Subnational mobility and consumption-based environmental accounting of US corn in animal protein and ethanol supply chains

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Corn production, and its associated inputs, is a relatively large source of greenhouse gas emissions and uses significant amounts of water and land, thus contributing to climate change, fossil fuel depletion, local air pollutants, and local water scarcity. As large consumers of this corn, corporations in the ethanol and animal protein industries are increasingly assessing and reporting sustainability impacts across their supply chains to identify, prioritize, and communicate sustainability risks and opportunities material to their operations. In doing so, many have discovered that the direct impacts of their owned operations are dwarfed by those upstream in the supply chain, requiring transparency and knowledge about environmental impacts along the supply chains. Life cycle assessments (LCAs) have been used to identify hotspots of environmental impacts at national levels, yet these provide little subnational information necessary for guiding firms' specific supply networks. In this paper, our Food System Supply-Chain Sustainability (FoodS^3) model connects spatial, firm-specific demand of corn purchasers with upstream corn production in the United States through a cost minimization transport model. This provides a means to link county-level corn production in the United States to firm-specific demand locations associated with downstream processing facilities. Our model substantially improves current LCA assessment efforts that are confined to broad national or state level impacts. In drilling down to subnational levels of environmental impacts that occur over heterogeneous areas and aggregating these landscape impacts by specific supply networks, targeted opportunities for improvements to the sustainability performance of supply chains are identified.

supply chains | environmental accounting | commodity flow modeling | food systems sustainability | life cycle assessment

One of the most pressing challenges facing society, globally, is how to meet the growing demand for food, fuel, and fiber in the face of climate change while sustaining ecosystem services. Broad scientific and practitioner agreement exists around the impact of food systems on local and global sustainability (1, 2). Food consumption contributes between 15% and 28% to total greenhouse gas emissions of developed countries (3). Agriculture uses 70–80% of global water withdrawals; it is a dominant cause of biodiversity loss; and the dramatic growth in its use of fertilizers has disrupted global nitrogen and phosphorus cycles, impacting water quality, aquatic ecosystems, and marine fisheries (4–7). Food supply chains are also among the highest energy users, with food-related energy use responsible for nearly 16% of the total US energy budget (8).

Appreciation of the environmental burdens of food production often emphasize the disproportionate role of livestock (9–17)—the 20 billion animals in global production graze on 30% of the world's terrestrial land area, consume one-third of global cropland production in feed, and account for 32% of total global freshwater consumption (18, 19). As an economic activity, livestock contributes up to 50% of global agricultural gross domestic product (20). Animal agriculture is also a major contributor of consumptive impacts. From a US dietary perspective, protein and dairy consumption represent nearly three-fourths (73%) of total annual per capita greenhouse gas (GHG) emissions of food (21). To combat these challenges, governments and voluntary initiatives have focused largely on the bookends of the food system—environmental and social impacts of high-input commercial agriculture on one end, and availability and access to healthy, affordable calories on the other. However, efforts toward improved coordination across food supply networks—e.g., among producers, processors, distributors, and retailers—occur amid severe informational deficits (22).

Although environmental impacts associated with food systems are relatively well quantified—particularly regarding carbon emissions and water impacts—most of this work has been conducted at spatial scales inconsistent with broad-reaching value chains, driven by national or subnational geopolitical boundaries, or field studies within specified biophysical and ecosystem boundaries (23–27). Numerous life cycle assessment (LCA) approaches have been carried out on food production chains, with the majority of these focused on GHG emissions (21, 23, 25, 26, 28–31). Recent research has expanded this approach to incorporate aspects of water quantity and quality, land use change, and biodiversity loss (32, 33). Although instructive, these approaches have largely been restricted in coverage to specific farm

Significance

Companies and society alike are increasingly concerned with environmental impacts across complex supply chains. Suppliers engaged in upstream intermediate transactions commonly contribute over 75% of the carbon and water impacts of products ultimately consumed by users. These impacts pose risks to downstream customer-facing companies in the form of firm image, supply disruptions, and regulatory action. Policymakers and nonprofit advocacy organizations are increasingly looking to engage actors across supply chains to encourage conservation and environmental impact reduction. Unfortunately, traceability across complex, heterogeneous supply hinders these efforts. We provide a method for estimating mobility of corn from farms through feed and fuel supply chains, making it possible to characterize the variable environmental impacts of US corn inputs into animal protein and ethanol production.

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processes, and often rely on coarse national inventory data and impact characterization factors (23–25, 29). Because of variation due to geography, year-to-year fluctuations in agricultural production environments and differences in farm management practices, current LCAs are unlikely to represent subnational production regions, let alone the numerous production locations that supply a particular value chain (26, 34–37).

At the country level, and more recently at subnational scales, consumption-based environmental accounting and footprinting approaches have been suggested. In contrast to the method of accounting for the territorial emissions of a nation in the Kyoto Protocol (also called producer responsibility), other concepts have been proposed that hold the consumer of goods and services responsible for the emissions that are caused during their production (consumer responsibility) (38, 39).

We connect the concepts of consumer and producer responsibility through a spatially explicit environmental impact analysis of the US corn supply chain. Environmental indicators are estimated for corn production at the county level, and using an optimization model, we simulate the subnational mobility of corn from production to primary use and then to final processing facilities. The model spatially links the supply chain of end-use company and facility-level buyers of corn-intensive products with corn production locations, and their associated environmental impacts. By linking the movement of corn from farms to final processing facilities of animal protein and fuel products, we make it possible to characterize spatially explicit environmental impacts associated with company-specific, corn-intensive product supply chains and locations.

This model substantially improves organizational LCA efforts, which currently are based on broad national or state level impacts over heterogeneous areas that may or may not accurately represent the specifics of a particular supply chain (40, 41). Understanding the spatial differences in environmental impacts of current corn farming practices is necessary to develop a baseline environmental profile for a facility or company supply chain, and to identify opportunities for improvements in management practices to increase the sustainability of supply chains. The spatially explicit supply chain information developed in this paper helps inform corporate-level sustainability investments (41); sector-level environmental product declarations and certification initiatives; and governmental policymakers and regulators assessing the distribution of benefits and costs across geographies and markets.

To demonstrate the variability of environmental impacts within sector-, company-, and facility-specific supply chains—i.e., subnational commodity-flow information detailing the trade of goods throughout upstream supply chain stages—we estimated the greenhouse-gas emissions [i.e., global warming potential (GWP)] and irrigated (blue) water consumption (i.e., water use) of corn production for each county in the contiguous United States. Due to the significant overall contributions from the agricultural industry and, in particular, corn production, these impact categories are important environmental metrics for agricultural producers and consumers, and are among the few impact categories that corporations and nongovernmental organizations have set targets to manage.

Methods

We estimate US corn mobility—first as a primary commodity, then as an embedded input (e.g., upstream corn consumed in intermediate animal agriculture operations)—from on-field crop production through the supply chain to primary processing (e.g., animal slaughter). We separate the supply chain into two broad stages. Stage 1 encompasses the movement of corn from the county of production to the county of direct consumption, and includes the entire supply and demand of corn. Consumption includes corn processed into ethanol and distiller's dried grains with solubles (DDGS), consumed as animal feed (corn and DDGS), exported to international markets, and processed for other uses such as in wet mills. Stage 2 incorporates the movement of animals—with embedded corn from feed—from animal farms and feedlots to final processing facilities. These approaches are presented as an integrative Food System Supply-Chain Sustainability (FoodS^3) model (see www.foods3.org for more information). FoodS^3, as described below, includes a data accounting component, a spatially explicit environmental impact LCA, and a transportation optimization component. The data accounting component estimates the supply and demand of corn at the county level in stage 1, and the supply of animals on farms at the county level and the demand for animals for each individual processing facility in stage 2. The LCA component estimates the environmental impacts of corn production in each county. Last, the transportation optimization solves the system by connecting suppliers and demanders in stages 1 and 2. The result is a link between the processing facilities of animals and ethanol and the locations and environmental impacts of the corn supplied.

Corn Data Accounting.

Stage 1: US corn supply and demand. In stage 1 of FoodS^3, the supply of, and demand for, corn is estimated at the county level for years 2007 and 2012. The years were chosen based on the available data in the two most recent Census of Agriculture (COA) reports from the US Department of Agriculture (USDA) (42, 43). Given that the year 2012 is the most recent data available in the COA, the primary focus of our results is on that year. However, US corn yields in 2012 were substantially below the average of the last 10 y, so we also include an analysis of 2007 data to verify the magnitude of the difference in movement of corn in these 2 y. We show, in Fig. 1, that there is substantially similar interstate movement of corn between the 2 y, suggesting that even in a low-yield environment there are rigid aspects to supply chains. However, for the hardest-hit regions in 2012, the environmental impacts of corn production (on a per bushel basis) were substantially higher than other years. This does not represent a trend of increasing impacts over time; rather, higher yields in recent years suggest greater efficiencies that translate into improved per unit environmental performance. Our values are meant to represent spatial differences in impacts, which may change year to year.

To estimate US county-level supply and demand, we used a top-down approach, taking national accounts of corn supply and demand by category, and then allocating each category's national total to the county level. To ensure internal consistency between supply and demand, we used a single national dataset of corn production and consumption from the Economic Research Service (ERS) of the USDA (44). COA data were used to allocate total national corn production and demand for corn as animal feed to the county level, whereas corn demand for other key categories were allocated to the county level using data from the USDA Federal Grain Inspection Service for corn exports, and the Renewable Fuels Association for ethanol (45, 46). (*Stage 1: Corn Supply and Demand Data Accounting* describes in detail the supply and demand data accounting methodology.)

The animal feed market includes an important coproduct from the corn ethanol production process: DDGS. DDGS are a large component of many animals' diets, and are a key component in the corn supply chain. FoodS^3 incorporated DDGS as a separate set of supply and demand interactions in stage 1. We account for DDGS in terms of corn equivalents, or embedded corn, from corn ethanol production. A portion of the corn consumed in an ethanol facility is allocated to ethanol and the remaining to DDGS. Although several allocation methods exist, we used the relative energy content of ethanol and DDGS to allocate impacts. This is the method advocated for by the EPA under the Renewable Fuels Standard because both ethanol and DDGS are used for their energy in respective fuel and feed applications (47). The percentage of the total energy in the ethanol facility outputs contained in the DDGS is estimated to be 40.1%.

Stage 2: Embedded corn in animals. Stage 2 of FoodS^3 connects the embedded corn in the animals as feed—from consumption of corn and DDGS—to the facilities that provide primary processing of the animals. We restricted stage 2 of FoodS^3 to the three major animal protein sectors: beef, pork, and broiler chickens. Data for stage 2 account for the supply of animals on farms and feedlots to meet the demand for animals in processing facilities.

Environmental Impact LCA. By linking the movement of corn from regions of production to downstream animal processing facilities, it is possible to characterize spatially explicit environmental impacts of animal protein supply chains. Many environmental indicators could be evaluated with this methodology. We examine GHG emissions—as CO_2 equivalents (CO_2e)—and irrigated (blue) water consumption of corn production for each county in the continental United States, using a streamlined hotspot approach as an illustration of the method's application (48–50). Given the transaction orientation of a

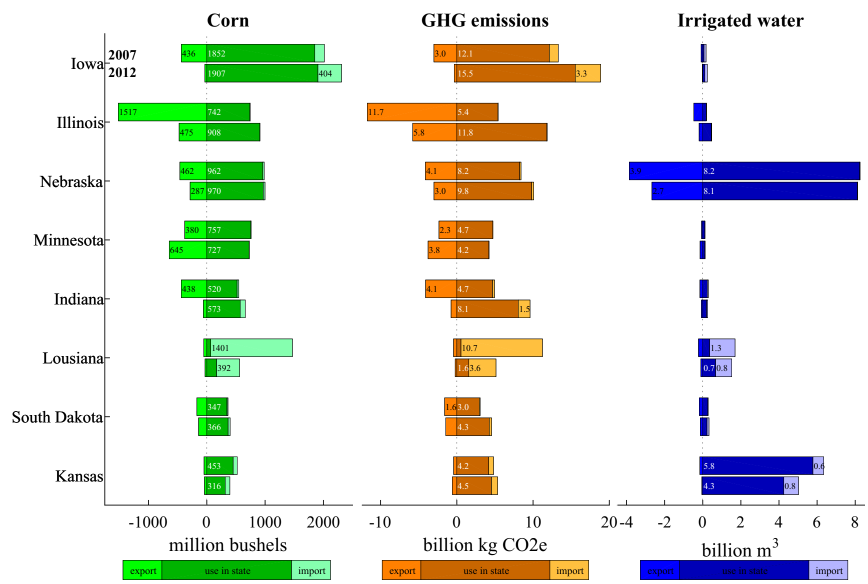

Fig. 1. State-level estimates of interstate corn trade, and consumption-based GHG and irrigated water use accounting. Note that negative values indicate exports (physical quantities and impacts) out of state. Upper bars for each state represent 2007 estimates, and lower bars represent 2012.

supply chain approach, the unit of analysis is the environmental impacts per bushel of corn produced and consumed.

GHG emissions. To represent total GHG emissions associated with the material and energy inputs and outputs of corn production, the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model was used (51). The GREET model represents US average corn production processes and impact factors, which are used to calculate the life cycle GHG emissions of producing a bushel of corn. A primary contributor, or hotspot, to the generation of corn production GHG emissions is the application of nitrogen fertilizer inputs, which accounts for more than 70% of total average corn GHGs, and includes the emissions associated with production and use of nitrogen fertilizers (51). Nitrogen fertilizer management practices also significantly fluctuate between locations in terms of application rates and types of nitrogen fertilizers applied. Due to the large share of total corn GHG emissions associated with nitrogen fertilizers, and spatial differences in fertilizer management practices, we replaced national average nitrogen inputs in the GREET model with inputs parameterized for each county based on the specific mix of nitrogen fertilizer types used and the state-level nitrogen fertilizer application rates per acre of corn planted.

Irrigated water use also exhibit large spatial variations. To account for the spatial variability in the GHG emissions associated with irrigation, we apply county-specific irrigation water quantities to the GREET electricity emission factor for irrigation. The GHG emissions from electricity used for irrigation are small, but in states with intensive irrigation, these emissions are a substantial fraction of the total. (*Environmental Impact LCA* has a detailed description of GHG emission estimate methodology, and Table S1 includes an emissions inventory.)

Blue water consumption. The agricultural industry is the largest user of water in the United States (52). Irrigation practices are the primary driver of anthropogenic water use decisions, and these vary by production location. To incorporate water use implications from corn production, we applied blue irrigation water use (i.e., water originating from surface and ground water sources) data from the Global Crop Water Model, which estimated water use for 1998–2002 at a scale of 0.5 degrees (53). We used 1998–2002 average county-level irrigated acres and county-level volume (m^3) to estimate average cubic meters of irrigated water used per acre. This rate was applied to the 2007 and 2012 irrigated corn acres obtained from the COA to estimate total water used to irrigate corn produced in each county.

Corn Mobility in the United States. Some corn moves a long distance, because local corn production cannot often meet local demand (54, 55). Despite the substantial availability of agricultural data in the United States, information associated with particular commodity mobility, including corn, at subnational levels is scarce (56, 57). To address this deficiency, we developed a two-stage spatial cost minimization model to estimate corn mobility. Specifically, stage 1 estimates county-level supply networks meeting primary corn demand (ethanol, animal feed, exports, etc.). Stage 2 estimates embedded corn mobility associated with animal transportation from counties of production to processing facilities. We model the optimal allocation in both stages 1 and 2 to minimize the system's transportation costs. Costs were based on existing transport lines, using railways and roads for corn movement and roads for animal movement. (*Corn Mobility Optimization Model* has a detailed description of the transportation model.)

To our knowledge, no publicly available data exist that report or estimate the movement of corn from county to county. At the state level, the Freight Analysis Framework Version 4 (FAF4) produced by Oak Ridge National Laboratory, has survey responses of the movement of animal feed from origin to destination (56). To validate the results of FoodS^3, we compare the combined quantity of corn and DDGS that we estimate are transported from state to state for use as animal feed to the survey results from FAF4 for 2012. The FAF4 data are an imperfect comparison with our model because it includes several additional categories of feed, which may explain some of the difference in the results. On average, corn and DDGS for animal feed travels 334 miles in FoodS^3, and all animal feeds travel, on average, 285 miles in the FAF4 survey. (*Stage 1: Corn Mobility from County of Production to County of Primary Demand* includes a comparison of state-to-state movement of animal feed between FoodS^3 and FAF4.)

Results

Environmental Indicators. Spatial variability associated with estimated GHG emissions and water use intensity of a bushel of corn produced across the United States in 2007 and 2012 is presented in Fig. 2. Our estimates reflect variability of key hotspot fertilization (for GHG emissions) and irrigation processes (for water use and GHG emissions) currently implemented across the US corn production system as well as spatial variation in corn yield outputs, which together drive the differences in intensity estimates. Results suggest that despite year-over-year changes in agricultural output, the underlying trends associated with production, consumption, and environmental consequences remained relatively stable between 2007 and 2012.

The substantial heterogeneity of corn production impacts is illustrated in Fig. 2 where, for example, GHG emissions associated with a bushel of corn produced in western South Dakota is estimated to be 3–4 times more carbon intensive than a similar bushel of corn produced in southern Minnesota (21 kg CO_2e per bushel vs. 6 kg CO_2e per bushel). Without estimating the subnational variation of environmental impacts, we would have only a single national estimate of GHG impacts for each bushel of corn of 9.9 kg CO_2e. In addition to spatial variation in GHG emissions, our results are also sensitive across growing years. For

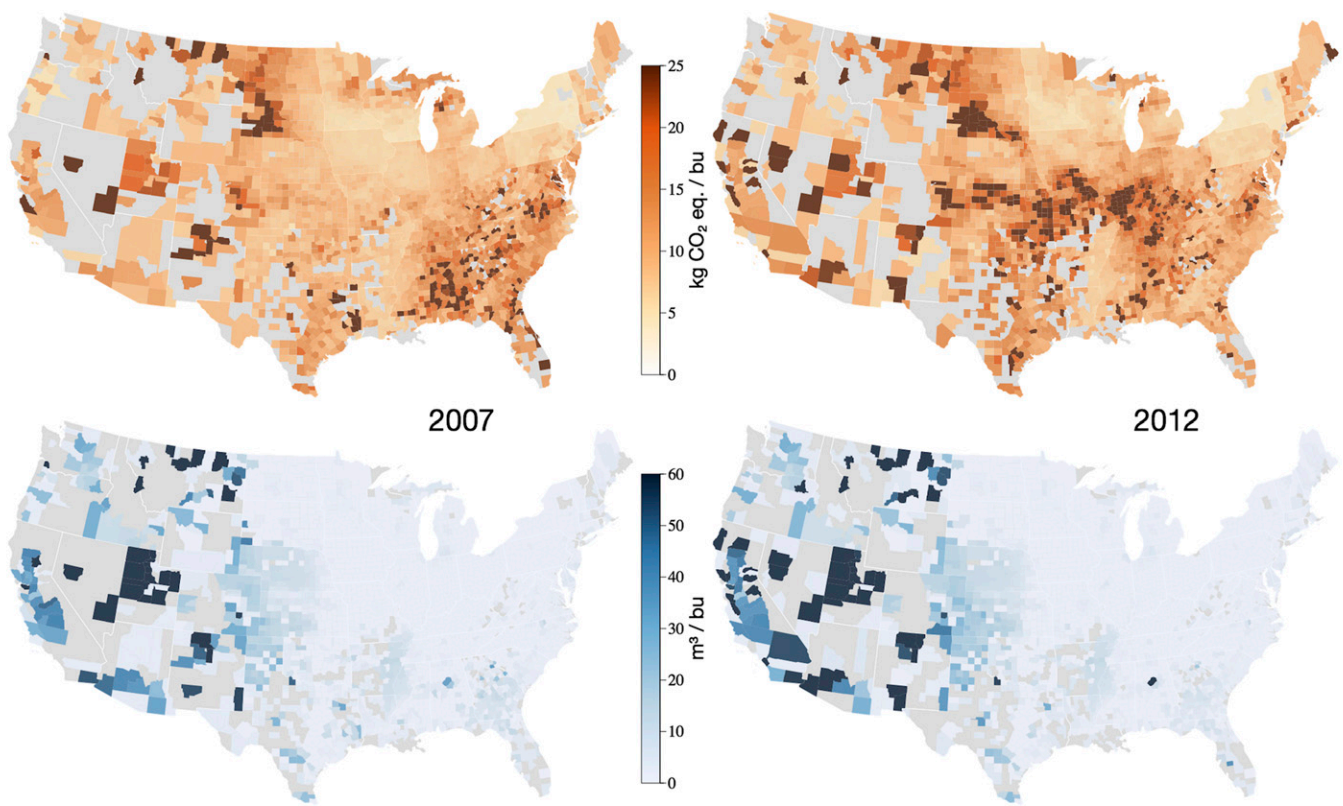

Fig. 2. Spatial and temporal variation of GHG emissions and irrigated (blue) water use intensity of US corn production.

example, drought conditions in 2012, most severely impacting the central region of the United States, are reflected in the high estimates of GHG emissions per bushel of corn produced in these regions. Compared with 2007, corn yields in Kansas, Missouri, Illinois, and Indiana, in particular, were significantly lower in 2012—~31%, 46%, 40%, and 36% lower, respectively. As such, the impact intensities of a bushel of corn produced in these areas were estimated to be significantly higher in 2012 because relatively fixed inputs (e.g., fertilizer application, farm equipment emissions, etc.) were allocated across fewer harvested bushels of corn—corn yields in 2012 were a significant outlier to the trend of increasing yields over time. The source of the spatial heterogeneity in GHG emissions per bushel is largely from the differences in yield, whereas the differences in nitrogen fertilizer type and application rate provide important, but less variability.

Irrigated water used in corn production also varied significantly across the United States. In 2012, 86% of US corn acres were not irrigated. The nonirrigating counties are largely in the Corn Belt and east into the Ohio River Valley. The largest users of water tend to be in the western plains region and the few corn producing counties in the West. Western Kansas and Nebraska tended to rely heavily on irrigation—as high as 28 m^3 per bushel—and Minnesota, Iowa, Illinois, and Indiana used very little irrigation—97.5% of corn acres in these states did not use irrigation. Our results of irrigation water intensity were much less sensitive to changes in yield from 2007 to 2012. This was largely due to the regions most impacted by the 2012 drought tending not to have irrigation equipment installed and being therefore unable to respond to the drought by irrigating their fields. GHG emissions associated with irrigation average 4% of total corn production emissions, with large variability between states. In Iowa, 0.1% of total emissions are related to irrigation, whereas in Nebraska and Kansas, irrigation emissions are 14% of the total, suggesting the potential for irrigation to be a hotspot in certain production locations.

Stage 1: Corn Mobility and Environmental Impacts. Results of our stage 1 corn mobility model are presented in Fig. 1 for years 2007 and 2012, showing the interstate transportation of corn and the associated environmental impacts. From a consumption-based environmental accounting perspective, each of the states illustrated played an important role in the US corn system, in that they produced or used substantial quantities of corn and/or high-intensity corn: Iowa is a dominant state in the corn system, producing and consuming largely nonirrigated corn; Illinois and Indiana are typically high CO_2e intensity producing states with significant exports; Nebraska is a high-producing, exporting state of irrigated corn; and Minnesota is a high-producing, exporting state of low CO_2e intensity, nonirrigated corn.

Iowa was the largest producing and consuming state in the United States—producing 1.9 billion bushels and importing another 400 million bushels from other states in 2012. Exports to other states from Iowa are estimated at less than 2% in 2012, but were nearly 19% of production in 2007, due to stronger relative production in 2007 and greater ethanol demand in 2012. Total GHG emissions associated with Iowa's production and imports were the highest in the country—19 billion kg CO_2e from the total quantity of corn consumed in the state in 2012—whereas irrigated water use was minimal at 0.2 billion m^3.

In contrast, Minnesota, Nebraska, and Illinois were major producers of corn, but their consumption is roughly half that of Iowa's, and their embedded CO_2e and irrigated water varied significantly. In 2007 and 2012, these three states exported 42% of their corn production, but growing conditions significantly shifted the share of exports across years—for example, Illinois exported 67% of production in 2007 and 34% in 2012. As a result, these three states also exported a significant share of their CO_2e impacts—18.2 and 12.6 billion kg in 2007 and 2012, respectively. Nebraska's corn production was water intensive, using 12.1 and 10.8 billion m^3 of water in 2007 and 2012—exporting 32% and 25% of irrigated

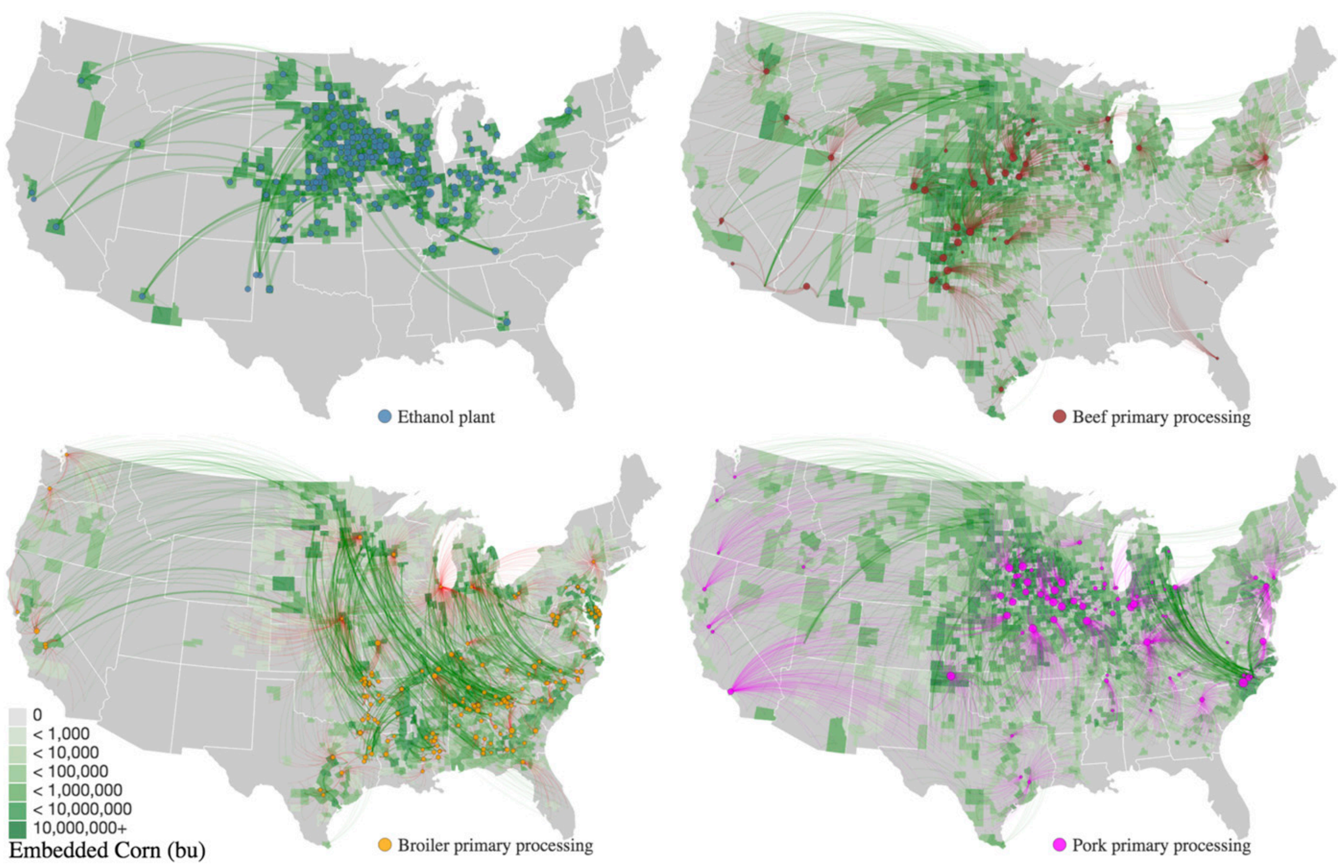

Fig. 3. The 2012 sector-level corn supply chain connections. Link between corn production and downstream demand: ethanol (stage 1 only) and animal protein processing facilities (embedded corn from stages 1 and 2). Dots represent the location and processing capacity of facilities in each sector. The shaded regions identify the location of quantity of corn sourced for each sector.

water use each year, respectively. Louisiana's large imports of corn across the United States were primarily for international export from the Port of South Louisiana.

Across the United States, we estimate that 75% of corn was consumed in the state of production for 2012, an increase from 63% in 2007. On average, corn traveled ∼220 miles from the county of production to the county of primary demand in 2012. Corn exported across state lines often traveled much greater distances—e.g., corn exports from North Dakota traveled 1,700 miles, on average. The distance corn traveled for imports varied substantially by state. Iowa's largest interstate trade partners are the neighboring corn-belt states of Illinois and Minnesota, and these imports traveled an average of only 44 miles. Imports to North Carolina, however, traveled over 900 miles, primarily from Michigan and Ohio.

Stage 2: Embedded Corn Mobility and Supply Chain Impacts. For stage 2 of the model we display the results only for the 2012 data environment. Fig. 3 illustrates the network of facilities associated with the key downstream sectors of ethanol production and animal protein processing. From each facility, the colored arcs display counties from which animals are estimated to be sourced, and green arcs depict where embedded corn is estimated to be sourced.

As commodities are produced farther from consumption, delivered prices increase, reflecting higher transport costs. In the optimization, minimizing transportation costs of corn, some corn will likely travel large distances—often shipped across the county—given the regional differences in corn production and demand. Regional differences in corn sourcing from the $FoodS^3$ model, presented in Fig. 3, reflect the structural spatial differences of corn supply and demand. Corn embedded in ethanol is relatively tightly sourced from the Midwest production regions, whereas beef supply chains tend to be more dependent on corn produced in the western plains of the United States. Broilers are thought to be more dependent on corn production from the Southeast, and pork's corn supply is dominated by Midwestern and north-central production.

Our $FoodS^3$ model estimates that corn for ethanol travels, on average, 90 miles from the farm to the facility, whereas corn for animal feed traveled much longer distances—corn for pigs, cattle, and broilers travels, on average, 160, 240, and over 500 miles, respectively. Minnesota, unintuitively, was the largest source of corn for broilers, despite producing less than 1% of US broilers, helping to explain the long distance corn traveled to meet broiler corn demand. Stage 2 of our model estimates the distance animals on farms or feedlots travels to processing facilities. We estimate broilers travel the shortest distance, 48 miles, on average, whereas pigs and cattle for beef travel ∼115 miles. These animal distances fall within the range of travel distances found in the literature. For small livestock operations (representing 40% of total US farms), the 25th to 75th percentile range for poultry (12–60 miles) and pigs (25–180 miles) encompass our modeled results (58). The 25th to 75th percentile range for cattle was below our average at 15–40 miles; however, another study of 21 large feedlots found that cattle travel an average of 434 miles (59).

Collectively, the four sectors examined account for the majority (59%) of 2012 corn used in the United States. After allocating the US corn embedded in DDGS, ethanol consumed 25%, pork consumed 12%, beef consumed 14%, and broilers

Table 1. Estimated 2012 corn supply chain CO_2e and irrigated water use for ethanol and animal protein sectors and large downstream companies

Corn consumers	Corn, million bushels	CO_2e, million kg	Irrigated water, million m^3	CO_2e, kg/bushel	Irrigated water, m^3/bushel
Sectors					
Ethanol	2,780	27,029	5,877	9.72	2.1
Beef	1,565	15,710	10,871	10.04	7.0
Pork	1,354	13,799	2,147	10.19	1.6
Broilers	854	8,240	2,076	9.65	2.4
Companies					
Tyson*,†,‡	907	8,498	3,379	9.4	3.7
JBS*,†,‡	686	6,551	3,156	9.6	4.6
Cargill*,†,§	534	6,197	3,061	11.6	5.7
ADM§	361	3,390	529	9.4	1.5
Smithfield†	352	3,593	459	10.2	1.3
POET§	327	3,504	79	10.7	0.2
Valero§	249	2,352	230	9.4	0.9
Green Plains§	202	1,929	711	9.6	3.5
National Beef*	178	1,848	2,085	10.4	11.7
Flint Hills§	153	1,232	208	8.1	1.4
Hormel†	121	1,038	144	8.6	1.2
US total	11,082	109,489	30,684	9.9	2.8

*Beef processor; †pork processor; ‡broiler processor; §produces ethanol.

consumed 8% of corn. CO_2e emissions and irrigation water embedded in the supply chains of these four sectors accounted for 59% of corn system emissions and 68% of corn system's use of irrigation water.

Table 1 provides a consumption-based accounting summary of GHG emissions and irrigation water use for each of the major downstream sectors examined. GHG emissions per bushel of corn consumed are highest for the pork industry, but differences across sectors are small. This suggests that the substantial variability in CO_2e emissions per bushel of corn grown across counties (illustrated in Fig. 2) tends to balance out when summarized at the sector level. Irrigated water use at the sector level, however, varies substantially. Corn for beef production is substantially more water-intensive than the other major sectors—four and a half times greater than corn for pork production. These differences are largely explained by beef sourcing nearly half its corn from the high-irrigating states of Nebraska, Kansas, and Texas, whereas pork sourced a majority of its corn from Iowa, Minnesota, and Illinois.

Table 1 also displays the environmental impacts of corn sourced by each company in the ethanol and animal protein sectors that consumed more than 100 million bushels of corn in 2012. Although results are based on commodity mobility simulations, and do not necessarily reflect actual sourcing locations and supply networks, the FoodS^3 model can help identify locations and the related environmental impacts that are more likely to be associated with company-specific supply chains based on the heuristic of minimizing economic costs.

The 11 largest corn-sourcing companies listed accounted for 37% of total US corn consumption in 2012. Compared with sector averages, GHG emission intensity of corn consumption across companies is substantial—ranging from as low as 8.1 kg CO_2e per bushel for Flint Hills (who, we estimate, obtained 72% of their corn from the low-impact, high-yield corn in Iowa) to as high as 11.6 kg CO_2e per bushel associated with Cargill's corn inputs (where all three animal protein sectors were included, with their highest GHG impact from Illinois- and Kansas-sourced corn).

Irrigated water use intensity also exhibited greater variability among the top companies. The least-irrigated corn was used in ethanol production. For example, corn estimated to be sourced by POET biorefineries consumed only 0.2 m^3 of irrigated water per bushel—91% below the national average. Our model estimated that the largest irrigation water user per bushel of corn was National Beef Packing, sourcing three quarters of their corn inputs from Kansas and Nebraska and consuming more than four times the irrigated water per bushel than the national average.

Discussion

The approaches and results provided make two primary and significant contributions to the environmental accounting and footprinting literatures. Using publicly available production and consumption data, we develop a unique cost-minimization approach to approximate subnational mobility of US corn from production to major primary and secondary consumptive activities. Although we make several simplifying assumptions (e.g., supply and demand balance annually, costs minimized are restricted to regional commodity price and transport, operational limitations such as transport congestion or organizational and regional preferences are ignored, etc.), the findings provide a reasonably robust approximation of spatial supply networks for a key commodity input of significant environmental impact to downstream fuel and animal protein sectors.

Across the 2 y examined (2007 and 2012), our results suggest that the structural relationships of supply networks across subregions may be rigid, despite significant variability between production years. We hypothesize that the physical and natural capital requirements of production–consumption systems and long-term investments in transportation and capital infrastructure serve to lock in subregional supply relationships, leading to relatively stable supply chains across time and geographies. Future research is needed to further explore the robustness of estimated supply network relationships over time and its impact on food and energy systems' ability to adapt to changing climate, water stresses, or market shocks.

By linking geographically heterogeneous indicators of environmental impact to commodity supply chain networks, we expand upon the largely country-level approaches of environmental LCA and consumption-based accounting to subnational product and organizational supply chain scales. Importantly, this work contributes to the growing call for greater transparency and accountability of sustainability performance across diverse product supply chains. Using a hotspot approach, we have focused on key processes significantly contributing to geographic variability in environmental impacts—namely, fertilizer type and application rates, and irrigation water use. In each case, estimates of spatial variability are rarely reported on a production output basis—a critical metric for the assessment of supply chain consumption-based accounting. Perhaps more important is how these embedded indicators are aggregated through the consumption of downstream ethanol and animal protein supply chain actors, providing the transparency necessary to begin managing these impacts. Although it is often reported that US ethanol and animal protein products contain significant volumes of embedded corn, and that corn inputs are major drivers of these products' emissions and water use profiles, our findings illustrate significant variability across these broad-brushed heuristics, depending upon the location of sourced corn (25, 27, 60).

As with many other commodity inputs, consumed corn is pulled through complex supply chains. For example, beef processed and packed in the Texas panhandle likely sources its cattle from east Texas and Oklahoma. Our model's results suggest that feed for cattle in these regions is most cost-effectively sourced from local farmers, but these same cattle producers will also likely purchase corn feed from as far away as Nebraska and South Dakota. In addition, these cattle will likely consume significant amounts of corn produced in Iowa and Minnesota, indirectly, in the form of DDGS. In contrast, the same beef product processed in eastern Nebraska may source, directly and indirectly, very little corn from Nebraska due to significant local competition for corn from other sectors (e.g., ethanol, pork, etc.). Instead, the supply networks for a Nebraska beef processor are much more dependent on cattle and feed from the Dakotas and Minnesota. Managing sustainability performance and regulating environmental burdens require a more sophisticated understanding of the sources and uses of high-impact commodities through supply networks.

These results shift the unit of analysis from geographic footprinting at regional or national scales to a spatially explicit consumptive-based metric for complex supply networks. Although consumption-based accounting methods have made significant contributions in the footprinting literature—attributing embedded impacts based on global country-to-country trade relationships—the approaches described in this paper attribute subnational consumptive impacts at a geographic scale more closely aligned with the heterogeneity of environmental impacts across landscapes. Future research is required to improve commodity mobility models, advance sustainability indicator measures, and develop marginal characterization factors to better assess shifts in field management or procurement decisions. However, this research takes an important step toward estimating supply chain environmental impacts of a key commodity input. Expanded to include additional heterogeneous inputs across a production system, it could potentially reduce the occurrence of wildly disparate LCA study results currently observed in the literature.

From a public policy and managerial perspective, the results presented in this paper are important spatially explicit estimates of environmental and economic performance for a major US commodity embedded in downstream consumption. The implications of these data are numerous because they provide supply chain managers with critical information for intervention strategies addressing upstream impacts important to the environmental performance of their products. These impacts are often identified in strategic and stakeholder-engaged "materiality assessments" as high-priority aspects of corporate sustainability planning; however, information and operational constraints identifying and targeting specific opportunities is difficult (61). The FoodS^3 model allows downstream firms to address sustainability performance of key input commodities through two broad strategies. First, our results can assist firm efforts to target interventions and collaborations. A growing number of large food manufacturing firms have recently made commitments to work with farmers to reduce the use of fertilizers, water use, and transport emissions. Our results help these companies and their partners—often environmental non-governmental organizations—identify where significant carbon and water risks occur within their supply chains and where efficient solutions might reside.

Second, downstream firms can use the FoodS^3 model to shift commodity sourcing strategies away from high-impact regions to lower-impact ones as a cost-effective way to improve their relative sustainability performance vis-à-vis competitors. It should be noted that this strategy may produce little or no environmental benefit to the overall corn production–consumption system in the short term. However, it does facilitate paths for future research to explore the economic effects of large-scale demand shifts away from high-impact cropping systems. Increased demand for corn from the most ecoefficient production regions may bolster prices, supporting increased investments in improved management practices (e.g., precision fertilizer application, drip irrigation, or the adoption of cover crops through financial or purchasing agreement mechanisms).

Although our model stops at processors who are mid-supply chain actors, it does allow decision-makers to aggregate consumption-based impacts across facility, business unit, enterprise, and geopolitical boundaries. This provides new information for public–private partnerships addressing environmental and economic development efforts. Specifically, results can assist companies and local policymakers when considering the closing or acquisition of production facilities. Incorporating indirect economic, CO_2e, and water impacts, policymakers may be able to leverage resources across multiple political jurisdictions in seeking to provide economic development incentives for new facilities in locations sourcing low-impact inputs. Similarly, far-reaching unintended consequences of aggressive economic development incentives currently made in areas of high-risk sourcing could potentially be avoided. Furthermore, the FoodS^3 modeling approach allows companies and local governments with aligning risk and opportunity profiles to explore innovative approaches toward improved ecoefficiency. For example, a large corn-producing state like Minnesota may find new opportunities to engage the broiler industry in developing conservation strategies, given that a large percentage of its corn production is used to feed broilers, even though very few broiler farms reside in that state.

Another important consideration for policy and decision-making is that our approach allows for improved environmental characterizations that link domestic and global production–consumption systems. The United States, along with central Europe and small portions of South America and Asia, are the only areas operating at close to 100% yield potential (62). Therefore, it may be that high-impact corn in the United States is low relative to other regions, and thus a decrease in US production of corn could lead to a global increase in impacts if corn production increases elsewhere.

Because the United States and world struggle to deal with environmental challenges, our model provides a starting point for reducing barriers to transparency within commodity supply chains. Our work improves upon the existing methods for consumption-based environmental footprinting and creates a new tool for decision-makers seeking to target interventions for environmental improvements within supply chains.

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