Environmental Research Letters

PAPER

Unique water scarcity footprints and water risks in US meat and ethanol supply chains identified via subnational commodity flows

Kate A Brauman 1, Andrew L Goodkind 2, Taegon Kim 1,3, Rylie E O Pelton 1, Jennifer Schmitt 1 and Timothy M Smith 1,3

1 Institute on the Environment, University of Minnesota, St. Paul, MN, United States of America
2 Department of Economics, University of New Mexico, Albuquerque, NM, United States of America
3 Department of Bioproducts and Biosystems Engineering, University of Minnesota, St. Paul, MN, United States of America

E-mail: kbrauman@umn.edu

Keywords: water sustainability, water scarcity, water footprint, embedded water, supply chain

Abstract

Within the US, supply chains aggregate agricultural production and associated environmental impacts in specific downstream products and companies. This is particularly important for meat and ethanol, which consume nearly half of global crop production as feed and feedstocks. However, lack of data has thus far limited the ability to trace inputs and impacts of commodity crops through domestic supply chains. For the first time, we use a commodity-flow model to link spatially distributed water resource impacts of corn and soy to individual meat and ethanol processing facilities. This creates transparency in the supply chains, illuminating substantial variation in embedded irrigation water and water scarcity footprints among meat and ethanol processed at different facilities. By calculating unique blue water scarcity footprints for end-products, we show that beef processed in Iowa or Illinois, for example, has fewer water impacts than chicken processed in California and pork processed in Oklahoma. We find that over 75% of irrigated feed embedded in meat is consolidated in six companies and 39% of irrigated feedstock for ethanol is consolidated in five companies, with potentially negative impacts to supply costs and risk management. This subnational variation and consolidation of impacts in key supply chains creates opportunities for producers and consumers of agriculture-based products to make management, investment, and sustainability decisions about those products.

1. Introduction

Agricultural production in the 21st century is both fundamental to human wellbeing and a major source of humanity’s global environmental impact, but the benefits and impacts of agriculture are unevenly distributed across the globe [1]. Aggregation of agricultural feed production into meat and ethanol, which encompass nearly half of global crop production, exacerbates the effects of uneven benefits and impacts [2]. The impacts of animal agriculture on climate and water quality have received considerable attention [3, 4], and there is growing interest in quantifying and managing the impacts of meat and ethanol on water use [5, 6], which we focus on here.

To address environmental impacts, manufacturers and marketers of agriculture-based products are increasingly called upon to produce their goods more sustainably [6, 7]. This requires them to evaluate their supply chains, where the vast majority of the environmental impacts of agricultural products occur [8, 9]. For water, studies have consistently found that more than 98% of the water footprint of meat is attributable to feed [10]. However, across the landscape there is substantial heterogeneity in environmental conditions and associated environmental impacts among farms at subnational scales [9, 11, 12]. The impacts of water use are particularly heterogeneous, as irrigated corn and soy used for feed is grown in regions across the world and within the US with vastly different irrigation demands [11] and facing strikingly different contexts of water scarcity [12]. Producers and consumers of agriculture-based products need to understand how this upstream heterogeneity in water...
impacts translates through supply chains in order to make management, investment, and sustainability decisions about those products.

While the need to link end products to spatially distributed environmental impacts through supply chains is widely accepted, existing tools for agriculture-based products have limited ability to do so at the subnational scale [9, 13]. Companies generally do not have information about locations from which the commodity crops in their supply chains are sourced, so they turn to tools such as life cycle analysis (LCA) and environmentally-extended input-output (EEIO) assessment [13]. However, LCA and EEIO databases usually contain only country level or broad regionalized data [14–17], particularly for commodity crop production [9], meaning their ability to account for within-country variation is limited. More importantly, these tools cannot account for subnational commodity flows [15, 17–19]. As a result, though many studies use high resolution data models to capture spatial heterogeneity of production [20, 21], opacity in subnational supply chain networks means it has not been possible to discern these heterogeneous impacts in end products [22].

Spatial or regionalized LCAs that translate heterogeneous production impacts through subnational commodity flows have become a significant focal point for research. However, without data characterizing subnational supply chains to trace the flow of commodity crops to end products, studies of the water impacts of meat and ethanol functionally omit the spatial heterogeneity of primary production [9, 23, 24]. Of the embedded or ‘virtual’ water studies of meat and ethanol that have emerged over the past decade, most are production-based estimates: embedded water in feed sources may be calculated at subnational scales with high resolution data, but with no mechanism to link feed production to feed demand, national average embedded water is assumed for each feed type, even when animal location, and thus feed demand, is spatially distributed, (e.g. [25]).

When subnational water footprints for the US have been calculated, they are limited by the assumption that feed is sourced from the same region in which animals are located [26] or limited to reported trade and EEIO data that aggregate into ‘food commodity groups’ or industries. Thus, these studies cannot address specific types of crops, livestock, or companies [24, 27, 28].

Aggregation limits the ability of any particular end producer (i.e. company) to manage upstream water impacts and for consumers to make informed purchasing decisions.

Here, we examine subnational, consumption-based blue water scarcity footprints of ethanol and beef, pork, and chicken, the top three most commonly consumed meats in the US, by modeling the subnational trade of feed and animals. For the first time, we link high resolution consumptive irrigation water use and water scarcity impacts of corn and soy in the US to downstream demand of individual animal and bioenergy processing facilities, and thereby to the largest meat processing and ethanol producing companies. This allows us to match spatial heterogeneity in embedded water and water shortage impacts of specific commodity crops to final agriculture-based products, overcoming the essential challenge of missing subnational trade data in water footprint and LCA studies and providing a key contribution to the water footprint and spatial LCA literature [5, 24, 29, 30]. Increasing supply-chain transparency benefits decision-makers throughout the value chain. Our results can help specific companies spatially target interventions within the US, while social actors and policy-makers can use this information to identify key stakeholders for policy reform and to allocate resources to address water scarcity. Transparency in industry and company-specific blue water scarcity footprints also empowers consumers to effectively alter their consumption behaviors.

2. Methods

Our findings are based on a spatial optimization model, the original version of which is described in detail in [19]. Briefly, this descriptive model uses linear optimization to match county-specific supply and county-specific demand of commodity crops and animals while minimizing transportation costs. Supply and demand totals are determined using publicly available data from the USDA, US Census of Agriculture (COA), industry reports, and company websites, representing the supply and demand landscape for the year 2012 [31]. The original model routed only corn; here we have added soy, enabling the model to estimate commodity flows for the two largest inputs to US animal production, corn (as kernels and DDGS) and soybean meal, as well as the largest input to ethanol, corn. We have also updated the optimization criteria, using county level impedance factors rather than rail-or-truck cost estimates. Additional details on the model structure and data are included in the Supplementary Material.

In addition to commodity flows, the model tracks embedded environmental impacts from the county of origin of the feed and feedstock to the processing facility. To assess the fate and impact of water extracted from lakes, rivers, and aquifers for irrigation, we consider irrigation water embedded in feed and downstream meat and ethanol products, sometimes called a virtual or blue water footprint [5]. Because nearly all of the water footprint of meat is attributable to feed [10], our analysis focuses on irrigated feed, omitting water consumption by forage, the direct drinking water of animals, and water used in feedlots or processing. In the updated model, we added irrigated water use of soy using county-specific values for irrigation water consumed for 2012 irrigated areas [21].
Figure 1. Embedded irrigation water varies among facilities within sectors. For each sector and feed type, irrigation water consumption is reported per kcal irrigated feed by facility (left axis, blue bars). For meat, embedded irrigation water is reported per kg meat by facility (right axis, red bars). Boxplot shows the distribution of irrigation water intensity across facilities, weighted by the kcal of feed energy consumed at each facility; the median (black line), mean (black dot), 25th and 75th percentile (top and bottom of box), 10th and 90th percentile (top and bottom of vertical lines) and outliers (x) are shown. Percentages in parenthesis on feed labels indicate the share of feed that is irrigated.

In the US, the beef, pork, and chicken blue water footprint represents, on average, 4%, 14%, and 10%, respectively, of their total water footprint, which includes water consumption from both irrigated and rainfed feed; for corn and soy, irrigation water accounts for, on average, 11% and 6% of the total water footprint \[32\]. While irrigation water represents a fraction of total water consumption, we focus on it here because it represents an important intervention lever for reducing water shortage impacts, tying directly to changes in crop management practices. To evaluate the water impact potential, we added county water shortage status—chronically water short, seasonally water short, water short in dry-years, or not water short—to the model. We based the status on the category that the majority of each county area falls into. Water shortage categories are from Brauman \textit{et al} (2016), which assessed water shortage as the 30-year ratio of monthly water consumption to renewable freshwater availability in watersheds of approximately 1000 km\(^2\).

This analysis focuses on the US because of its importance in the global production system—approximately 1/3 of global corn and soy production occurs in the US \[33\], where 75% of corn and 52% of soy goes to domestic meat and ethanol production \[34\]. In the US, agriculture accounts for 80%–90% of the nation’s total consumptive irrigation water use, with the majority due to irrigated crop acres destined for livestock or biofuel feedstuffs and feedstocks \[12\]. Our analysis addresses what we believe to be all corn ethanol producers and all beef, pork, and chicken broiler producers in the US as of 2012 \[35\].

3. Results

Our results align with previous analyses \([10, 25, 36, 37];\) see comparison in figure S1 (available online at stacks.iop.org/ERL/15/105018/mmedia)) showing that, on average, beef carries far more embedded irrigation water than do other types of meat (figure 1: black dots in red bars). More strikingly, however, our analysis shows that the variation in embedded irrigation water among facilities is often greater than the variation between animal types (figure 1: red bars). We find that 25% of beef has less embedded irrigation water than the highest 10% of chicken, and 43% of beef has less embedded irrigation water than the highest 10% of pork. Of particular
Figure 2. Spatial clustering of facilities and their source regions for irrigated feed drives the water intensity and water shortage risks for meat and ethanol. Circles represent the volume of irrigated water embedded in feed originating in each US county. Circle color reflects the water shortage status of the majority of watersheds in that county. Locations of primary processing facilities are marked with a black triangle.

Note, individual facilities producing meat and ethanol with very high embedded irrigation water have a disproportionate impact on sector-wide irrigation water consumption.

Variation in irrigation water embedded in meat stems from three main sources: feed-to-animal conversion ratios (i.e. feed-conversion efficiency), feed composition (in this analysis: corn, soy, and dried distillers grains with solubles (DDGS)), and feed source [10]. When comparing across industrialized production systems, differences in embedded water between animal types are generally attributed to differences in feed-to-animal conversion efficiency [10]. However, our analysis shows variation among facilities within each animal-type, illustrating that conversion efficiency is not the sole or even driving factor. Regarding feed composition, another source of variation in embedded irrigation water, corn makes up 50% or more of US beef, pork, and chicken diets [38]. Soy-meal and DDGS are also ubiquitous in these diets. As a result, at the national average level, aggregated across an entire year, there are minimal differences in the mix of these three feed types within meat sectors (figure S2). We do account for slight regional variations in our feed composition among animals across the US (see [20] and Methods), but when looking at national average data across animal species, feed composition plays a limited role in explaining the variation we find in embedded irrigation water. What we do find is that the water footprint of the feed that animals consume is not the same: the mean irrigation water intensity of any particular feed-type is higher for beef than pork or chicken, and a higher share of beef feed is irrigated (figure 1: blue bars). This is attributable to the location of feed lots and processing facilities, which is related to where they source their feed (figure 2). Decomposition analysis of our model output attributes approximately three-quarters of the national sectoral-mean variation in irrigation water embedded in US meat to feed source (table S1).

Spatial clustering of processing facilities for each sector leads to strong trends in both the irrigation intensity of feedstocks and in the water shortage status of source regions (figure 2). For historical and logistical reasons, processing facilities exhibit clustering based on animal type, with ethanol and pork near the agricultural ‘heartland’ of the Midwest, beef near grazing lands, and chicken located in the Southeast [39]. Beef facilities are distributed widely across the US and so have a wide distribution of blue water scarcity footprints, but the facility cluster over the high plains aquifer leads to substantial sourcing from areas experiencing water shortage. The share of feed for beef that is irrigated is several times higher than the other sectors, and beef obtains 96% of its irrigated feed from regions facing water shortage of some kind.
Figure 3. Processing facilities using more irrigated feed are likely to obtain that feed from water short regions. For each primary processing facility, the figure displays the percentage of all kcal of feed coming from irrigated sources (x-axis) compared to the irrigation water intensity of the irrigated feed (y-axis). Each bubble represents one facility, bubble size indicates feed quantity consumed, and bubble color indicates the water shortage status of the largest share of irrigated feed used by that facility. Dotted lines indicate production-weighted mean values.

Chicken, by contrast, eat feed sourced from areas with a low irrigated fraction, and only 50% of their irrigated feed originates from places affected by water shortage. Chicken facilities are strongly clustered and have limited overlap with other sectors; even chicken facilities have a diversity of feed sources, however, and the irrigation water intensity of soymeal for chicken feed has the widest range of any feed input in our study. Of the small fraction of feed for pork that is irrigated, 81% originates in regions experiencing some type of water shortage. The cluster of pork facilities overlaps with ethanol facilities. Sector-wide, ethanol consumes more feedstock than any individual meat type, but because ethanol facilities are located near, and primarily source from (84%), rain-fed corn, beef carries more than double the total embedded irrigation water as ethanol (figure S2). However, of the 16% of feedstock for ethanol that is irrigated, 80% originates from regions experiencing water shortage.

Despite the spatial clustering of primary processing facilities, irrigation intensity of feed and feedstocks are not a strong predictor of the water-shortage status of the source region (figure 3). When irrigated feed makes up a large fraction of total feed, feed is likely to originate from water-short regions. However, feed with high irrigation intensity is estimated to be sourced from regions across the water shortage spectrum. Additionally, many facilities for ethanol and all meat sectors source feed from areas of low irrigation intensity that do not face water shortage.

The water impact of meat and ethanol processed and packaged in different places across the country thus varies dramatically. For example, we find that chicken processed in California (raised primarily in California, with feed grown mainly in Nebraska) and pork processed in Oklahoma (raised primarily in Oklahoma and Kansas, with feed grown mainly in Kansas and Colorado) hold more severe water
consequences than beef processed in Iowa or Illinois, where feed is largely rainfed.

A substantial share of irrigation water consumption by meat and ethanol production in the US is consolidated within just nine companies, with 78% of irrigated feed for meat consolidated in six companies and 39% of irrigated feedstock for ethanol consolidated in five companies (figure 4). Though our model indicates that no company other than National Beef has more than a third of its feed supported by irrigation, all companies face some degree of supply chain risk to their irrigated feed. For example, JBS (77%), Cargill (87%), Tyson (66%), National Beef (91%), and Smithfield (71%) all have large shares of their irrigated feed sourced from places facing chronic or seasonal water shortage (figure 4: red and orange portion of bar).

4. Discussion

Our study extends efforts to increase spatial heterogeneity in embedded irrigation water and water scarcity footprint studies [5, 23, 28, 30]. Previous studies have found substantial variation in water consumption and scarcity impacts for meat products at the global scale, such that, for example, the water footprint of chicken produced in some countries is higher than that of beef from other countries [9, 10]. We find that variation of this same magnitude exists subnationally due to unique supply chain configurations, and this has important implications for sustainable management for both consumers and companies.

For consumers who wish to make purchasing decisions based on environmental impacts, information about the variation in water scarcity footprints provides a foundation to adjust the type and provenance of meat they consume, thus decreasing the water impact of their consumption [13, 40]. In turn, consumer actions can and do affect decision making in agribusiness, especially when specific companies that could manage interventions are identified [41]. Companies are increasingly asked to incorporate environmental impacts into corporate operations and
supply chain activities not only by consumers but by investors, policy-makers, and social actors [42]. Some evidence suggests that smaller firms are more easily influenced by stakeholders, but there is also evidence that large companies like the ones highlighted here are more likely to engage in sustainability actions [43]. For all actors, environmental degradation, especially water shortage, presents the food system with material risk. This risk causes strain through contracting supplies, increased transportation costs, and increased commodity prices. The relatively static nature of supply chains and the localized nature of water shortages cause these risks to consolidate more heavily for some companies.

Water shortage is a highly localized problem, and transition costs of interventions like changing irrigation technologies or changing crops are often costly for farmers operating on the margin and have not always been shown to reduce water stress [44]. By linking regions of production where interventions are most necessary with end products, our model provides companies and industries with greater capacity to influence production practices. With these connections, they can target expertise, implement sourcing incentives, and offer cost sharing initiatives to mitigate environmental risks. Such actions will help increase their own resilience as well as resilience of the overall food system to future environmental risks, such as drought. For a further discussion of tools to help mitigate on-farm risks, see [42].

Because the food and biofuel companies highlighted in our findings have consolidated water risk within their supply chains, they have both the incentive and the potential ability to act [42]. Companies sourcing from regions currently experiencing seasonal or dry-year water shortage can anticipate growing competition for water, particularly as the climate changes, with potential impacts to supply costs and reliability [12]. While commoditization, which allows interchangeability among sources [45], allows firms to reduce some risk by substituting feed sources in the face of, for example, drought, shocks to supply are often accompanied by increased costs that lead to additional operational risk. Further, as consumer, investor, and policy-maker demand for accountability increases [6, 45], reputational risk to the firm from local environmental impacts such as water shortage grows [42]. Meat and ethanol industries have been targeted for their contributions to greenhouse gas emissions and water quality [3, 4], and companies could face increased reputational risk if they are perceived to be sourcing from regions facing water shortage.

Connecting farms, where environmental impacts and efforts to mitigate them take place, and the consumer-facing companies (i.e. intermediate demand) and consumers (i.e. final demand) that are increasingly prioritizing sustainable production is a key goal for both researchers and companies [13, 17–19]. However, this is hindered by the lack of subnational trade data [17, 22] and supplier transparency [13, 42], except when there is vertical integration or contract farming, a challenge nearly always noted in the studies themselves [9]. To connect to downstream intermediate and end-products, most studies average upstream environmental impacts [22], constraining discussions about direct and indirect water footprints and impacts of meat and ethanol to the sector level [13, 32].

We use a subnational trade model to overcome the challenge of linking the substantial subnational spatial heterogeneity of production-based environmental impacts to downstream demand, allowing us to illuminate the unique aggregation of primary production in downstream agricultural-product supply chains and attribute upstream impacts to specific products and companies. Our model was created to address data gaps about the subnational flow of commodity crops. As a result, validation is difficult, though our findings compare well to other studies ([18, 19, 46]; see Supplementary Methods for discussion). In addition, our work underscores the need for actual commodity flow data, and we hope to spur the creation of supply chain structures and initiatives to integrate traceability into supply chains such as supplier reporting or block chain technologies.

Acknowledgments

This work was supported by the University of Minnesota Institute on the Environment

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Additional data visualization is available at http://foods3.org

ORCID iDs

Kate A Brauman https://orcid.org/0000-0002-8099-285X
Taegon Kim https://orcid.org/0000-0002-7931-6627
Rylie E O Pelton https://orcid.org/0000-0002-6015-2263

References

[1] Foley J A et al 2011 Solutions for a cultivated planet Nature 478 337–42
[2] Cassidy E S, West P G, Gerber J S and Foley J A 2013 Redefining agricultural yields: from tonnes to people nourished per hectare Environ. Res. Lett. 8 034015
