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Retrospective analysis of the U.S. corn ethanol industry for 2005–2019: implications for greenhouse gas emission reductions

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Abstract: Since 2000, corn ethanol production in the USA has increased significantly – from 1.6 to 15 billion gallons (6.1 to 57 billion liters) – due to supportive biofuel policies. In this study, we conduct a retrospective analysis of the changes in US corn ethanol greenhouse gas emission intensity, sometimes known as carbon intensity (CI), over the 15 years from 2005 to 2019. Our analysis shows a significant decrease in CI: from 58 to 45 gCO_2e/MJ of corn ethanol (a 23% reduction). This is due to several factors. Corn grain yield has increased continuously, reaching 168 bushels/acre (10.5 metric tons/ha, a 15% increase) while fertilizer inputs per acre have remained constant, resulting in decreased intensities of fertilizer inputs (e.g., 7% and 18% reduction in nitrogen and potash use per bushel of corn grain harvested, respectively). A 6.5% increase in ethanol yield, from 2.70 to 2.86 gal/bushel corn (0.402 to 0.427 $L\,kg^{-1}$ corn), and a 24% reduction in ethanol plant energy use, from 32 000 to 25 000 Btu/gal ethanol (9.0 to 6.9 $MJ\,L^{-1}$ ethanol) also helped reduce the CI. The total GHG emission reduction benefits through the reduction in the CI and increased ethanol production volume are estimated at 140 million metric tons (MMT) from 2005 to 2019 in the ethanol industry. Displacement of petroleum gasoline by corn ethanol in the transportation fuel market resulted in a total GHG emission reduction benefit of 544 MMT CO_2e during the period 2005 to 2019. © 2021 Argonne National Laboratory. *Biofuels, Bioproducts and Biorefining* published by Society of Industrial Chemistry and John Wiley & Sons Ltd

Supporting information may be found in the online version of this article.

Key words: corn ethanol; carbon intensity; life-cycle analysis; greenhouse gas emissions; well-to-wheels

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Introduction

Corn ethanol plays an important role in enhancing energy security and the rural economy while contributing to decarbonizing the transportation sector in the USA. Ethanol accounted for more than 10% of the US gasoline market share in 2019.[1] Corn ethanol production in the USA has increased from 1.6 billion gallons per year (BGY) (6.1 billion liters per year [BLY]) in 2000 to more than 15 BGY (57 BLY) in 2019[2] with the help of supportive biofuel policies such as the US Environmental Protection Agency's (EPA's) Renewable Fuel Standard (RFS) and California's Low-Carbon Fuel Standard (LCFS).

The RFS and LCFS programs evaluate the life-cycle greenhouse gas (GHG) emissions of fuel production pathways to quantify the GHG emission reduction benefits of using renewable fuels. Life-cycle analysis (LCA) is used to quantify the life cycle GHG emissions of fuels, the metric for comparing relative GHG emission impacts among different fuel production pathways. The RFS and LCFS evaluate GHG emissions of fuels on a full life-cycle basis. These life-cycle GHG emissions are sometimes referred to as the fuel's carbon intensity (CI). For example, RFS classifies corn ethanol production pathways in the D6 category, which means the life cycle GHG emissions are expected to be 20% lower than those of the baseline gasoline.[3] California's LCFS, on the other hand, estimates the CI of each renewable fuel production pathway to estimate the actual reductions in GHG emissions made by displacing the petroleum fuels. For example, Rosenfeld *et al.*[4] presented that in the first quarter of 2019, LCFS-certified ethanol production pathways had an average CI of 66 gCO_2e/MJ, including land-use change (LUC) GHG emissions, which is 35% lower than that of the California gasoline blendstock (100.82 gCO_2e/MJ).[5]

The corn ethanol production pathway, including both corn farming and biorefineries, has substantially evolved in the past two decades. From 2000 to 2019, US corn production ranged from a low of 9.0 billion bushels (230 million metric tons [MMT]) in 2002 to a high of 15.1 billion bushels (380 MMT) in 2016, with 13.6 billion bushels (350 MMT) produced in 2019. Since the enactment of the Energy Independence and Security Act in 2007,[6] corn used for ethanol production increased to about 5.3 billion bushels (130 MMT) in 2015, which is about 40% of the corn grain produced in the USA.[7] In addition, corn yield per hectare has grown continuously, while chemical inputs per hectare remain constant.

Biorefineries have also increased the yield of ethanol per unit of corn while producing co-products. Along with distillers grains with solubles (DGS), an important animal feed, more facilities now recover corn oil and CO_2. This helps increase revenue while potentially reducing the emission burdens of ethanol production.

Previous LCA studies have demonstrated the GHG emission reduction benefits of corn ethanol as a gasoline alternative. The EPA's LCA study for RFS in 2010[3] showed a reduction of 21% in GHG emissions by corn ethanol. Wang *et al.*[8] evaluated the CI of corn ethanol and other cellulosic ethanol production pathways, then incorporated the ethanol production pathways into the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET)® model developed by Argonne National Laboratory (Argonne).[9] The California Air Resources Board (CARB) developed CA-GREET from Argonne's base GREET model for LCFS compliance. Results from Wang *et al.*[8] in 2012 have been the basis for developing default LCFS CIs for corn ethanol.

Additional LCA studies evaluating the CI of corn ethanol have confirmed that the use of corn ethanol results in GHG emission reductions. Two reports by Life Cycle Associates in 2014 and 2021[10,11] evaluated the CIs of biofuels, including US corn ethanol, using the GREET model. The 2014 report estimated the CI of corn ethanol to be 65.5 gCO_2e/MJ, including LUC GHG emissions of 9.0 gCO_2e/MJ.[10] The 2021 report[11] calculated the CI of corn ethanol to be 53.2 gCO_2e/MJ (including LUC GHG emissions of 7.4 gCO_2e/MJ) in 2020. The US Department of Agriculture (USDA) published several reports on the CI of US corn ethanol using the GREET model.[4,12–14] These reports, with a LUC GHG value of 6.7 gCO_2e/MJ, show a CI of 52.8–56.6 gCO_2e/MJ for corn ethanol between 2014 and 2019, and project a CI of 47.9–51.7 gCO_2e/MJ for 2022. Pereira *et al.*[15] compared the CIs of corn ethanol in three major regions (US, Europe, and Canada) using representative public LCA tools (GREET, BioGrace, and GHGenius, respectively), and found CIs of 57.7, 43.4, and 61.9 gCO_2e/MJ (including LUC) in the US, Europe, and Canada, respectively. Most recently, Scully *et al.*[16] used historical versions of the GREET model to show the changes in the CI of US corn ethanol over time. In 2020, they estimated a CI of 51.4 gCO_2e/MJ, including a LUC GHG emission of 3.9 gCO_2e/MJ.

There have been continuous requests to update LCA results with primary data for corn ethanol that reflect the improvements in this industry.[13] The objective of this study is to evaluate the historic trends in corn ethanol CI over the 15 years from 2005 to 2019, using primary data for US corn farming and ethanol production with survey data collected by USDA and the ethanol industry. This retrospective LCA helps demonstrate the impacts on corn ethanol CI trends made by key parameters such as corn and ethanol yield, fertilizer use, and energy consumption in both corn farming and biorefineries. With an understanding of these impacts, GHG reductions by the corn ethanol industry made in the past and potential reductions in the future can be better assessed. All the collected data from this study are also used to update key corn ethanol parameters in GREET 2021, to be released in October 2021 (https://greet.es.anl.gov/).

Methodology

System boundary

Having a consistent, complete system boundary is one of the important factors for a reliable LCA of biofuels. As presented in Fig. 1, there are four major stages – corn farming, ethanol production, ethanol transportation and distribution (T&D), and ethanol combustion – in the corn ethanol production supply chain. We account for all GHG emissions (i.e., CO_2, CH_4, and N_2O) for each stage as well as upstream GHG emissions of the inputs to each stage (e.g., electricity, natural gas, fertilizer, etc.).

The corn farming stage accounts for GHG emissions from farm manufacturing (upstream) inputs as well as corn growth, where the various farming inputs, such as fertilizers/chemicals, on-farm fuels for agricultural equipment, and electricity, are utilized.

In the ethanol production stage, biorefineries convert corn into ethanol via fermentation, with the help of enzymes/yeast. Fermentation, downstream distillation, and DGS drying all require a large amount of steam and heat that are produced primarily from natural gas. A small amount of electricity is used for plant operation. During the conversion process, biorefineries generate DGS, an animal feed. Many ethanol plants now recover corn oil and CO_2 to increase revenue. Corn oil is sold for production of biodiesel and renewable diesel, while CO_2 can be used mainly for food processing and beverage production. Therefore, the impact of the production of co-products should be accounted for.

The ethanol T&D stage includes transporting ethanol from the biorefinery to the end use (pump) via trucks and trains. The ethanol combustion stage accounts for ethanol combustion emissions during vehicle operation. However, since the CO_2 emissions from ethanol combustion are offset by a corn plant uptake of CO_2 during growth, biogenic CO_2 emissions from ethanol combustion are considered to be zero with the carbon neutrality assumption. The CH_4 and N_2O emissions of ethanol combustion are accounted for.

The functional unit in this study is a megajoule (MJ) of ethanol produced and used. Greenhouse gas emissions are expressed in terms of grams (g) of carbon dioxide equivalent (CO_2e) using global warming potentials (GWPs) with a 100-year time horizon based on the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).[17]

In this study, we used corn farming data and biorefinery survey results for the first two stages, marked in red in Fig. 1, which are explained in the following sections in detail. For other stages and parameters, we relied on the default parameters that the GREET model employs.[9] The GREET model enables the estimation of the upstream emissions of various inputs for corn farming and biorefineries and emissions associated with T&D and fuel combustion in vehicles. We assumed that the co-products displace their counterparts. Note that all the results presented in this study are based on undenatured ethanol.

Corn farming

State-level estimates of key parameters affecting the CI of corn farming (Table 1) were based on data from the USDA's

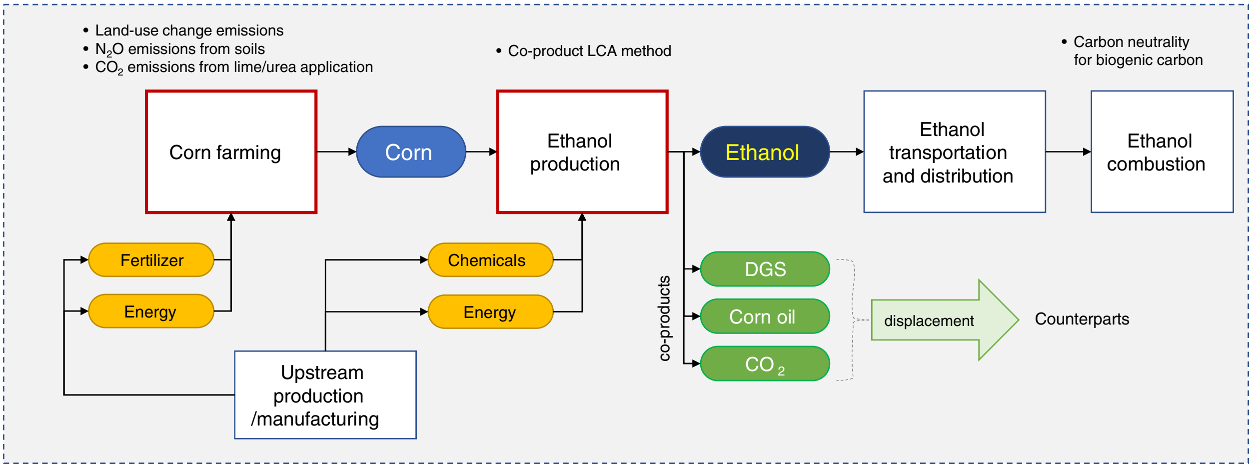

Figure 1. The LCA system boundary and major parameters for corn ethanol.

Table 1. Data source, regional, and temporal coverage of the state-level estimates of key parameters for corn farming.

Spatial coverage	Data (and source) used to derive key parameters[*]	Unit	Year															Parameter	Unit
			2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019		
Conterminous 41 states[**]	Grain yield (NASS)	bu/ac	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	Grain yield	bu/ac
Selected 15–19 states[***]	N, P_2O_5, and K_2O used on corn, rate per fertilized acre receiving the nutrients (ERS)****	lb/ac[*****]	▨					▨				▨		▨		▨		N, P_2O_5, and K_2O use	lb/bu
	Corn planted area receiving each fertilizer (NASS)	%	▨					▨				▨		▨		▨			
	Corn planted area (NASS)	ac	▨					▨				▨		▨		▨			
	Grain production (NASS)	bu	▨					▨				▨		▨		▨			

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Table 1. (Continued)

Spatial coverage	Data (and source) used to derive key parameters*	Unit	Year															Parameter	Unit
			2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019		
Nine states****	Grain yield (NASS)	bu/ac	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
	Diesel (OCE and ARMS)	gal/ac	▨					▨						▨				Diesel	gal/bu
	Gasoline (OCE and ARMS)	gal/ac	▨					▨						▨				Gasoline	gal/bu
	Liquefied petroleum gas (OCE and ARMS)	gal/ac	▨					▨						▨				LPG	gal/bu
	Electricity (OCE and ARMS)	kWh/ac	▨					▨						▨				Electricity	kWh/bu
	Natural gas (OCE and ARMS)	ft^3/ac	▨					▨						▨				Natural gas	ft^3/bu
	Lime (OCE)	lb/ac	▨					▨										Lime	lb/bu
	Chemicals (OCE)	lb/ac	▨					▨										Chemicals	lb/bu

Gray boxes indicate the years for which data is available.

*All the data published by NASS is accessible through Quick Stats (https://quickstats.nass.usda.gov/).[18]

**Among the 48 conterminous states, 41 states have reported corn grain yields for 2005–2019.

***The states selected in the ERS dataset for annual fertilizer use on corn are shown in Fig. S1.

****The nine states are Illinois, Indiana, Iowa, Minnesota, Nebraska, Ohio, Michigan, South Dakota, and Wisconsin (Fig. S1), which account for more than 70% of US total corn grain production in 2019.

*****The ERS dataset includes either actual pounds or percentage analysis of N, P_2O_5, and K_2O from custom-applied nutrients and fertilizers and commercially prepared manure or compost, but excludes unprocessed manure.[19] As a result, the rates could be underestimated in the states where manure application is often practiced, such as Minnesota and Wisconsin, compared with a survey that excluded manured fields.[20]

major survey programs, the National Agricultural Statistics Service (NASS)[18] the Economic Research Service (ERS),[21] and the Office of the Chief Economist (OCE) reports.[22,23] More details on the data sources can be found in the supporting information (SI).

Corn yield per area unit is used to calculate the farming inputs per bushel or per weight (a bushel of corn weighs 56 lb or 25.4 kg) of corn grain. The yield data coupled with the nitrogen (N) content in corn biomass and the harvest index provide the N in crop residues left in the field after harvest, which is one of the main sources for nitrous oxide (N_2O) emissions from soils. In this analysis, we extracted the historical corn yield data from the NASS Agricultural Survey, which reports state-level grain yields per harvested area in bushels/acre. The N_2O emissions from crop residue N were estimated by using the IPCC methodologies described in IPCC[24] and Liu *et al.*[25]

In this study, we included farming inputs such as N (e.g., urea), P (in the form of phosphate, P_2O_5), K (in the form of potash, K_2O), lime, and herbicides/pesticides. We extracted the rates of NPK used on corn (per fertilized area receiving the nutrients) and the percent of corn area receiving the NPK from the ERS dataset for annual fertilizer use on corn, which is based on NASS's Agricultural Resource Management Survey (ARMS) Phase II (details in SI 1.1). By coupling these data with the state-level corn planted area (from NASS), we calculated the total usage of NPK fertilizers for corn production in each state. Finally, we divided use by the state-level grain production (from NASS) to estimate the nutrient input intensities (lb nutrients/bushel of corn grain) (Table 1). We relied on the lime and chemicals use available from OCE reports, in which the energy balance of corn ethanol has been analyzed for the major nine corn-producing states (details in SI 1.1).

The estimates of nutrient / chemical input intensities were then multiplied by the GHG intensities of fertilizer / chemical manufacturing in the GREET model.[9] In particular, NPK intensities were allocated to different fertilizer types based on the US consumption of fertilizers in 2010[21] to assign a specific GHG intensity to the production of each fertilizer type (e.g., ammonia production emits 2620 kg CO_2e/metric ton, while urea emits 1219 kg CO_2e/metric ton). The usage share of each fertilizer type was tracked by ERS until 2015. For example, the share of ammonia-N (anhydrous plus aqua) in total N fertilizer usage decreased by 3% from 2010 to 2015, while that of urea-N increased by 5% for the same period. We did not consider the 2015 shares for this analysis, because the shares are not specific to corn farming but to all crops growing in the USA. Instead, the shares of fertilizer types specific to corn farming from the 2010 data, as in GREET, were used. We also employed the rates of N fertilizer and urea / lime applications to calculate fertilizer-driven N_2O and CO_2 emissions by using empirical emission factors.[26,27]

Various farming operations such as tilling fields, planting and harvesting biomass, and drying corn grain require energy: diesel, gasoline, liquefied petroleum gas (LPG), electricity, and natural gas. Since the early 1990s, on-farm energy consumption specific to corn farming has been periodically surveyed through ARMS and summarized in the OCE reports. For this study, we used the data for nine states to calculate farm energy consumption. Note that the estimates for the most recent year of data for corn (2016) were calculated by using the state-level fuel costs for corn production available from the ARMS Phase III dataset farm business survey[21] and the fuel and electricity prices reported by the US Energy Information Administration (EIA).[28] For example, as of 2016, the electricity cost for corn farming in Illinois was $2.88/acre ($7.11/ha) from the ARMS dataset[21] and the residential price of electricity in the state was 12.5 cents/kWh (3.5 cents/MJ) from EIA data,[28] resulting in the estimate of 23 kWh/acre (205 MJ/ha).

Finally, we calculated the average emissions of farming inputs per bushel of corn grain by using corn production in each state as a weighting factor to represent the farming CIs at the national level. We interpolated weighted averages to fill in any missing estimates in years when records / data were not available and used for analyzing corn ethanol CI (Table S1). We assumed that the diesel fuel and gasoline consumed in corn farming are related to the area of field operations rather than corn yields harvested. Diesel and gasoline use (gal/ac) were first interpolated between years and then divided by bushels of corn grain. This process is different from the interpolation of the NPK use and other fuel types, such as LPG, electricity, and natural gas, which are first divided by yield and then interpolated between years (Table S1). Because of this interpolation approach, and the lack of data for corn farming in 2012 (Table 1), when a severe to extreme drought caused a loss of more than one quarter of the year's corn production,[29] our analysis reflects the drought's impacts on diesel and gasoline use only.

Corn ethanol production

Christianson (www.christiansoncpa.com), a corn ethanol benchmarking and agricultural consulting company, has been conducting quarterly surveys of dry mill corn ethanol facilities every year since 2003. Dry mills produce 91% of US fuel ethanol (the remaining 9% is from wet mills).[30] The survey covers ethanol yields (with corn inputs and ethanol production), all energy inputs by type (natural gas, coal, and electricity), chemical inputs, the yields of co-products, and financial information. For this study, Christianson agreed to provide Argonne its annual corn ethanol industry benchmarking statistics for 2005 to 2019. Argonne implemented the Christianson statistical data into the GREET model to evaluate the impact of the changes in the inputs / outputs of corn ethanol production facilities. Figure S2 in the supplementary material presents the share of total ethanol production of the plants in Christianson's benchmark database out of the total ethanol volume in the USA. The survey covers 40% (65 facilities) of ethanol production in 2019 and the minimum coverage of 22% (25 facilities) in 2008. While the survey has limited coverage, especially in earlier years, coverage of later years has been adequate. The dataset (ethanol yield, DGS and corn oil production, and energy usage) was further verified by an independent Argonne survey, which covered 66 US facilities in 2017.[31]

In addition to corn ethanol, biorefineries produce other products, such as DGS, syrup, corn oil, and CO_2. Distillers grains with solubles, a feed for livestock, comes in three types: DDGS (dry DGS), WDGS (wet DGS), and MWDGS (modified wet DGS), depending on the preferred end use,[32] and the benchmarking database has information on the amount of each DGS type. The benchmarking database also includes information about syrup and corn oil production (lb/gal ethanol) and the amount of CO_2 captured (lb/gal ethanol).

In this study, we assumed that DGS and syrup are used to displace conventional animal feeds (corn, soybean, and urea).[8,33] As corn oil can be used for other fuel production, it is assumed that corn oil displaces soy oil for the production of biodiesel and renewable diesel.[9] The GREET model estimates emissions credits from the displaced conventional animal feeds or soy oil by ethanol co-products, which helps to reduce the emissions burden of ethanol production. In this study, we consider CO_2 to be a byproduct that does not impact the emission burdens of ethanol. Even though CO_2 can be considered as a co-product potentially displacing conventional CO_2 production, current merchant CO_2 is mainly supported by the facilities generating CO_2 as a byproduct (e.g., during ammonia or hydrogen production). Thus, the emission reduction benefits of captured CO_2 in ethanol plants may be limited. In cases in which CO_2 from biorefineries is captured and sequestered, we expect corn ethanol may present an opportunity for further reductions in GHG emissions.[34] The CO_2 captured from biorefineries can also be used for fuels and chemicals production.[35]

For chemical inputs such as enzymes and yeast, we used the GREET default values, which rely on Wang *et al.*[8] instead of using the Christianson benchmarking results. This is because the benchmarking statistics for these inputs are presented in terms of \$/gallon ethanol, which cannot be converted reliably into the amount of chemical inputs. Note that the total impacts of the biorefinery chemical inputs on corn ethanol GHG emissions are estimated at about 1.8 gCO_2e/MJ. Although the impact is not negligible, the impact of the changes from 2005 to 2019 in chemical inputs should be small. For example, a 10% change in these chemicals inputs results in a change of less than 0.2 gCO_2e/MJ for the ethanol CI.

Results and discussion

Corn farming and ethanol production trends

Corn yield has grown continuously, from 119 bushels/acre (7.4 metric tons/ha) in 1990 to 168 bushels/acre (10.5 metric tons/ha) in 2019 (Fig. 2(a)). Except in the drought year, 2012, corn yield has been well above 140 bushels/acre (8.8 metric tons/ha) for the past 15 years. Meanwhile, fertilizer inputs per acre remained constant, resulting in decreasing intensities of fertilizer/chemical inputs: for example, 7% and 18% reduction in N and potash uses per bushel of corn grain from 2005 to 2019, respectively (Fig. 2(b)). Similarly, farming energy use per bushel of corn has been slightly reduced from 9.7 to 8.4 thousand Btu (0.40 to 0.35 MJ/kg; a 14% reduction) (Fig. 2(c)). The sudden increase in diesel and gasoline use in 2012 was due to our interpolation approach and to the large decrease in corn yield as stated above. Using a three-year moving-average yield from 2011 to 2013 for 2012, we estimated a CI reduction of 0.23 gCO_2e/MJ in 2012 for corn ethanol (limited to 2012 only).

Another significant change over the 15 years is the continuous increase in the ethanol yield (Fig. 3(a)). From 2005 to 2019, the ethanol yield has increased by 6.5%. In 2005, the weighted average ethanol yield was estimated at 2.70 gal/bushel (0.402 $L\,kg^{-1}$), which increased to 2.86 gal/bushel (0.427 $L\,kg^{-1}$) in 2019. The distribution (P10 to P90) in Fig. 3(a) shows that the ethanol industry in general has improved ethanol yield. The lowest 10 percentiles in 2019 represents a higher ethanol yield than the weighted average value in 2005. The ethanol yield in each year also shows a variation of around 10% of the average. In 2005 and 2019, the variation ranged from 2.53–2.80 gal/bushel (0.377–0.417 $L\,kg^{-1}$) in 2005 to 2.74–2.95 gal/bushel (0.408–0.440 $L\,kg^{-1}$) in 2019. The variation in 2019 may mean there is still room to improve yield if low-yield plants can be improved to reach the yield of high-yield plants.

Ethanol plants have made efforts to reduce energy consumption. From 2005 to 2019, a 24% reduction in

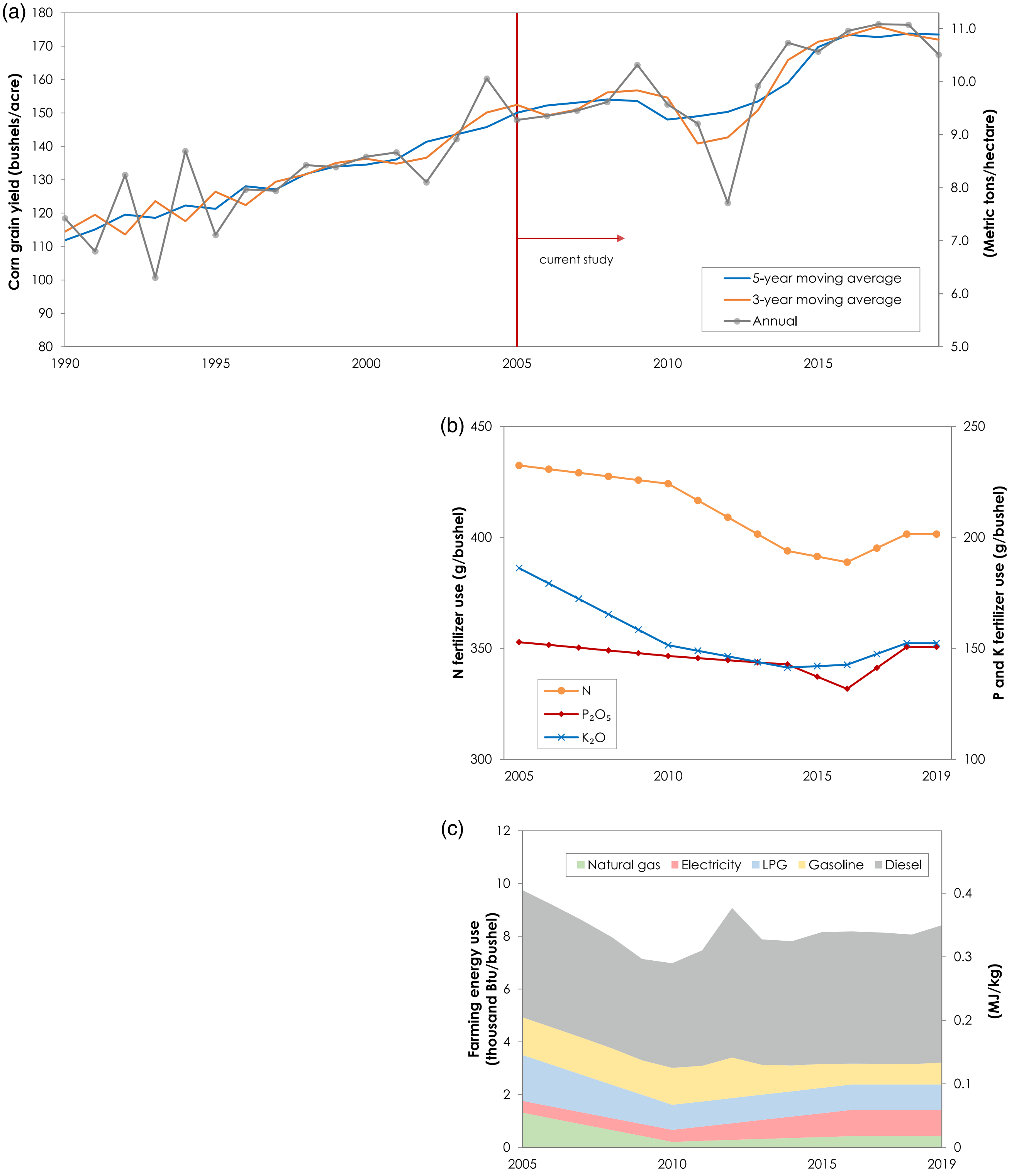

Figure 2. Historical trends of US corn farming parameters from 2005 to 2019. (a) US corn grain yield in bushels/acre with annual, 3- and 5-year moving average values, (b) corn farming fertilizer use in g of nutrient/bushel, and (c) corn farming energy use in thousand Btu (low heating value)/bushel. Note that the drought of 2012 caused a huge decrease in corn yield.

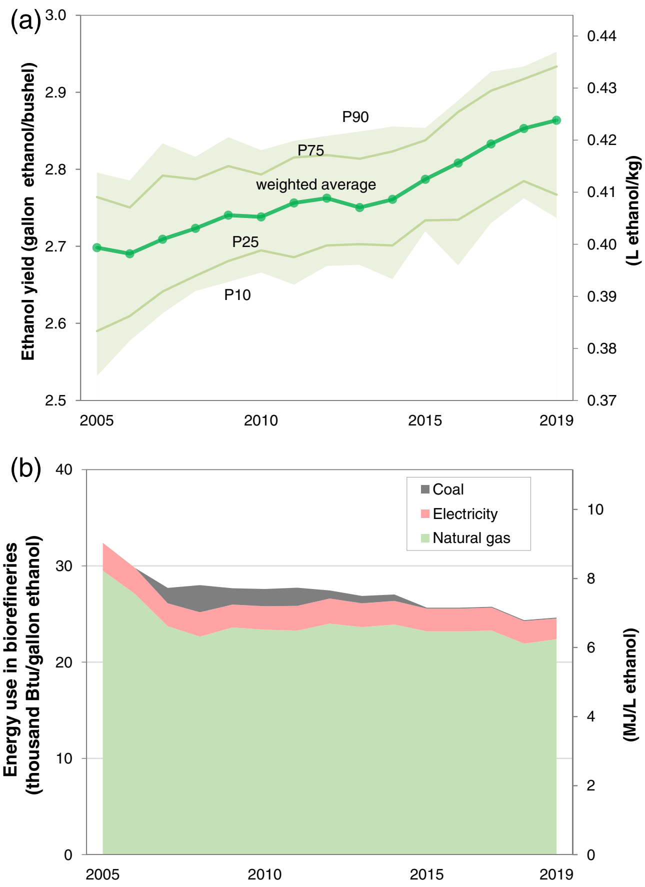

Figure 3. Historical trends of US corn ethanol production parameters from 2005 to 2019. (a) Corn ethanol yield in gallons of undenatured ethanol/bushel) and (b) energy use in biorefineries in thousand Btu (lower heating value)/gallon of ethanol.

energy inputs has been achieved: from 32 000 to 25 000 Btu/gal ethanol or 9.0 to 6.9 MJ L^{-1} ethanol (Fig. 3(b)). At the same time DGS production has decreased by 21%, from 5.1 to 4.0 dry lb DGS/gal ethanol (0.61 to 0.48 kg L^{-1}), from 2005 to 2019 (Fig. S3). This is mainly because of the increase in ethanol yield as well as other new co-products (corn syrup and corn oil). For example, corn syrup has been produced by ethanol plants since 2008 (Fig. S3), and corn oil production started in 2008 and doubled by 2019 (Fig. S4).

During the fermentation process, high-purity CO_2 is generated, which can be captured and used for other purposes. Ethanol plants in the USA have been a major merchant CO_2 supplier.[36] As of 2013, more than 30% of ethanol production plants captured CO_2 (Fig. S5). Carbon dioxide capture rates have also increased by 63% from 2005 to 2019: from 2.3 to 3.7 lb CO_2/gal ethanol (0.27 in to 0.45 kg L^{-1}).

Carbon intensities of corn ethanol

Figure 4 presents the life-cycle GHG emissions (CIs) of US corn ethanol, showing the contribution of each stage for the 15 years from 2005 to 2019 without considering the LUC impact (which is 7.4 gCO_2e/MJ from GREET modeling; see the following section). The major GHG emission contributors are corn farming and ethanol production. In 2019, corn farming (energy and fertilizers/chemicals) and ethanol production contributed 95% of the total GHG emissions (50% and 45%, respectively), while transportation (for both feedstock and fuel) contributed 5%. Since the system produces co-products such as DGS, syrup, and corn oil, there is a displacement emissions credit, which is estimated at −12 gCO_2e/MJ for 2019. The emission credits from corn oil and syrup production have contributed 3–6% and 1–3%, respectively, since 2011, and the largest GHG credit is from DGS.

Due to significant reductions in the inputs for the farming and ethanol production processes, corn ethanol CIs (black bars) have been reduced by 23% (14 gCO_2e/MJ), from 58 gCO_2e/MJ in 2005 to 45 gCO_2e/MJ in 2019. Specifically, the ethanol production stage shows a 11 gCO_2e/MJ reduction during our 15 year period, in which ethanol yield has increased by 6.5% (Fig. 3(a)), and energy use has decreased by 24% (Fig. 3(b)). Ethanol yield determines the amount of corn used for ethanol production. Thus, an increase in ethanol yield helps reduce the emissions of corn production per MJ of ethanol. Reduction in natural gas use in ethanol plants results in lowered ethanol CIs from both reduced natural gas combustion emissions and upstream emissions (natural gas recovery and transportation). We identified that natural gas use in ethanol plants is subject to large variations, about ±40% of the median natural gas use in 2019, which means that there is the potential to further reduce GHG emissions if high natural gas consuming facilities can improve their efficiencies to levels closer to those of the low natural gas consuming ones. In addition, a switch to renewable energy sources can further reduce ethanol plant CIs. For example, using renewable natural gas produced from organic waste materials, such as food waste, animal waste, and wastewater sludge, can be an alternative option for meeting the heat demand for ethanol production with reduced CIs for ethanol.

Corn-farming-related GHG emissions also show reductions over time. From 2005 to 2019, GHG emissions from fertilizers / chemicals and farming energy consumption decreased 4.1 and 0.8 gCO_2e/MJ, respectively. Note that a portion of emissions reduction can be attributed to the increase in ethanol yield (1.5 and 0.22 gCO_2e/MJ for fertilizers/chemicals and farming energy, respectively).

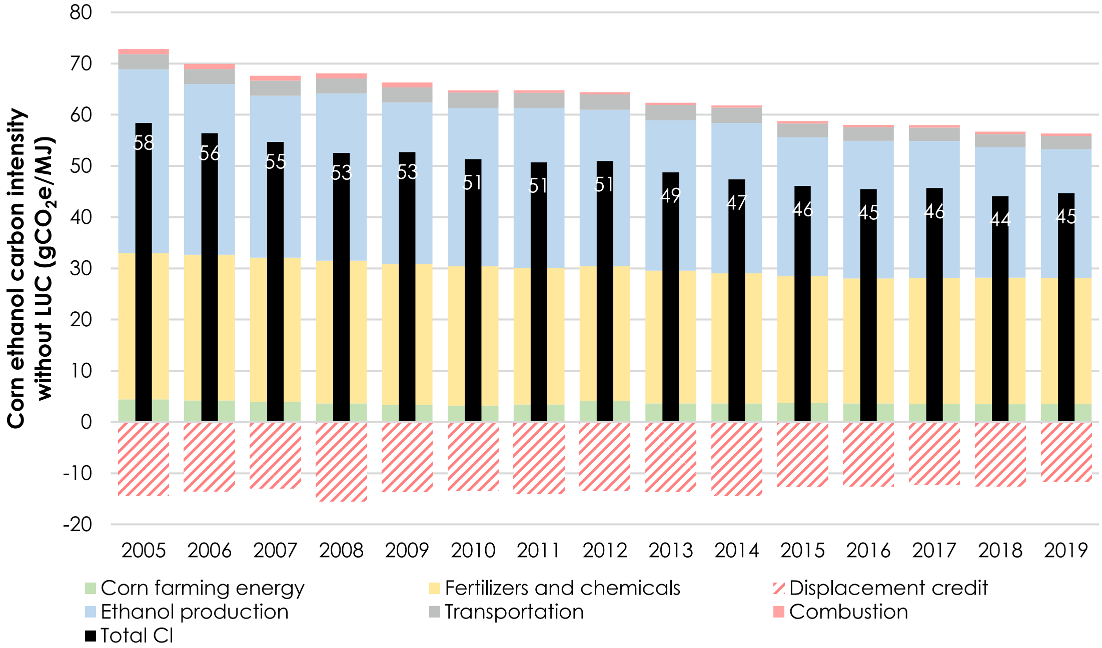

Figure 4. Carbon intensity (gCO_2e/MJ undenatured ethanol) of corn ethanol without LUC for 2005–2019.

Co-products can displace their counterparts, which can indirectly reduce the CIs of corn ethanol. We observe that the red hatched bars in Fig. 4 indicate an increase from −14 to −12 gCO_2e/MJ from 2005 to 2019 because of reductions in DGS yield per gallon of ethanol. As mentioned earlier, higher ethanol yield and corn oil production have a reduced DGS yield over time, which impacts the corn CIs.

Although most reductions in CI can be attributed mainly to improvements in farming and ethanol production, upstream processes also have been improved. For example, electricity use in 2019 led to much lower emissions (449 gCO_2e/kWh [125 gCO_2e/MJ]) than in 2005 (722 gCO_2e/kWh [201 gCO_2e/MJ]).[9]

The CARB has reported the average CI of ethanol certified by LCFS every quarter since 2011.[37] Although the comparison of absolute CI values between the CARB-reported CIs and those in the current study may not be appropriate, due to potential plant overlaps in the CARB and the Christianson databases and different considerations of LCA between CARB and this study, a similar trend can be found (Fig. S6). Except for the sudden drop in LCFS's CI in 2019, reductions in CI from 2011 to 2018 were estimated at 15% and 13%, respectively, by the CARB's database and the current study (when LUC is excluded in both cases). Rosenfeld *et al.*[4] investigated the technologies that help reduce the CI and provided the level of CI reduction through each strategy. They also provided the state-specific CIs for LCFS, which presents regional variations in the corn ethanol CI.

Land use change

The LUC GHG emissions from large-scale corn production for corn ethanol have been simulated since 2008. Early studies showed extremely high LUC emissions (e.g., Searchinger *et al.*[38]), and recent studies show significantly lower LUC emissions (Fig. 5). The downtrend in simulated LUC emissions is a result of better developed and calibrated economic models and better modeling of GHG emissions from LUC. Economic models such as the Global Trade Analysis Project (GTAP) model are much improved in addressing land intensification (i.e., existing lands are managed to be more productive) versus land extensification (i.e., croplands extend into new areas of pasture and forest),[39] crop yield increases over time, crop yield differentials in existing croplands and in newly cultivated croplands, double cropping in regions such as Asia, availability and restriction of certain land conversions (e.g., restriction of public forest land for conversion to croplands), price elasticities for crop yield responses, and food demand responses to price changes. For GHG modeling of LUC, models have been improved, with better spatial and temporal resolutions.

The GREET model estimates a LUC GHG emission rate of 7.4 g CO_2e/MJ for US corn ethanol by using Argonne's Carbon Calculator for Land Use and Land Management Change from Biofuels Production (CCLUB).[50] While relying on LUC results from the improved GTAP versions, CCLUB

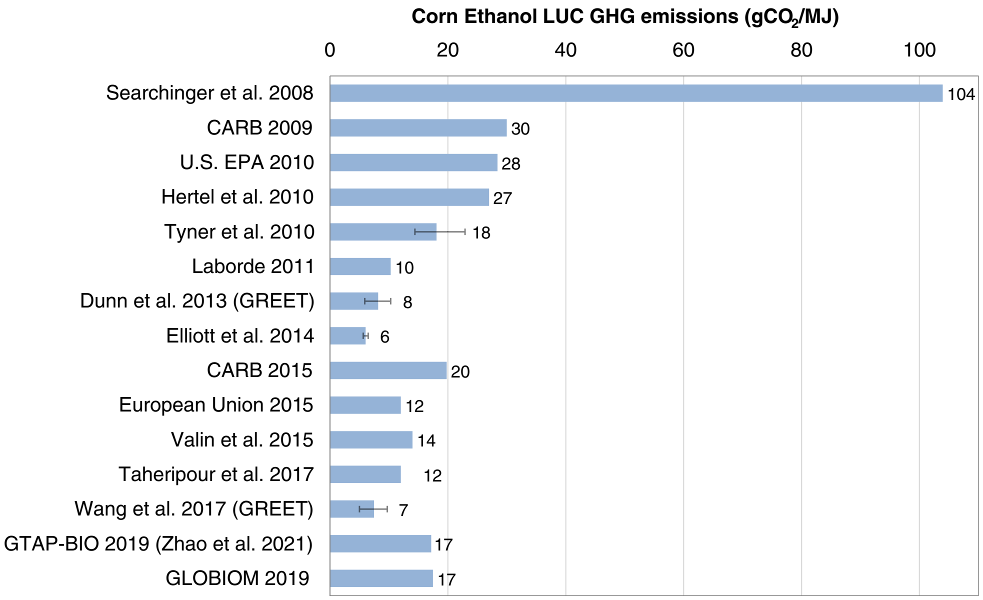

Figure 5. Trend of simulated LUC GHG emissions for US corn ethanol.[39–52] For GTAP-BIO 2019 (Zhao *et al*. 2021[52]) and GLOBIOM 2019, LUC values calculated for corn ethanol-derived jet fuels in ICAO[53] were converted into per-MJ of ethanol. The error bars reflect maximum and minimum values in individual studies.

has developed GHG emission results from GTAP LUC results by adopting detailed modeling results with a process-based model of soil carbon changes, which are an outcome of the modeling's inclusion of the effects of management practices (i.e., tillage) and assumptions that are spatially explicit (e.g., US county-level crop yields).[53]

Aggregate GHG emission reductions for corn ethanol

Reductions in corn ethanol CI, together with expanded ethanol production volume, result in significant emission reduction benefits. In 2005, undenatured ethanol production was estimated at 3.8 BGY (14 BLY),[2] with a CI value of 58 g/MJ (Fig. 4). For the 2005 ethanol production volume level, accumulated emission reduction benefits of the ethanol industry, due to the decrease in CI of corn ethanol from 2005 to 2019, is estimated at 39 MMT CO_2e (Fig. 6). Ethanol production in the USA has also gradually increased, with fuel ethanol production in 2019 reaching 16 BGY (59 BLY). Additional emission reduction benefits through ethanol production expansion are 101 MMT CO_2e from 2005 through 2019. Note that the individual CI values in Fig. 4, plus the LUC value of 7.4 g/MJ (Wang *et al.*[8]) in Fig. 5, were used to estimate the aggregate GHG emission reductions of the ethanol industry from 2005 to 2019.

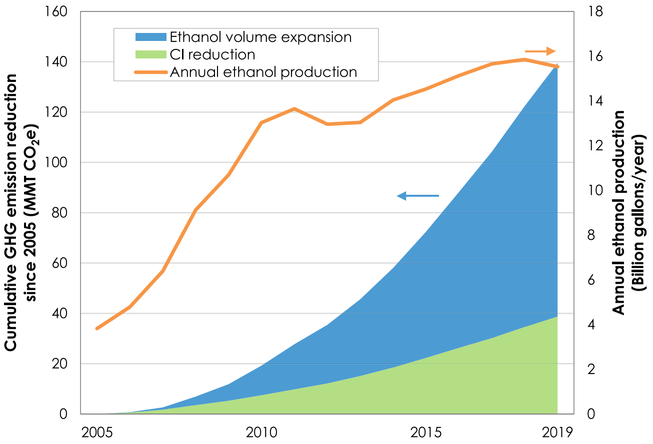

Figure 6. Cumulative GHG emission reduction benefits (area) of the corn ethanol industry from 2005 through 2019 (in MMT CO_2e) through CI reduction and ethanol volume expansion, with annual ethanol production (curve). Emission reduction benefits are estimated using the CI in Fig. 4 plus LUC emissions of 7.4 g/MJ from GREET.

The reduction in the 58 gCO_2e/MJ CI of corn ethanol in 2005 to 45 g/MJ in 2019 (plus the LUC value of 7.4 g/MJ) provides significant GHG emission reductions compared to the CI of 93 gCO_2e/MJ for the US average petroleum gasoline blendstock. The displacement of gasoline by corn ethanol on an energy-equivalent basis from 2005 to 2019 has resulted in a cumulative GHG emissions reduction of 544 MMT CO_2e.

There has been a growing interest in further reducing the overall CI of crop-based biofuels by cutting down the

GHG emissions of biofuel feedstock, which correlates significantly with agronomic practices and chemical and energy inputs in individual farms. Proposals are being made about incentivizing low-carbon biofuel feedstocks in US fuel regulatory programs to promote sustainable farming practices. This will offer further opportunities to advance the sustainability of farming and reduce biofuel CIs.[25]

Conclusions

Corn ethanol production in the USA quadrupled from 2005 to 2019, and US corn farming continues to increase yield. Ethanol biorefinery plants have employed technologies to increase ethanol yield, reduce energy use, and add extra by-products. These trends certainly help reduce the GHG emissions of corn ethanol. We evaluated the downward trend in US corn ethanol CI for 15 years, using primary data of corn farming and ethanol production from the USDA and the ethanol industry. Our study shows that while the corn ethanol industry has experienced significant volume expansion, it has reduced the GHG intensity of corn ethanol through improved US corn farming and ethanol biorefinery operations. Corn yield has increased, and chemical and energy use intensities of corn farming have decreased. In ethanol biorefineries, ethanol yield has increased, and energy use has decreased significantly. In addition, by-products such as corn oil, CO_2, and DGS are produced. These improvements have helped reduce the CI of US corn ethanol by 14 gCO_2e/MJ – from 58 gCO_2e/MJ in 2005 to 45 gCO_2e/MJ in 2019. Ethanol plants have reduced ethanol production emissions by 30% (or 11 gCO_2e/MJ) over the 15-year period, mainly by reducing the energy inputs per unit of ethanol produced. Corn farming reduced chemical and energy input intensities, which contributes to a 17% reduction in farming-related emissions (4.9 gCO_2e/MJ).

From the reduction in corn ethanol GHG emission intensity and ethanol volume expansion, we estimate that the ethanol industry has achieved an additional 140 MMT cumulative GHG emission reduction from 2005 to 2019. The ethanol produced in our 15 years has been introduced to the transportation sector to displace petroleum gasoline. With the displacement, on the LCA basis, corn ethanol has helped the US transportation sector reduce GHG emissions by 544 MMT over the period.

Additional measures exist to reduce corn ethanol GHG emissions further. In the farming stage, sustainable farming practices such as no-till and cover crops can help reduce fertilizer inputs and increase soil organic carbon content. In ethanol biorefineries, fermentation CO_2 can be captured and sequestered, and fossil natural gas can be replaced with renewable natural gas and biomass gasification. Biofuels, including corn ethanol, can play a critical role in the US desire for deep de-carbonization of its economy.

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