

LETTER • OPEN ACCESS

Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use

To cite this article: Michael Wang *et al* 2012 *Environ. Res. Lett.* 7 045905

View the [article online](#) for updates and enhancements.

Related content

- [Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types](#)
Michael Wang, May Wu and Hong Huo
- [Can ethanol alone meet California's low carbon fuel standard? An evaluation of feedstock and conversion alternatives](#)
Yimin Zhang, Satish Joshi and Heather L MacLean
- [Lifecycle greenhouse gas implications of US national scenarios for cellulosic ethanol production](#)
Corinne D Scown, William W Nazaroff, Umakant Mishra *et al.*

Recent citations

- [Fermentation technology to improve productivity in dry grind corn process for bioethanol production](#)
Deepak Kumar *et al*
- [A General Techno-Economic Analysis of CO₂ Electrolysis Systems](#)
Matthew Jouny *et al*
- [Cointegration and nonlinear causality among ethanol-related prices: evidence from Brazil](#)
Anupam Dutta

Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use

Michael Wang, Jeongwoo Han, Jennifer B Dunn, Hao Cai and Amgad Elgowainy

Systems Assessment Group, Energy Systems Division, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439, USA

E-mail: mqwang@anl.gov, jhan@anl.gov, jdunn@anl.gov, hcai@anl.gov and aelgowainy@anl.gov

Received 29 August 2012

Accepted for publication 22 November 2012

Published 13 December 2012

Online at stacks.iop.org/ERL/7/045905

Abstract

Globally, bioethanol is the largest volume biofuel used in the transportation sector, with corn-based ethanol production occurring mostly in the US and sugarcane-based ethanol production occurring mostly in Brazil. Advances in technology and the resulting improved productivity in corn and sugarcane farming and ethanol conversion, together with biofuel policies, have contributed to the significant expansion of ethanol production in the past 20 years. These improvements have increased the energy and greenhouse gas (GHG) benefits of using bioethanol as opposed to using petroleum gasoline. This article presents results from our most recently updated simulations of energy use and GHG emissions that result from using bioethanol made from several feedstocks. The results were generated with the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model. In particular, based on a consistent and systematic model platform, we estimate life-cycle energy consumption and GHG emissions from using ethanol produced from five feedstocks: corn, sugarcane, corn stover, switchgrass and miscanthus.

We quantitatively address the impacts of a few critical factors that affect life-cycle GHG emissions from bioethanol. Even when the highly debated land use change GHG emissions are included, changing from corn to sugarcane and then to cellulosic biomass helps to significantly increase the reductions in energy use and GHG emissions from using bioethanol. Relative to petroleum gasoline, ethanol from corn, sugarcane, corn stover, switchgrass and miscanthus can reduce life-cycle GHG emissions by 19–48%, 40–62%, 90–103%, 77–97% and 101–115%, respectively. Similar trends have been found with regard to fossil energy benefits for the five bioethanol pathways.

Keywords: corn ethanol, sugarcane ethanol, cellulosic ethanol, greenhouse gas emissions, energy balance, life-cycle analysis, biofuels

 Online supplementary data available from stacks.iop.org/ERL/7/045905/mmedia



Content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](http://creativecommons.org/licenses/by/3.0/). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

1. Introduction

Globally, biofuels are being promoted for reducing greenhouse gas (GHG) emissions, enhancing the domestic energy

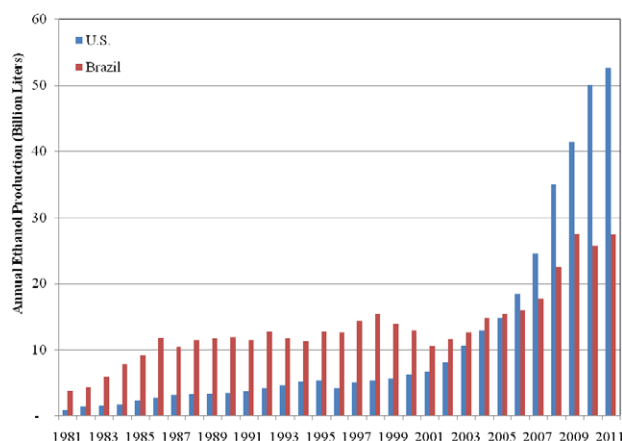


Figure 1. Annual ethanol production in the US and Brazil (based on data from the Renewable Fuels Association (RFA 2012) and Brazilian Sugarcane Association (UNICA 2012)).

security of individual countries and promoting rural economic development. In a carbon-constrained world, liquid transportation fuels from renewable carbon sources can play an important role in reducing GHG emissions from the transportation sector (IEA 2012). At present, the two major biofuels produced worldwide are (1) ethanol from fermentation of sugars primarily in corn starch and sugarcane and (2) biodiesel from transesterification of vegetable oils, with ethanol accounting for the majority of current biofuel production. Figure 1 shows the growth of annual ethanol production between 1981 and 2011 in the US and Brazil, the two dominant ethanol-producing countries.

The production of corn ethanol in the US has increased to more than 52 billion liters since the beginning of the US ethanol program in 1980. The increase after 2007, the year the Energy Independence and Security Act (EISA) came into effect, is remarkable. Growth in the production of Brazilian sugarcane ethanol began in the 1970s when the Brazilian government began to promote its production. The most recent growth in sugarcane ethanol production, since 2001, has mainly resulted from the popularity of ethanol flexible-fuel vehicles and from the advantageous price of ethanol over gasoline in Brazil.

Over the long term, the greatest potential for bioethanol production lies in the use of cellulosic feedstocks, which include crop residues (e.g., corn stover, wheat straw, rice straw and sugarcane straw), dedicated energy crops (e.g., switchgrass, miscanthus, mixed prairie grasses and short-rotation trees) and forest residues. The resource potential of these cellulosic feedstocks can support a huge amount of biofuel production. For example, in the US, nearly one billion tonnes of these resources are potentially available each year to produce more than 340 billion liters of ethanol per year (DOE 2011). This volume is significant, even when compared to the annual US consumption of gasoline, at 760 billion ethanol-equivalent liters (EIA 2012).

The GHG emission reduction potential of bioethanol, especially cellulosic ethanol, is recognized in policies that address reducing the transportation sector’s GHG emissions (i.e., California’s low-carbon fuel standard (LCFS; CARB

2009), the US renewable fuels standard (RFS; EPA 2010) and the European Union’s renewable energy directive (RED; Neeft *et al* 2012)). Nonetheless, the life-cycle GHG emissions of bioethanol, especially those of corn-based ethanol, have been subject to debate (Farrell *et al* 2006, Fargione *et al* 2008, Searchinger *et al* 2008, Liska *et al* 2009, Wang *et al* 2011a, Khatiwada *et al* 2012). With regard to corn ethanol, some authors concluded that its life-cycle GHG emissions are greater than those from gasoline (Searchinger *et al* 2008, Hill *et al* 2009). Others concluded that corn ethanol offers reductions in life-cycle GHG emissions when compared with gasoline (Liska *et al* 2009, Wang *et al* 2011a). On the other hand, most analyses of cellulosic ethanol reported significant reductions in life-cycle GHG emissions when compared with those from baseline gasoline. Reductions of 63% to 118% have been reported (Borrion *et al* 2012, MacLean and Spatari 2009, Monti *et al* 2012, Mu *et al* 2010, Scown *et al* 2012, Wang *et al* 2011a, Whitaker *et al* 2010). Most of these studies included a credit for the displacement of grid electricity with electricity co-produced at cellulosic ethanol plants from the combustion of lignin. Some, however, excluded co-products (e.g., MacLean and Spatari 2009). Uniquely, Scown *et al* (2012) considered land use change (LUC) GHG emissions (for miscanthus ethanol) and estimated total net GHG sequestration of up to 26 g of CO₂ equivalent (CO₂e)/MJ of ethanol. In the case of sugarcane ethanol, Seabra *et al* (2011) and Macedo *et al* (2008) reported life-cycle GHG emissions that were between 77% and 82% less than those of baseline gasoline. Wang *et al* (2008) estimated this reduction to be 78%.

A detailed assessment of the completed studies requires that they be harmonized with regard to the system boundary, co-product allocation methodology, and other choices and assumptions that were made. Other researchers (e.g., Chum *et al* 2011) have undertaken this task to some extent. Here we instead use a consistent modeling platform to examine the GHG impacts from using corn ethanol, sugarcane ethanol and cellulosic ethanol. The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model that we developed at Argonne National Laboratory has been used by us and many other researchers to examine GHG emissions from vehicle technologies and transportation fuels on a consistent basis (Argonne National Laboratory 2012). The GREET model covers bioethanol production pathways extensively; we have updated key parameters in these pathways based on recent research. This article presents key GREET parametric assumptions and life-cycle energy and GHG results for bioethanol pathways contained in the GREET version released in July 2012. Moreover, we quantitatively address the impacts of critical factors that affect GHG emissions from bioethanol.

2. Scope, methodology, and key assumptions

We include bioethanol production from five feedstocks: corn grown in the US, sugarcane grown in Brazil, and corn stover, switchgrass and miscanthus, all grown in the US. Even though the wide spread drought in the US midwest in the summer of 2012 may dampen corn ethanol production in 2012, corn

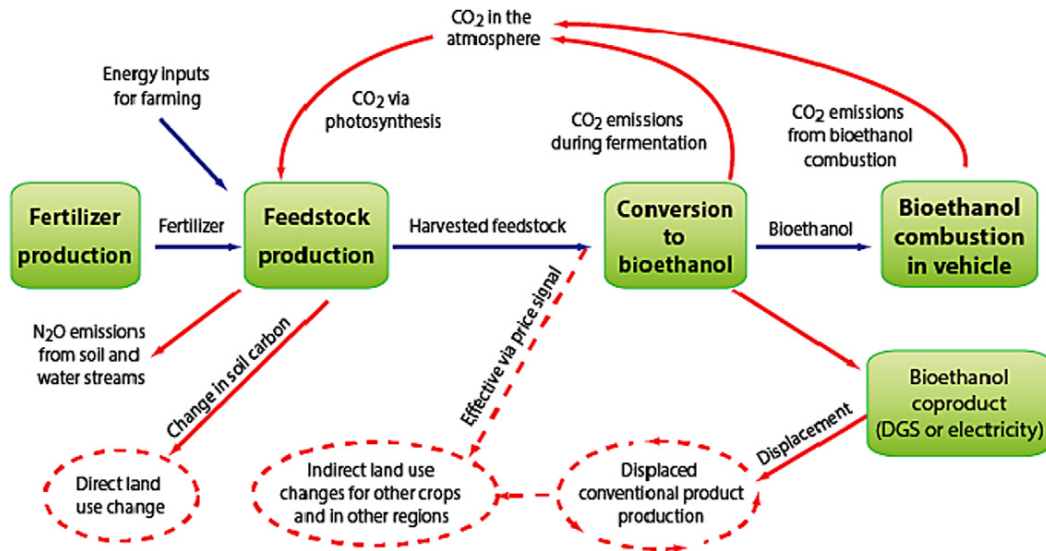


Figure 2. System boundary of well-to-wheels analysis of bioethanol pathways.

ethanol production will continue to grow, possibly exceeding the goal of 57 billion liters per year in the 2007 EISA. Likewise, Brazil’s sugarcane ethanol production will continue to grow. In the US midwest corn belt, up to 363 million tonnes of corn stover can be sustainably harvested in a year (DOE 2011). Large-scale field trials have been in place to collect and transport corn stover (Edgerton *et al* 2010). Switchgrass is a native North American grass. Field trials of growing switchgrass as an energy crop have been in place since the 1980s. Miscanthus, on the other hand, has a high potential yield per acre. In the past several years, significant efforts have been made in the US to develop better varieties of miscanthus with higher yields (Somerville *et al* 2010).

We conducted the well-to-wheels (WTW, or, more precisely for bioethanol, field-to-wheels) analyses of the five bioethanol pathways with the GREET model (Argonne National Laboratory 2012, Han *et al* 2011, Dunn *et al* 2011, Wang *et al* 2012). In particular, we used the most recent GREET version (GREET1.2012) for this analysis to conduct simulations for the year 2015. Figure 2 presents the system boundary for the five bioethanol pathways in our analysis. Parametric details of the five pathways are presented below. For comparison, we included petroleum gasoline in our analysis.

The GREET model is designed with a stochastic modeling tool to address the uncertainties of key parameters and their effects on WTW results. For this article, we used that feature to conduct simulations with probability distribution functions for key parameters in the WTW pathways. In addition, we conducted parametric sensitivity analyses to test the influence of key parameters on GHG emissions for each of the five pathways.

2.1. Corn-to-ethanol in the US

For the corn-to-ethanol pathway, corn farming and ethanol production are the two major direct GHG sources (Wang *et al* 2011a). From farming, N₂O emissions from the nitrification and denitrification of nitrogen fertilizer in cornfields, fertilizer

production and fossil fuel use for farming are significant GHG emission sources. GHG emissions during ethanol production result from the use of fossil fuels, primarily natural gas (NG), in corn ethanol plants. GREET takes into account GHG emissions from NG production and distribution (such as methane leakage during these activities (see Burnham *et al* 2012)) as well as those from NG combustion. The treatment of distillers’ grains and solubles (DGS), a valuable co-product from corn ethanol plants, in the life-cycle analysis (LCA) of corn ethanol is important because it can affect results regarding corn ethanol’s GHG emissions (Wang *et al* 2011b). Table 1 presents key parametric assumptions in GREET for corn-based ethanol. In this and subsequent tables, P10 and P90 represent the 10th and 90th percentiles, respectively, of these parameters.

2.2. Production of ethanol from sugarcane in Brazil for use in the US

Brazilian sugarcane mills produce both ethanol and sugar, with the split between them readily adjusted to respond to market prices. Bagasse, the residue after sugarcane juice is squeezed from sugarcane, is combusted in sugar mills to produce steam (for internal use) and electricity (for internal use and for export to the electric grid). Sugarcane farming is associated with significant GHG emissions from both upstream operations such as fertilizer production and from the field itself. For example, the nitrogen (N) in sugarcane residues (i.e., straw) on the field as well as the N in fertilizer emit N₂O. The sugar mill by-products vinasse and filter cake applied as soil amendments also emit N₂O as a portion of the N in them degrades (Braga do Carmo *et al* 2012). Open field burning, primarily with manual harvesting of sugarcane (which is being phased out), and transportation logistics (truck transportation of sugarcane from fields to mills and of ethanol from mills to Brazilian ports; ocean tanker transportation of ethanol from southern Brazilian ports to US ports; and US ethanol transportation) are also key GHG emission sources in the sugarcane ethanol life cycle. Table 2

Table 1. Parametric assumptions about the production of ethanol from corn in the US.

Parameter: unit	Mean	P10	P90	Distribution function type
Corn farming: per tonne of corn (except as noted)				
Direct energy use for corn farming: MJ	379	311	476	Weibull ^a
N fertilizer application: kg	15.5	11.9	19.3	Normal ^a
P fertilizer application: kg	5.54	2.86	8.61	Lognormal ^a
K fertilizer application: kg	6.44	1.56	12.5	Weibull ^a
Limestone application: kg	43.0	38.7	47.3	Normal ^a
N ₂ O conversion rate of N fertilizer: %	1.525	0.413	2.956	Weibull ^b
NG use per tonne of ammonia produced: GJ	30.7	28.1	33.1	Triangular ^c
Corn ethanol production				
Ethanol yield: l/tonne of corn	425	412	439	Triangular ^a
Ethanol plant energy use: MJ/l of ethanol	7.49	6.10	8.87	Normal ^a
DGS yield: kg (dry matter basis)/l of ethanol	0.676	0.609	0.743	Triangular ^a
Enzyme use: kg/tonne of corn	1.04	0.936	1.15	Normal ^d
Yeast use: kg/tonne of corn	0.358	0.323	0.397	Normal ^d

^a The type and shape of distribution functions were developed in Brinkman *et al* (2005). The means of the distributions were scaled later to the values in Wang *et al* (2007, 2011a).

^b Based on our new assessment of the literature, see supporting information (available at stacks.iop.org/ERL/7/045905/mmedia) for details.

^c From Brinkman *et al* (2005).

^d Selected among 11 distribution function types, with maximization of the goodness-of-fit method to the data compiled in Dunn *et al* (2012a).

Table 2. Parametric assumptions about the production of sugarcane ethanol in Brazil and its use in the US (per tonne of sugarcane, except as noted).

Parameter: unit	Mean	P10	P90	Distribution function type
Sugarcane farming				
Farming energy use for sugarcane: MJ	100	90.2	110	Normal ^a
N fertilizer use: g	800	720	880	Normal ^a
P fertilizer use: g	300	270	330	Normal ^a
K fertilizer use: g	1000	900	1100	Normal ^a
Limestone use: g	5200	4680	5720	Normal ^a
Yield of sugarcane straw: kg	140	126	154	Normal ^a
Filter cake application rate: kg (dry matter basis)	2.87	2.58	3.16	Normal ^a
Vinasse application rate: l	570	513	627	Normal ^a
Share of mechanical harvest: % of total harvest	80	NA ^b	NA ^b	Not selected
N ₂ O conversion rate of N fertilizer: %	1.22	1.05	1.39	Uniform ^c
Sugarcane ethanol production				
Ethanol yield: l	81.0	73.1	89.0	Normal ^a
Ethanol plant energy use: fossil kJ/l of ethanol	83.6	75.3	92.0	Normal ^a
Electricity yield: kWh	75	57.8	100	Exponential ^a
Sugarcane ethanol transportation				
Ethanol transportation inside of Brazil: km	690	NA ^b	NA ^b	Not selected
Ethanol transportation from Brazil to the US: km	11 930	NA ^b	NA ^b	Not selected

^a By maximization of goodness-of-fit to the data in Macedo *et al* (2004, 2008) and Seabra *et al* (2011).

^b NA = not available.

^c Data on N₂O emissions from sugarcane fields is very limited, so we assumed uniform distribution. See supporting information (available at stacks.iop.org/ERL/7/045905/mmedia) for details.

lists key parametric assumptions for the sugarcane-to-ethanol pathway. We did not have data on enzyme and yeast use for sugarcane ethanol production, so their impacts are not considered in this analysis. Given that enzymes and yeast have a minor impact on corn ethanol WTW results (Dunn *et al* 2012a), we expect that their effect on sugarcane WTW results are small as well.

2.3. Corn stover-, switchgrass- and miscanthus-to-ethanol

The yield of corn stover in cornfields could match corn grain yield on a dry matter basis. For example, for a corn grain yield of 10 tonnes (with 15% moisture content) per hectare, the corn stover yield could be 8.5 tonnes (bone dry) per hectare. Studies concluded that one-third to one-half of corn stover in cornfields can be sustainably removed without causing

Table 3. Cellulosic ethanol production parametric assumptions (per dry tonne of cellulosic biomass, except as noted).

Parameter: unit	Mean	P10	P90	Distribution function type
Corn stover collection				
Energy use for collection: MJ	219	197	241	Normal ^a
Supplemental N fertilizer: g	8488	6499	10 476	Normal ^a
Supplemental P fertilizer: g	2205	1102	3307	Normal ^a
Supplemental K fertilizer: g	13 228	7491	18 964	Normal ^a
Switchgrass farming				
Farming energy use: MJ	144	89.1	199	Normal ^b
N fertilizer use: g	7716	4783	10 649	Normal ^b
P fertilizer use: g	110	77	143	Normal ^b
K fertilizer use: g	220	154	287	Normal ^b
N ₂ O conversion rate of N fertilizer: %	1.525	0.413	2.956	Weibull ^c
Miscanthus farming				
Farming energy use: MJ	153	138	168	Normal ^d
N fertilizer use: g	3877	2921	4832	Normal ^d
P fertilizer use: g	1354	726	1981	Normal ^d
K fertilizer use: g	5520	3832	7209	Normal ^d
N ₂ O conversion rate of N fertilizer: %	1.525	0.413	2.956	Weibull ^c
Cellulosic ethanol production^e				
Ethanol yield: l	375	328	423	Normal ^f
Electricity yield: kWh	226	162	290	Triangular ^f
Enzyme use: grams/kg of substrate (dry matter basis)	15.5	9.6	23	Triangular ^g
Yeast use: grams/kg of substrate (dry matter basis)	2.49	2.24	27.4	Normal ^g

^a By maximization of goodness-of-fit to the data compiled in Han *et al* (2011).

^b By maximization of goodness-of-fit to the data compiled in Dunn *et al* (2011).

^c Based on our new assessment of the literature, see supporting information (available at stacks.iop.org/ERL/7/045905/mmedia) for details.

^d By maximization of goodness-of-fit to the data compiled in Wang *et al* (2012).

^e Although we anticipated differences in plant yields and inputs among the three cellulosic feedstocks, we did not find enough data to quantify the differences for this study.

^f The type and shape of distribution functions were developed in Brinkman *et al* (2005). The means of the distributions were scaled later to the values in Wang *et al* (2011a).

^g By maximization of goodness-of-fit to the data compiled in Dunn *et al* (2012a).

erosion or deteriorating soil quality (Sheehan *et al* 2008, DOE 2011). When stover is removed, N, P and K nutrients are removed, too. We assumed in GREET simulations that the amount of nutrients lost with stover removal would be supplemented with synthetic fertilizers. We developed our replacement rates based on data for nutrients contained in harvested corn stover found in the literature (Han *et al* 2011).

Switchgrass can have an annual average yield of 11–13 tonnes ha⁻¹, with the potential of more than 29 tonnes ha⁻¹ (Sokhansanj *et al* 2009). To maintain a reasonable yield, fertilizer is required for switchgrass growth. In arid climates, irrigation may be also required. In our analysis, we assumed that switchgrass would be grown in the midwest, south and southeast US without irrigation. Miscanthus can have yields above 29 tonnes ha⁻¹ (with up to 40 tonnes) (Somerville *et al* 2010). Similar to switchgrass, fertilizer application may be required in order to maintain good yields.

In cellulosic ethanol plants, cellulosic feedstocks go through pretreatment with enzymes that break cellulose and hemicellulose into simple sugars for fermentation. The lignin

portion of cellulosic feedstocks can be used in a combined heat and power (CHP) generator in the plant. The CHP generator can provide process heat and power in addition to surplus electricity for export to the grid. Ethanol and electricity yields in cellulosic ethanol plants are affected by the composition of cellulosic feedstocks (although we did not find enough data to identify the differences in ethanol and electricity yield for our study). Lignin can also be used to produce bio-based products instead of combustion. In our analysis, we assume combustion of lignin for steam and power generation. Table 3 presents key assumptions for the three cellulosic ethanol pathways.

2.4. Land use change from bioethanol production

Since 2009, we have been addressing potential LUC impacts of biofuel production from corn, corn stover, switchgrass and miscanthus with Purdue University and the University of Illinois (Taheripour *et al* 2011, Kwon *et al* 2012, Mueller *et al* 2012, Dunn *et al* 2012b). We developed estimates of LUC GHG emissions with a GREET module called the Carbon

Calculator for Land Use Change from Biofuels Production (CCLUB) (Mueller *et al* 2012). In CCLUB, we combine LUC data generated by Purdue University from using its Global Trade Analysis Project (GTAP) model (Taheripour *et al* 2011) and domestic soil organic carbon (SOC) results from modeling with CENTURY, a soil organic matter model (Kwon *et al* 2012) that calculates net carbon emissions from soil. Above ground carbon data in CCLUB for forests comes from the carbon online estimator (COLE) developed by the USDA and the National Council for Air and Stream Improvement (Van Deusen and Heath 2010). International carbon emission factors for various land types are from the Woods Hole Research Center (reproduced in Tyner *et al* (2010)). We provide a full analysis of CCLUB results for these feedstocks elsewhere (Dunn *et al* 2012b) and summarize them briefly here.

When land is converted to the production of biofuel feedstock, direct impacts are changes in below ground and above ground carbon content, although the latter is of concern mostly for forests. These LUC-induced changes cause SOC content to either decrease or increase, depending on the identity of the crop. For example, if land is converted from cropland-pasture to corn, SOC will decrease, and carbon will be released to the atmosphere. However, conversion of this same type of land to miscanthus or switchgrass production likely sequesters carbon (Dunn *et al* 2012b). This sequestration will continue for a certain length of time until an SOC equilibrium is reached. Equilibrium seems to occur after about 100 years in the case of switchgrass (Andress 2002) and 50 years in the case of miscanthus (Hill *et al* 2009, Scown *et al* 2012). This time-dependence of GHG emissions associated with LUC presents a challenge in biofuel LCA. The most appropriate time horizon for SOC changes and the treatment of future emissions as compared to near-term emissions is an open research question (Kløverpris and Mueller 2012, O'Hare *et al* 2009). On one hand, a near-term approach in which the time frame is two or three decades could be used. The advantages of this approach include assigning more importance to near-term events that are more certain. Some LCA standards, such as PAS 2050 (BSI 2011) advocate a 100 year time horizon for the LCA of any product. If such an extended time horizon is used, however, future emissions should be discounted, although the methodology for this discounting is unresolved. In addition, the uncertainty associated with land use for over a century is very large. Given these factors, we assume a 30 year period for both soil carbon modeling and for amortizing total LUC GHG emissions over biofuel production volume during this period. This approach, which aligns with the EPA's LCA methodology for the RFS (EPA 2010), may result in a slightly conservative estimate for the soil carbon sequestration that might be associated with switchgrass and miscanthus production, because lands producing these crops will continue to sequester carbon after the 30 year time horizon of this analysis. On the other hand, this selection gives a higher GHG sequestration rate per unit of biofuel since the total biofuel volume for amortization is smaller.

Our modeling with CCLUB indicates that of the feedstocks examined, corn ethanol had the largest LUC GHG

emissions (9.1 g CO₂e MJ⁻¹ of ethanol), whereas LUC emissions associated with miscanthus ethanol production caused substantial carbon sequestration (−12 g CO₂e MJ⁻¹). Switchgrass ethanol production results in a small amount of LUC emissions: 1.3 g CO₂e MJ⁻¹. LUC emissions associated with corn stover ethanol production result in a GHG sequestration of −1.2 g CO₂e MJ⁻¹. It is important to note that these results were generated by using one configuration of modeling assumptions in CCLUB. Elsewhere we describe how these results vary with alternative CCLUB configurations (Dunn *et al* 2012b).

We have not conducted LUC GHG modeling for sugarcane ethanol. The EPA reported LUC GHG emissions for sugarcane ethanol of 5 g CO₂e MJ⁻¹ (EPA 2010). This value does not include indirect effects of LUC beyond SOC changes, such as changes in emissions from rice fields and livestock production. The United Kingdom Department of Transport (E4Tech 2010) estimated indirect land use change (iLUC) associated with sugarcane ethanol as ranging between 18 and 27 g CO₂e MJ⁻¹. Another recent report estimates sugarcane LUC GHG emissions as 13 g CO₂e MJ⁻¹ (ATLASS Consortium 2011). CARB estimated that these emissions were 46 g CO₂e MJ⁻¹ (Khatiwada *et al* 2012) but is revisiting that value. The EU is proposing LUC GHG emissions of 13 g CO₂e MJ⁻¹ (EC 2012). Without considering the CARB value, we decided to use LUC GHG emissions of 16 g CO₂e MJ⁻¹ for sugarcane ethanol.

2.5. Petroleum gasoline

We made petroleum gasoline the baseline fuel to which the five ethanol types are compared. The emissions and energy efficiency associated with gasoline production are affected by the crude oil quality, petroleum refinery configuration, and gasoline quality. Of the crude types fed to US refineries, the Energy Information Administration (EIA 2012) predicts that in 2015 (the year modeled for this study), 13.4% of US crude will be Canadian oil sands. Based on EIA reports, we estimated 5.1% of US crude would be Venezuelan heavy and sour crude, and the remaining 81.5% would be conventional crude. The former two are very energy-intensive and emissions-intensive to recover and refine. US petroleum refineries are configured to produce gasoline and diesel with a two-to-one ratio by volume, while European refineries are with a one-to-two ratio. A gasoline-specific refining energy efficiency is needed for gasoline WTW analysis, and it is often calculated with several allocation methods (Wang *et al* 2004, Bredeson *et al* 2010, Palou-Rivera *et al* 2011). Also, methane flaring and venting could be a significant GHG emission source for petroleum gasoline. Table 4 lists the key parametric assumptions for petroleum gasoline.

2.6. Treatment of co-products in bioethanol and gasoline LCA

Table 5 lists co-products, the products they displace and the co-product allocation methodologies for the six pathways included in this article. The displacement method is

Table 4. Petroleum gasoline parametric assumptions (per GJ of crude oil, except as noted).

Parameter: unit	Mean	P10	P90	Distribution function type
Conventional crude				
Conventional crude recovery efficiency: %	98.0	97.4	98.6	Triangular ^a
Heavy and sour crude recovery efficiency: %	87.9	87.3	88.5	Triangular ^b
CH ₄ venting: g	7.87	6.26	9.48	Normal ^c
CO ₂ from associated gas flaring/venting: g	1355	1084	1627	Normal ^c
Oil sands—surface mining (48% in 2015)				
Bitumen recovery efficiency: %	95.0	94.4	95.6	Triangular ^d
CH ₄ venting: g	12.8	7.42	198	Normal ^e
CO ₂ from associated gas flaring: g	187	83.9	289	Normal ^e
Hydrogen use for upgrade: MJ	84.2	67.4	101	Normal ^d
Oil sands—in situ production (52% in 2015)				
Bitumen recovery efficiency: %	85.0	83.6	86.5	Triangular ^d
Hydrogen use for upgrade: MJ	32.3	25.9	38.8	Normal ^d
Crude refining				
Gasoline refining efficiency: %	90.6	88.9	92.3	Normal ^f

^a From Brinkman *et al* (2005).

^b Based on Rosenfeld *et al* (2009).

^c By maximization of goodness-of-fit to the data compiled in Palou-Rivera *et al* (2011).

^d From Larsen *et al* (2005).

^e Based on Bergerson *et al* (2012).

^f The type and shape of distribution functions were developed in Brinkman *et al* (2005). The means of the distributions were scaled later to the values in Palou-Rivera *et al* (2011).

Table 5. Co-products of bioethanol and gasoline pathways and co-product allocation methodologies.

Pathway	Co-product	Displaced products	LCA method used in this study	Alternative LCA methods available in GREET	References
Corn ethanol	DGS ^a	Soybean, corn, and other animal feeds	Displacement	Allocation based on market revenue, mass or energy	Wang <i>et al</i> (2011b); Arora <i>et al</i> (2011)
Sugarcane ethanol	Electricity from bagasse	Conventional electricity	Allocation based on energy ^b	Displacement ^c	Wang <i>et al</i> (2008)
Cellulosic ethanol (corn stover, switchgrass and miscanthus)	Electricity from lignin	Conventional electricity	Displacement ^d	Allocation based on energy	Wang <i>et al</i> (2011b)
Petroleum gasoline	Other petroleum products	Other petroleum products	Allocation based on energy	Allocation based on mass, market revenue and process energy use	Wang <i>et al</i> (2004); Bredeson <i>et al</i> (2010); Palou-Rivera <i>et al</i> (2011)

^a Dry mill corn ethanol plants produce dry and wet DGS with shares of 65% and 35% (on a dry matter basis), respectively. We include these shares in our analysis.

^b Electricity output accounts for 14% of the total energy output of sugarcane ethanol plants. With such a significant share of electricity, we decided to use the energy allocation method for ethanol and electricity rather than the displacement method.

^c With the displacement method, if we assume that the co-produced electricity displaces the Brazilian average electricity mix (with 83% from hydro power), the sugarcane ethanol results are similar to those when the energy allocation method is used. If the co-produced electricity displaces NG combined cycle power, WTW sugarcane ethanol GHG emissions are reduced by 21 g CO₂e MJ⁻¹.

^d We assumed that co-produced electricity replaces the US average electricity mix in 2015 (with 44% from coal and 21% from NG (EIA 2012) and a GHG emission rate of 635 g CO₂e kWh⁻¹). If co-produced electricity displaces the US midwest generation mix (with 74% from coal and 4% from NG and a GHG emission rate of 844 g CO₂e kWh⁻¹), cellulosic ethanol WTW GHG emissions are reduced by 5.7 g CO₂e MJ⁻¹. If co-produced electricity displaces NG combined cycle power (with a GHG emission rate of 539 g CO₂e kWh⁻¹), cellulosic ethanol GHG emissions are increased by 2.5 g CO₂e MJ⁻¹ from the base case.

recommended by the International Standard Organization and was used by EPA and CARB. However, the energy allocation method was used by the European Commission. Wang *et al* (2011b) argued that while there is no universally accepted

method to treat co-products in biofuel LCA, the transparency of methodology and the impacts of methodology choices should be presented in individual studies to better inform readers.

Table 6. Energy balance and energy ratio of bioethanol.

	Corn	Sugarcane	Corn stover	Switchgrass	Miscanthus
Energy balance (MJ l ⁻¹) ^a	10.1	16.4	20.4	21.0	21.4
Energy ratio	1.61	4.32	4.77	5.44	6.01

^a A liter of ethanol contains 21.3 MJ of energy (lower heating value).

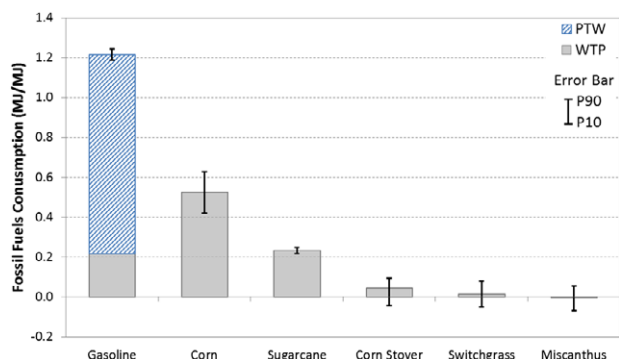


Figure 3. Well-to-wheels results for fossil energy use of gasoline and bioethanol.

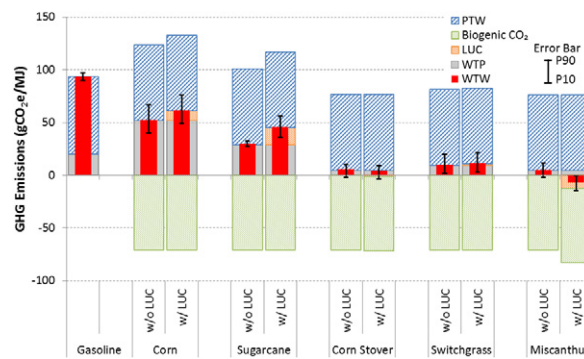


Figure 4. Well-to-wheels results for greenhouse gas emissions in CO₂e for six pathways.

3. Results

We present WTW results for energy use and GHG emissions for the five bioethanol pathways and baseline gasoline (a blending stock without ethanol or other oxygenates). Energy use results for this study include total energy use, fossil energy use, petroleum use, natural gas use and coal use. Because of space limitations, only fossil energy use results (including petroleum, coal and natural gas) are presented here. GHG emissions here are CO₂-equivalent emissions of CO₂, CH₄ and N₂O, with 100 year global warming potentials of 1, 25 and 298, respectively, per the recommendation of the International Panel on Climate Change (Eggleston *et al* 2006).

Figure 3 presents WTW results for fossil energy use per MJ of fuel produced and used. The chart presents the well-to-pump (WTP) stage (more precisely, in the bioethanol cases, field-to-pump stage) and pump-to-wheels (PTW) stage. The WTP and PTW bars together represent WTW results. The error bars represent values with P10 (the lower end of the line) and P90 (the higher end of the line) for WTW results.

Selection of the MJ functional unit here means that energy efficiency differences between gasoline and ethanol vehicles are not taken into account. On an energy basis (or gasoline-equivalent basis), vehicle efficiency differences for low-level and mid-level blends of ethanol in gasoline are usually small. If engines are designed to take advantage of the high octane number of ethanol, however, high-level ethanol blends could improve vehicle efficiency.

For petroleum gasoline, the largest amount of fossil energy is used in the PTW stage because gasoline energy is indeed fossil-based. In contrast, the five ethanol pathways do not consume fossil energy in the PTW stage. With regard to WTP fossil energy use, corn ethanol has the largest amount due to the intensive use of fertilizer in farming and use of energy (primarily NG) in corn ethanol plants. Other ethanol pathways have minimum fossil energy use. In fact, the P10

fossil energy values for the three cellulosic ethanol types are negative for two reasons. First, fossil energy use during farming and ethanol production for these pathways is minimal. Second, the electricity generated in cellulosic ethanol plants can displace conventional electricity generation, which, in the US, is primarily fossil energy based. Relative to gasoline, ethanol from corn, sugarcane, corn stover, switchgrass and miscanthus, on average, can reduce WTW fossil energy use by 57%, 81%, 96%, 99% and 100%, respectively.

An energy balance or energy ratio is often presented for bioethanol to measure its energy intensity. Table 6 presents energy balances and ratios of the five bioethanol pathways. The energy balance is calculated as the difference between the energy content of ethanol and the fossil energy used to produce it. Energy ratios are calculated as the ratio between the two. All five ethanol types have positive energy balance values and energy ratios greater than one.

Figure 4 shows WTW GHG emissions of the six pathways. GHG emissions are separated into WTP, PTW, biogenic CO₂ (i.e., carbon in bioethanol) and LUC GHG emissions. Combustion emissions are the most significant GHG emission source for all fuel pathways. However, in the five bioethanol cases, biogenic CO₂ in ethanol offsets ethanol combustion GHG emissions almost entirely. LUC GHG emissions, as discussed in an earlier section, are from the CCLUB simulations for the four bioethanol pathways (corn, corn stover, switchgrass and miscanthus). LUC emissions of Brazilian sugarcane ethanol are based on our review of available literature. It is not possible to maintain a consistent analytical approach among these unharmonized literature studies of sugarcane ethanol and between them and CCLUB modeling results. Because of the ongoing debate regarding the values and associated uncertainties of LUC GHG emissions, we provide two separate sets of results for ethanol: one with LUC emissions included, and the other with LUC emissions excluded.

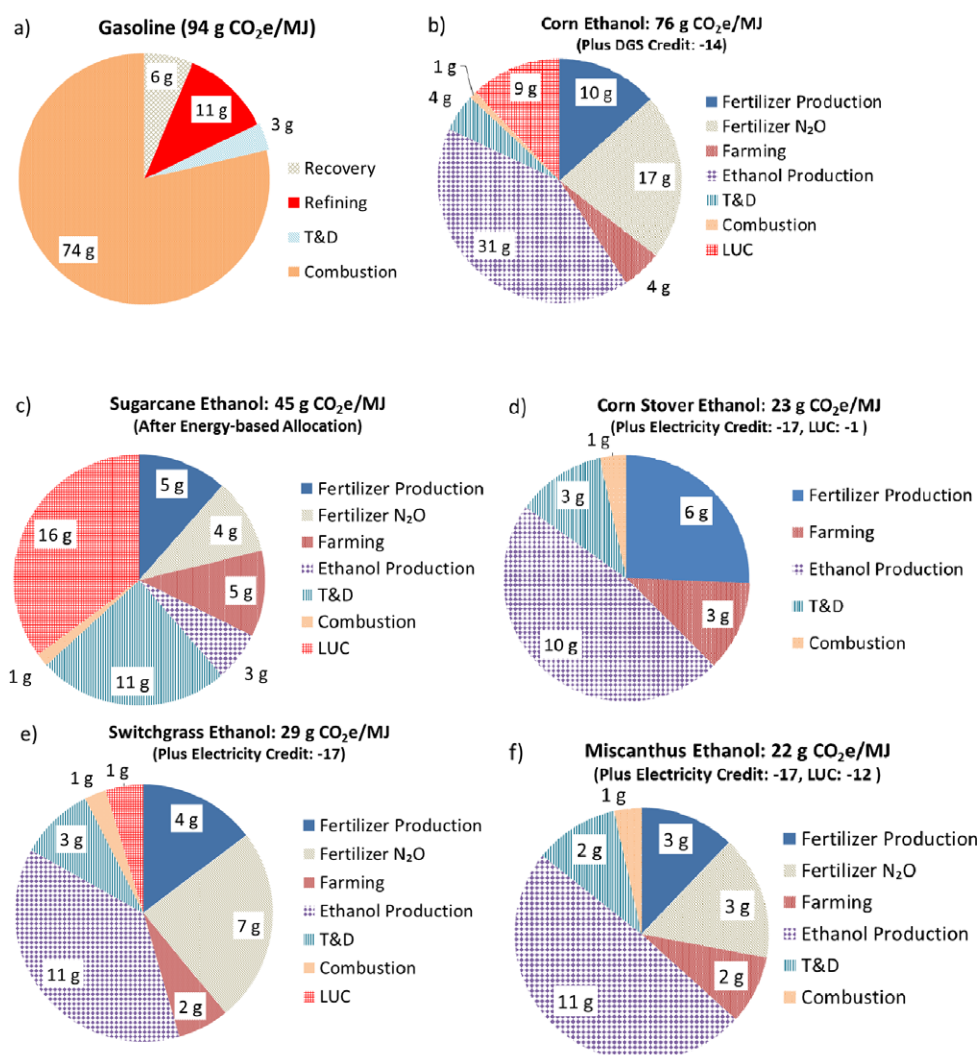


Figure 5. Shares of GHG emissions by activities for (a) gasoline, (b) corn ethanol, (c) sugarcane ethanol, (d) corn stover ethanol, (e) switchgrass ethanol and (f) miscanthus ethanol (results were generated by using the co-product allocation methodologies listed in table 6).

Table 7. WTW GHG emission reductions for five ethanol pathways (relative to WTW GHG emissions for petroleum gasoline). (Note: Values in the table are GHG reductions for P10–P90 (P50), all relative to the P50 value of gasoline GHG emissions.)

WTW GHG emission reductions	Corn	Sugarcane	Corn stover	Switchgrass	Miscanthus
Including LUC emissions	19–48% (34%)	40–62% (51%)	90–103% (96%)	77–97% (88%)	101–115% (108%)
Excluding LUC emissions	29–57% (44%)	66–71% (68%)	89–102% (94%)	79–98% (89%)	88–102% (95%)

Of the five bioethanol pathways, corn and sugarcane ethanol have significant WTP GHG emissions and LUC GHG emissions. Miscanthus ethanol has significant negative LUC GHG emissions due to the increased SOC content from miscanthus growth. Sugarcane ethanol shows great variation in LUC emissions, mainly due to differences in assumptions and modeling methodologies among the reviewed studies. Table 7 shows numerical GHG emission reductions of the five ethanol pathways relative to those of petroleum gasoline.

The pie charts in figure 5 show contributions of key life-cycle stages to WTW GHG emissions for the six pathways. With regard to gasoline WTW GHG emissions,

79% are from combustion of gasoline and 12% are from petroleum refining. Crude recovery and transportation activities contribute the remaining 9%. For corn ethanol, ethanol plants account for 41% of total GHG emissions; fertilizer production and N₂O emissions from cornfields account for 36%; LUC accounts for 12%; and corn farming energy use and transportation activities account for small shares. For sugarcane ethanol, LUC accounts for 36% of total GHG emissions (however, LUC GHG emissions data here are from a literature review rather than our own modeling). Transportation of sugarcane and ethanol contributes to 24% of total GHG emissions. Together, fertilizer production and N₂O

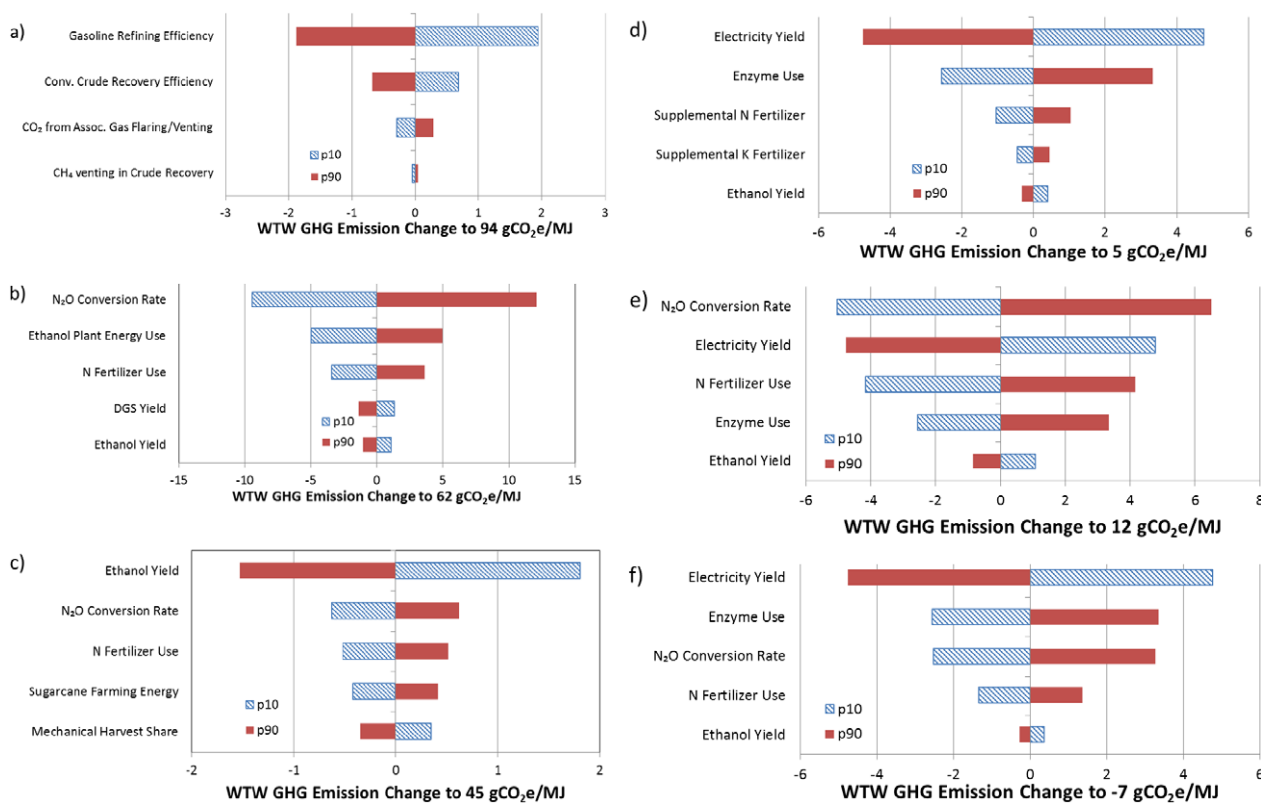


Figure 6. Sensitivity analysis results for (a) conventional crude to gasoline, (b) corn ethanol, (c) sugarcane ethanol, (d) corn stover ethanol, (e) switchgrass ethanol and (f) miscanthus ethanol.

emissions from sugarcane fields account for 20% of these emissions. Finally, the contribution of sugarcane farming to WTW GHG emissions is 11%.

Although for corn ethanol, the greatest contributor to life-cycle GHG emissions is the production of ethanol itself, this step is less significant in the life cycle of sugarcane ethanol because sugar mills use bagasse to generate steam and electricity. Another contrast between these two sugar-derived biofuels is the transportation and distribution (T&D) stage. Corn ethanol, produced domestically in the US, is substantially less affected by T&D than is sugarcane ethanol, which is trucked for long distances to Brazilian ports and transported across the ocean via ocean tankers to reach US consumers.

For the three cellulosic ethanol pathways, ethanol production is the largest GHG emission source. Fertilizer production and associated N₂O emissions (only in the case of switchgrass and miscanthus) are the next largest GHG emission source. Farming and transportation activities also have significant emission shares. One notable aspect of figure 5(e) is the positive contribution of LUC GHG emissions in the switchgrass ethanol life cycle when compared to the other cellulosic feedstocks, which may sequester GHG as a result of LUC. These results are explained elsewhere (Dunn *et al* 2012b).

To show the importance of key parameters affecting WTW GHG emissions results for a given fuel pathway, we conducted a sensitivity analysis of GHG emissions with GREET for all six pathways with P10 and P90 values as the minimum and maximum value for each parameter. We present

the five most influential parameters for each pathway in the so-called tornado charts in figure 6.

For petroleum gasoline, the gasoline refining efficiency and recovery efficiency of the petroleum feedstock are the most sensitive parameters. For corn ethanol, the N₂O conversion rate in cornfields is the most sensitive factor, followed by the ethanol plant energy consumption. Enzyme and yeast used in the corn ethanol production process are not among the five most influential parameters in the corn ethanol life cycle. For sugarcane ethanol, the most significant parameters, in order of importance, are ethanol yield per unit of sugarcane, the N₂O conversion rate in sugarcane fields, nitrogen fertilizer usage intensity, sugarcane farming energy use and the mechanical harvest share. Sugarcane farming is evolving as mechanical harvesting becomes more widespread and mill by-products are applied as soil amendments. We thus expect to see shifts in the identity and magnitude of influence of the key parameters in the sugarcane-to-ethanol pathway in the future.

The three cellulosic ethanol pathways have similar results. The electricity credit is the most significant parameter (except for switchgrass ethanol, for which the N₂O conversion rate is the most significant). Enzyme use is a more significant factor in cellulosic ethanol pathways than in the corn ethanol pathway because the greater recalcitrance of the feedstock currently requires higher enzyme dosages in the pretreatment stage (Dunn *et al* 2012a). The impact of fertilizer-related parameters on WTW GHG emissions results depends, as one would expect, on the fertilizer intensity of feedstock farming (see table 3).

The strong dependence of results on the N₂O conversion rate is notable for four out of the five ethanol pathways (the exception is corn stover, where the same amount of nitrogen in either in the stover or supplemental fertilizer results in same amount of N₂O emissions, with or without stover collection). Great uncertainty exists regarding N₂O conversion rates in agricultural fields because many factors (including soil type, climate, type of fertilizer and fertilizer application method) affect the conversion. We conducted an extensive literature review for this study to revise N₂O conversion rates in GREET (see supporting information available at stacks.iop.org/ERL/7/045905/mmedia). The original GREET conversion rate was based primarily on IPCC tier 1 rates. With newly available data, we adjusted our direct conversion rates in cornfields upward (see supporting information available at stacks.iop.org/ERL/7/045905/mmedia for details). In particular, we developed a Weibull distribution function for direct and indirect N₂O emissions together with a mean value of 1.525%, a P10 value of 0.413% and P90 value of 2.956%. In comparison, our original distribution function for total N₂O conversion rates was a triangular distribution, with a most likely value of 1.325%, a minimum value of 0.4% and a maximum value of 2.95%.

4. Discussion

Our results for cellulosic ethanol are in line with two recent studies that reported life-cycle GHG emissions of switchgrass and miscanthus ethanol. Monti *et al* (2012) reported that switchgrass ethanol life-cycle GHG emissions are 63% to 118% lower than gasoline, based on a literature review. Scown *et al* (2012) conducted an LCA of miscanthus ethanol and reported its life-cycle GHG emissions as being $-26 \text{ g CO}_2\text{e MJ}^{-1}$ of ethanol when impacts of both co-produced electricity and soil carbon sequestration were included. We estimate slightly lower reductions for sugarcane ethanol than did Seabra *et al* (2011) and Macedo *et al* (2008). Our results for corn ethanol, however, contrast with those of Searchinger *et al* (2008) and Hill *et al* (2009), who predicted that corn ethanol would have a greater life-cycle GHG impact than gasoline, mainly due to LUC GHG emissions among those studies and ours.

Advances and complexities in ethanol production technologies, especially for cellulosic ethanol, could alter bioethanol LCA results in the future. For example, although we examined corn and cellulosic ethanol plants separately in this article, when cellulosic ethanol conversion technologies become cost competitive, it is conceivable that cellulosic feedstocks could be integrated into existing corn ethanol plants, with appropriate modifications. Thus, an integrated system with both corn and cellulosic feedstocks (especially corn stover) could be evaluated. Such an integrated ethanol plant might have some unique advantages if one feedstock suffered from decreased production (e.g., the anticipated reduction in corn production in key Midwestern states in 2012 as a result of the severe drought).

In addition, cellulosic ethanol plants and their ethanol yields could be significantly different among different

feedstocks. The source of the energy intensity data for converting a cellulosic feedstock to ethanol via a biochemical conversion process that we used in our WTW simulations was with the process of converting corn stover (Humbird *et al* 2011). We did not obtain separate conversion energy intensity data for other cellulosic feedstocks. In the future, we will examine the differences in both ethanol yield and co-produced electricity among different cellulosic feedstocks.

Co-produced electricity is another significant yet uncertain factor contributing to cellulosic ethanol's GHG benefits. Electricity yields in cellulosic ethanol plants, however, are highly uncertain. In fact, it is not entirely certain that cellulosic ethanol plants will install capital-intensive CHP equipment that would permit the export of electricity to the grid.

Considering the feedstock production phase, the significant difference in WTW results between switchgrass and miscanthus ethanol is caused mainly by the large difference in yield between the two crops ($12 \text{ tonnes ha}^{-1}$ for switchgrass versus $20 \text{ tonnes ha}^{-1}$ for miscanthus). The high yield of miscanthus results in a significant increase in SOC content in simulations that use the CENTURY model (Kwon *et al* 2012), which is based on the common understanding that a high biomass yield can result in high below ground biomass accumulation. This implies that any cellulosic feedstock with a high yield, such as miscanthus, could sequester significant amounts of GHGs. Thus, instead of interpreting the results presented here as unique to switchgrass and miscanthus, we suggest that the results can indicate the differences between high-yield and low-yield dedicated energy crops.

For all bioethanol pathways, the strong dependence of GHG emission results on the N₂O conversion rate of N fertilizer suggests the need to continuously improve the efficiency with which N fertilizer is used in farm fields and the need to estimate that parameter more precisely. The needs are especially important with regard to nitrogen dynamics in sugarcane fields and cornfields.

In addition, the seasonal harvest of cellulosic feedstocks to serve the annual operation of cellulosic ethanol plants requires the long-time storage of those feedstocks. Feedstock loss during storage as well as during harvest and transportation is an active research topic. We will include cellulosic feedstock loss in our future WTW analysis of cellulosic ethanol pathways.

The WTW GHG emissions of petroleum gasoline are also subject to significant uncertainties. Some researchers estimated GHG emissions associated with indirect effects from petroleum use, such as those from military operations in the Middle East (Liska and Perrin 2010). Depending on the ways that GHG emissions from military operations are allocated, those emissions could range from 0.9 to 2.1 g MJ^{-1} of gasoline (Wang *et al* 2011a). Moreover, GHG emissions associated with oil recovery can vary considerably, depending on the type of recovery methods used, well depth, and flaring and venting of CH₄ emissions during recovery (Rosenfeld *et al* 2009, Brandt 2012).

5. Conclusions

Bioethanol is the biofuel that is produced and consumed the most globally. The US is the dominant producer of

corn-based ethanol, and Brazil is the dominant producer of sugarcane-based ethanol. Advances in technology and the resulting improved productivity in corn and sugarcane farming and ethanol conversion, together with biofuel policies, have contributed to the significantly expanded production of both types of ethanol in the past 20 years. These advances and improvements have helped bioethanol achieve increased energy and GHG emission benefits when compared with those of petroleum gasoline.

We used an updated, upgraded version of the GREET model to estimate life-cycle energy consumption and GHG emissions for five bioethanol production pathways on a consistent basis. Even when we included highly debated LUC GHG emissions, when the feedstock was changed from corn to sugarcane and then to cellulosic biomass, bioethanol's reductions in energy use and GHG emissions, when compared with those of gasoline, increased significantly. Thus, in the long term, the cellulosic ethanol production options will offer the greatest energy and GHG emission benefits. Policies and research and development efforts are in place to promote such a long-term transition.

Acknowledgments

This study was supported by the Biomass Program in the US Department of Energy's Office of Energy Efficiency and Renewable Energy under Contract DE-AC02-06CH11357. We are grateful to Zia Haq and Kristen Johnson of the Biomass Program for their support and guidance. We thank the two reviewers of this journal for their helpful comments. The authors are solely responsible for the contents of this article.

References

- Andress D 2002 *Soil Carbon Changes for Bioenergy Crops* (report prepared for Argonne National Laboratory and US Department of Energy) (<http://greet.es.anl.gov/publication-rfihxb2h>, accessed 26 October 2012)
- Argonne National Laboratory 2012 *GREET Model* (<http://greet.es.anl.gov/>)
- Arora S, Wu M and Wang M 2011 *Update of Distillers Grains Displacement Ratios for Corn Ethanol Life-Cycle Analysis* Argonne National Laboratory Report ANL/ESD/11-1
- ATLASS Consortium 2011 *Assessing the Land Use Change Consequences of European Biofuel Policies* (provided to the Directorate General for Trade of the European Commission) (http://trade.ec.europa.eu/doclib/docs/2011/october/tradoc_148289.pdf, accessed 8 August 2012)
- Bergerson J A, Kofoworola O, Charpentier A D, Sleep S and MacLean H L 2012 Life cycle greenhouse gas emissions of current oil sands technologies: surface mining and *in situ* applications *Environ. Sci. Technol.* **46** 7865–74
- Borrion A L, McManus M C and Hammond G P 2012 Environmental life cycle assessment of lignocellulosic conversion to ethanol: a review *Renew. Sustain. Energy Rev.* **16** 4638–50
- Braga do Carmo J *et al* 2012 Infield greenhouse gas emissions from sugarcane soils in Brazil: effects from synthetic and organic fertilizer application and crop trash accumulation *GCB Bioenergy* at press (doi:10.1111/j.1757-1707.2012.01199.x)
- Brandt A 2012 Variability and uncertainty in life cycle assessment models for greenhouse gas emissions from Canadian oil sands production *Environ. Sci. Technol.* **43** 1253–64
- Bredeson L, Quiceno-Gonzalez R and Riera-Palou X 2010 Factors driving refinery CO₂ intensity, with allocation into products *Int. J. Life Cycle Assess.* **15** 817–27
- Brinkman N, Wang M, Weber T and Darlington T 2005 *Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems—A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions* (Argonne, IL: Argonne National Laboratory)
- BSI 2011 *PAS 2050: 2011 Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services* (London: British Standards)
- Burnham A, Han J, Clark C E, Wang M Q, Dunn J B and Palou-Rivera I 2012 Life-cycle greenhouse gas emissions of shale gas, natural gas, coal, and petroleum *Environ. Sci. Technol.* **46** 619–27
- CARB (California Air Resources Board) 2009 *Proposed Regulation for Implementing Low Carbon Fuel Standards (Staff Report: Initial Statement of Reasons vol 1)* (Sacramento, CA: California Environmental Protection Agency, Air Resources Board) (www.arb.ca.gov/regact/2009/lcfs09/lcfsisor1.pdf)
- Chum H *et al* 2011 *Bioenergy IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* ed O Edenhofer *et al* (Cambridge: Cambridge University Press)
- DOE (US Department of Energy) 2011 *US Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry* (Washington, DC: Oak Ridge National Laboratory for DOE Office of Energy Efficiency and Renewable Energy, Biomass Program)
- Dunn J B, Eason J and Wang M Q 2011 *Updated Sugarcane and Switchgrass Parameters in the GREET Model* (http://greet.es.anl.gov/publication-updated_sugarcane_switchgrass_params)
- Dunn J B, Mueller S, Wang M Q and Han J 2012a Energy consumption and greenhouse gas emissions from enzyme and yeast manufacture for corn and cellulosic ethanol production *Biotechnol. Lett.* **34** 2259–63
- Dunn J B, Mueller S and Wang M Q 2012b Land-use change and greenhouse gas emissions from corn and cellulosic ethanol *Biotechnol. Biofuels* submitted
- E4Tech 2010 *A Causal Descriptive Approach to Modeling the GHG Emissions Associated with the Indirect Land Use Impacts of Biofuels* (provided to the UK Department of Transport) (www.e4tech.com/en/overview-publications.cfm, accessed 8 August 2012)
- EC (European Commission) 2012 *Proposal for a Directive of the European Parliament and of the Council of Biofuel Land Use Change Emissions* (Brussels: EC)
- Edgerton M D *et al* 2010 Commercial scale corn stover harvests using field-specific erosion and soil organic matter targets *Sustainable Alternative Fuel Feedstock Opportunities, Challenges, and Roadmaps for Six US Regions (Proc. Sustainable Feedstocks for Advanced Biofuels Workshop)* ed R Braun, D Karlen and D Johnson (Ankeny, IA: Soil and Water Conservation Society) pp 247–56
- Eggleston S L, Buendia L, Miwa K, Ngara T and Tanabe K 2006 *2006 IPCC Guidelines for National Greenhouse Gas Inventories (General Guidance and Reporting vol 1)* (Hayama: Institute for Global Environmental Strategies)
- EIA (Energy Information Administration) 2012 *Annual Energy Outlook 2012* (Washington, DC: US Department of Energy) ([www.eia.gov/forecasts/aeo/pdf/0383\(2012\).pdf](http://www.eia.gov/forecasts/aeo/pdf/0383(2012).pdf), accessed 20 July 2012)
- EPA (US Environmental Protection Agency) 2010 *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis* (Washington, DC: US Environmental Protection Agency)
- Fargione J, Hill J, Tilman D, Polasky S and Hawthorne P 2008 Land clearing and the biofuel carbon debt *Science* **319** 1235–3
- Farrell A E, Plevin R J, Turner B T, Jones A D, O'Hare M and Kammen D M 2006 Ethanol can contribute to energy and environmental goals *Science* **311** 506–8

- Han J, Elgowainy A, Palou-Rivera I, Dunn J B and Wang M Q 2011 *Well-to-Wheels Analysis of Fast Pyrolysis Pathways with GREET* Argonne National Laboratory Report ANL/ESD/11-8
- Hill J, Polasky S, Nelson E, Tilman D, Huo H, Ludwig L, Neumann J, Zheng H and Bonta D 2009 Climate change and health costs of air emissions from biofuels and gasoline *Proc. Natl Acad. Sci.* **106** 2077–82
- Humbird D et al 2011 *Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol* National Renewable Energy Laboratory Report NREL/TP-5100-47764
- IEA (International Energy Agency) 2012 *Energy Technology Perspective 2012: Pathways to a Clean Energy System* (Paris: International Energy Agency)
- Khatiwada D, Seabra J, Silveira S and Walter A 2012 Accounting greenhouse gas emissions in the lifecycle of Brazilian sugarcane bioethanol: Methodological references in European and American regulations *Energy Policy* **47** 384–97
- Kløverpris J H and Mueller S 2012 Baseline time accounting: considering global land use dynamics when estimating the climate impact of indirect land use change caused by biofuels *Int. J. Life Cycle Assess.* at press (doi:10.1007/s11367-012-0488-6)
- Kwon H, Wander M M, Mueller S and Dunn J B 2012 Modeling state-level soil carbon emissions factors under various scenarios for direct land use change associated with United States biofuel feedstock production *Biomass Bioenergy* at press
- Larsen R, Wang M, Wu Y, Vyas A, Santini D and Mintz M 2005 Might Canadian oil sands promote hydrogen production for transportation? Greenhouse gas emission implications of oil sands recovery and upgrading *World Resour. Rev.* **17** 220–42
- Liska A J and Perrin R K 2010 Securing foreign oil: a case for including military operations in the climate change impact of fuels *Environment* **52** 9–22
- Liska A J et al 2009 Improvements in life cycle energy efficiency and greenhouse gas emissions of corn-ethanol *J. Indust. Ecol.* **13** 58–74
- Macedo I D C, Leal M R L V and Seabra J E A R 2004 *Assessment of Greenhouse Gas Emissions in the Production and Use of Fuel Ethanol in Brazil* (prepared for the state of Sao Paulo, Brazil) (www.wilsoncenter.org/sites/default/files/brazil.unicamp.macedo.greenhousegas.pdf)
- Macedo I D C, Seabra J E A and Silva J E A R 2008 Greenhouse gases emissions in the production and use of ethanol from sugarcane in Brazil: the 2005/2006 averages and a prediction for 2020 *Biomass Bioenergy* **32** 582–95
- MacLean H and Spatari S 2009 The contribution of enzymes and process chemicals to the life cycle of ethanol *Environ. Res. Lett.* **4** 014001
- Monti A, Lorenzo B, Zatta A and Zegada-Lizarazu W 2012 The contribution of switchgrass in reducing GHG emissions *GCB Bioenergy* **4** 420–34
- Mu D, Seager T, Rao P S and Zhao F 2010 Comparative life cycle assessment of lignocellulosic ethanol production: biochemical versus thermochemical conversion *Environ. Manag.* **46** 565–78
- Mueller S, Dunn J B and Wang M Q 2012 *Carbon Calculator for Land Use Change from Biofuels Production (CCLUB) Users' Manual and Technical Documentation* (Argonne, IL: Argonne National Laboratory) (<http://greet.es.anl.gov/publication-cclub-manual>)
- Neeft J et al 2012 *BioGrace—Harmonized Calculations of Biofuel Greenhouse Gas Emissions in Europe* (www.biograce.net)
- O'Hare M, Plevin R J, Martin J I, Jones A D, Kendall A and Hopson E 2009 Proper accounting for time increases crop-based biofuels' greenhouse gas deficit versus petroleum *Environ. Res. Lett.* **4** 024001
- Palou-Rivera I, Han J and Wang M 2011 *Updates to Petroleum Refining and Upstream Emissions* (Argonne, IL: Argonne National Laboratory) (<http://greet.es.anl.gov/publication-petroleum>)
- RFA (Renewable Fuels Association) 2012 *2012 Ethanol Industry Outlook: Accelerating Industry Innovation* (Washington, DC: Renewable Fuels Association)
- Rosenfeld J, Pont J, Law L, Hirshfeld D and Kolb J 2009 *Comparison of North American and Imported Crude Oil Life Cycle GHG Emissions* (Calgary, AB: TIAX LLC and MathPro Inc. for Alberta Energy Research Institute) TIAX: Case No. D5595
- Scown C D et al 2012 Lifecycle greenhouse gas implications of US national scenarios for cellulosic ethanol production *Environ. Res. Lett.* **7** 014011
- Seabra J E A, Macedo I C, Chum H L, Faroni C E and Sarto C A 2011 Life cycle assessment of Brazilian sugarcane products: GHG emissions and energy use *Biofuels, Bioprod. Biorefining* **5** 519–32
- Searchinger T et al 2008 Use of US croplands for biofuels increases greenhouse gases through emissions from land use change *Science* **319** 1238–40
- Sheehan J, Aden A, Paustian K, Killian K, Brenner J, Walsh M and Nelsh R 2008 Energy and environmental aspects of using corn stover for fuel ethanol *J. Ind. Ecol.* **7** 117–46
- Sokhansanj S, Mani S, Turhollow A, Kumar A, Bransby D, Lynd L and Laser M 2009 Large-scale production, harvest and logistics of switchgrass (*Panicumbirgatum L.*)—current technology and envisioning a mature technology *Biofuels, Bioprod. Biorefining* **3** 124–41
- Somerville C, Young H, Taylor C, Davis S C and Long S P 2010 Feedstocks for lignocellulosic biofuels *Science* **329** 791–2
- Taheripour F, Tyner W E and Wang M Q 2011 *Global Land Use Changes Due to the US Cellulosic Biofuel Program Simulated with the GTAP Model* (Argonne, IL: Argonne National Laboratory) (http://greet.es.anl.gov/publication-luc_ethanol)
- Tyner W, Taheripour F, Zhuang Q, Birur D and Baldos U 2010 *Land Use Changes and Consequent CO₂ Emissions due to US Corn Ethanol Production: A Comprehensive Analysis* (West Lafayette, IN: Department of Agricultural Economics, Purdue University)
- UNICA (Brazilian Sugarcane Association) 2012 *UNICA Data Center* (www.unicadata.com.br/index.php?idioma=2, accessed 16 July 2012)
- Van Deusen P C and Heath L S 2010 Weighted analysis methods for mapped plot forest inventory data: tables, regressions, maps and graphs *Forest Ecol. Manage.* **260** 1607–12
- Wang M, Han J, Haq Z, Tyner W, Wu M and Elgowainy A 2011a Energy and greenhouse gas emission effects of corn and cellulosic ethanol with technology improvements and land use changes *Biomass Bioenergy* **35** 1885–96
- Wang M, Huo H and Arora S 2011b Methodologies of dealing with co-products of biofuels in life-cycle analysis and consequent results within the US context *Energy Policy* **539** 5726–36
- Wang M, Lee H and Molburg J 2004 Allocation of energy use and emissions to petroleum refining products: implications for life-cycle assessment of petroleum transportation fuels *Int. J. Life Cycle Assess.* **9** 34–44
- Wang M, Wu M and Huo H 2007 Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types *Environ. Res. Lett.* **2** 024001
- Wang M, Wu M, Huo H and Liu J 2008 Life-cycle energy use and greenhouse gas emission implications of Brazilian sugarcane ethanol production simulated with the GREET model *Int. Sugar J.* **110** 527–45
- Wang Z, Dunn J B and Wang M Q 2012 *GREET Model Miscanthus Parameter Development* (Argonne, IL: Argonne National Laboratory) (<http://greet.es.anl.gov/publication-miscanthus-params>)
- Whitaker J, Ludley K E, Rowe R, Taylor G and Howard D C 2010 Sources of variability in greenhouse gas and energy balances for biofuel production: a systematic review *GCB Bioenergy* **2** 99–112