LETTER

Land use leverage points to reduce GHG emissions in U.S. agricultural supply chains

Rylie E O Pelton 1, Seth A Spawn-Lee 2,3, Tyler J Lark 3, Taegon Kim 4, Nathaniel Springer 1, Peter Hawthorne 1, Deepak K Ray 1 and Jennifer Schmitt 1

1 Institute on the Environment, University of Minnesota-Twin Cities, St. Paul, MN, United States of America
2 Department of Geography, University of Wisconsin-Madison, Madison, WI, United States of America
3 Nelson Institute Center for Sustainability and the Global Environment, University of Wisconsin-Madison, Madison, WI, United States of America
4 Department of Smart Farm, Jeonbuk National University, Jeonju-si, Jeollabuk-do, Republic of Korea

E-mail: ryliepelton@umn.edu

Keywords: life cycle assessment, carbon footprint, land use change, GHG mitigation, food system sustainability, supply chain sustainability

Supplementary material for this article is available online

Abstract

Recognizing the substantial threats climate change poses to agricultural supply chains, companies around the world are committing to reducing greenhouse gas (GHG) emissions. Recent modeling advances have increased the transparency of meat and ethanol industry supply chains, where conventional production practices and associated environmental impacts have been characterized and linked to downstream points of demand. Yet, to date, information and efforts have neglected both the spatial variability of production impacts and land use changes (LUCs) across highly heterogeneous agricultural landscapes. Developing effective mitigation programs and policies requires understanding these spatially-explicit hotspots for targeting GHG mitigation efforts and the links to downstream supply chain actors. Here we integrate, for the first time, spatial estimates of county-scale production practices and observations of direct LUC into company and industry-specific supply chains of beef, pork, chicken, ethanol, soy oil and wheat flour in the U.S., thereby conceptually changing our understanding of the sources, magnitudes and influencers of agricultural GHG emissions. We find that accounting for LUC can increase estimated feedstock emissions per unit of production by a factor of 2- to 5-times that of traditionally used estimates. Substantial variation across companies, sectors, and production regions reveal key opportunities to improve GHG footprints by reducing land conversion within their supply chains.

1. Introduction

In response to growing public concern and the substantial threats posed by climate change, companies around the world have pledged to reduce greenhouse gas (GHG) emissions in their supply chains [1]. As a socio-ecological enterprise responsible for nearly 28% of annual GHG emissions, agriculture is a sector that is both vulnerable to and responsible for climate change impacts [2–4]. Agricultural activities now cover nearly half of the world’s ice and desert free land [2] and will likely expand further to meet projected growth in demand for food throughout the 21st century [4–6]. Furthermore, production will likely intensify on current croplands via increased fertilizer and irrigation application [4–6]. These changes will collectively increase the GHG footprint of a sector that is simultaneously vulnerable to its own effects.

Given the important relationship between climate change and agriculture, efforts to mitigate emissions from agriculture in supply networks (from crop production to final product) have become a key area of focus for companies [1, 7]. Yet, to date, identifying which mitigation interventions are effective and where to prioritize the implementation of these interventions has been a challenge [8, 9].

The U.S. is one of six countries responsible for producing the majority of global agriculture’s environmental impacts and may therein serve as a key staging ground for mitigation efforts [9, 10]. Broad-scale analyses indicate irrigation consumption, excess nitrogen and N2O emissions are important leverage
points in the U.S. for reducing impacts [9]. However, the aggregate nature of these estimates at the country-scale masks the heterogeneity of impacts and mitigation opportunities at the subnational levels necessary for informing actionable and effective interventions across supply chains.

Recent modeling advances have increased the transparency of U.S. meat and ethanol industry supply chains, revealing the interconnected geographies of these sectors and initial estimates of associated environmental impacts. By spatially characterizing production practices and their environmental impacts, these studies further enable the ability to link landscape-level management changes to downstream points of demand [11–13]. These advances may, in turn, uncover new, more precise opportunities for emissions reductions.

Yet, despite these advances, the spatially varied effects of land use changes (LUCs)—a substantial source of agriculture’s GHG emissions [2, 14], have thus far been neglected. Moreover, the relative amount of LUC tied to a given supply chain likely varies by company and sector due to the spatial differences in sourcing regions and sectoral clustering [11, 13]. LUC emissions are also rarely considered in national GHG emission factors of meat production [15–17] which potentially veils the role that livestock may play in the expansion of croplands.

Recent assessments of U.S. LUC show that agricultural cropland area increased by a net 300–500 thousand hectares per year between 2008 and 2016 [18], driven at least in part by increased corn demand for ethanol and livestock feed [19, 20]. In fact, across all types of LUC in the U.S. between 2008 and 2016, 1.2, 1.1, and 0.92 million hectares of non-cropland was converted directly to corn, soybean, and wheat production, respectively [18]. Combining an earlier version of these high-resolution LUC maps with high-resolution carbon stock data, Spawn et al [21] estimated that just corn, soy and wheat expansion is collectively responsible for 85% of GHG emissions from all cropland expansion, with corn contributing the majority of aggregate emissions over the timespan [21].

Here we build on these recent advances by linking observed field-specific LUC and associated emissions to high-resolution (county-to-county and county-to-facility) commodity flow supply chain and spatial life cycle assessment (LCA) models to compare LUC emissions to life cycle emissions from all management aspects of corn, soy, and wheat production (e.g. fertilizers, irrigation, energy use, N₂O emissions). In doing so, we provide first-ever estimates of company-level and industry specific GHG emissions that incorporate the effects of LUC across corn, soy and wheat consumed in beef, pork, chicken, ethanol, soy oil, and wheat flour industry supply chains. These findings reveal potential risks to supply chains and leverage points for targeted GHG intervention.

2. Methods

2.1. Commodity flows

To connect impacts from LUC and production to downstream products and actors, we build on a supply chain optimization model initially developed in Smith et al [11] and further updated by Brauman et al [13] to connect subnational feed supplies to subnational points of demand throughout the value chain. The model, known as the Food System Supply-chain Sustainability (FoodS²) model, performs a least cost optimization that uses transportation impedance factors [22] between counties as a robust proxy of costs for transporting commodities between origin-destination county pairs. These impedance factors account for time delays, tolls, road restrictions, etc. that cause logistical impedances in transporting goods between locations [22]. The previous FoodS² model captures all county annual supplies of corn, soy and annual livestock populations in the contiguous U.S. (including domestic production, imports, and existing stocks), and all county and facility sources of demand for corn and soy-based feed and livestock, across all sectors of demand (including all domestic consumption, exports, and ending stocks) for 2012. Here, we update the FoodS² model to represent the most recent 2017 census year’s supply and demand quantities and changes to company/production facility capacities (see table S1(b) available online at stacks.iop.org/ERL/16/115002/mmedia). We also expand the model to include estimates of winter, spring and durum wheat supply chains, where county annual wheat supplies are directly and indirectly (through wheat middlings, a co-product of wheat milling) fed to livestock. The model thereby lends greater transparency into crop and livestock supply networks by overcoming the major data limitation that subnational trade data does not exist for individual commodities [11, 23]. The model outputs therefore provide critical information on multiple supply chain links between (a) counties producing/supplying corn, soy and wheat to counties using the crop commodities directly for livestock feed (e.g. across fed beef cattle, hog and broiler chicken operations), (b) counties producing/supplying corn to ethanol facilities, soy to crushing facilities, and wheat to four milling facilities (c) ethanol facilities, soybean crushing facilities, and flour milling facilities supplying DDGS, soybean meal, and wheat middling co-products, respectively to counties using the products for feeding livestock, and (d) counties supplying livestock to facilities that process the livestock for meat and non-meat co-products.
Because commodity price differences are driven largely by logistics costs, this model has provided results consistent with findings from the Freight Analysis Framework version 4 (FAF4) survey data [11–13, 23], and other studies using such data for supply network modeling [23]. While the FAF4 data provides insights into the subnational trade networks of commodity groups between broader trade regions within the U.S. (i.e. groups that contain multiple commodities, such as ‘live animals/fish’ and ‘cereal grains’), it cannot be used to understand individual commodity-level differences and specific actors in the supply chain, which are together important for identifying where specific leverage points may be for reducing impacts of supply network operations.

2.2. Spatial life cycle analysis (LCA)

In addition to the FoodS³ commodity flow supply chain optimization model, FoodS³ also contains information on the underlying impacts of crop production determined through LCA models, that together enable FoodS³ to link these production-based impacts geospatially to downstream sources of demand [11, 13]. While these initial underlying spatial LCA models are able to capture some spatial heterogeneity by accounting for county-level differences in corn and soy yield, water consumption, and in the case of corn, types of nitrogen fertilizers used (with state-level application rates), more recent efforts have further increased county-level granularity of the heterogeneity of the impacts. Pelton [24] for example, builds on these initial efforts of Smith et al [11] and improves county-level corn GHG emission estimates by considering not only long-term expectations of yield differences, but also county-scale fertilizer application rates (in addition to type of fertilizer), N₂O direct and indirect emissions rates (kgN₂O-N/kgN applied), and energy emissions from irrigation considering water consumption quantity, method of irrigation application, energy source for irrigation, water source for irrigation, and grid source for powered irrigation systems [11, 24].

We expand this work by applying these initial methods to estimate spatialized production-based GHG emissions for soy and wheat, and update previous corn estimates to account for changes to county average yields (2007–2017), changes in electricity grid mixes, and changes in average soil textures that corn is grown on, thereby updating N₂O emission rates. We further build on these estimates to additionally consider N₂O from cropland manure application (with variability in county-scale application rates), county-scale CO₂ emissions from urea application, emission from fuel use from machinery used on farm (e.g. for planting, harvesting, tillage, fertilizer and pesticide application) based on county variability in tillage practices, and changes to N₂O emission rates based on current county level penetration of no tillage, N inhibitor use, differences in residue management and use of cover crops (see section 2.3 in SI part b for details). On average, about 85%, 72%, and 89%–92% of the cradle-to-farm gate life cycle GHG emissions of corn, soy, and wheat (across winter, spring and durum varieties) are spatially explicit, with substantial variation across counties (see figures S12(a) and S1(b)). The remaining portion of average emissions (driven primarily by emissions from lime application) are captured using national average emission factors (see section 2.7 in the SI part b for details). Resulting county variation in production-based GHG emissions are shown in figure S13(a).

While the Pelton [24] study is powerful for understanding the drivers of impacts for corn production at subnational levels, it, like many other comparable agricultural LCAs, neglects the potentially large GHG emissions associated with the quantity of land recently converted to cropland, known as LUC emissions. For such information, we turn to Lark et al [18], which provides information on the total acres of land converted based on recommended best practices for measuring LUC using field-level crop data from the USDA [25, 26]. We subsequently estimated the carbon emissions associated with land conversion at a 30 m × 30 m resolution for each year between 2008 and 2016 using the C emissions model of Spawn et al [21]. Estimated carbon emissions are based on the committed carbon concept which attributes the total amount of carbon that would be oxidized and released over time by LUC to the year in which the LUC occurred. This avoids life cycle accounting issues of needing to track annually released carbon from past LUC, and helps illuminate the long-term effects of halting LUC on reducing GHG emissions by reflecting the total amount of emissions that would have been released over time, based on the historical long-term average amount of land annually converted to cropland that could be avoided through broad-scale purchasing policies avoiding crops produced on lands recently converted. This model improves the spatial differentiation of LUC impacts by spatially estimating emissions for precise areas of observed LUC rather than applying average emission factors to aggregated acreage statistics. In doing so, it represents an explicit estimate of direct LUC and thereby avoids issues associated with methods that aggregate emissions across large regions like the Global Trade Analysis Project dependent Carbon Calculator for Land Use Change from Biofuels Production model [27]. We build on these estimates by accounting not only for the carbon released, but also for the additional direct and indirect N₂O released from N mineralization resulting from land conversion (see SI part b section 2.8 for details).
In order to append the production-based emission factors to the LUC data, we first need to normalize LUC estimates. To do so, we first aggregate the raster level committed carbon emissions and extent of land conversion from annual LUCs across years by finding the county weighted average from raster cells overlaid with county boundaries. We averaged across years in order to capture average annual conversion trends to minimize the influence of any one year's rate of conversion. These county total LUC estimates are then normalized by the average annual total quantity of corn, soy, winter, spring and durum wheat produced, respectively, over the 2007–2017 time period as determined from the USDA census to give LUC emission factors (e.g. kg CO₂ e kg grain) and conversion intensity (e.g. ha kg⁻¹ grain) estimates for each corn, soy and wheat growing county over the study period (figures S14(a)–S16(a)). For counties that grew crops in some years and not others, we normalized over the years in which crops were produced. Finally, we constrain all estimates to the 99th percentile in order to reduce the potential for outliers, which affect 0.7%, 1.8%, 0.04%, 0.01%, 8% of the corn, soy, and winter, spring and durum wheat growing counties, respectively. While we account for the imported commodity flows, we examine and present the impacts of only domestic production, leaving the potential to examine embedded production and LUC emissions from U.S. imported commodity feed and feedstock supplies for future research.

While emissions from corn and wheat production and LUC are entirely attributed to the downstream livestock sectors that directly consume the feed, the emissions going to ethanol and DDGS, soybean oil and soymeal, and wheat flour and middlings, respectively are instead split between the co-products based on the relative energy output per unit of crop input. This energy allocation was chosen due to the end-use of the co-products; food-grade and feed-grade co-products (DDGs, soybean oil, flour and middlings) are used for caloric energy, and ethanol is used for fuel energy. This method of energy allocation attributes approximately 41%, 63%, and 30% of the impacts, respectively of corn, soy, and wheat grain production, LUC, and intermediate processing to DDGS, soymeal and wheat middling outputs, which is later attributed to downstream livestock sectors that use the co-products as feed, with the remaining portion of emissions attributed to ethanol, soybean oil, and wheat flour outputs, respectively. In addition, because of the tendency for wheat straw to be harvested in addition to wheat grains, we initially attribute a portion of the production and LUC emissions to straw based on the degree of utilization and relative mass, resulting in a straw allocation factor of 28%.

We incorporate these updated estimates of corn, soy and wheat production-based GHG emissions and LUC emissions into the FoodS₂ model, enabling updated outputs linking high resolution production impacts to downstream sectors, including protein, ethanol, soy and flour processors.

3. Results

3.1. Geographies of LUC in corn, soy and wheat supply chains

Between 2008 and 2016, we find that corn, soybeans, and wheat were planted either as the first break-out crop or in rotation on 63%, 57%, and 50% of newly converted croplands, respectively. Using our estimated annual average expansion per kg of grain produced, we find that in 2017, soybean expansion contributed greatest to the total hectares of expansion across the three crop types, at almost 185 000 ha of LUC, followed by corn expansion at around 172 000 ha, and wheat expansion at 45 000 ha (figure S1(a), tables S1(a)–S3(a)). The geographies of LUC embedded in each demand sector vary, for corn and soy, LUC in beef production are predominantly through the Great Plains and upper Midwest, the Midwest for ethanol, soy oil, chicken and pork, and the Eastern U.S. for soy embedded in chicken and pork supply chains (figure 1). LUC from wheat expansion is predominantly in the Northern Great Plains and Western U.S., primarily associated with flour and pork production.

Of the LUC emissions associated with new corn, soy and wheat-growing croplands, 56%, 33%, and 44% respectively are attributed to domestic use by the four major use sectors of (a) beef (through feedlot cattle), (b) pork, (c) chicken (broiler), and (d) crop-specific processing of corn ethanol, soy oil and wheat flour supply chains. These four sectors (respective to each crop type, refer to the columns in figure 1) collectively accounted for 55%, 33%, and 46% of all corn, soybean and wheat demanded in the U.S. in 2017. Including the large quantities of crop and derivative feed products exported in 2017 (at about 21%, 57%, 47% of the total demand, respectively), which will ultimately be destined for similar livestock and processing demand sectors outside the U.S., these sectors together are associated with 72%, 92% and 91% of the average annual corn, soy and wheat cropland expansion (table 1).

The U.S. ethanol and chicken meat industries are linked with the largest overall quantity of direct LUC from corn cropland expansion (table 1; table S1(a)), with 26 000–30 000 ha of annual LUC and 15%–17% of the total annual expansion of corn cropland. However, on a per unit of corn grain basis, the ethanol industry has relatively low land conversion and LUC emissions intensities (ha kg and kgCO₂ e kg) compared to the average across all sectors of demand (table S1(a)), whereas the broiler industry has relatively high amounts of direct conversion and LUC emissions per unit of feed consumed. Beef and pork
industry supply chains are associated with more than 24 000 and 17 000 ha of annual corn LUC in 2017, respectively, reflecting the higher land conversion and LUC emissions intensities consumed in beef supply chains compared to pork supply chains, since both consume about 12% of the total corn supply (table S1(a)). These rates compare well to previous estimates with a few key differences, as discussed more in the supplemental information part A (see figures S17(a) and S18(a)). For U.S. soybean supply chains, the soy oil processing and chicken industries are associated with the largest quantities of direct LUC, resulting in similar magnitudes of expansion—24 000–31 000 ha of annual LUC—as those of corn (table 1; table S2(a)).

For domestic wheat supply chains, the flour industry is linked with the majority of expansion, at about 16 000 ha, followed by the pork industry at just over 3500 ha (table 1; table S3(a)).

Despite similar levels of cropland conversion between the chicken and ethanol industries, and similarly, the chicken and soy oil industries, there are notably different drivers underlying these outcomes. High annual rates of corn and soy cropland conversion within the chicken industry are linked primarily to high land conversion intensities. Conversely, LUC conversion intensities and GHG emission intensities within the ethanol and soy oil industries are some of the lowest across all sectors of demand. Instead,
Table 1. Comparison of weighted average emission factors, with and without land use change (LUC), for corn, soy and wheat consumed by beef, pork, chicken and processing sectors including ethanol, soy oil and flour that produce co-product feed consumed by livestock including DDGS, soybean meal and middlings respectively (kg CO₂e/kg feed or feedstock consumed). 

| Feed/feedstock | Industry | From production\(^d\) | From production from incl. LUC | \% Increase from incl. LUC in emission factors | Total metric tons CO₂e from LUC (2017) | Total hectares LUC (2017) |
|----------------|----------|----------------------|--------------------------------|---------------------------------------------|--------------------------------|--------------------------|
| Corn and DDGS | Beef\(^a\) | 0.53                 | 0.64                           | 21%                                         | 4604 855                       | 24 380                   |
|                | Pork\(^a\) | 0.45                 | 0.55                           | 23%                                         | 4318 030                       | 17 553                   |
|                | Broiler   | 0.42                 | 0.68                           | 61%                                         | 6758 918                       | 26 425                   |
|                | Chicken\(^a\) | 0.24                 | 0.29                           | 19%                                         | 6466 039                       | 29 895                   |
|                | Ethanol\(^b\) | 0.44                 | 0.52                           | 18%                                         | 5760 833                       | 26 038                   |
|                | Exports   | 0.39\(^c\)          | 0.50\(^c\)                     | 26%                                         | 27 908 675\(^d\)              | (71%)\(^h\)             |
|                | Total across industries |                   |                                |                                             | (72%)\(^h\)                    |                          |
| Soybean and Soymeal | Beef\(^b\) | 0.32                 | 0.51                           | 57%                                         | 228 570                        | 1128                     |
|                | Pork\(^b\) | 0.27                 | 0.47                           | 73%                                         | 1421 541                       | 5779                     |
|                | Broiler   | 0.30                 | 0.73                           | 140%                                        | 5853 565                       | 23 568                   |
|                | Chicken\(^b\) | 0.13                 | 0.27                           | 100%                                        | 7499 026                       | 31 166                   |
|                | Soy oil\(^b\) | 0.46                 | 0.85                           | 86%                                         | 26 497 894                     | 107 630                  |
|                | Exports   | 0.36\(^c\)          | 0.83\(^c\)                     | 91%                                         | 41 482 596\(^d\)              | (92%)\(^b\)             |
|                | Total across industries |                   |                                |                                             | (92%)\(^b\)                    |                          |
| Wheat & Wheat Middling | Beef\(^c\) | 1.06                 | 1.49                           | 41%                                         | 203 447                        | 1427                     |
| Wheat Middling | Pork\(^c\) | 0.73                 | 0.89                           | 21%                                         | 601 598                        | 3567                     |
|                | Broiler   | 0.59                 | 0.84                           | 42%                                         | 104 943                        | 485                      |
|                | Chicken\(^c\) | 0.44                 | 0.54                           | 25%                                         | 2680 615                       | 15 799                   |
|                | Flour\(^d\) | 0.63                 | 0.84                           | 34%                                         | 3705 552                       | 23 665                   |
|                | Exports   | 0.59\(^d\)          | 0.77\(^d\)                     | 30%                                         | 7296 154\(^f\)                | (90%)\(^b\)             |
|                | Total across industries |                   |                                |                                             | 44 943\(^f\)                  | (91%)\(^b\)             |

\(^a\) Includes the emissions from corn and allocated emissions from DDGS.
\(^b\) Includes the allocated emissions from soybean meal.
\(^c\) Includes the emissions from wheat and allocated emissions from middlings (if applicable).
\(^d\) Includes synthetic fertilizers, irrigation, energy use, N₂O emissions from synthetic fertilizers and manure, pesticides, and urea application CO₂ emissions.
\(^e\) Represents weighted average emissions of corn, soy or wheat supplies across all demand industries (including across dairy cattle, layers, turkeys, other human consumption, and exports).
\(^f\) Total across highlighted industries in table.
\(^g\) Represents allocated emissions to ethanol outputs, soy oil outputs, and wheat flour for corn, soy, and wheat respectively (based on energy allocation).
\(^h\) Indicates the portion of land use change (LUC) emissions and hectares of conversion from cropland expansion associated with the supply chains of the top four sectors of domestic demand and exports (for each crop type) out of the total LUC emissions and hectares across all industries demanding each crop type.

3.2. Direct LUC substantially increases consumption-based GHG footprints

Our results suggest that inclusion of LUC emissions alongside traditional production-based emission estimates can substantially expand the GHG footprint associated with downstream agricultural, total expansion area and emissions are almost entirely driven by the overall large volume of corn and soy demanded for production, representing 23% and 18% of total demand, respectively, when allocating the embedded volumes in DDGS and soymeal to livestock consuming sectors (see SI part B).
industry crop demand (figures S5(a)–S7(a)). Including LUC in GHG estimates has the greatest implications for soy supply chains, followed by wheat and corn supply chains, where emissions estimates increase by an average of 91%, 30% and 26% with inclusion of direct LUC, respectively (table 1). Across each of the highlighted industries and crop types, the inclusion of LUC in life cycle GHG emission estimates had the greatest impact on broiler chicken supply chains, with variable implications for the other industries depending on crop type (table 1).

Comparing across the supply chains of individual companies in each industry however reveals even greater variation. Inclusion of direct LUC increases feed/feedstock emissions across companies by an average of 101%, 72%, 53%, 31%, 19%, and 25% for companies in the soy oil, chicken, pork, beef, ethanol, and wheat flour industries, respectively (figures 2 and S8(a)–S10(a)). We found a substantial range in the effects of including LUC for individual companies in each industry, with the soy oil industry having the highest standard deviation, where for example, inclusions of LUC emissions could minimally increase soy supply chain emissions by just 5% for one soy oil producer (American Natural Soy Processors), to as much as 465% for another soy oil producer (Producers Cooperative Association).

In the ethanol, soy oil and beef industries, several individual processing facilities have supply chains that are connected with more than 3000 annual hectares of conversion. These land conversions were largely concentrated in the Great Plains and upper Midwest regions, where large quantities of grasslands are being converted to high value cropland. In fact, in

* Across all companies in industry, relative to life cycle production emissions alone (i.e. fertilizer, N2O, fuel use, irrigation)
Figure 3. State level distribution of the previous land cover types converted to corn, soy and wheat during 2008–2016. Size of pie graph represents the total quantity of expansion within each state for (a) corn cropland expansion, (b) soybean cropland expansion, and (c) wheat cropland expansion.

almost every state, the majority of LUC from corn, soy and wheat cropland expansion occurs on grasslands, with expansions onto shrubland, forestland and wetland occurring at a much smaller rate (figure 3). Across corn, soy, and wheat, shrubland conversion more often occurs in Western states, with forestland conversion occurring more often in Eastern states, and wetland conversion predominantly occurring in Midwest and northern Great Plains states. Despite the prominence of grassland conversion, LUC emissions and emissions intensities of corn, soy and wheat supplies clearly vary among the supply chains of each industry (figures S5(a)–S6(a)).

While the majority of LUC emissions occur in the companies with the greatest overall market share due to the sheer quantity of feed/foodstock supplies they demand (figure S19), the rate of land conversion and GHG emission intensity, from both the inputs/outputs of production and LUC, vary substantially across companies (figures 2 and S8(a)–S10(a)). LUC emissions thus comprise a major portion of total GHG emissions in some supply chains—like those of USA Pork Products (69%), Creston Bean Processing (82%), Koch Foods (55%), FPL food (56%), and Blue Flint Ethanol (60%) and Big Spring Mill (46%), whereas in others, the contribution of LUC emissions is minor, such as for Calihan Packing (2%), CS Beef Packers (6%), Max Yield Cooperative (3%), Siemer Milling Co. (1%) and Golden Grain Energy (1%). Companies with large market shares tend toward average industry emission and conversion intensities because of the broad sourcing regions that average high and low intensities. Companies with small relative market shares tend to have smaller sourcing regions, with greater potential to source from regions of either low or high emission intensity. As a result, much of the variation across companies is driven by these low market share companies.

3.3. Leverage points for mitigating GHG emissions

Risks associated with LUC (e.g. climate change contributions, water shortage, biodiversity loss, reputational risks) appear to aggregate more heavily in some companies than others, due to their distinctive supply chains that uniquely amass feed/foodstock supplies from higher impact production regions. As such, interventions targeting corporate emissions reductions may necessitate different strategies depending on the regions from which a company is sourcing. Spatially explicit data like ours helps to illuminate specifically where and which actors should target various intervention strategies. For example, if moratoriums on LUC were implemented in JBS’s beef, chicken, and pork feed supply chains (across corn, soy and wheat), emissions could be reduced by as much as 12%, 47% and 18%, respectively (based on historical average annual expansion), representing an important strategy to help meet mitigation targets. Collectively, this would reduce U.S. annual committed carbon emissions from corn, soy
Figure 4. Annual production, county-weighted average emission intensity including land use change (LUC), and county-weighted average contribution analysis of total cradle-to-gate greenhouse gas emissions for (a) corn, (b) soybean, and (c) wheat (based on weighted average production across wheat types) for each state in the contiguous United States.

and wheat cropland expansion by almost 5%, with potential to reduce local LUC even more. Engaging state and local governments may thus be an important, mutually beneficial way for companies and agricultural industries to enact local abatement policies where LUC accounts for a large share of emissions (tables S9(a)–S17(a)).

Our analysis identifies several regions in which LUC accounts for an outsized share of total agricultural emissions and that may therein represent effective leverage points for abating emissions from agricultural supply chains. County weighted average emissions from crop production across all contiguous U.S. states reveal that LUC emissions contributions are most variable across states producing corn, followed by those producing soy, spring wheat, durum wheat and winter wheat, respectively (figure S11(a)). Both the variance and the relatively high average emissions of corn and soy production, compared to that of wheat, further indicates that no one-size-fits all strategy is possible for mitigating GHG emissions. Instead, GHG mitigation strategies need to consider geographical differences in farm management and cropland conversion practices, as some states could achieve substantially greater GHG reductions through policy mechanisms that reduce LUC than others. Consider corn as an example—in states with relatively low rates of annual production, particularly those along the east coast of the U.S., LUC accounts for nearly 70% of the region’s total emissions from corn production—an increase of 121%–612% relative to a narrower consideration of production factors alone (e.g. fertilizers, N2O emissions, fuel use, etc). LUC moratoriums in these states could substantially reduce agricultural emissions locally, but their effect is somewhat diminished at the national level by these states’ relatively small contribution to the U.S. total corn production (table S4(a)).

Conversely, while many of the most productive states have relatively low LUC emissions compared to emissions from other sources per unit of output, policies that target emissions reductions by LUC abatement in these states could still be effective nationally due to the sheer quantity of land that they would address. The top ten corn producing states account for about 81% of the U.S. total 2017 corn production. In these states LUC accounted for a relatively small proportion of overall emissions, ranging from just 4% of total corn emission sources in Illinois, to 37% in South Dakota, with a weighted average of 10%. These areas already have a large portion of land in agricultural production such that the emissions per kg of output of LUC are relatively small in comparison to the total emissions of existing production. Emissions are instead largely driven by nitrogen fertilizers and associated on-field N2O emissions, fuel use, and in the case of Nebraska and Kansas, energy use from irrigation inputs (figure 4, tables S4(a)–S8(a)). In these states, addressing emissions from the management of existing cropland may be more
potent leverage points than abating LUC to meet local mitigation targets. Such leverage points may manifest as policies that incentivize gravity fed irrigation, improved fuel efficiency, and increasing nitrogen-use efficiency [9, 28–31]. Nevertheless, the region still comprises 55% of the U.S. total corn-related LUC, suggesting that LUC moratoria remain an important strategy in the context of U.S. and industry-wide mitigation targets.

4. Discussion

Overall, we find that 42% of the total companies we assessed, representing an average of 49% of the total market share for their respective industries, could reduce their crop sourcing emissions by 20% or more by eliminating direct LUC from their supply chains. More specifically, across beef, pork, chicken, ethanol, soy oil, and flour companies, our results suggest that 23%, 53%, 81%, 22%, 73%, and 40% respectively, could reduce their projected annual corn, soy and wheat GHG emissions by at least 20% through prevention of direct LUC. Minimizing cropland expansion onto high carbon stock land is therefore an important lever by which many companies can reduce the life cycle GHG emissions of their products and supply chains and for states and local governments to reduce their total territorial emissions. For those companies and sectors (e.g. broilers and beef) sourcing from areas of high LUC and associated emissions, implementing targeted interventions such as preferential purchasing, adopting zero-conversion certification schemes, or offering premiums for conversion-free production could help discourage additional conversion. These interventions might be facilitated by sector level cooperation and coordination, such as industry-led moratoria on the sourcing from converted lands, paralleling that of zero-deforestation agreements for cattle, soybeans, and palm oil in other parts of the globe [32, 33]. It is important to note, however that our analysis focuses only on direct LUC emissions, though any associated changes in sourcing or supply strategy may have cascading effects on LUC and emissions elsewhere. While such displacement or leakage of LUC and other induced effects can represent materially significant GHG contributions, their assessment falls outside the scope of this analysis. Nevertheless, efforts designed to mitigate direct LUC should consider the potential for such indirect effects, as appropriate intervention design may be available to reduce or avoid them. Where LUC is unavoidable, consideration of ‘irrecoverable carbon’ on lands, and other costs to ecosystem services, could further assist in prioritizing conservation and minimizing lasting damage [34, 35].

Likewise, sectors like ethanol which embody low conversion and emission intensities but large cumulative contributions may be able to leverage their collective size to improve supply chain traceability and monitoring across the industry. For example, implementation of a producer- or coalition-based feedstock mapping and tracking system to discourage land conversion had been previously proposed for the U.S. ethanol industry, but has yet to be enacted [36]. In light of the attributional findings reported here, such an industry-wide program may now be more feasible and appropriate, and could also lay the groundwork for other sectors to follow suit.

Interventions to reduce emissions from production, such as increasing nitrogen fertilizer use efficiency, reducing fuel use, N₂O and changing irrigation practices may in some cases be more effective or additive leverage points for some supply chains. A risk of LUC moratoria is if producers intensify management practices on existing lands to maintain current levels of production (e.g. increasing fertilizers, irrigation, tillage) without achieving commensurate increases in yields, resulting in increased emission intensities of crops and net emissions. Pairing management-related leverage points with LUC interventions is likely to be most effective when also combined with strategic intensification and changes to diets to ensure the needs of future food demands are met [9, 31].

Aligning the Federal Farm Bill (FFB) and bioenergy policy to support such outcomes will be particularly important, as these policies influence how, where and why food and bioenergy crops are produced and distributed, and together, are largely responsible for the predominance of corn, soy, and wheat grown today [19, 37]. Amendments to the FFB may consider inclusion of incentives or new protected area designations, and/or retiring concessions to agriculture within areas of concentrated irrecoverable carbon, such as temperate and boreal forests, wetlands and high biomass density grasslands to reduce or offset the impacts of cropland conversion and align with 1.5 °C climate agendas for reaching carbon neutrality by 2050 [34]. Other amendments could consider incentives for management practices that may offset some of the expected carbon loss, such as cover cropping and development of new perennial and fallow season crops that have multiple ecological and economic co-benefits, and strategic adoption of conservation tillage regimes considering climate and soil characteristics [38–40]. While inclusion of spatially explicit LUC in emission estimates increases chicken feed emissions substantially relative to other sectors, potentially diminishing its environmental preferability over other protein sources, it is unlikely to change overall average rank orders among the different meat types [17, 41]. Nonetheless, there is potential for rank order changes at subnational levels similar to those found for water scarcity impacts [13], which should be examined in future research. Spatially explicit LCA results such as ours and others can further help prioritize these solutions across sectors and regions.
5. Conclusion

Our study analyzed, for the first time, county-scale drivers of life cycle GHG emissions across unique supply chains of corn, soy, and wheat considering differences in field management practices responsible for >90% of variation in emissions and including spatially explicit, empirically-based LUC and carbon stocks across the contiguous US. In doing so, we identify region-, industry- and even company specific ‘leverage points’ that could be targeted to effectively reduce emissions from the food system. Our results conceptually change our understanding of the sources, magnitudes and influencers of agricultural GHG emissions, and suggest that moratoria on LUC from corn, soy and wheat could be an effective GHG mitigation strategy for 20%–80% of companies in U.S. beef, pork, chicken, ethanol, soy oil, and flour processing industries to varying degrees. The results of this analysis are timely for stakeholders across the food and agriculture system to identify key emission sources and leverage points for mitigating future GHG emissions, including crop and livestock producers, company processors, industry associations, retailers, NGOs and state and local policy makers.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

We gratefully acknowledge the financial support of the World Wildlife Fund (WWF). Any findings, conclusions and recommendations expressed in this study are those of the authors, and do not necessarily reflect the views of WWF. This material is also based upon work supported by the National Science Foundation (NSF) under Grant No. 180508 and the NSF Graduate Research Fellowship Program under Grant No. DGE-1747503 to SAS. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. We also acknowledge the contributions of Dr Shamitha Keerthi and Eugene Yacobsen from the Nature Conservancy (TNC) for providing data on conservation practices and runoff potential, helping enable our relatively high-resolution estimation of direct and indirect N2O as well as Dr Nina Domingo from the University of Minnesota for assisting in data acquisition.

Author contributions

Pelton—conceptualization, formal analysis, investigation, visualization, writing—original draft; Spawn-Lee—conceptualization, formal analysis, investigation, writing—review and editing; Lark—conceptualization, funding acquisition, investigation, writing—review and editing; Kim—formal analysis, visualization; Springer—formal analysis, writing—review and editing; Hawthorn—formal analysis; Ray—formal analysis, writing—review and editing; Schmitt—conceptualization, funding acquisition, investigation, writing—review and editing.

Conflict of interest

To our knowledge, we have no conflicts of interest to declare.

ORCID iDs

Rylie E O Pelton  https://orcid.org/0000-0002-6015-2263
Seth A Spawn-Lee  https://orcid.org/0000-0001-8821-5345
Tyler J Lark  https://orcid.org/0000-0002-4583-6878
Taegon Kim  https://orcid.org/0000-0002-7931-6627
Nathaniel Springer  https://orcid.org/0000-0002-8433-474X
Peter Hawthorne  https://orcid.org/0000-0003-1125-5239
Deepak K Ray  https://orcid.org/0000-0002-2856-9608
Jennifer Schmitt  https://orcid.org/0000-0002-5427-5208

References

[1] Smith T 2013 Climate change: corporate sustainability in the supply chain Bull. At. Sci. 69 43–52
[2] Tubiello F, Salvatore M and Ferrara A 2015 The contribution of agriculture, forestry and other land use activities to global warming, 1990–2012 Glob. Change Biol. 21 2655–60
[3] Ray D, West P, Clarke M, Gerber J, Prischepov A and Chatterjee S 2019 Climate change has likely already affected global food production PLoS One 14 1–18
[4] Tilman D, Cassman K, Matson P, Naylor R and Polasky S 2002 Agricultural sustainability and intensive production practices Nature 418 671–7
[5] Tilman D, Balzer C, Hill J and Behfard B 2011 Global food demand and the sustainable intensification of agriculture Proc. Natl Acad. Sci. 108 20260–4
[6] Johnson J, Runge C, Senauer B, Foley J and Polasky S 2014 Global Agriculture and carbon trade-offs Proc. Natl Acad. Sci. 111 12342–7
[7] Thomson A et al 2017 Science in the supply chain: collaboration opportunities for advancing sustainable agriculture in United States Agric. Environ. Lett. 2 1–6
[8] O’Rourke D 2014 The science of sustainable supply chains Science 344 1124–7
[9] West P et al 2014 Leverage points for improving global food security and the environment Science 345 325–8
[10] Food and Agriculture Organization (FAO) 2020 FAOSTAT (Available at: www.fao.org/faostat/en/#data/GT) (Accessed 2020)
[11] Smith T, Goodkind A L, Kim T, Pelton R E O, Suh K and Schmitt J 2017 Subnational mobility and
consumption-based environmental accounting of US corn in animal protein and ethanol supply chains Proc. Natl. Acad. Sci. 114 E7891–E7899
[12] Yang Y, Pelton R, Kim T and Smith T 2019 Effects of spatial scale on life cycle inventory results Environ. Sci. Technol. 54 1293–303
[13] Brauman K, Goodkind A, Kim T, Pelton R and Schmitt J S T 2020 Unique water scarcity footprints and water risks in US meat and ethanol supply chains indentified via subnational commodity flows Environ. Res. Lett. 15 1–8
[14] Friedlingstein P et al 2019 Global carbon budget 2019 Earth Syst. Sci. Data 11 1783–838
[15] Asem-Hibbsie S, Battaglione T, Stackhouse-Lawson K and Rotz A 2018 A life cycle assessment of the environmental impacts of a beef system in the USA LCA Agric. 24 441–55
[16] Rotz A, Asem-Hibbsie S, Place S and Thom a G 2019 Environmental footprints of beef cattle production in the United States Agric. Syst. 169 1–13
[17] Eshel G, Shepon A, Makov T and Milo R 2014 Land, irrigation water, greenhouse gas, and reactive nitrogen burdens of meat, eggs, and dairy production in the United States Proc. Natl Acad. Sci. 111 11996–2001
[18] Lark T, Spawn S, Rougie M and Gibbs H 2020 Cropland expansion in the United States produces marginal yields at high costs to wildlife Nat. Commun. 11 1–10
[19] Lark T, Salmon M and Gibbs H 2015 Cropland expansion outpaces agricultural and biofuel policies in the United States Environ. Res. Lett. 10 1–11
[20] US Environmental Protection Agency (EPA) 2018 Biofuels and the Environment: The Second Triennial Report to Congress EPA/600/R-18/195 Washington, DC
[21] Spawn S, Lark S and Gibbs H 2019 Carbon emissions from cropland expansion Environ. Res. Lett. 14 1–11
[22] Transportation Networks CTA 2011 County-to-county Distance Matrix (Knoxville: Oak Ridge National Laboratory)
[23] Lin X, Ruesp P, Marston L and Konar M 2019 Food flows between counties in the United States Environ. Res. Lett. 14 1–17
[24] Pelton R 2018 Spatial greenhouse gas emissions from US county corn production Int. J. Life Cycle Assess. 24 12–25
[25] Lark T, Mueller R, Johnson D and Gibbs H 2017 Measuring land-use and land-cover change using the U.S. department of agriculture’s cropland data layer: cautions and recommendations Int. J. Appl. Earth Obs. Geoinf. 62 224–35
[26] Lark T J, Schelly I H, Gibbs H K 2021 Accuracy, bias, and improvements in mapping crops and cropland across the United States using the USDA cropland data layer Remote Sens. 13 968
[27] Kwon H et al 2020 Carbon calculator for land use and land management change from biofuels production (CCLUB) Argonne National Lab, Energy Systems Division 12–5 Rev. 6
[28] Camargo G, Ryan M and Richard T 2013 Energy use and greenhouse gas emissions from crop production using the farm energy analysis tool BioScience 63 263–73
[29] Zhang X, Davidson E, Mauzerall D, Searchinger T, Dumas P and Shen Y 2015 Managing nitrogen for sustainable development Nature 528 51–59
[30] Fargione J et al 2018 Natural climate solutions for the United States Sci. Adv. 4 1–14
[31] Carlson K et al 2017 Greenhouse gas emissions intensity of global croplands Nat. Clim. Change 7 63–68
[32] Lambin E et al 2018 The role of supply-chain initiatives in reducing deforestation Nat. Clim. Change 8 109–16
[33] Lark T 2020 Protecting our prairies: research and policy actions for conserving America’s grasslands Land Use Policy 97 104727
[34] Goldstein A et al 2020 Protecting irrecoverable carbon in Earth’s ecosystems Nat. Clim. Change 10 287–95
[35] Pennington D, Dalsell B, Nelson E, Mull D, Taff S, Hawthorne P and Polasky S 2017 Cost-effective land use planning: optimizing land use and land management patterns to maximize social benefits Ecol. Econ. 139 75–90
[36] Wright C, Larson B, Lark T and Gibbs H 2017 Recent grassland losses are concentrated around U.S. ethanol refineries Environ. Res. Lett. 12 1–16
[37] Spangler K, Burchfield E and Schumacher B 2020 Past and current dynamics of U.S. agricultural land use and policy Front. Sustain. Food Syst. 1–21
[38] Jansson C, Faiola C, Wingler A, Zhu X-G, Kravchenko A, De Graaff M A, Ogden A J, Handakumbura P P, Werner C and Beckles D M 2021 Crops for carbon farming Front. Plant Sci. 12 1–12
[39] Ogle S et al 2019 Climate and soil characteristics determine where no-till management can store carbon in soils and mitigate greenhouse gas emissions Nat. Sci. Rep. 9 1–8
[40] Jordan N et al 2016 Sustainable commercialization of new crops for the agricultural bioeconomy Elements 4 1–10
[41] Heller M and Keoleian G 2014 Greenhouse gas emissions estimates of U.S. dietary choices and food loss J. Ind. Ecol. 19 391–401