

Article

Spatially Explicit Life Cycle Global Warming and Eutrophication Potentials of Confined Dairy Production in the Contiguous US

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Abstract: Assessing the spatially explicit life cycle environmental impacts of livestock production systems is critical for understanding the spatial heterogeneity of environmental releases and devising spatially targeted remediation strategies. This study presents the first spatially explicit assessment on life cycle global warming and eutrophication potentials of confined dairy production at a county scale in the contiguous US. The Environmental Policy Integrated Climate model was used to estimate greenhouse gases (GHGs), NH₃, and aqueous nutrient releases of feed production. The Greenhouse gases, Regulated Emissions, and Energy use in Transportation model and Commodity Flow Survey were used to assess GHGs and NH₃ from feed transportation. Emission-factor-based approaches were primarily used to calculate GHGs from enteric fermentation, and GHGs, NH₃, and aqueous nutrient releases from manure management. Characterization factors reported by the Intergovernmental Panel on Climate Change and Tool for Reduction and Assessment of Chemicals and other Environmental Impacts model were used to compute global warming and eutrophication potentials, respectively. The analyses revealed that life cycle global warming and eutrophication potentials of confined dairy production presented significant spatial heterogeneity among the US counties. For example, the life cycle global warming potential ranged from 462 kg CO₂-eq/head to 14,189 kg CO₂-eq/head. Surprisingly, sourcing feed locally cannot effectively reduce life cycle global warming and eutrophication potentials of confined dairy production. The feed supply scenarios with the lowest life cycle environmental impacts depend on the life cycle environmental impacts of feed production, geographic locations of confined dairy production, and specific impact categories. In addition, installing buffer strips in feed-producing hotspots can effectively reduce life cycle nutrient releases of confined dairy production. If 200 counties with the highest life cycle EP of corn adopt buffer strips, the reduction in life cycle EP of confined dairy production could reach 24.4%.

Keywords: environmental sustainability; dairy production; greenhouse gas emissions; nutrient releases; spatial assessment



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1. Introduction

While confined dairy production plays an important role in providing nutritional milk products and promoting economic development, it is associated with critical environmental concerns, including greenhouse gases (GHGs) and water quality degradation [1–4]. The United States (US) ranked as the largest dairy-producing country [5], where 59% of dairy operations are confined operations [6]. Confined dairy operations mainly rely on grain-based feed, ranking as one of the top consumers of national grains [7]. Dairy production in the US results in approximately 2% of national total GHGs [8]. In addition, nutrient

releases from feed production and animal operations are among the leading causes of water quality degradation in the form of eutrophication and hypoxia [9,10]. Without effective mitigation efforts, the continuously increasing demand of dairy products will result in further environmental degradation [11]. Quantitative analyses of environmental releases from confined dairy production and associated mitigation strategies are urgently required for promoting long-term environmental sustainability.

The life cycle assessment (LCA) approach has a unique strength for quantifying environmental releases from both confined dairy operations and their feed supply chains. Existing LCA studies have greatly advanced our understanding in environmental impacts of dairy production [12–20]. However, knowledge gaps remain in the spatially explicit life cycle environmental impacts of confined dairy production and associated location-sensible mitigation strategies.

First, spatially explicit LCA of confined dairy production at a fine spatial scale (such as county scale) is lacking. The environmental releases from dairy production are inherently spatially heterogeneous, as influenced by distinct spatial origins of animal feed, different weather and soil conditions, and diverse management practices [21,22]. Existing LCAs have greatly contributed to our understanding of the environmental impacts of dairy production by comparing farming practices, and identifying key contributing processes for their life cycle GHGs and nutrient releases [14,16,18,23–25]. However, the majority of these analyses were either restricted to specific farms or reliant on coarse inventory (such as regional, national, or global datasets). The assessments on a few farms in specific counties were incapable of describing the spatial heterogeneity in life cycle environmental impacts of confined dairy production across contiguous US counties [14,16,18,23–25]. On the other hand, coarse national inventories were incapable of capturing spatial differentiations of life cycle environmental impacts at a county scale [19,20,26,27]. Spatially explicit LCAs at a county scale are required to better understand spatially explicit life cycle environmental impacts from confined dairy operations and their feed supply chains [14,16,18,20,23–27].

Moreover, the spatially explicit LCA serves as basis for designing spatially targeted remediation strategies. Previous studies revealed that reducing environmental impacts of feed supplies (i.e., feed production and transportation) were capable of effectively mitigating life cycle environmental impacts of dairy production [13,16]. However, influences of spatial origins of animal feed on life cycle GHGs and nutrient releases of confined dairy remain unknown. Assessing the influences of spatial origins of dairy feed is necessary for determining the environmentally preferred locations for sourcing dairy feed, consequently reducing life cycle impacts of feed supplies for confined dairy production. Additionally, understanding the influences of spatial origins of animal feed will support stakeholders in identifying and prioritizing feed exporting hotspots for implementing remediation strategies (such as installing buffer strips). Targeting feed exporting hotspots for adopting remediation strategies may serve as efficient and effective measures for reducing life cycle impacts of feed supplies for confined dairy production. The assessment of location-sensible management strategies (such as the environmentally preferred counties for sourcing feed and installing buffer strips) is needed to effectively reduce the life cycle environmental impacts of confined dairy production.

To fill these knowledge gaps, this study quantified life cycle GHGs and nutrient releases of confined dairy production in the US at the county scale through combining a process-based LCA approach with state-of-the-art agricultural models. Based on the spatially explicit LCA results, this study identified the targeted counties for sourcing dairy feed and for installing buffer strips required to minimize life cycle environmental releases of dairy feed supplies. To the best of our knowledge, this is the first study to report life cycle GHGs and nutrient releases from confined dairy production at a county scale. Moreover, such novel spatially explicit findings enable assessing the influences of the spatial origins of animal feed on life cycle environmental releases of confined dairy production, and identifying the spatial hotspots for implementing buffer strips in order to reduce life cycle environmental impacts of confined dairy production.

2. Method

The International Organization for Standardization's (ISO) 14040 series delineates the guidelines and framework for performing LCA. The main phases of LCA include goal and scope definition, inventory analysis, impact assessment, and interpretation. This study utilizes the LCA framework to quantify life cycle GHGs and nutrient releases of confined dairy production. Each step of the LCA is described below.

2.1. Goal and Scope

The goal of this study was to quantify the life cycle GHGs and nutrient releases from confined dairy production in the US at a county scale. We streamlined the confined dairy production into four major stages including feed production, feed transportation, enteric fermentation, and manure management. The system scope includes these four major stages and associated GHG and nutrient releases from each stage of confined dairy production. CO₂, CH₄, and N₂O emission to air from each stage were included for estimating global warming impact. NH₃ emission to air and NO₃[−] and PO₄^{3−} to water from each stage were incorporated for calculating eutrophication impact. The system boundary of this study is described in Figure 1.



Figure 1. System boundary for life cycle assessment of confined dairy production.

Three functional units were used in this study, including one head dairy cow, one county, and one kg milk. One head dairy cow is the basic biological and management unit of the farm operations. One county as functional unit is valuable for regional planning, whose basic administration unit is often a county. Additionally, this study includes one kg milk as a functional unit in order to ease comparisons between this study and other dairy LCA studies. To convert the per county results into per kg milk results, dairy herd population at county scale and milk productivity were used. The majority of dairy LCA studies use one kg milk as a functional unit, because one kg milk is capable of describing environmental impacts per unit of farm production and of facilitating fair comparison across farms. These three functional units together are comprehensive and flexible to aid stakeholders in comparing differences in the life cycle GHGs and nutrient releases of confined dairy operations among US counties, and designing environmental remediation strategies at region scales.

2.2. Life Cycle Inventory

2.2.1. Feed Production Stage

Life cycle GHGs and nutrients releases of feed production for confined dairy production were estimated based on animal nutritional requirements and life cycle environmental impacts of crop production at the county scale. Feed consumption of a dairy cow was estimated for each of ten life stages [28], according to the nutrient requirements of dairy published by the National Research Council [29]. The annual feed consumption for a dairy cow was averaged based on its total feed consumption over its lifetime. The life cycle environmental impacts of corn and soybean production (i.e., kg CO₂-eq/kg corn feed) were derived from Lee et al. [30] and Romeiko et al. [31]. These studies quantified spatially explicit life cycle environmental impacts of corn and soybean production by combining a process-based LCA model and Environmental Policy Integrated Climate (EPIC) model

at a county scale in the US [30]. The EPIC model is an agroecosystem model capable of simulating impacts of agricultural management on key biophysical and biogeochemical processes, such as plant growth, water balance, carbon and nutrient cycling, soil erosion, and GHGs [30,31]. While EPIC assesses the spatially explicit environmental releases as influenced by soil characteristics, weather conditions, and farming practices [32], LCA tracks the supply chain impacts of agricultural material and energy inputs. The integration of the processed-based LCA and EPIC models demonstrated by Lee et al. and Romeiko et al. not only captured the spatially explicit environmental releases from agricultural on-farm processes, but also the spatially explicit environmental releases from supply chain processes. The life cycle environmental impacts of grass and hay production were obtained from the ecoinvent database [33]. Milk production data were collected by the US Department of Agriculture (USDA) [6]. The county-level GHGs and nutrient releases were then estimated with numbers of dairy cows/county and life cycle GHGs and nutrient releases/dairy cow.

2.2.2. Feed Transportation Stage

The Greenhouse Gas, Regulated Emissions, and Energy use in Transportation (GREET) model [34], created by the Argonne National Laboratory of the US Department of Energy, was used to quantify life cycle GHGs and NH_3 from feed transportation, based on the feed amounts and transportation distances [18,35]. The GREET model is a publicly available life cycle analysis tool for consistently examining life cycle energy and environmental releases in transport and energy processes, and it is widely used by governmental agencies and industries to inform policies. As documented in Section 2.2.1, feed amounts were calculated based on animal nutritional requirements. The transportation distances were based on the Commodity Flow Survey (CFS) and the road network analysis. The CFS [36], published by the Census Bureau and the Bureau of Transportation Statistics, indicates the origin and destination states for transporting animal feed across the entire US. We downscaled the animal feed supply network from the state to county levels, based on an assumption that corn and hay export as animal feed from each county was proportional to the total corn and hay grain production in that county and the total corn and hay export from the corresponding state. The transport distances between origin and destination counties were calculated with Network Analyst in ArcGIS, based on the shortest distance between the county centroids.

2.2.3. Animal Respiration and Enteric Fermentation

The major sources of GHG in animal operation include animal respiration and fermentation [37,38]. GHG emission from animal respiration was estimated as a function of daily intake of feed dry matter and the average live weight of dairy cattle [39]. We assumed that the percentage of average dry matter for corn was 90% [40], and the average live weight of dairy cattle was 600 kg. GHGs from enteric fermentation were calculated following a linear modeling approach as proposed by Mills et al. [41]. In this study, dry matter intake was found to be the only variable that explained a significant amount of variation in daily methane production, while including other factors such as percentage of starch and water-soluble carbohydrate in animal feed did not significantly improve the model fit. Detailed description of equations and parameters used to evaluate GHGs from animal respiration and fermentation are presented in Table 1.

2.2.4. Manure Management Stage

GHGs from animal housing (e.g., barn floor), manure storage, and field application processes were calculated for the manure management stage. Ambient mean temperature and relative humidity were used to estimate CH_4 from animal housing [8,42]. Daily weather data (at a resolution of 1 degree of coordinates) were retrieved from the fourth version of the Community Climate System Model (CCSM4) from the Intergovernmental Panel on Climate Change (IPCC) [43], with each county assigned the weather simulations of the grid that was closest to the county centroid. Additionally, in order to reflect the influences of

barn types on CH₄, this study first estimated CH₄ for each barn type (i.e., free-stall barn, tie-stall barn, bedded pack barn, and open lots), and then calculated an average CH₄ based on the percentage of different barn types reported by the USDA [44] and Aguirre-Villegas and Larson [38]. According to the USDA report, on average, 81% barns were free-stall or tie stall in the eastern states including Minnesota, Missouri, and New York, while the proportion of free-stall or tie stall barns was 50.9% in western states, including Texas and California. The proportion of open lot was 5.2% and 30% in the eastern and western states, respectively. Among the 127 barns enrolled in the Aguirre-Villegas study, the percentage of bedded pack was 11.0%. For calculating GHGs from manure storage, the daily average manure production for confined dairy cows was assumed to be 86 kg manure/1000 kg live weight [45]. We used equations from Rotz et al. [46] to estimate CH₄ emission for liquid, slurry, and solid manure storage, respectively, and then weighted them with the percentage of these storage types in Aguirre-Villegas and Larson [38], where 48.4% adopted the liquid storage, 48.4% the slurry storage, and 3.2% the solid storage. The amount of N₂O from animal house and storage was estimated for each barn type with the emission factors provided by IPCC and the aforementioned percentage of different barn types. CH₄ from manure application was determined as a function of manure pH and F_{tan}, and the area covered with manure. This study assumed that the average pH of manure was 7.5, and the average fraction of total ammoniacal nitrogen (F_{tan}) in the manure was 5%. The land area that received manure was obtained from the USDA [47].

NH₃ and aqueous nutrient releases during animal housing, manure storage, and manure application processes were estimated. While 0.079 kg NH₃-N/1000 kg live weight was excreted [45], NH₃ from the barn floor was a major contributor, which was computed based on the emission factors provided by Rotz et al. for each barn type and averaged by the aforementioned percentage of different barn types [48]. NH₃ from manure application was estimated based on ammoniacal nitrogen content in manure and the area treated with manure [49]. In addition, the aqueous releases from manure application were estimated, based on nutrient contents of manure [50] and an emission factor approach developed by Xue et al. [51]. All relevant equations for estimating GHGs and nutrient releases from animals and manure management are listed in Table 1.

Table 1. Equations for computing GHGs and nutrient releases from animal operation and manure management stages.

Emissions	Stages	Models or Equations	References
CH ₄	Enteric fermentation stage	Methane (MJ/d) = 5.93 (SE 1.60) + 0.92 (SE 0.08) × DMI (kg/d)	[41]
	Manure Management stage (Barn floor)	From free-stall or tie barn floor = (max(0, 0.13) × T) × A _{barn} /1000 T = mean ambient temperature (°C) A _{barn} = area exposed to manure (m ²) From bedded barn floor = VS × (Bo) × 0.67 × MCF/100 × 365 VS = volatile solids excreted in manure, kg CH ₄ /day Bo = maximum CH ₄ -producing capacity for dairy manure, 0.24 m ³ CH ₄ /kg VS MCF = CH ₄ conversion factor for the manure management system (%)	[46]
	Manure Management stage (Manure storage)	From liquid or slurry storage = (24 × Vs,d × b1/1000) × exp(ln(A) − E/RT) + (24 × Vs,nd × b2/1000) × exp(ln(A) − E/RT) Vs,d and Vs,nd = degradable and nondegradable VS in the manure (g) which differs for the liquid and slurry storage A = Arrhenius parameter (g CH ₄ kg ^{−1} VSh ^{−1}) E = apparent activation energy (J mol ^{−1}) R = gas constant (J K ^{−1} mol ^{−1}) T = temperature (K)	[52]

Table 1. Cont.

Emissions	Stages	Models or Equations	References
CH ₄	Manure Management stage (Manure storage)	From solid storage = $VS \times (Bo) \times 0.67 \times MCF/100 \times 365$ VS = volatile solids excreted in manure, kg CH ₄ /day Bo = maximum CH ₄ -producing capacity for dairy manure, 0.24 m ³ CH ₄ /kg VS MCF = CH ₄ conversion factor for the manure management system (%)	[46]
	Manure Management stage (Field application)	From slurry application = $(0.17 \times F_{VFA} + 0.026) \times Acrop \times 0.032$ F_{VFA} = daily concentration of VFAs in the slurry (mmol kg ⁻¹ slurry) $Acrop$ = the land area (ha) where the manure is applied	[52]
N ₂ O	Enteric fermentation stage	0.4 g N ₂ O/head/day	[8]
	Animal operation stage (Barn floor)	Negligible when manure is removed daily For free stall and tie stall barn 2% for open lot 1% for bedded pack system	[46]
	Manure Management stage (Manure storage)	Liquid storage = 0.001 kg N ₂ O-N/kg Nitrogen excreted Solid storage = 0.02 kg N ₂ O-N/kg Nitrogen excreted Slurry storage = 0.001 kg N ₂ O-N/kg Nitrogen excreted	[46,53]
	Manure Management stage (Field application)	0.01 kg N ₂ O-N/kg of N applied after NH ₃ losses	[53]
NH ₃	Animal operation stage (At excretion)	0.079 kg NH ₃ -N/1000 kg live weight	[45]
	Animal operation stage (Barn floor)	Tie stall: 8% of the total N excreted Free stall: 16% of the total N excreted Bedded pack barn: 35% of the total N excreted Feedlot: 50% of the total N excreted	[48,54]
	Manure Management stage (Manure storage)	5 g NH ₃ m ⁻² d ⁻¹ (Lagoon storage)	[55]
	Manure Management stage (Field application)	For slurry = $TAN \times (20 + 5 \times TS \times 17/14/100)$ TAN = total ammoniacal N in manure (kg NH ₃ -N) TS = total solids in manure (%)	[49]
Aqueous N/P releases	Manure Management stage (Field application)	$R_N = A_N \times f_{em,N} \times (1 - f_{nitrate} \times f_{denitrification})$ R_N is aqueous N release; A_N is the total nitrogen in the applied manure as fertilizer; $f_{em,N}$ is nitrogen discharge coefficient; $f_{nitrate}$ is the ratio of nitrate to total nitrogen; $f_{denitrification}$ is denitrification fraction. $R_P = A_P \times f_{em,P}$ R_P is aqueous P release; A_P is total phosphorus in the applied manure as fertilizer; $f_{em,P}$ is nitrogen discharge coefficient;	[51]

2.2.5. Life Cycle GHGs and Nutrient Releases per County

The life cycle GHGs of confined dairy production per county were estimated by multiplying the cow numbers within a county and the life cycle GHGs per cow for the same county. The same procedure was used to calculate the life cycle nutrient releases per county. The mean values over the 5 year period of 2013–2017 from the USDA were used to represent the numbers of confined dairy cows for each county in the US [6]. The life cycle environmental releases per cow were determined based on the total environmental releases per dairy cow during the four major stages in Sections 2.2.1–2.2.4.

2.3. Life Cycle Impact Assessment and Interpretation

Life cycle global warming (GWP) and eutrophication (EP) potentials of confined dairy production were computed based on life cycle inventory described in Section 2.2

and corresponding characterization factors. The global warming potentials of CH_4 and N_2O were 25 and 298 times the global warming potential of CO_2 , respectively, under a 100-year time frame [56]. The characterization factors reported by the Tool for Reduction and Assessment of Chemicals and other Environmental Impacts (TRACI) model version 2.1 were used to compute eutrophication impacts [57]. TRACI, developed by the US EPA, is an environmental impact assessment tool widely used in North America for life cycle impact assessment analyses [57]. The characterization factors for eutrophication potentials were $0.779 \text{ kg N-eq/kg NH}_3$, $0.237 \text{ kg N-eq/kg NO}_3^-$, and $2.38 \text{ kg N-eq/kg PO}_4^{3-}$, respectively.

Sensitivity analyses were performed to determine the influences of key input parameters on the LCA results using the “one at a time perturbation” technique [58]. This approach determines the responses of model outputs by sequentially varying single model input, while keeping all other inputs fixed. The assessed inputs for life cycle GWP of confined dairy production included corn consumption rate, percent dry matter of corn, area of barn floor exposed to manure, volatile solids excreted in manure, CH_4 conversion factor during manure storage, and areas receiving dairy manure as an alternative fertilizer. The tested inputs for life cycle EP of confined dairy production consisted of corn consumption rate, fraction of total ammoniacal nitrogen, total nitrogen in manure, and pH of manure. We have varied these parameters by $\pm 10\%$ for the sensitivity analyses.

Scenario analyses were conducted to estimate the influences of feed sourcing strategies on life cycle environmental impacts of confined dairy production. We used five representative counties (Deaf Smith in Texas, Roosevelt in New Mexico, Grant in Wisconsin, Sioux in Iowa, and Antelope in Nebraska) to illustrate the variation in GWP and EP across the four scenarios of feed supply. These five counties ranked as the top dairy production counties in great need of feed supply, and represented distinct geographical contexts. We compared the life cycle environmental impact of four hypothetical feed supply scenarios including local, nearby, regional, and national scenarios. The four feed sourcing scenarios represented distinct spatial origins of animal feed (Figure 2). Under the local scenario, feed is supplied from the same county where dairy production is located. For the nearby scenario, the feed is from the nearest county bordering the dairy-producing county. Under the regional scenario, feed is supplied from neighboring counties of the dairy-producing county. Under the national scenario, feed is primarily supplied from Midwest counties, as described in CFS.

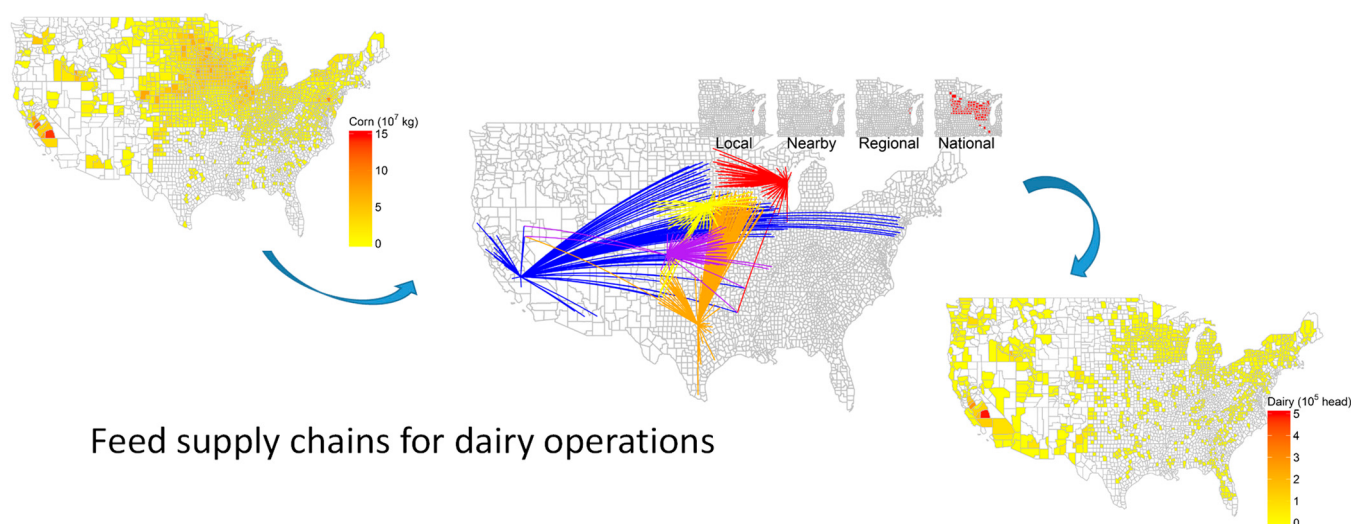


Figure 2. Four feed sourcing scenarios including local, nearby, regional and national sourcing. The colored networks in the middle map represents the national sourcing scenarios for dairy operations in Erath county of Texas, Hamilton county of Kansas, Manitowoc county of Wisconsin, Tulare county of California, Wayne county of Nebraska.

This study also assessed the influences of installing buffer strips in feed-producing counties on life cycle environmental impacts of confined dairy production. The width of buffer strips was assumed to be 30 m. The average nutrient removal rates of buffer strips were obtained from previous publications and estimated to be 70% in this study [51,59].

3. Results

3.1. Magnitudes of Life Cycle GWP (kg CO₂-eq/Cow, County) and EP (kg N-eq/Cow, County)

Life cycle GWP of dairy production in the U.S. counties presented significant variability, ranging from 462 kg CO₂-eq/head in Colfax County of New Mexico to 14,189 kg CO₂-eq/head in Lancaster County in South Central Pennsylvania (Figure 3). The distributions of the life cycle GWP per head of dairy production across states were also significantly different ($F = 21.7$, $p < 0.001$). The national median value at a county level for life cycle GWP of confined dairy production was 1142 kg CO₂-eq/head. Among all states, the median life cycle GWPs in Wisconsin (2880 kg CO₂-eq/head) and Iowa (2291 kg CO₂-eq/head) were significantly higher than other states (median range: 515–2880 kg CO₂-eq/head).

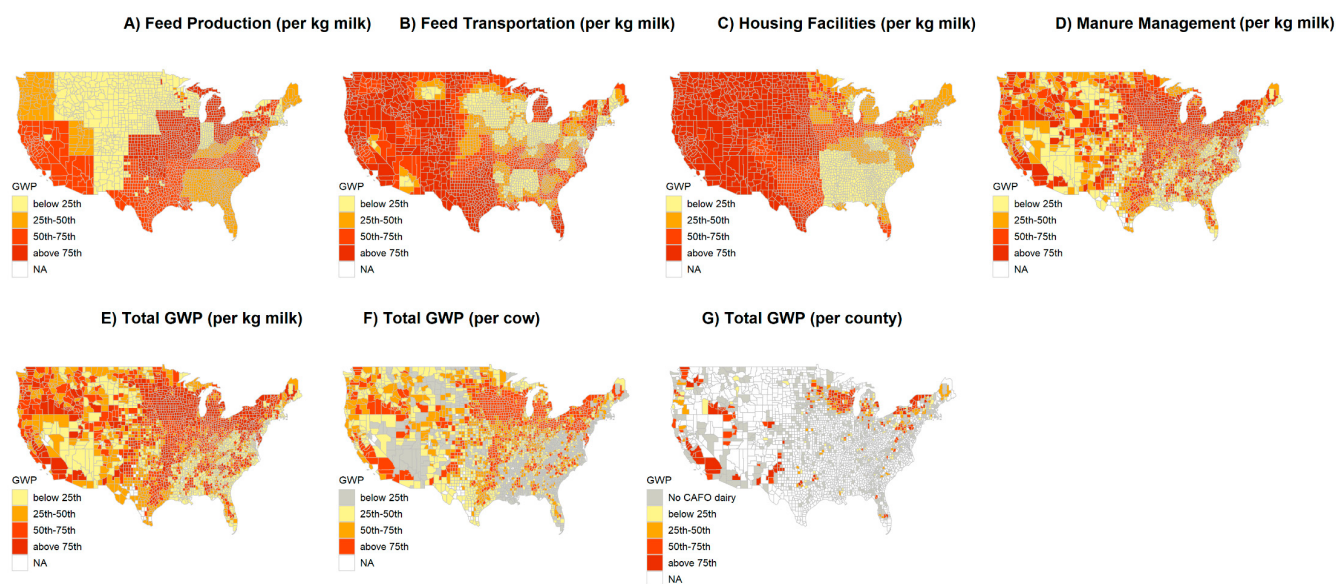


Figure 3. Life cycle global warming potential (GWP) of confined dairy production per head and per county in the contiguous United States.

Among the counties reported with dairy production, the total life cycle GWP of dairy production ranged from 674,723 kg CO₂-eq for St. Joseph County of Indiana to 5.1×10^{10} kg CO₂-eq in Tulare County of California. The median life cycle GWP of dairy production was 8.6×10^7 kg CO₂-eq/county across all counties. Wisconsin (2.2×10^8 kg CO₂-eq/county), Idaho (1.6×10^8 kg CO₂-eq/county), New York (1.0×10^8 kg CO₂-eq/county), and California (6.4×10^7 kg CO₂-eq/county) ranked as the top four states in terms of median values of life cycle GWP/county for confined dairy production.

As shown in Figure 4, we also observed significant geographical variations in life cycle EP of dairy production per head ($F = 12.4$, $p < 0.001$). The highest life cycle EP of dairy production occurred in Ashtabula County, Ohio, with an estimate of 31.74 kg N-eq/head. The estimates for Ohio (median: 31.73 kg N-eq/head) and Minnesota (median: 30.70 kg N-eq/head) were slightly larger than other states whose median estimates ranged from 20.54 to 30.59 kg N-eq/head. For the total life cycle EP of dairy production at the county level, the national median value was 131,240 kg N-eq/county. Jones County in Iowa (18,369 kg N-eq/county) and Tulare County in California (1.46×10^8 kg N-eq/county) represented the lowest and highest values across all counties. Additionally, the spatial

variation in life cycle EP of dairy production per county was also significant ($F = 5.06$, $p < 0.001$).

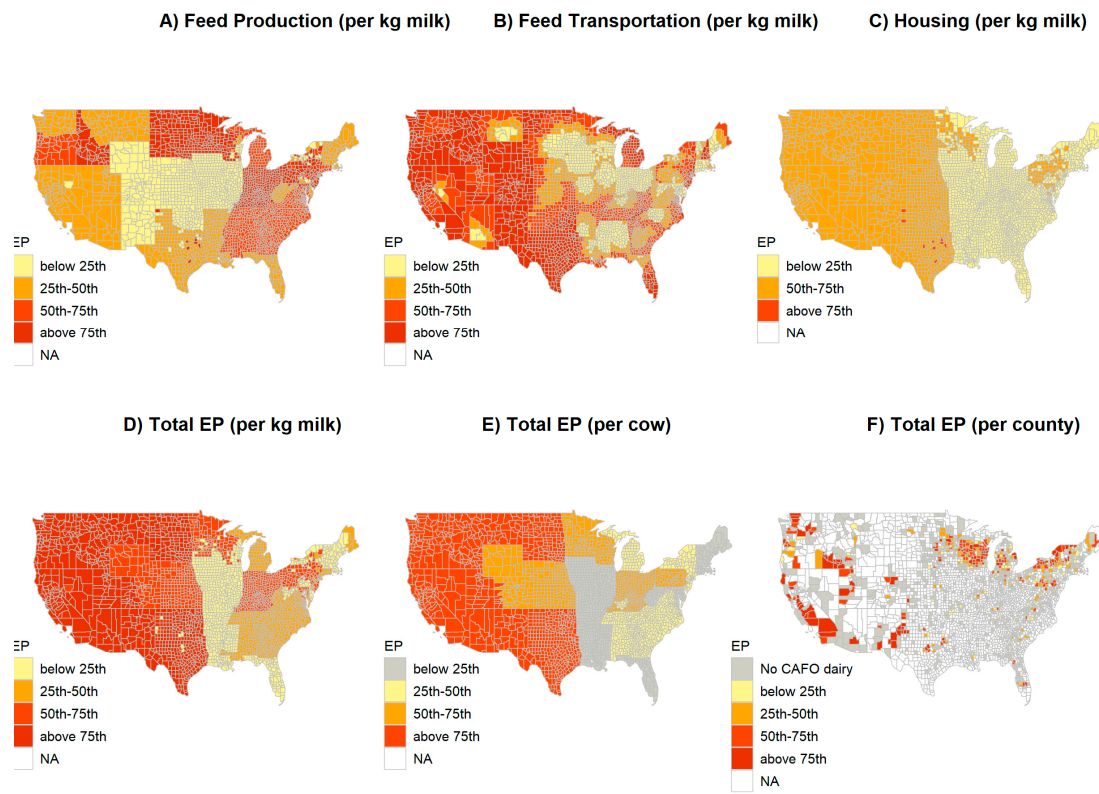


Figure 4. Life Cycle Eutrophication Potential (EP) of Confined Dairy Production in the Contiguous United States.

Overall, country and state average values of life cycle impacts of dairy production are often inaccurate to represent the life cycle impact of a specific county. County-level assessment is necessary to reveal the large variability of life cycle environmental impacts from dairy production.

3.2. Spatial Distribution and Stage Contribution of Life Cycle GWP and EP

The spatial patterns of total life cycle GWP per kg milk and per head were similar to those of manure management. Confined dairy production in Wisconsin, Minnesota, Kansas, New York, Pennsylvania, and California had higher life cycle GWP per head than those located elsewhere (Figure 3). Their higher life cycle GWP per head was caused by their high CH_4 emissions from manure management and application, as a result of larger manure application area. For all counties, manure management and enteric fermentation were the top two contributors to the life cycle GWP per head, together resulting in over 90% of total life cycle GWP per head (Figure 5). Moreover, feed production offsets a significant portion of total GHGs (ranging from -4.8% to -78.2%), due to soil carbon sequestration and net uptake of atmospheric CO_2 by photosynthesis. In addition, the contribution of emissions from feed transportation was relatively small (less than 1% of total GHGs) as compared with emissions from other stages. The life cycle GWP of feed transport was observed to be higher in Texas, Kansas, Nebraska, and the Dakotas due to their longer transportation distances for feed supplies than the rest of the states.

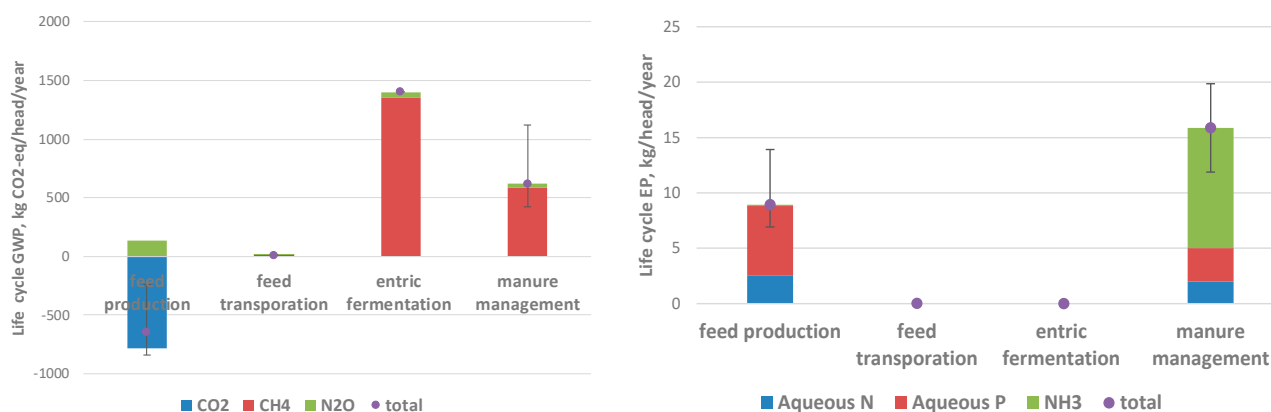


Figure 5. The contributions of various stages to the total life cycle global warming potential (GWP) and eutrophication potential (EP) of confined dairy production.

The spatial pattern of total life cycle EP per head was similar to EP from feed production (see Figure 4). Such a spatial pattern for life cycle EP per head was mainly driven by spatial variations in life cycle EP of feed production. For example, confined dairy production in Vega Baja County and San Lorenzo County of Nebraska had the lowest life cycle EP, because they purchased corn feed from Nebraska and Iowa, where the life cycle EPs of corn production were the lowest. Feed production was a significant contributor, resulting in approximately 33% of the total life cycle EP (Figure 5). The life cycle EP from manure management accounted for about 50% of the total life cycle EP. Despite being a top contributor to the total life cycle EP, the life cycle EP from manure management did not vary substantially across counties. In addition, EP from feed transportation was negligible as compared with other stages of confined dairy production.

The spatial distributions of life cycle GWP and EP per county were mainly driven by the spatial density of dairy cows. Multiple factors such as variations in amounts and spatial origins of dairy feed, in amounts of manure applied as fertilizer, and in temperatures contribute to the spatial differences in life cycle GWP per county (varying by a standard deviation of 952) and life cycle EP per county (varying by a standard deviation of 1.85). Among these factors, the number of confined dairy cows was the dominating factor for spatial distributions of life cycle GWP and EP per county (Figures 3 and 4). The number of confined dairy cows in the dairy counties ranged from 0 to 488,946, with a large standard deviation of 22,335. The substantial variation in numbers of dairy cows among US counties masked the variation in life cycle GWP per dairy cow. Therefore, the spatial distribution of the dairy population is a dominating factor for the spatial distribution of life cycle GWP of dairy production per county.

3.3. Influences of Feed Sourcing Strategies on Life Cycle GWP and EP of Confined Dairy Production

Local sourcing has been suggested as a sustainable means to reduce the life cycle GWP of food and feed supply chains. However, our spatial assessment suggested that local sourcing does not necessarily yield the lowest life cycle GWP and EP of feed supply chains for dairy production. In fact, the feed supply scenario with the lowest life cycle impacts depended on the life cycle impacts of feed production, geographic locations of dairy production, and targeted life cycle impact categories (Figure 6).

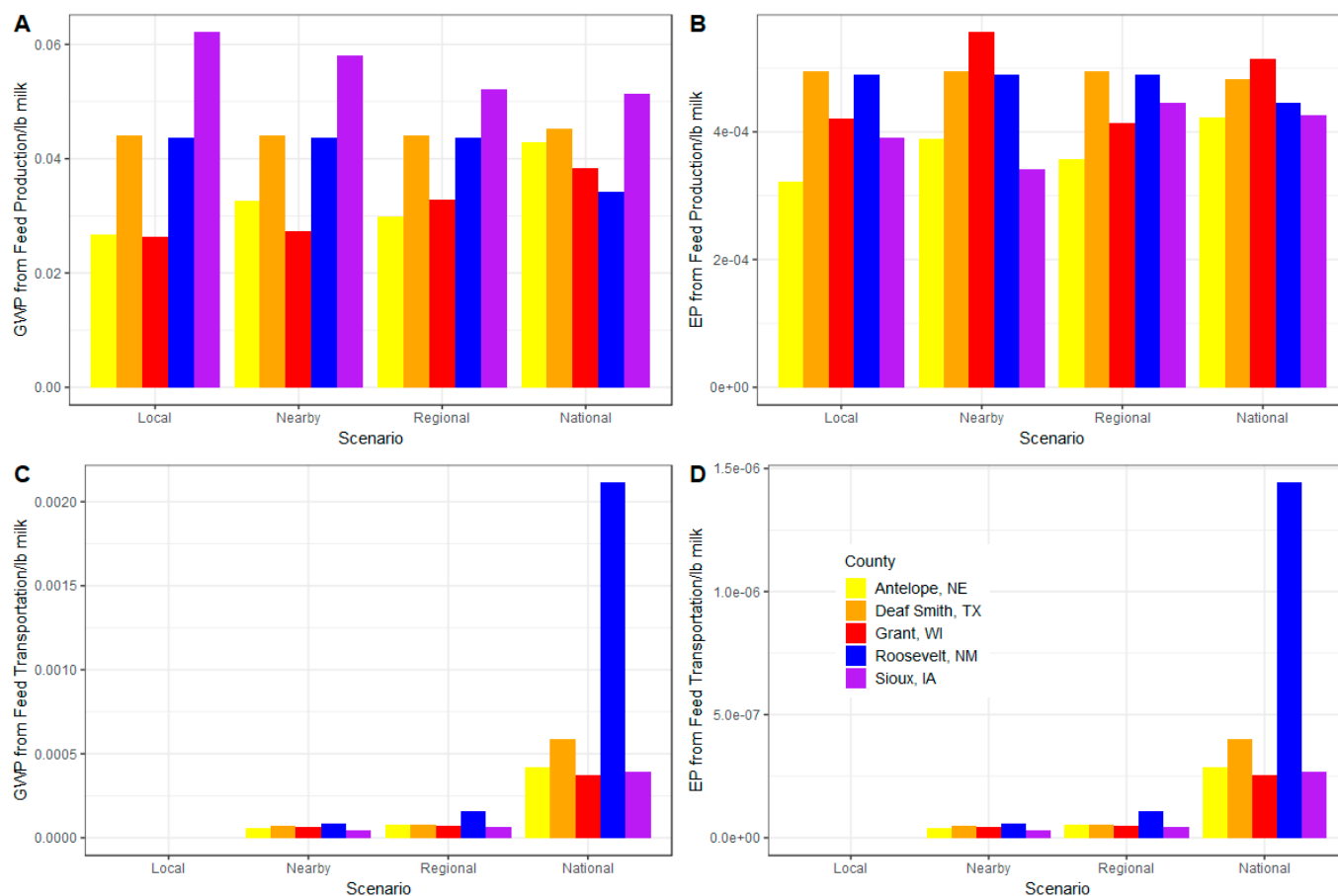


Figure 6. Life cycle global warming potential (GWP) and eutrophication potential (EP) of feed supply for top confined dairy-producing counties under local, nearby, regional and national sourcing scenarios. These counties include Antelope in Nebraska, Deaf Smith in Texas, Grant in Wisconsin, Roosevelt in New Mexico, and Sioux in Iowa.

The life cycle impacts of feed production, rather than feed transportation, dominated the life cycle impacts of feed supply for dairy production. For example, with increases in transportation distances across local, nearby, regional, and national scenarios, the life cycle GWP of feed transportation increased accordingly from 0 kg CO₂-eq/head for the local scenario to 1.13 kg CO₂-eq/head for the nearby scenario, 1.62 kg CO₂-eq/head for the regional scenario, and 10.4 kg CO₂-eq/head for the national scenario for Hamilton County, Kansas. Meanwhile, the life cycle GWP of feed production varied from −223 to −697 kg CO₂-eq/head among the four scenarios for Hamilton County. Based on the syntheses of these values across four feed supply scenarios for Hamilton County, we found that the absolute magnitude of life cycle GWP of feed transportation (0 to 10.4 kg CO₂-eq/head) is much smaller than the magnitude of life cycle GWP of feed production (−402 to −842 kg CO₂-eq CO₂-eq/head). The same finding applies to the life cycle EP of feed supply scenarios. For example, feed transportation resulted in less than 0.01 kg N-eq/head for all feed supply scenarios, which is negligible compared with 6.2–12.2 kg N-eq/head caused by feed production. Overall, the life cycle GWP and EP of feed supply is largely determined by crop farming (as influenced by local weather, soil, and farming practices) rather than feed transportation.

The most environmentally preferred feed supply option was county-specific and varied across the geographic locations of dairy production. The regional supply scenario was the lowest life cycle GWP for Hamilton, Tulare, and Wayne counties, due to their lowest life cycle GWP of feed production under the nearby supply scenario. Using Hamilton as a case example, the regional scenario presented the lowest life cycle GWPs of feed

production at -698 kg CO₂-eq, because Greeley, Kearny, Stanton, and Wichita counties, with an average life cycle GWP of -0.47 kg CO₂-eq/kg corn, supplied feed for Hamilton County under the nearby scenario. In contrast, the national supply scenario presented the lowest life cycle GWP for Erath and Manitowoc counties. For example, confined dairy production in Erath County purchased feed from Appanoose, Clarke, and Lucas counties in Iowa for the national supply scenario, which showed the lowest life cycle GWP of corn production at -764 kg CO₂-eq/kg corn. The most environmentally preferred supply option was not consistent across the five investigated counties. If the dairy-producing county is adjacent to corn-producing counties, whose life cycle impacts are lower than national levels, the dairy-producing county is recommended to purchase corn from the adjacent counties. Otherwise, the dairy-producing county is recommended to travel further to purchase corn from counties where soil and climate conditions promote the highest carbon sequestration for corn production.

Environmental tradeoffs among life cycle GWP and EP exist for choices of feed supply scenarios. For example, although the regional supply scenario showed the lowest life cycle GWP, it exhibited the highest life cycle EP for dairy production in Hamilton County. Also, the national supply scenario was the best option from a GWP perspective, and the second worst option from an EP perspective for Erath county. These findings suggest that achieving the reduction in GHGs by switching supply chain options may increase life cycle nutrient releases, resulting in water quality degradation. Such tradeoffs highlight the multifaceted nature of environmental challenges and serve as a basis for avoiding potential problem shifting.

3.4. Influences of Installing Buffer Strips in Feed-Producing Counties on Life Cycle EP of Confined Dairy Production

Installing buffer strips in feed-producing counties can reduce the life cycle EP of feed production, therefore mitigating the life cycle EP of confined dairy production. The reduction in life cycle EP of confined dairy production is influenced by the numbers and locations of counties where buffer strips are installed. As shown in Figure 7, when buffer strips are installed in the top 50 counties with the highest life cycle EP of corn, the total life cycle EP of confined dairy production in the US is mitigated by 9.4%. If 200 counties with the highest life cycle EP of corn adopt buffer strips, the reduction in life cycle EP of confined dairy production could reach 24.4%. However, when the bottom 200 counties, which present the lowest life cycle EP of corn, implement buffer strips, the life cycle EP of confined dairy production in the US will be reduced by only 0.16%. Essentially, prioritizing the installment of buffer strips in feed-producing hotspots, which are counties presenting the highest life cycle EP of corn, is capable of achieving a significant reduction in life cycle EP of confined dairy production.

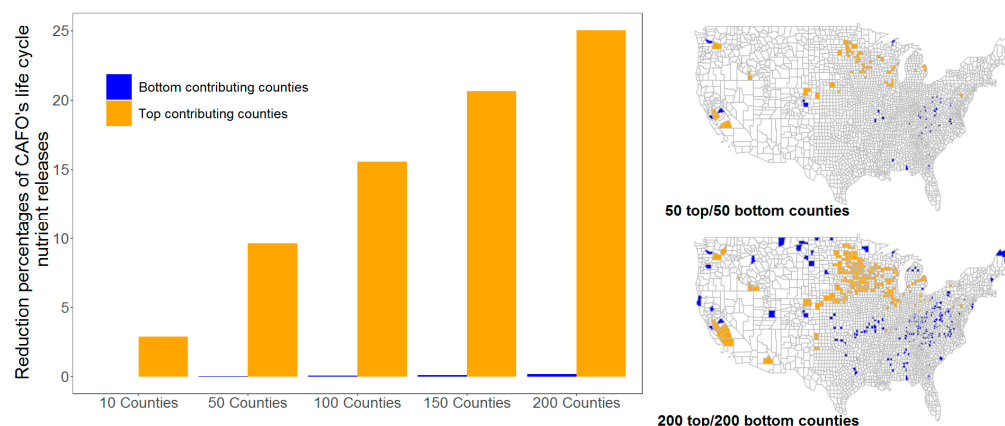


Figure 7. Reduction percentages in life cycle EP of confined dairy production impacts due to installing buffer strips in feed-producing counties.

4. Discussion

4.1. Sensitivity Assessment

The sensitivity assessment indicated that corn consumption rate was the top influencing factor for both life cycle GWP and EP (Figure 8). When corn consumption rate varied by $\pm 10\%$, life cycle GWP and EP changed by $\pm 9\%$, and $\pm 6\%$, respectively. For life cycle GWP, the second equal most influential factors were the percentage of stored manure applied as fertilizer and area of farmland that received manure as fertilizer. A 10% change in these two factors led to a 6% change in life cycle GWP. In addition, barn floor area, volatile solids excreted in manure, and the CH_4 conversion factor for manure management had minimal influences on the life cycle GWP (less than 1%). For life cycle EP, the second most influential factor was fraction of total ammoniacal nitrogen. When the fraction of total ammoniacal nitrogen varied by $\pm 10\%$, life cycle EP changed by $\pm 5\%$. Overall, the sensitivity assessment confirmed the importance of the feed production stage for life cycle GWP and EP of confined dairy production.

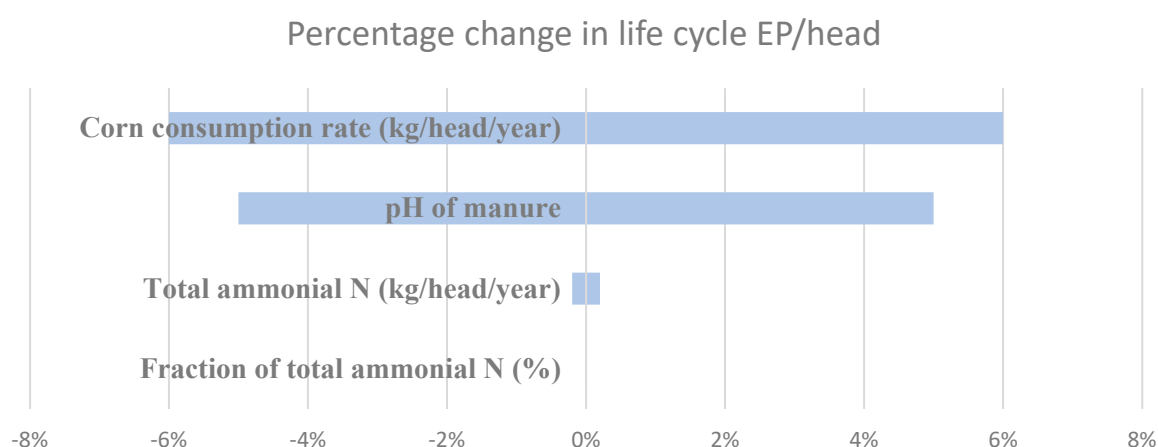


Figure 8. Sensitivity analyses of life cycle GWP and EP/head for confined dairy production.

4.2. Comparison with Existing Studies

We compared our estimates of life cycle environmental impacts of dairy production with other US-based studies. When using the milk productivity of 9700 kg/cow/year and caloric content of milk at 0.26 ECM/kg, our median life cycle GWP of dairy production, 1.9 kg CO_2 /kg milk, was within the reported range of the existing values in the US spanning from 0.8 to 4 kg CO_2 /kg milk [8,20,27]. Our estimate resided at the lower end of this reported range, mainly due to the inclusion of soil carbon change for life cycle GWP of feed production. In addition, our study showed a much wider range of life cycle GWP for dairy production. Our broader geographic scope and more granular resolution led to a wide range of GWP estimates for dairy production. Differing from the existing studies, our study was the only study capturing the spatial heterogeneity of life cycle GHG for confined dairy production among US counties, due to their distinct weather, soil, and supply chain characteristics.

While the majority of the existing LCA studies focused on life cycle GWP, only a few recent studies quantified the life cycle EP of dairy production in the US [19,20]. The discrepancies in system boundaries, different metrics, and distinct modeling approaches among these studies reporting life cycle EP of dairy production made the comparison difficult. First, system boundary varied from a single stage of food supply chains (i.e., agriculture phase only) to the entire food supply chain. Costello et al.'s work and this study primarily focused on the agricultural production phase [19]. Xue and Landis evaluated the life cycle EP of food supply chains including production, packaging, processing, and distribution stages [20]. Moreover, Xue and Landis's work and this study use equivalent NO_3 -release to unify both nitrogen and phosphorus releases for EP estimates. Costello et al.

focused on the life cycle nitrogen input for agricultural production. In addition, various modeling approaches have been used in previous studies. Costello et al. was primarily based on the NANI model. Xue and Landis used a nutrient emission factor approach coupled with Monte Carlo analyses. This study combined both biogeochemistry modeling (i.e., EPIC estimates) and emission-factor-based equations in order to derive county-level estimates. The median life cycle EP value of dairy production in this study was smaller than the other two studies, mainly because of the narrower system boundary and different computational methods.

4.3. Implications for Environmental Sustainability of Confined Dairy Production

Assessing the spatial differences in life cycle environmental impacts of confined dairy production systems is necessary to develop a reasonable baseline and to identify improvement opportunities for the environmental sustainability of confined dairy production. The county-scale results enable stakeholders (such as academia, farms, food industries, government, and consumers) to identify spatial patterns of the environmental impacts of dairy products better than traditional assessments at country and state scales. The spatial LCAs will aid dairy businesses in prioritizing remediation and investment strategies, supporting environmental certification efforts for the dairy sector, and providing a scientific basis for consumers' environmentally conscious consumption.

Moreover, this study highlights the opportunities and challenges in mitigating life cycle environmental impacts of feed supply for confined dairy production. Optimizing the feed supply networks such as shifting feed sources from high-impact to low-impact counties is an effective measure for improving the confined dairy system's life cycle performances. If confined dairy operations purchase all their corn feed from counties with the lowest life cycle EP of corn production, the life cycle EP of confined dairy operations will be reduced by approximately 20%. However, corn is required for multiple sectors such as confined livestock production, corn-based fuel production, and corn-based food processing industries. The competition for low-impact corn among corn-consuming sectors will likely increase the prices of low-impact corn and decrease the availability of low-impact corn for confined dairy operations. Implementing best farming practices in feed-producing counties is another effective approach for reducing the life cycle environmental impacts of confined dairy production. If the top 200 counties with the highest life cycle EP of corn adopt buffer strips, the reduction in life cycle EP of confined dairy production could reach 24%. However, the installation of buffer strips depends on farmers' willingness, economic and policy incentives, and technical support.

Furthermore, this study supports adopting conservation policies at feed-producing hotspots, where the implementation of conservation policies will achieve the maximum reduction in life cycle GHGs and nutrient releases of dairy feed production. USDA's Conservation Reserve Program (CRP) and Environmental Quality Incentives Program (EQIP) [60–62] both aim to mitigate the negative environmental impacts of agricultural production. The challenge faced by both federal programs is determining how to form solutions capable of achieving the greatest positive impact with the least resources. This study identified which corn-producing counties should be prioritized for implementing buffer strips, for effectively minimizing life cycle GHGs and nutrient releases from confined dairy production. Focusing conservation efforts in spatial hotspots of feed-producing counties can significantly reduce the life cycle EP of confined dairy production in the US.

Additionally, multidimensional assessment of confined dairy production is needed to identify effective strategies for achieving environmental sustainability. Confined dairy production consumes water and energy, and emits greenhouse gas emissions and aqueous pollutants. Considering the synergies and tradeoffs among different environmental impact categories, the food–energy–carbon–water nexus approach is needed to provide a comprehensive assessment of environmental impacts and to suggest effective strategies [63–65].

5. Conclusions and Outlook

By coupling biogeochemistry, geospatial, emission factor, and life cycle assessment models, this study is the first to analyze the life cycle GHG and EP of confined dairy production in the US at the county scale. Our results revealed the spatial variability of life cycle GHG and EP of confined dairy production, and identified spatially targeted remediation approaches to effectively mitigating environmental impacts.

Designing sustainable agricultural systems requires continuous modeling development and multidisciplinary collaboration. Further improvements in modeling efficiency for spatially explicit assessment are required for better supporting decision making. Although spatially explicit assessment is effective for understanding and mitigating adverse environmental impacts of agricultural production, the spatially explicit assessment often requires spatially explicit datasets and modeling, and is much more time-consuming than spatially generic assessment. We recommend future studies to explore novel and efficient modeling techniques capable of rapidly conducting spatially explicit assessment. Furthermore, this study primarily focused on confined dairy production. Future spatially explicit LCA studies are recommended to evaluate the spatially explicit life cycle environmental impacts of other animal production systems. In addition, future collaborations among LCAs, supply chain logistics, system dynamic and socioeconomic analyses will further identify the spatial distributions of social benefits and burdens for various remediation strategies.

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