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Energy footprint of food: The case of corn production in Delaware

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Abstract

Food production is an energy-intensive process, especially for crops and meat. However, the link between food and the energy consumed to produce it is less transparent to customers and there is a lack of energy footprint information for food production in the market. This study develops a geospatial approach for estimating the direct energy use for food production, that is, the Energy Footprint of Food (EFF), and tests it for one crop in one U.S. state, that is, field corn in Delaware. Delaware was chosen because it is a relatively small state (with only three counties) with publicly available high-resolution geospatial datasets and with corn as the dominant crop type. We find that the energy use for field operation is the largest energy component for corn production on small farms while the drying process requires the highest energy on medium and large farms. Our results also indicate that producing corn on large and medium farms is more energy-efficient than on small farms, although small farms consume less electricity and less groundwater for irrigation per unit corn product. Of the three counties in Delaware, Sussex has the highest energy consumption for corn production while Kent has the lowest. On average in Delaware, the corn production requires 42,789 MWh of electricity, 4.2 million gallons of diesel, 1.4 million gallons of gasoline, and 3.1 million gallons of LPG, giving an EFF of 38,171 Btu per corn bushel or 682 Btu/lb. The EFF assessment can inform consumers about the energy inputs of food and provide useful insights for stakeholders and policy makers to develop more sustainable strategies for the food industry. The novelty of this study is to develop a geospatial inventory of EFFs for corn production. Moreover, the proposed methodology is based entirely on public data and is likely generalizable to most other states and crops.

KEYWORDS

corn production, energy footprint, food, fuel use, irrigation

1 | INTRODUCTION

The food industry is recognized globally as an energy-intensive sector. The food production and supply chain account for about 30% total global energy consumption (FAO, 2011). However, the link between food and the corresponding energy consumption is far from clear in public and scientific discourse in the United States. Whereas labels exist on calories, nutritional content, and ingredients of packaged food, information on energy use of food products, such as the amount of kilowatt hours (kWh) or gallons of oil or total Btu (British thermal unit) needed to produce a hamburger or an apple, is unknown. Even in the scientific community, the link between food and energy in the United States is not well-understood. For example, the U.S. Energy Information Administration (EIA) identifies four energy consumption sectors (industrial, commercial, residential, and transportation) but food industry is embedded in several subcategories of the four sectors and not separated out in its own sector.

Research on the topic of energy use for food at the global scale has been conducted by a few international organizations. For instance, the water–food–energy nexus is central to sustainable development. The inextricable linkages between these critical domains require a suitably integrated approach to ensure water and food security, and sustainable agriculture and energy production worldwide. Energy use assessment for food production can provide a clear way to understand how to develop a more sustainable food industry. The direct on-farm yearly energy demand (e.g., pumping irrigation water, housing livestock, and cultivating, harvesting, drying and storing crops) is roughly 1,700 TWh (Terawatt hour), while the indirect yearly energy demand (e.g., operating tractors and other farm machinery, fertilizer manufacturing) is even larger, approximately 2,500 TWh (WWAP, 2014). Similarly, the global direct and indirect energy consumption in fisheries are 550 and 140 TWh, respectively. Primary production of food and corresponding agricultural management strategies (e.g., tractors and machinery, irrigation, and fertilizers) are not even the largest energy-demanding components, only around 20%; the remaining 80% is actually needed for retailing, preparation and cooking, processing, and distribution (FAO, 2011).

The most comprehensive study of the energy and food links in the United States is that by Canning, Charles, Huang, Polenske, and Waters (2010), funded by the U.S. Department of Agriculture (USDA), which is focused on the decade 1997–2007. According to it, 15.7% of the total energy in the United States is used by the food sector, of which only about 14% is due to primary production while 19% is due to food processing. Although extremely valuable, the statistics presented are as follows: for the country as a whole, without geographical, state-, or county-level granularity; grouped into broad categories, such as fresh fruits; and relatively old (the latest year was 2007). The Farm Energy Analysis Tool (FEAT) developed by the Pennsylvania State University (Camargo, Ryan, & Richard, 2011) is a database model that can evaluate energy and greenhouse gas (GHG) emissions for different agricultural systems. FEAT focuses on the effects of different agricultural managements on the energy output and GHG emissions of crops, and the energy analysis excludes the energy use for irrigation.

The objective of this study is to estimate the energy use for food production, that is, the Energy Footprint of Food (EFF), by developing a new methodology that can be applicable to all food products and to all regions/states in the United States. Field corn production in Delaware is selected as the test case. Field corn is usually used to make animal feed and renewable fuels in the United States. Moreover, field corn can be processed to be food products and ingredients such as corn syrup, corn flakes, yellow corn chips, corn starch, or corn flour. This study investigates field corn production to demonstrate how the energy consumption can be assessed and how the energy data can be incorporated into geographic information system (GIS) in order to examine the variations in energy footprint of corn production in different farms. The direct energy consumption of corn production for different farms will be aggregated at the county level. Moreover, two other footprints are commonly used in relation to crops and food. The first is the carbon footprint (CF), which quantifies carbon emissions associated with the entire life cycle of selected food/crop products, including production, distribution, sale, and disposal (Hillier et al., 2009; Mesfin M. Mekonnen et al., 2018). The most common approach for the CF estimation is life cycle assessment (LCA). As the scope of the CF is broader than that of the EFF, the EFF, which is more accurate because of its geospatial nature, can be used as the energy use input to estimate the CF. The second metric is the water footprint (WF) (Mekonnen & Hoekstra, 2011), a water consumption indicator that comprises the green (from precipitation), blue (from irrigation), and gray (causing water pollution) water consumption by crop and food type (including meat) at the national (e.g., the United States) and subnational (e.g., each state in the United States) levels (Mekonnen & Hoekstra, 2011). The EFF focuses on just the blue water consumption of the WF, and thus, the two footprints can be used to verify one another.

The corn production system for food includes activities such as planting and growing corn, harvesting, transporting, processing and packaging, and marketing as food products. However, the scope of this study is the assessment of direct energy inputs in the corn planting, growing, and harvesting processes only. Corn is usually grown from April to October. From planting to harvesting, managements such as seeding, fertilizing, and irrigating use machines and pumps. Then corn is harvested with a high moisture to protect the kernel. Corn needs to be dried before it is ready to be market. The direct energy inputs within the research scope therefore include the following: electricity for irrigation and corn drying, and fuel for field operation (e.g., diesel and gasoline for fertilizing and harvesting). The uses of diesel and electricity rank first and second for direct energy inputs in the agricultural sector (Hitaj & Suttles, 2016). The indirect energy inputs, such as fertilizer and chemical use, are out of this research scope.

2 | DATA

Two types of data were used for this study: geospatial and nongeospatial data. For both, the required characteristics are granularity as fine as possible and availability nationwide.

2.1 | Geospatial data

Geospatial data used in this study include the 2017 Delaware Cropland Data Layer (CDL), the 2016 National Land Cover Database (NLCD), and Delaware county parcel layer. The details of geospatial data are described as follows.

The Cropland Data Layer (CDL) that was created by the USDA and National Agricultural Statistics Service (NASS) is a geo-referenced raster data layer for crop-specific land cover information for the continental United States (USDA-NASS, 2019b). The CDL is created by using moderate resolution satellite imagery and extensive agricultural ground truth data to provide acreage estimates of specific crop commodities. The 2017 CDL has a ground resolution of 30 × 30 m. The overall accuracy of the 2017 CDL is 82.3% and the accuracy of corn land cover is 92.4% based on the accuracy assessment report (USDA-NASS, 2019b). The differences in acreage statistics between CDL and Agriculture Census are due to the different methods used for acreage estimates: in CDL it is dependent upon pixel counting, while in the Census it is the result of direct surveys. In this study, the estimated acreage of corn for grain in Delaware is obtained from the 2017 national CDL (see Figure 1a). The problem with this geo-dataset is that some pixels are misclassified as corn due to spectral responses similar to other noncultivated land. In order to eliminate the inaccurate assignment of a pixel to corn, the NLCD is used to overlap with the CDL for obtaining the actual corn area.

The Delaware land cover geospatial database is derived from the NLCD released by the U.S. Geological Survey (USGS) (Yang et al., 2018). The NLCD is based on 30-m resolution Landsat images, and the NLCD 2016 is the most up-to-date available version. It contains 28 different land cover types characterizing land cover and land cover change across 7 epochs from 2001 to 2016, urban imperviousness and urban imperviousness change across 4 epochs from 2001 to 2016, tree canopy and tree canopy change across 2 epochs from 2011 to 2016 and western U.S. shrub

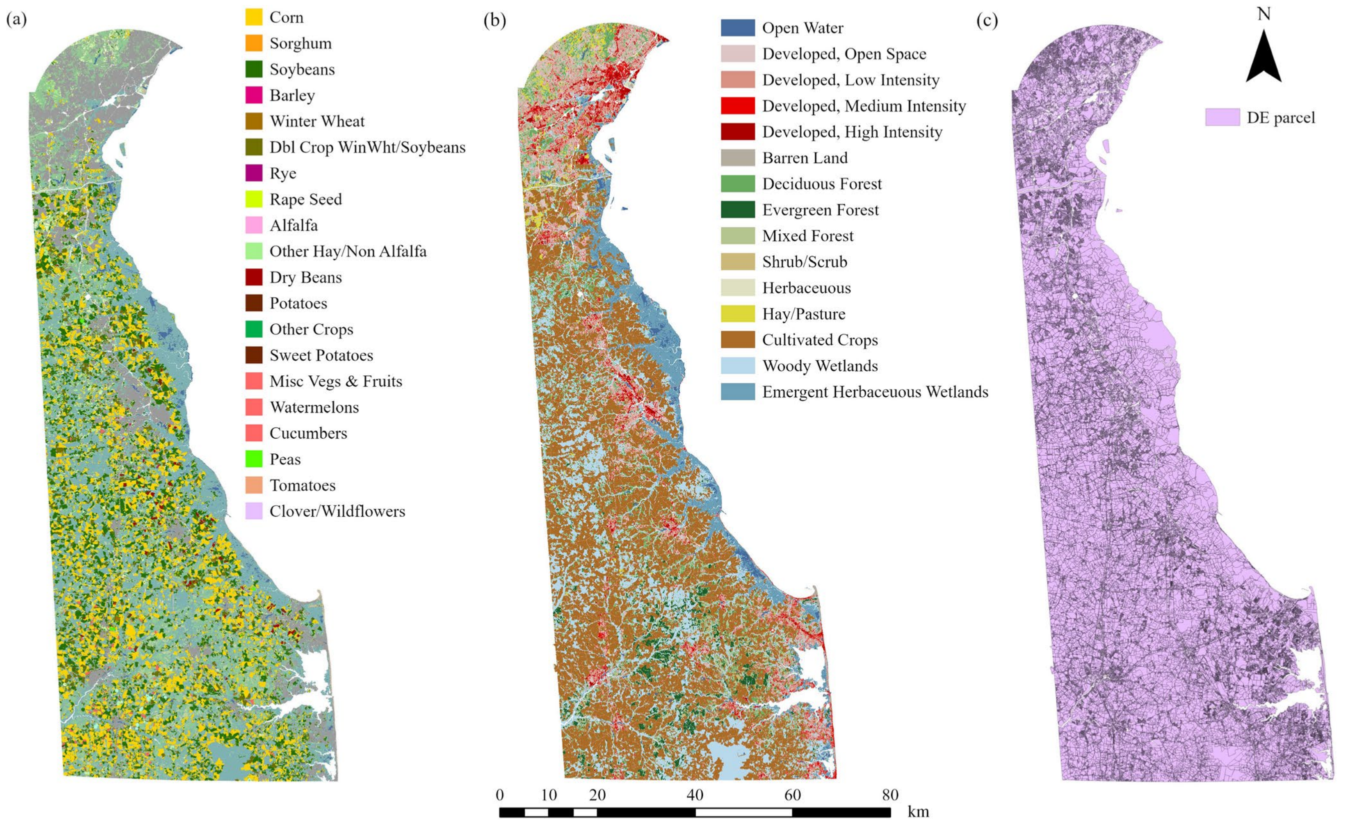

FIGURE 1 (a) Delaware Cropland Data Layer (e.g., yellow pixels are corn area and green pixels are soybean area) for 2017, (b) Delaware Land Cover Layer derived from the 2016 NCLD (e.g., brown pixels are cultivated crop land), (c) Delaware County Parcel Layer for 2019

and grassland areas for 2016 (Yang et al., 2018). Figure 1b is the land cover database of Delaware in 2016. Even after overlapping the CDL and the NLCD layers to obtain geospatial information about corn area on the cropland, it was impossible to tell which of these corn pixels belonged to the same farm. Since the energy data, described shortly, were available at the aggregated farm level only, it is necessary to acquire additional geospatial information about the parcel area and their owners. This information was provided by the Delaware county parcel layer.

The Delaware county parcel layer was aggregated from the three county parcel layers that include the information about acreage and ownership of each parcel (see Figure 1c). Three county parcel layers are updated annually, and this study uses the latest version of 2019 county parcel layers obtained from the government land use service of New Castle, Kent, and Sussex county. Each parcel has its own land use class such as residential land, commercial land, and agricultural land. Parcels classified as "agricultural land" were identified as farms. A farm can have many parcels, and not all of them are necessarily corn. The exact cropland and corn area of each parcel will be obtained by intersecting the county parcel layer with the CDL and the NLCD layers.

The 2017 Census of Agriculture (U.S. Department of Agriculture, 2019) conducted by the USDA and NASS provides updated statistics on U.S. farms and ranches every five years. It is the leading source of uniform, comprehensive agricultural data for every state and county. Among the many tables available in it, the table titled "Summary by size of farm" in the 2017 Delaware Census of Agriculture data was utilized to estimate the irrigated area of corn and fuel consumption for the field operation for farms in different farm size categories in this study, as explained in the Methods section.

Irrigation is critical to agriculture in the United States: 50 percent of the value of all crops sold comes from irrigated farms, accounting for only 28 percent of all harvested cropland (USDA-NASS, 2014b). Irrigated farms account for nearly 27% of the total farms in Delaware and more than 94% of the irrigated farms use electricity to pump groundwater for irrigation (USDA-NASS, 2019a). The other 6% of farms use diesel and gasoline for pumping water.

The irrigation data conducted by the Farm and Ranch Irrigation Survey (USDA-NASS, 2014a) is also updated every five years, and the latest available irrigation data are the year of 2018. It includes the irrigated acreage, water applied, and energy cost on-farm from different water resources and irrigation systems in 2018. The irrigation data are aggregated for irrigated farms that are uniform for different farm size classes. For instance, the information of on-farm groundwater applied and electricity expense for irrigation is shown in Table 1. The irrigation data in 2013 differentiate the water use and electricity expenses by the economic class of farms. However, such information is not available in the latest irrigation data. The average irrigated acres by groundwater per farm can be calculated by the total acres irrigated and the number of farms in each farm size category.

In addition, the groundwater applied to irrigated corn area is derived from USDA/NASS QuickStats (USDA, 2011), which is an online database containing official published aggregate estimates related to U.S. agricultural production that offers a quick search for demographic, economic, and environmental information of a specific crop commodity (USDA-NASS, 2019.). NASS develops these estimates from data collected through annual U.S. agricultural survey and the Census of Agriculture conducted every five years.

The machinery equipment in a farm for corn field operation mainly consumes diesel and gasoline. Therefore, the fuel expenses for corn field operation only include the costs of diesel and gasoline. The prices of diesel and gasoline in 2017 are found from the statistics of petroleum and other liquids in the Central Atlantic region conducted by the U.S. Energy Information Administration (EIA).

Drying is a necessary process for corn grain storage through warm weather. The need for drying depends on the planting date, the weather during the growing season and harvest, and the adapted maturity level for the growing location. The amount of moisture to be removed can vary widely, sometimes by as much as 10 percentage points or more. The conventional gas-fired dryer consumes liquefied petroleum gas (LPG) and electricity to dry and cool corn grains. The mostly used LPG is propane. To remove 1 percentage point of moisture content per bushel of corn grains, a conventional high-temperature dryer uses about 0.02 gal of propane and 0.01 kWh of electricity (Wilcke, 2018). In this study, corn will be harvested at 21% moisture content and will be dried at 16% moisture content in order to be marketed immediately based on the previous study conducted by Wilcke (2018). The prices of propane and electricity in 2017 are referred to the statistics of propane and electricity in Central Atlantic region conducted by U.S. EIA (2019c). The market price of propane received by farmers is estimated to be the average price of retail and wholesale propane prices.

3 | METHODS

3.1 | Assumptions

Due to the limitations and the resolution of the aggregated data that are used for estimating the energy footprint of corn production, the following key assumptions are made to enable the applicability of the proposed methodology to other food products and at different scales:

1. Each farm has a proportion of irrigated corn area that depends on the farm size. This means that no corn

TABLE 1 Data used from the 2017 Delaware Census of Agriculture and the 2018 U.S. Irrigated Agriculture dataset

Farm size (acres)	Corn Acres irrigated	Total corn acres	Fraction of irrigated corn ($A_{irr,j}^{corn}$)	Irrigated groundwater (gallons per acre[a])	Electricity expense (dollars per irrigated acre)	Electricity use (e^{tot}) (kWh per irrigated acre[b])
1–9	7	20	33%	130,340	48.82	646.1
10–49	207	1,394	15%			
50–69	412	1,086	38%			
70–99	549	1,405	39%			
100–139	1,086	2,677	41%			
140–179	900	2,763	33%			
180–219	1,448	3,250	45%			
220–259	2,103	4,874	43%			
260–499	6,000	15,394	39%			
500–999	20,894	38,685	54%			
1,000–1999	24,436	53,197	46%			
2000 or more	27,663	63,218	44%			

[a]This value is converted from the irrigated groundwater of 0.4 acre-feet per acre. One acre-foot is equal to 325,851 gallons.

[b]The average industrial electricity price in 2018 is 7.56 cents/kWh (U.S. EIA, 2019a).

area is either 100% irrigated or not irrigated at all and that all the corn areas in the same farm size category will have the same fraction of irrigated corn area. In Delaware, this may introduce an error as some farms exist that do not use any irrigation systems at all while many others are entirely irrigated. However, this assumption is necessary to disaggregate the energy and irrigation data to the parcel layers and it guarantees that the state-level totals will be preserved.

2. The source of water applied on each farm is groundwater because groundwater is dominant (90% of irrigated farms use groundwater for irrigation) in the irrigation system in Delaware. Farms in each farm size group have same fuel consumptions for field operation.
3. Fuel use of machinery equipment for field operation only consists of diesel and gasoline. The LPG is only used to dry corn on each farm.
4. Corn grains need to be dried as food products with further processing. Gas-fired dryers using LPG and electricity are commonly used for the drying process.

It should be noted that some of these assumptions may need to be varied according to different scenarios, data availability, and agricultural practices in different states.

3.2 | Calculations

The energy footprint assessment of corn production consists of two steps. First, the geospatial data are analyzed using the ArcGIS Pro software. The objective of the geospatial analysis is to estimate the area of grown corn A_i^{corn} and the total cropland A_i^{tot} in each parcel i. Note that the most granular level of our GIS analysis is ultimately the parcel, not the farm, because large farms may have multiple parcels, not all of which grow corn. The cropland data layer is intersected with the Delaware land cover layer to extract the corn areas that are grown on farmland (e.g., black circle area in Figure 2a and b). Corn pixels that did not fall in cropland or pasture parcels were treated as errors. Then, the extracted corn area on the farmland is intersected with the Delaware county parcel layer so that the corn area is assigned to each farm based on the parcel boundary (e.g., red circle area in Figure 2c and d). Finally, the acreage of corn area and the proportion of corn field to the total cropland on-farm can be evaluated.

The second step combines the geospatial data from the previous step with the nongeospatial data from multiple sources (Figure 3). The total energy inputs for each parcel $i(E_i^{corn}\,(\text{Btu}), i = 1 \ldots 10{,}144)$ are equal to the sum of energy content of electricity and fuels used in the process of corn production as follows:

$$E_i^{corn} = \left(E_{elec,irr,i}^{corn} + E_{elec,dry,i}^{corn}\right) \times C_{elec} + \sum_f Q_{f,i}^{corn} \times C_f, \qquad (1)$$

where $E_{elec,irr,i}^{corn}$ and $E_{elec,dry,i}^{corn}$ (kWh) are the electricity use for corn irrigation and drying on parcel i; $Q_{f,i}^{corn}$ (gallons) is the amount of fuel of type f (f = *diesel*, *gasoline*, or *LPG*) for field operation on parcel i; and C_{elec} and C_f are the energy conversion factors for electricity and fuels (C_{elec} = 3,412 Btu/kWh, C_{diesel} = 137,381 Btu/gallon, $C_{gasoline}$ = 120,333 Btu/gallon, and C_{LPG} = 91,333 Btu/gallon) (U.S. EIA, 2019b).

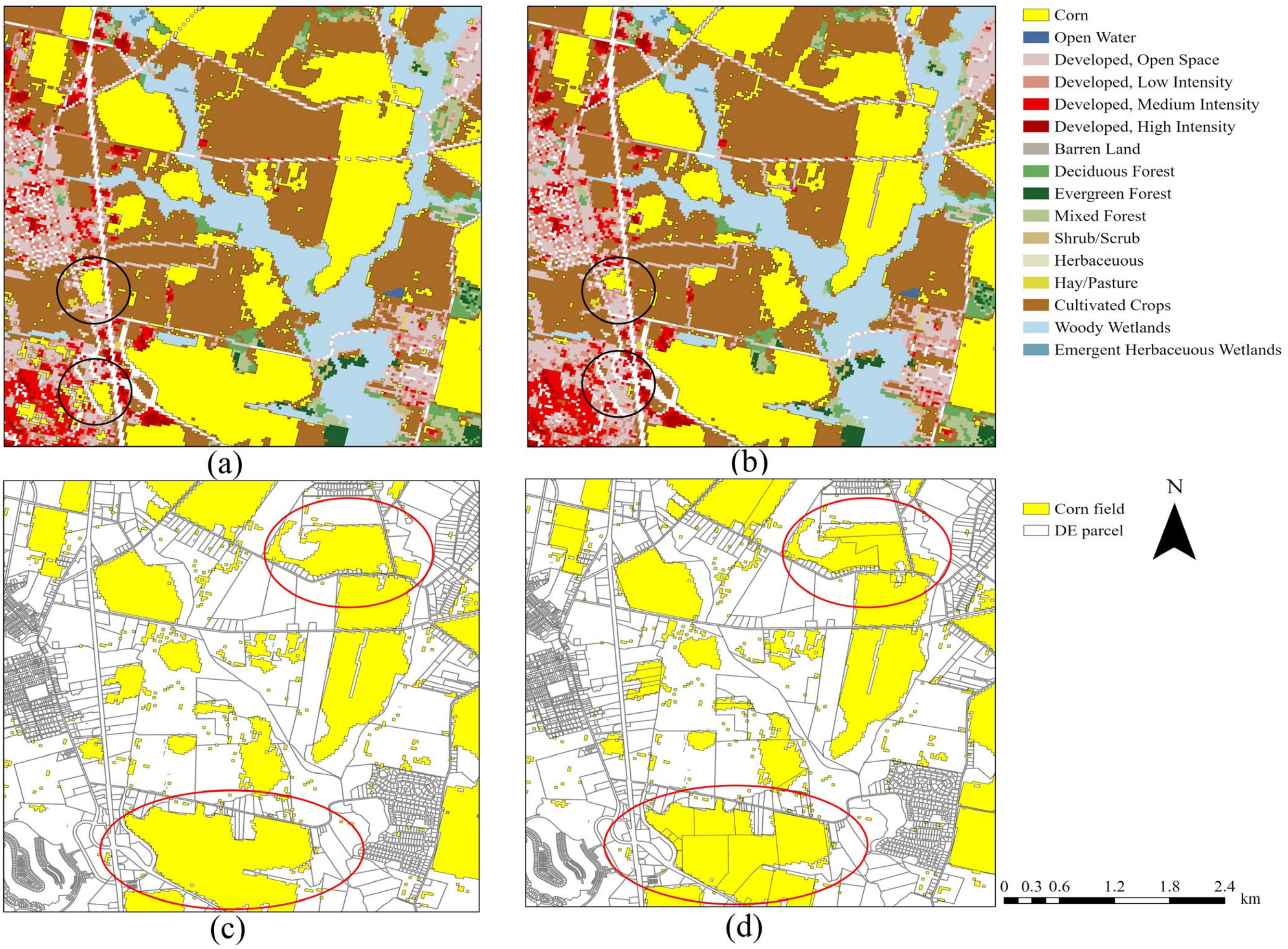

FIGURE 2 Geospatial analysis of corn area in parcels in selected region: (a) corn area overlapped with all kinds of land use; (b) corn area only on the cultivated crop and pasture lands; (c) corn area before assignment to parcels; and (d) corn area after assignment to parcels. The black and red circles indicate some hard-to-see differences

The energy use for corn irrigation $E_{\mathrm{elec,irr},i}^{\mathrm{corn}}$ is assessed based on the aggregated data of electricity consumption for pumping groundwater, and it is assumed to be equal to the ratio of the water applied to the corn field W_i^{corn} to the total water applied to the parcel W_i^{tot} as follows:

$$E_{\mathrm{elec,irr},i}^{\mathrm{corn}} = E_{\mathrm{elec,irr},i}^{\mathrm{tot}} \times \frac{W_i^{\mathrm{corn}}}{W_i^{\mathrm{tot}}}, \tag{2}$$

where $E_{\mathrm{elec,irr},i}^{\mathrm{tot}}$ is the total electricity use for irrigation, estimated as follows:

$$E_{\mathrm{elec,irr},i}^{\mathrm{tot}} = e_i^{\mathrm{tot}} \times A_{\mathrm{irr},i}^{\mathrm{tot}} \approx e_j^{\mathrm{tot}} \times A_{\mathrm{irr},i}^{\mathrm{tot}} = e^{\mathrm{tot}} \times A_{\mathrm{irr},i}^{\mathrm{tot}}, \tag{3}$$

where e_i^{tot} is the kWh per irrigated acre of parcel i (belonging to size category j), estimated as e_j^{tot} from Table 1, which is actually the same value e^{tot} for all size categories; and $A_{irr,i}^{tot}$ is the total irrigated area (for all crops) in parcel i, which is ultimately not needed. Note that each parcel belongs to one farm size category j and there are 12 size categories (Table 1). The second term in Equation (2) is estimated as:

$$\frac{W_i^{\mathrm{corn}}}{W_i^{\mathrm{tot}}} \approx \frac{W_j^{\mathrm{corn}} \times A_{irr,i}^{\mathrm{corn}}}{W_j^{\mathrm{tot}} \times A_{\mathrm{irr},i}^{\mathrm{tot}}} = \frac{W^{\mathrm{corn}} \times A_{irr,i}^{\mathrm{corn}}}{W^{\mathrm{tot}} \times A_{\mathrm{irr},i}^{\mathrm{tot}}} = \frac{W^{\mathrm{corn}} \times \frac{A_{\mathrm{irr},j}^{\mathrm{corn}}}{A_j^{\mathrm{corn}}} A_i^{\mathrm{corn}}}{W^{\mathrm{tot}} \times A_{\mathrm{irr},i}^{\mathrm{tot}}}, \tag{4}$$

where w_j^{corn} and w_j^{tot} (both are equal to 130,340 gals/irrigated acre) are the intensities of groundwater irrigation for corn and the cropland, which are in principle differentiated by the farm size j, but in fact only one value for each was available for all size categories (w^{corn} and w^{tot} in Table 1); $A_{\mathrm{irr},i}^{\mathrm{corn}}$ (acres) is the corn irrigated area, estimated with the ratio $\frac{A_{\mathrm{irr},j}^{\mathrm{corn}}}{A_{\mathrm{irr},j}^{\mathrm{tot}}}$ for the farm size category j to which parcel i belongs (Table 1); and A_i^{tot} and A_i^{corn} (acres) are the cropland and corn areas on parcel i. Equation (2) can therefore be simplified as:

$$E^{\mathrm{corn}}_{\mathrm{elec,irr},i} = \frac{e^{\mathrm{tot}} \times w^{\mathrm{corn}}}{w^{\mathrm{tot}}} \times \frac{A^{\mathrm{corn}}_{\mathrm{irr},j}}{A^{\mathrm{corn}}_{j}} \times A^{\mathrm{corn}}_{i} \tag{5}$$

For the energy use in corn field operation, the direct energy inputs for machinery equipment are mainly diesel and gasoline. The fuel use for corn field operation is correlated with the acreage of corn field on-farm as follows:

$$Q^{\mathrm{corn}}_{f,i} = Q^{\mathrm{tot}}_{f,i} \times \frac{A^{\mathrm{corn}}_{i}}{A^{\mathrm{tot}}_{i}} \approx Q^{\mathrm{tot}}_{f,j} \times \frac{A^{\mathrm{corn}}_{i}}{A^{\mathrm{tot}}_{i}}, \tag{6}$$

where f is either diesel or gasoline, and $Q^{\mathrm{corn}}_{f,i}$ (gallons) is the f fuel use for field operation on parcel i, which is approximated as $Q^{\mathrm{tot}}_{f,j}$ (gallons), the f fuel use for field operation in farm size category j. The fuel use for field operation on each parcel i is related to the number of machinery equipment that a parcel owns. Machinery equipment such as trucks, medium and large horsepower tractors, and grain combiners have diesel engines, while small horsepower tractors consume gasoline for field operation. This study assumes that the operating hours of all machines on all parcels are the same. Hence, the expenses of diesel and

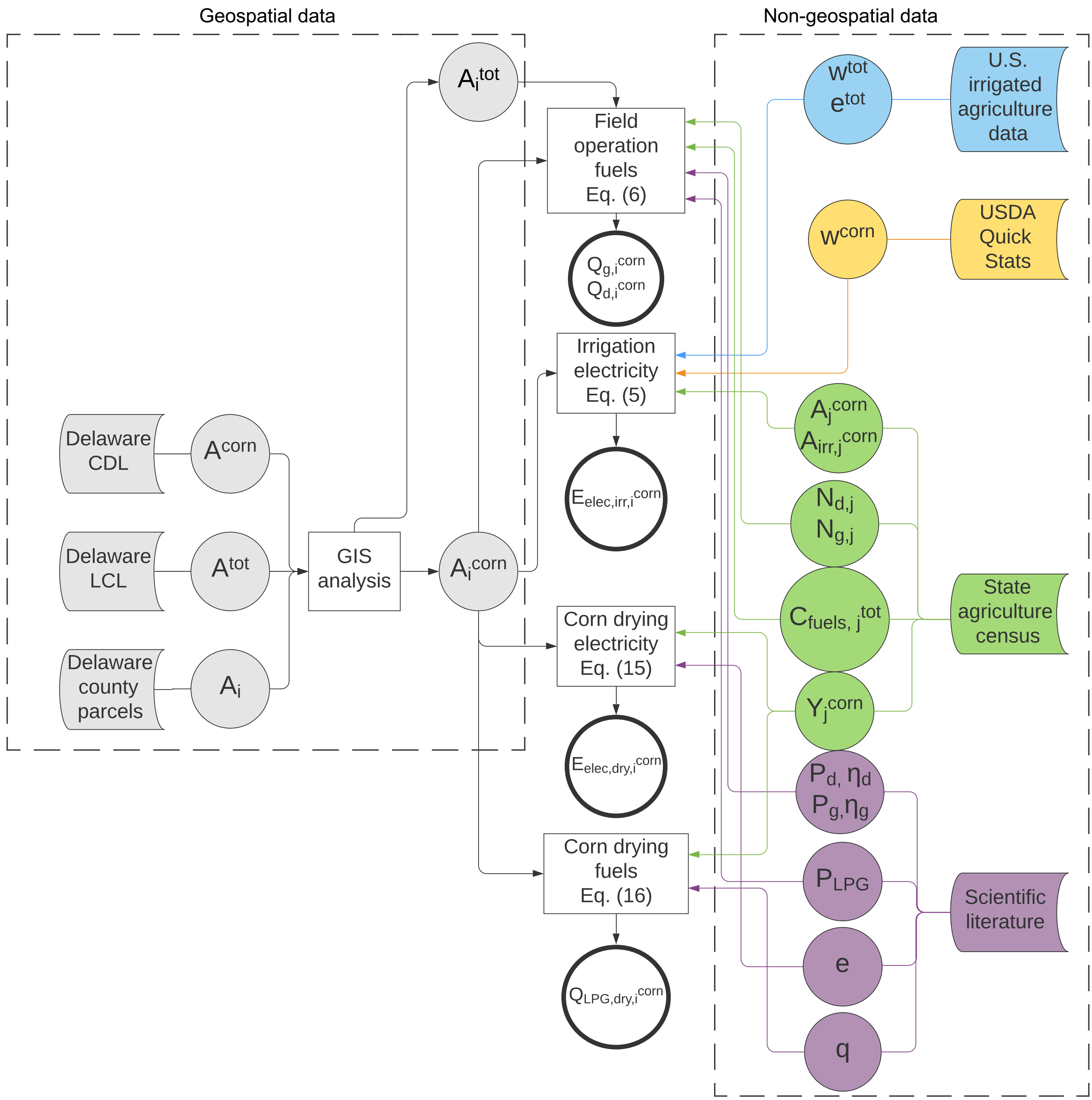

FIGURE 3 Flow chart of energy assessment for corn production. The index i refers to the parcel and j is the farm size category

gasoline are mainly related to the fuel efficiency and fuel prices. The total amount of diesel and gasoline use, $Q_{d,j}^{tot}$ and $Q_{g,j}^{tot}$ (gallons), are calculated through Equations (7) to (11) as follows:

$$Q_{d,j}^{tot} = \frac{C_{dg,j}^{tot}}{1+r_j} \times r_j \div P_d, \tag{7}$$

$$Q_{g,j}^{tot} = \frac{C_{dg,j}^{tot}}{1+r_j} \div P_g \tag{8}$$

where $C_{dg,j}^{tot}$ is the average expense of diesel and gasoline ($) in farm size category j, calculated shortly in Equation (12); P_d and P_g ($/gallon) are the prices of diesel and gasoline in 2017; and r_j is:

$$r_j = \frac{c_{d,j}}{c_{g,j}} \tag{9}$$

where $C_{d,j}$ and $C_{g,j}$ ($/hr) are the fuel cost per hour workload of diesel and gasoline engine machines, respectively, in farm size category j, calculated as in Downs and Hansen (1998):

$$c_{d,j} = N_{d,j} \times \eta_d \times P_d \tag{10}$$

$$c_{g,j} = N_{g,j} \times \eta_g \times P_g \tag{11}$$

where $N_{d,j}$ and $N_{g,j}$ are the numbers of diesel and gasoline machines owned by a parcel in farm size category j; η_d (0.048 gallons/hr) and η_g (0.068 gallons/hr) denote the average fuel consumption per rated power takeoff horsepower of diesel and gasoline engines, respectively. Since only the total expense for all fuels by farm size category $j(C_{fuels,j}^{tot})$ is known, $C_{dg,j}^{tot}$ needs to be calculated from it as the residual after the LPG used for corn drying ($C_{LPG,j}^{corn}$) is subtracted:

$$C_{dg,j}^{tot} = C_{fuels,j}^{tot} - C_{LPG,j}^{corn} \tag{12}$$

$$C_{LPG,j}^{corn} = Q_{LPG,j}^{corn} \times P_{LPG} \tag{13}$$

$$Q_{LPG,j}^{corn} = \Delta M \times q \times Y_j \times A_j^{corn} \tag{14}$$

where P_{LPG} ($/gallon) is the price of LPG in 2017;Y_j (bushel/acre) is the yield of corn in farm size category j; $Q_{LPG,j}^{corn}$ (gallons) is the LPG use for drying corn on parcels in farm size category j; ΔM (%) is the percentage points moisture removed; q (gallon/bushel/%) is the LPG use for drying per bushel per point. In this study, the removed percentage points of moisture content (ΔM) is set as 5%.

TABLE 2 Key parameter information

Parameter	Value
P_{elec} (electricity price in 2017, cents/kWh)	7.73
P_{LPG} (propane price in 2017, $/gal)	2.00
P_d (diesel price in 2017, $/gal)	2.79
P_g (gasoline price in 2017, $/gal)	2.68
η_d (fuel use of diesel engine per hour load, gallons/hr)	0.048
η_g (fuel use of gasoline engine per hour load, gallons/hr)	0.068
ΔM (removed percentage points of moisture content)	5%
q (LPG use for drying per bushel per point, gallon/bushel/%)	0.02
e (electricity use for drying per bushel per point, kWh/bushel/%)	0.01
C_{elec} (electricity conversion factor, Btu/kWh)	3,412
C_{diesel} (diesel conversion factor, Btu/gallon)	137,381
$C_{gasoline}$ (gasoline conversion factor, Btu/gallon)	120,333
C_{LPG} (propane conversion factor, Btu/gallon)	91,333

Lastly, the energy inputs for the corn drying process include liquified petroleum gas (LPG) and electricity by using a conventional gas-fired dryer on-farm. The LPG and electricity use on a parcel depend on the amount of corn production and the moisture content removed (see Equations (15) and (16)):

$$Q_{LPG,i}^{corn} = \Delta M \times q \times Y_i \times A_i^{corn} \approx \Delta M \times q \times Y_j \times A_i^{corn} \tag{15}$$

$$E_{elec,\, dry,i}^{corn} = \Delta M \times e \times Y_i \times A_i^{corn} \approx \Delta M \times e \times Y_j \times A_i^{corn} \tag{16}$$

where $E_{elec,dry,i}^{corn}$ (kWh) is the total electricity use for drying corn on parcel i; e (kWh/bushel/%) is the electricity use for drying per bushel per point; and Y_i(bushel/acre) is the yield of corn on parcel i. The values of q and e in this study are 0.02 gallons of propane and 0.01 kWh of electricity, respectively (Wilcke, 2018).

Since the geospatial and nongeospatial data used in this study are available national widely, the methodology developed here is potentially applicable for calculating the EFF of corn production, as well as that of other crops, across the U.S. states. The key parameters used in the methodology are listed in Table 2.

4 | RESULTS AND DISCUSSION

The EFF of corn production of each county (or in the entire state) is the sum of the energy consumed for corn production by all parcels in each county (or state) divided by the total corn yield of each county (or state). In the rest of this section, the terms "parcel" and "farm" will be used interchangeably for generality of the discussion, even though they are not exactly the same, as a farm can have multiple parcels on it.

TABLE 3 Total energy consumption for corn production in DE counties in 2017

County	Groundwater M gallons	Elec. for irrigation MWh	Diesel Gallons	Gasoline Gallons	LPG Gallons	Elec. for drying MWh	Total energy M Btu	Corn yield M bushels	Corn yield M lbs
New Castle	908	4,500	413,846	133,023	323,003	162	118,266	3.2	181
Kent	2,760	13,684	1,044,322	331,615	973,206	487	320,612	9.7	545
Sussex	4,653	23,065	2,771,307	925,804	1,783,682	892	736,781	17.8	999
Delaware	8,321	41,249	4,229,474	1,390,442	3,079,891	1,540	1,175,659	30.8	1,724

TABLE 4 EFF and other energy statistics per unit corn product in DE counties in 2017

County	Groundwater Gallons/bushel	Elec. for irrigation kWh/bushel	Diesel Gallons/bushel	Gasoline Gallons/bushel	LPG Gallons/bushel	Elec. for drying kWh/bushel	Energy footprint Btu/bushel	Energy footprint Btu/lb
New Castle	284	1.41	0.13	0.04	0.1	0.05	36,958	660
Kent	285	1.41	0.11	0.03	0.1	0.05	33,052	590
Sussex	261	1.30	0.16	0.05	0.1	0.05	41,392	739
Delaware	270	1.34	0.14	0.05	0.1	0.05	38,171	682

4.1 | EFFs of corn production at the county and state levels

The results shown in Table 3 are the total energy consumption for corn production in the three counties in Delaware. Sussex county has the largest corn yield, which accounts for 58% of the total corn yield in Delaware, and therefore, it tends to have the highest values of all total energy statistics. For example, the maximum groundwater applied for corn irrigation is in Sussex county, at over 4.6 billion gallons, corresponding to an electricity consumption of 23 GWh. By comparison, the other two counties combined consume about 18 GWh for irrigation. However, once we divide the irrigation statistics by the corn yield (Table 4), Sussex county exhibits the lowest groundwater applied for unit corn product (261 gal/bushel versus. 284 and 285 in New Castle and Kent counties, respectively).

Annual electricity for irrigation is at least an order of magnitude larger than the electricity used for drying corn, 41 versus. 1.5 GWh, respectively, in the entire state of Delaware. However, drying corn is more commonly done with gas-fired driers that burn LPG, which is the process responsible for the large consumption of LPG (over 3 million gallons in the state, compared to 4.2 million gallons for diesel and 1.4 million gallons for gasoline). The process of drying corn (mostly with LPG) consumes about 6 times more energy than the irrigation process (mostly with electricity) in Delaware. The diesel use for corn field operation is the largest among the fuels, with over 4.2 million gallons in the entire state, whereas gasoline is the smallest, at 1.4 million gallons.

Putting everything together, corn production consumes 1,175,659 MBtu in Delaware, with Sussex consuming about 63% of it. With 58% of the corn production, Sussex county is therefore the least efficient among the three counties in Delaware, with the highest EFF of 739 Btu/lb (Table 4), due to the highest energy inputs of diesel and gasoline. By contrast, Kent county is the most efficient, with 31% of the corn yield and only 27% of the energy consumed, giving an EFF of 590 Btu/lb. The EFF of corn production in Delaware is 38,171 Btu/bushel or 682 Btu/lb.

4.2 | EFFs of corn production by farm sizes

In order to identify possible reasons for variability in the EFF of corn production among farms, in this section we examine the effect of the farm size. Table 5 lists the medium value of energy consumption per unit corn product for farms in each farm size category. Small farms have lower groundwater consumption and electricity use for corn irrigation than medium and large farms. The largest farms (between 500 and 999 acres) have the highest electricity use for corn irrigation. Small farms are likely to install the center-pivot sprinklers which are more efficient irrigation system to irrigate small corn area. Compared to center-pivot irrigation system, large farms are likely to install furrow or subsurface dripping irrigation systems (less efficient) to irrigate large corn area (Lamm, 2002). Moreover, large corn area may have more runoff water. However, small farms have the highest fuel use

TABLE 5 Median values of energy consumption statistics per unit corn product by farm size category

	Small farms			
Farm size (acres)	**1–9**	**10–49**	**50–69**	**70–99**
No. of parcels	3,423	4,224	809	751
Total acres	15,683	98,957	47,303	61,989
Total corn acres	8,820	52,160	25,668	33,903
Groundwater (gals/bushel)	228	141	306	333
Elec. for irrigation (kWh/bushel)	1.13	0.70	1.52	1.65
Diesel (gals/bushel)	0.8 (1.06 ± 0.02)	0.24 (0.27 ± 0.004)	0.07 (0.07 ± 0.0005)	0.08 (0.08 ± 0.0006)
Gasoline (gals/bushel)	0.28 (0.37 ± 0.008)	0.08 (0.09 ± 0.001)	0.03 (0.03 ± 0.0002)	0.026 (0.026 ± 0.0002)
EFF (Btu/bushel)	158,645 (203,669 ± 3,999)	55,328 (60,332 ± 697)	28,085 (28,160 ± 94)	29,239 (29,257 ± 103)
EFF (Btu/lb)	2,833 (3,637 ± 71)	988 (1,077 ± 12)	502 (503 ± 2)	522 (522 ± 2)

Note: The values in the parentheses are the 95% confidence intervals.

for field operation. Compared to medium and large farms, small farms consume more diesel and gasoline for growing corn. Therefore, the energy efficiency of producing corn on small farms is substantially lower than that on medium and large farms in Delaware, with an EFF exceeding 150,000 Btu/bushel (2,679 Btu/lb) for the smallest farm size, while the EFF of medium and large farms is around 20,000 Btu/bushel (357 Btu/lb). This means that the energy savings by using less water for irrigation in small farms than in large farms are more than compensated for by the higher use of fuels for field operation. The medium farms between 140 and 179 acres are somewhat anomalous, with an EFF corn production similar to that of small farms, associated with the large quantity of machinery equipment in those farms. There are no considerable variations in EFF of corn production among large farms. Large farms tend to have best management practices for corn production such as ridge tillage or no tillage to improve the soil quality and fuel cost. However, these practices need specialized equipment with higher investment.

In order to better understand and visualize the variability of energy consumption on different farms, an EFF map of corn production is presented in Figure 4. The effect of the farm size is consistent with the previous findings: Larger parcels/farms are characterized by higher electricity use for irrigation but lower fuel use for field operation, giving an overall lower EFF. The parcels/farms with the highest EFF (darkest green in Figure 4d) are the smallest. The EFF for the state is estimated by the average energy consumption of corn production for all farms, which preserves the total energy consumption in a state scale. The big discrepancy between the EFF of small farms (1 to 49 acres) and the state average EFF indicates that improving the energy efficiency of producing corn should be focused on those small farms.

To put these results in perspective, the energy inputs for corn production estimated by the USDA include the direct energy use for fuel and electricity in the planting, harvesting, and drying process. Their results indicate that diesel and gasoline consumption for corn production from the 9 states located in the corn belt are 4.95 gallon/acre and 1.95 gallon/acre in 2010, respectively (Gallagher, Yee, & Baumes, 2016). These results are comparable to our estimated diesel (3.2–5.3 gallon/acre) and gasoline (0.8–1.4 gallon/acre) use for corn production on large farms in this study. According to the USDA report (Gallagher et al., 2016), the average energy requirement for corn production excluding the energy inputs of seeds and fertilizers is reported to be nearly 13,000 Btu/bushel in 2010. Compared to this result, it seems that the EFF of corn production on large farms might be overestimated. However, the energy use for irrigation was not addressed in the USDA report. After subtracting the energy inputs for irrigation, the average EFF of corn production on large farms is estimated to be 13,488 Btu/bushel, which is consistent with the reported results by USDA. The U.S. Energy Information Administration finds that farms where there is high demand for irrigation account for a significant share of the industrial electricity sector (Hitaj & Suttles, 2016). According to the results in this study, electricity use for irrigation cannot be neglected for estimating the energy requirements for corn production.

Table 5. Median values of energy consumption statistics per unit corn product by farm size category.

Medium farms			Large farms		
100–139	140–179	180–219	220–259	260–499	500–999
511	230	87	46	56	7
59,320	36,075	17,094	10,757	18,410	4,973
31,551	19,375	9,392	5,368	8,889	1,486
317	268	339	353	315	399
1.58	1.33	1.68	1.75	1.56	1.98
0.03 (0.03 ± 0.0003)	0.09 (0.09 ± 0.0008)	0.03 (0.03 ± 0.0004)	0.03 (0.03 ± 0.0003)	0.02 (0.02 ± 0.0008)	0.03 (0.03 ± 0.006)
0.004 (0.004 ± 0.00003)	0.02 (0.02 ± 0.0001)	0.007 (0.007 ± 0.00008)	0.008 (0.008 ± 0.00009)	0.005 (0.005 ± 0.0002)	0.007 (0.008 ± 0.0015)
19,775 (19,772 ± 43)	28,001 (27,948 ± 131)	19,722 (19,714 ± 55)	20,493 (20,442 ± 63)	18,362 (18,236 ± 140)	20,455 (21,087 ± 950)
353 (353 ± 1)	500 (499 ± 2)	352 (352 ± 1)	366 (365 ± 1)	328 (326 ± 2)	365 (377 ± 17)

4.3 | Energy use by processes and energy forms

In this section, we compare the energy use in different processes and from different energy types. The results of the proportion of energy use by energy type and process by farm size are depicted in Figure 5. For small farms (Figure 5a and d), the average energy use for field operation accounts for 78% of the total energy inputs of corn production, with a maximum of 98% and a minimum of 44%. The irrigation and drying processes consume substantially less energy than field operation, with 6% and 16% of the total energy inputs, respectively. Diesel is the most consumed fuel for corn production on small farms with an average energy share of 60% of the total energy inputs. Gasoline and LPG account for 18% and 16% of the total energy use, respectively. However, the average electricity use for irrigation only accounts for 6% of the total energy consumption for corn production on small farms.

By contrast, the drying process, not the field operation, takes the largest proportion of the total energy consumption for both medium and large farms. The average energy shares of drying, irrigation, and field operation on medium farms are 43%, 24%, and 32%, respectively (Figure 5b and e). The energy consumption for field operation can vary between 22% and 53% of the total energy consumption for medium farms. LPG used for drying corn on medium farms accounts for 42% of the total energy of corn production. Compared to small farms, medium farms use more energy for electricity and diesel and less energy for gasoline.

For large farms (Figure 5c and f), the energy for irrigation (29%) is the second largest after corn drying (48%), while field operation has the smallest share (22%). This difference between larger farms and relatively small farms is due to the larger corn and irrigated corn areas and possibly to the large capital cost of installing groundwater pumping and irrigation systems, which are often unaffordable for small farms. For large farms, this investment and the consequent use of electricity to extract and distribute the pumped groundwater are worthwhile because less energy is needed for field operation as a result. Similarly, small farms are more likely to sell fresh corn locally and not invest in relatively expensive corn drying equipment, whereas large farms are almost exclusively selling corn after drying it, as required for further processing by the food industry.

These results are consistent with the fact reported by Hanna and Sawyer (2012) that the energy requirements for drying account for nearly 50% of the total energy consumption for corn production in Iowa. In addition, the energy share of different processes and energy sources have smaller ranges for large farms compared to small and medium farms. This implies that the energy consumption for corn production is relatively uniform across large farms in Delaware.

This assessment of the EFF of corn production is at an early stage and has uncertainties based on the data availability and assumptions used in the methodology. For example, it is challenging to estimate the exact irrigated corn area of a specific farm based on the aggregated data. In this study, it is assumed that all corn farms of the same size have the same fraction of irrigated and nonirrigated corn area as the state average for that size, although each farm has a different size of total irrigated area. This means that no corn farm in the analysis is completely nonirrigated and none is fully irrigated. This will overestimate the energy consumption of corn production in the farms that in reality have no irrigated

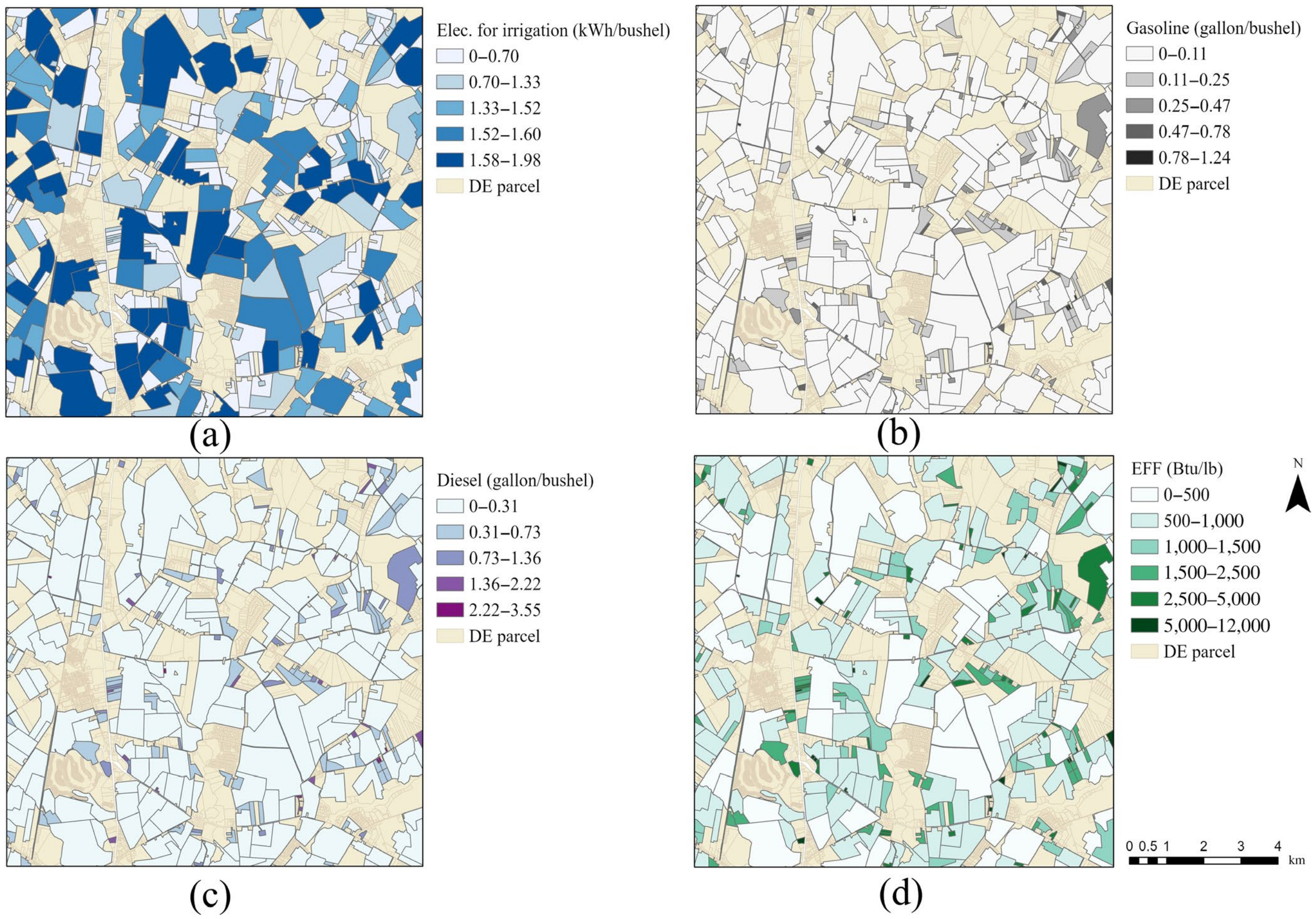

FIGURE 4 Energy consumption per unit corn product for different parcels in a selected region in Delaware. (a) Electricity use for corn irrigation, (b) Gasoline use for corn field operation, (c) Diesel use for corn field operation, and (d) EFF of unit corn product

corn area and underestimate the energy consumption in those that are 100% irrigated. The U.S. Geological Survey (Brown, Howard, Shrestha, & Benedict, 2019) provides a moderate resolution imaging dataset of irrigated agriculture for the United States (MIrAD-US). We used this geospatial data to validate the estimated irrigated corn area in this study. We could not use it directly as geospatial input data in our study due to its coarser spatial resolution (250 × 250 m) compared to the finer resolution (30 × 30 m) of the other geospatial data. The total irrigated corn area in this study is estimated to be 63,844 acres, which is consistent with the estimated result of irrigated corn area (63,099 acres) based on the MIrAD-US dataset. Moreover, the water applied for corn is estimated to be 40 m^3/ton, which shows the similarity to blue water use of corn production (34 m^3/ton) estimated by Mekonnen and Hoekstra (2011).

In addition, the uniform irrigation data used for all farms might limit the estimation precision in the electricity consumption for irrigation and the dynamic changes in the water consumption should be considered in a different temporal scale. Moreover, the geospatial data of farm parcels have a high granularity, such that a farm may be divided into several small parcels. A possible reason for the small discrepancy is that some small farms that have at least one acre of corn land are not surveyed as commercial farms in the Census of Agriculture. Therefore, the number of small farms might be overestimated in this study. Nevertheless, it is important to understand the variations in energy footprint of corn production on different farms. The proposed methodology can be improved comprehensively by including more indirect energy inputs (e.g., fertilizers and seeds). In the future work, it will be necessary to collect empirical data of energy consumption for corn production through survey or fieldwork, and the practical data can be used for validating the estimated results.

5 | CONCLUSIONS

This research develops a methodology for evaluating the energy footprint of corn production for different farms spatially by utilizing a GIS approach. The results indicate that the EFF of corn production has large variations for different farm sizes and that growing corn on large farms in Delaware is more energy-efficient than growing corn on small farms. While small farms consume less electricity

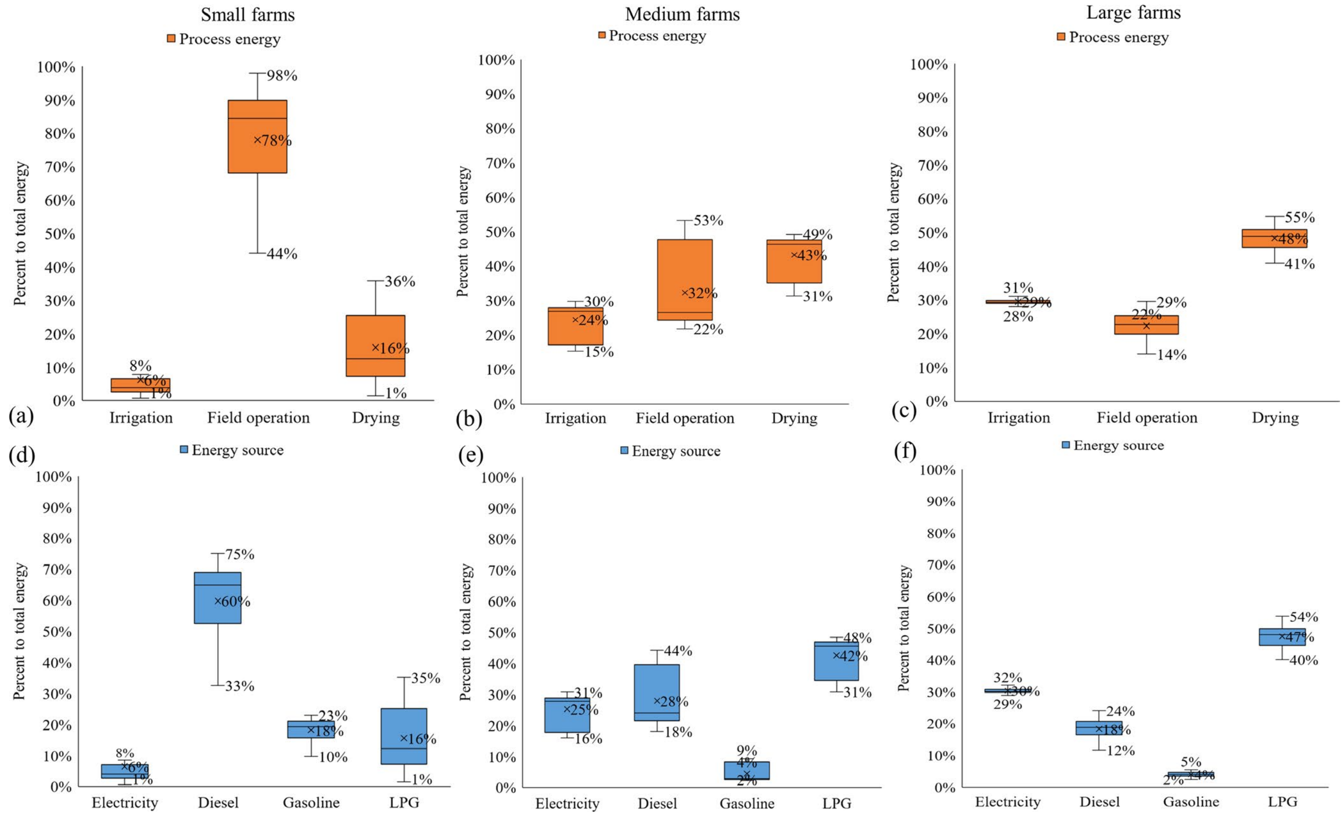

FIGURE 5 Energy share of different processes (first row, a-c) and energy types (second row, d-f) on small (first column), medium (second column), and large (third column) farms

for irrigation, even per unit corn product, they use so much more fuels, especially diesel, for field operation that the EFF of small farms is roughly 40% to 800% greater than the EFF of large farms. Accounting for the variability due to the farm size, the EFF of corn production in Delaware is estimated as 682 Btu/lb or 38,171 Btu/bushel; the EFFs of the three counties are 590, 660, and 739 Btu/lb for Kent, New Castle, and Sussex, respectively. Surprisingly, the county with the largest corn yield (58% of the state total), Sussex, is also the least efficient, consuming over 63% of the energy per unit corn product. Whereas large and medium farms have similar EFFs, small farms are not only the least efficient, but also the ones with the largest variability. This suggests that small farms in Sussex county would be a potential hotspot to target for future improvements in energy consumption for corn production.

The proposed methodology will be applied to investigate other agricultural commodities and foods in other states by using the data from the same sources, such as corn and soybean in Ohio. Further, a spatial platform of EFF of various food productions is anticipated to be developed in order to identify potential energy footprint hotspots of food production spatially. It should be noted that the uncertainties could exist in the geospatial data for identifying the farm size and some assumptions may limit the precision of the EFFs of corn production. Validation is needed for improving the methodology of EFF estimation with empirical data. Despite these uncertainties, the EFF assessment of food production can build the connection between food and energy sectors and provide useful insights for food producers to improve the energy management of food production. In addition, knowledge of the EFF of food production can enhance the consumers' awareness of the environmental sustainability of food products. Governments and policy makers can utilize the EFF to make concrete decisions and strategies for supporting local food producers.

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