumption counties and feedlots. Typically, real-world networks have highly skewed degree distributions with a few highly connected nodes and most nodes having a small number of connections.[52] This is observed in the beef network as the majority of the nodes (counties) have very few connections, with a small number of counties that are highly connected. For example, in-degree in the cattle network ranged between 1 and 624, with most slaughterhouses being linked to less than 40 feedlot counties. In addition, analysis of out-degree in the consumption network shows that most slaughterhouses send their products to less than 100 counties. This trend is also observed in feedlots and cow−calf operations. Analysis of the cattle network reveals that the majority of feedlots are connected to the single nearest slaughterhouse. This is not a surprising model outcome and is consistent with previously published survey results, showing that the distance to the slaughterhouse was one of the most important factors to consider when establishing new operations and that most animal producers (95th percentile) transport animals (feedlot to slaughterhouse) to a maximum distance of 75 miles.[53]

The above observations suggest that the county-level beef network might be a scale-free network. Scale-free networks are characterized by the presence of hubs, small diameter, resistance to random disruptions, and preferential attachment.[54] Mathematically, scale-free networks have degree distributions that follow a power law, with probability of nodes connecting to other nodes being proportional to $x - \alpha$. The value of α is typically the number between 2 and 3 for scale-free networks.[55]Figure 1b shows the empirical cumulative distribution of the total degree in the beef network. Statistical testing with the Kolmogorov−Smirnov test[56] supports that the beef network has an underlying power-law distribution (p-value = 0.72).

Exponential and log-normal distributions were also tested as plausible distributions for the total degree;[55] however, the Kolmogorov−Smirnov test revealed low goodness of fit (p-value < 0.10). We further compared the strength of the similarity of the real-world network with the scale-free network described by Broido and Clauset.[57] Broido and Clauset classify the strength of scale-free networks based on the number of nodes, regions where power-law distribution cannot be rejected, and α values. Analysis reveals that the beef network would be a weakest to weak scale-free network as the power-law region has at least 50 nodes (with 89 counties above the cutoff), but the alpha parameter is 1.89 and thus outside the $2 < \alpha < 3$ range.

Beef Production and Consumption. Approximately 9.5 million tons of beef (carcass weight) were transferred between counties in 2017, corresponding to 24.6 million cattle. Although cow−calf operations were identified in all 48 states, most feedlots are located in a handful of states including Nebraska, Kansas, Texas, and Colorado. As such, the largest inflows in the cow−calf to feedlot network were observed in this region. Analysis indicated that on average, cattle traveled to feedlot for approximately 275 miles, with a median traveled distance of 101

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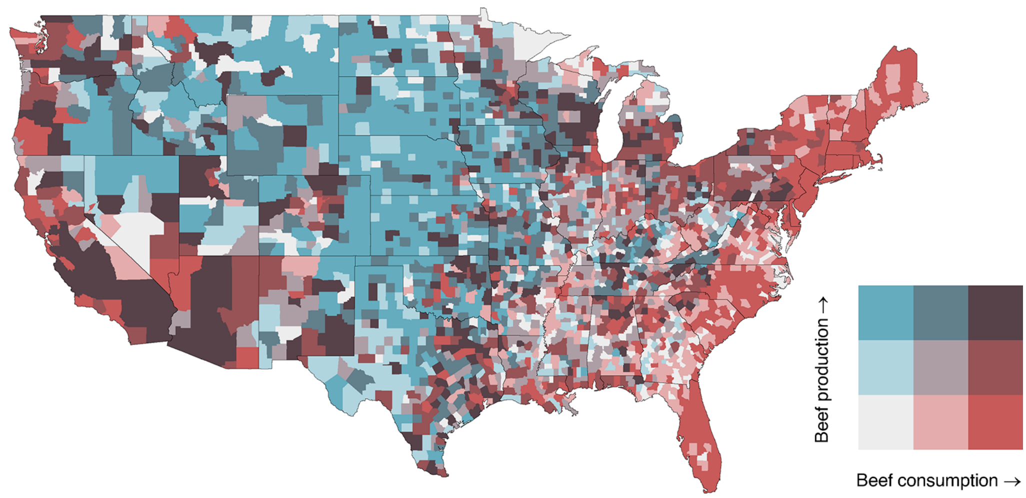

Figure 2. Bivariate distribution of beef cattle production and beef consumption. Categories were assigned based on tertiles (33.3, 66.6, and 100%), dividing the two variables in three groups (low, medium, and high). Production tertile cutoffs are 0.37, 3.64, and 356 ktons of carcass weight. Consumption tertile cutoffs are 0.45, 1.36, and 297 ktons of carcass weight. The color scale indicates the combination of consumption and production, respectively, explained by row: white (low−low), pink (medium−low), red (high−low), light blue (low−medium), gray (medium−medium), dark red (high−medium), teal (low−high), steel teal (medium−high), and brown (high−high).

miles, where the distance refers to the great-circle distance between two county centroids. Out of a total of 2165 counties with feedlot operations, the top 10 counties were responsible for 20% of sales for slaughter (heads) and the top 50 produced 54% of all beef consumed. Top feedlot counties are Deaf Smith (TX), Scott (KS), Haskell (KS), Weld (CO), and Cuming (NE) with values ranging from 500 to 710 thousand heads sold for slaughter. The same four states also slaughter the majority of the cattle in 25 facilities, accounting for 18 million animals, or 75% of slaughtered fed cattle. From a consumption perspective, inflows to Los Angeles (CA), New York City counties (NY), Cook (IL), Harris (TX), and Maricopa (AZ) represent approximately 10% of the total inflows of meat in the network.

Figure 2 shows the bivariate relationship between beef cattle production and beef consumption for counties in the contiguous United States. At a higher level, both west and east coasts are big consumption centers, while the Mountain-West, the West North Central, and the West South Central have the highest levels of production. States like Arizona, California, Indiana, New York, Ohio, and Pennsylvania have mainly dark red- and brown-colored counties, indicating high consumption and moderate-to-high production within the same county. In contrast, states such as Florida, Georgia, South Carolina, and North Carolina and the region of New England are characterized by pink and red colors, indicating moderate-to-high consumption and low production. States in the east central region have very mixed colors, with a few counties in a gray shade that represents moderate consumption and production.

Virtual Water. Beef cows are the category with the most intensive blue water requirements with an average of approximately 426 m^3/animal, followed by finishing (202 m^3/animal), background (121 m^3/animal), and calves (48 m^3/animal). However, beef cows are also in the longest phase in beef cattle production (cow−calf) with the combined period between gestation and nursing lasting longer than a year, while all other phases last between 3 and 7 months. The feed intake intensity of beef cows is slightly lower than the feedlot cattle (22 and 23.6 lbs/animal/day, respectively).

The average blue water footprint at the end of the animals' lives is approximately 798 m^3/animal. Brauman et al.[29] compared irrigation water footprints for beef cattle and found great variation, from approximately 200 to 1200 m^3/animal. We found a range of 309 to 1702 m^3/animal depending on the state where the animals are raised. On a mass basis, our results show a mean of 2.3 m^3/ton of carcass weight and is in excellent agreement with findings by Rotz et al.[7] of approximately 2.1 m^3/ton of carcass weight.

Figure 3 shows the virtual water flows between states associated with the beef network. The amount of water corresponds to the water consumed in cow−calf and feedlot operations transferred virtually between states via supply chain links. Approximately 22.2 billion m^3 of blue virtual water was transferred between counties in the United States. This result

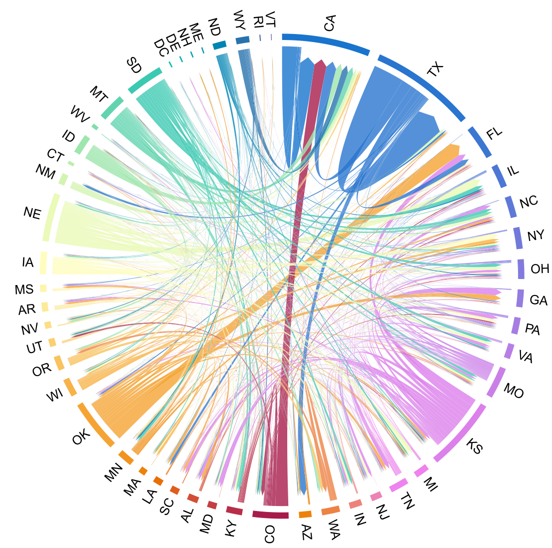

Figure 3. Chord diagram of virtual water flows between states in the contiguous United States. Flows represent the virtual water from the cow−calf and feedlot operations sent to respective consumption locations. The states are ordered by consumption starting at the 90-degree mark, with the State of California. Inflows are identified by arrows and larger gap between segment and axis.

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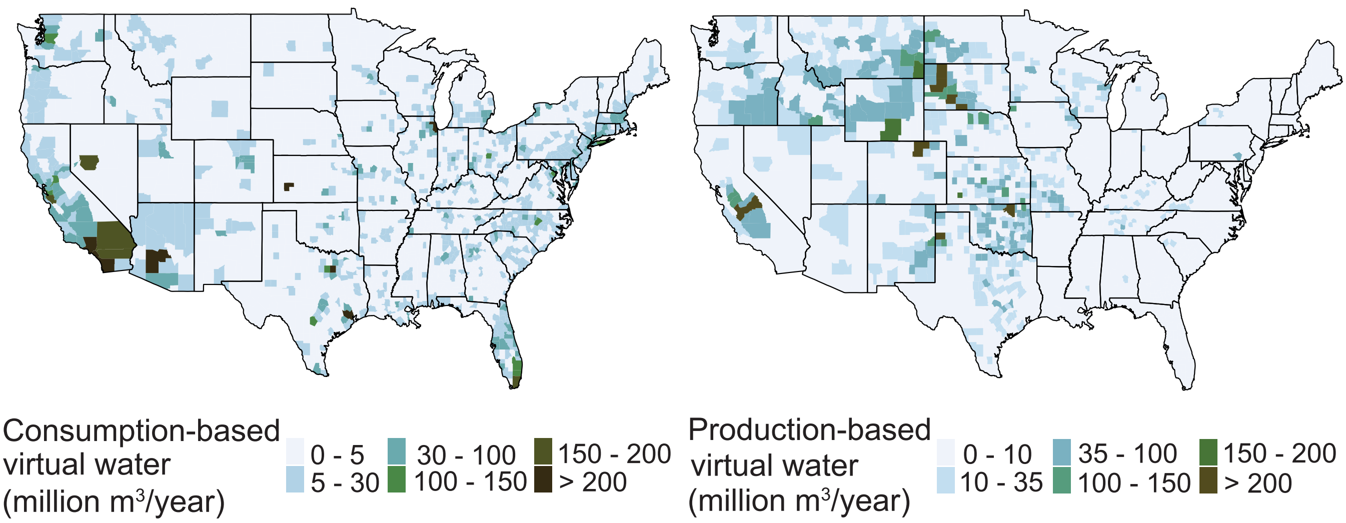

Figure 4. County-level virtual water from consumption- (a) and production-based (b) perspectives associated with beef in 2017. Class intervals were based on head/tails breaks, appropriate for heavy-tailed distributions.

compares well with total blue water requirements for beef cattle from Rotz et al.[7] of 23.2 billion m^3. In addition, Brauman et al.[29] found embedded irrigation water for beef production to be approximately 11 billion m^3 when considering only corn and soybeans.

California, Texas, Florida, Illinois, North Carolina, and New York have the highest virtual water inflows, whereas Texas, Oklahoma, South Dakota, Kansas, and Montana have the highest outflows. California, Florida, North Carolina, Illinois, and New York have the highest values of net positive inflows, which is indicative of high total consumption and hence virtual water demand. Oklahoma, South Dakota, Montana, Kansas, and Idaho have net negative virtual water inflows, indicating high virtual water exports. In relative terms, South Dakota stands out with the highest outflow to inflow ratio (ratio = 23.9), followed by Montana (18.9), Wyoming (15.6), North Dakota (15.5), and Oklahoma (8.9). These states are also characterized by low consumption and moderate-to-high virtual water exports. On the other hand, New England states have the outflow to inflow ratio equal to zero or very low, indicating no to low virtual water exports. Values for state-level water inflows and outflows are provided in the SI, Table S13.

Although the virtual water inflows are highly correlated with population (R^2 = 0.95), Figure 3 also reveals that sourcing of beef also influences the order of highest total inflows. For example, North Carolina appears above New York, even though it is less populated (10.4 versus 19.5 billion). The model resulted in North Carolina being more heavily linked to states such as South Dakota and Montana, which presented relatively higher blue water footprints (Figure S9) than Iowa and Wisconsin, two states that New York is more heavily linked to. This resulted in North Carolina having a higher consumption-based water footprint (3070 m^3/ton carcass consumed) in relation to New York (1563 m^3/ton carcass consumed).

Figure 4a shows the distribution of consumption-based virtual water at the county level. When considered relative to each other, most counties in the United States (95%) consumed lower amounts of blue virtual water from beef in 2017, up to or lower than 30 million m^3 (Figure 4a). The results highlight that the distribution of consumption-based virtual water at the county level is highly skewed with few outliers such as Los Angeles (CA) with 800 million m^3. Only eight counties had consumption-based virtual water higher than 200 million m^3. These include highly populated areas such as Cook (IL), Maricopa (AZ), and Harris (TX) that account for approximately 10% of the total U.S. population. Consumption-based virtual water of the five counties comprising the New York City totals around 366 million m^3. The trends in Figure 4 underscore the role of highly populated areas in the consumption of water due to beef intake patterns.

Figure 4b shows the spatial distribution of production-based blue virtual water at the county level. The distribution is highly skewed with a median value of 2.4 million m^3 of virtual water. Eight counties have values larger than 200 million m^3: Deaf Smith (TX), Fresno (CA), Weld (CO), Meade (SD), Perkins (SD), Osage (OK), Jackson (SD), and Todd (SD). These counties are characterized by a large number of animals in both cow−calf and feedlot phases and account for approximately 8.8% of the total virtual water exports. Collectively, the results in Figure 4a,b highlight the spatial disparity between consumption- and production-based virtual water impacts and more specifically between the largest producers and consumers.

DISCUSSION AND OUTLOOK

This work aimed to fill a knowledge gap in our understanding of county-level flows of cattle and beef and associated virtual water flows from calf production to beef consumption. Using information on production, sales, slaughter capacity, and per-capita consumption coupled with an optimization-based framework, we developed a county-to-county level network of beef production and consumption for the United States. We focused on domestically produced, domestically consumed beef products as more data is needed to evaluate international dependencies on grains and beef from the United States and accurately link environmental impacts to beef consumed in other countries. Recent studies in the literature have focused on tracking food flows using empirically available datasets such as freight data from FAF (Freight Analysis Framework) or CFS (Commodity Flow Survey)[28,58] consisting of information for broad categories of food products, making analysis of specific products challenging. The framework developed in our work adds a complementary perspective to this existing body of research by exploiting production datasets and thus bypassing

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the need to rely on available aggregated datasets. Further, freight data are not always available, especially in countries other than the United States, and are based on survey data, which can be underreported or incomplete.

The results from the optimization-based framework contribute to ongoing efforts to improve supply chain transparency and the understanding of the origin of food products consumed within the United States. One limitation is the modeling of a direct link between slaughterhouses and the county of consumption due to the lack of data on distribution and marketing of beef products. The addition of steps between slaughter and consumption might change the structure and linkages between consumption and production and would allow a fairer comparison with commodity flows datasets. The modeling assumption results in consumption being linked to the nearest processing plants, which is reasonable from a freshness and ease of transportation point of view, but may not reflect the diversity of branded beef products within a county. Thus, the framework might be underestimating the number of linkages between consumption county and counties bearing the environmental impacts and consequently overestimating the specific link intensities. Further improvements can be made but will require a market analysis to characterize market share, brand presence, and competition, along with socioeconomic variables to account for heterogeneity in county-level consumption patterns and product diversity as constraints in the network model. In addition, a more market-aware network model could potentially inform decision-making in ongoing discourses around antitrust laws, whose relaxation effectively changed the beef industry in the last decades and allowed for a concentrated industry with four large companies controlling most of the supply chain.[59]

Another potential limitation of the optimization model is the adoption of rational decision-making. In reality, decision-makers may choose a satisfactory option instead of an optimal one, and they might not have complete information needed to achieve an optimal outcome. In addition, a decision may also be dependent on other decision-makers' decisions due to differences in information, product availability, time, and personal connections. Dynamic agent-based models where each agent represents an independent decision-maker[60] can address this limitation in future studies but will require additional quantitative and qualitative information.

We also adopted a simplifying assumption that the feed is produced within the same county as the animal operations. In addition, the production-based discussion around water footprint attributes water to the county where animals are produced; thus, the number of counties linked to the county of consumption via the virtual water network might be limited. This assumption is also consistent with recent published work. Beam et al.[53] showed that most animal producers who responded to a survey (70%) were responsible for shipping feed to the animal operations, with the 95th percentile for the farthest distance being 60 miles. Surveys also indicate that it is common for cattle producers to produce feed within the farm, most often corn grain and alfalfa, but barley, oats, sorghum, soybeans, and rye are also occasionally cultivated.[37] In addition, the operations with corn and alfalfa fields often harvest more than the amount required by cattle, thus obviating the need for feed trade from other regions.[7]

Given the fact that the results are based on product flows simulated with an optimization model, actual routing and linkages may not necessarily reflect real-life links. The network is also based on great-circle distances rather than actual road distances. Recent work by Wang et al.[61] addressed this limitation through the use of roadway miles between counties when modeling cold-chain flows, which can be used in future studies. Our model still aids in the understanding of the role of sourcing and spatial irrigation patterns on the relative consumption-based water footprints. For example, our model resulted in North Carolina and Illinois receiving more virtual water flows than more populous New York due to their connections to states that had higher water footprints. This is likely a result of the optimization model that will prioritize higher volumes with shorter distances and smaller volumes with longer distances for cost reduction. Our study does not aim to indicate that these states bear more responsibility or that consumption within their boundaries is more harmful, but rather to elucidate that consumption-based water footprints may be heterogeneous due to routing and sourcing. Further, we do not distinguish the source of blue water between ground and surface water. Future work can specifically look at the sustainability of water sources and their relation to the consumption-based water footprint. In addition, future work can also consider different weighting schemes to understand consumption-based impacts by unit of calorie, protein, or price. For the purposes of this study, a different weighting scheme would not change the overall conclusions because we do not distinguish between the quality differences in the final beef products consumed. Studies with more detailed data can consider different beef cuts, their price points, and respective water footprints.

Our work shows that a modeling approach based on optimization can leverage publicly available datasets on supply and demand and contribute to discussion on the quantification and tracing of environmental impacts associated with consumption. Future work can leverage this framework to study other livestock products and additional environmental impacts accordingly. The network developed in this study provides a snapshot of a supply chain associated with year-long beef consumption in 2017. However, the datasets employed in this study can also aid supply chain disruption research by adopting a modeling approach that includes a dynamic distribution of products based on time, inventory, and stocks, for example.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.2c03986.

> Additional data, results, and further methodological details in the accompanying Supporting Information document (PDF)
>
> Data for cattle and beef flows between counties in the United States (XLSX)

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Notes

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