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OPINION

A geography-based critique of new US biofuels regulations

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Abstract

The new renewable fuels standard (RFS 2) aims to distinguish corn-ethanol that achieves a 20% reduction in greenhouse gas (GHG) emissions compared with gasoline. Field data from Kim *et al.* (2009) and from our own study suggest that geographic variability in the GHG emissions arising from corn production casts considerable doubt on the approach used in the RFS 2 to measure compliance with the 20% target. If regulators wish to require compliance of fuels with specific GHG emission reduction thresholds, then data from growing biomass should be disaggregated to a level that captures the level of variability in grain corn production and the application of life cycle assessment to biofuels should be modified to capture this variability.

Keywords: biofuels, corn-ethanol, evidence-based decision making, geography, greenhouse gas emissions, life cycle assessment, regulation, renewable fuels standard

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Introduction

A guiding principle often invoked during the creation of new regulations is 'evidence-based' or 'evidence-informed decision-making' where science, rather than politics, is the driving force behind public policy (Sanderson, 2002; Aucoin, 2005). Experience has shown that government regulations may be ineffective or may have unintended consequences for the economy, the natural environment, and society. For this reason, the creation of new rules is always done with great care and only pursued after the benefits and potential negative impacts of new regulations have been estimated and evaluated. Such regulatory impact assessments require a consideration of how clear regulations are formulated and how well they can be implemented.

In this article, we argue that the new regulation for biofuels in the United States (and EU) are *not* compliant with the spirit of evidence-based decision making because greenhouse gas (GHG) reduction targets cannot currently be measured with sufficient precision. Worse is the fact that, without substantial new efforts, data will likely not become available because the geography of growing biomass for fuels exhibits too great a variance to allow for measurements that are both practical and sufficiently precise.

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We start our analysis by identifying two methodological issues within the scientific assessment that underpins the new US biofuels regulations. We then compare the handling of these two issues with real-world data and conclude that regulatory methods and predictions fall short of reality. We continue with a review of lessons learned from application of the life cycle assessment (LCA) method in other sectors, and then compare the US biofuel LCA approach with the EU biofuel LCA approach. In the final discussion, we suggest ways to incorporate evidence of variance in biofuel feedstock production emissions in regulation using LCA. Our concluding message is that assessments cognizant of the geography of biomass production are possible and needed for evidence-based biofuel policies.

Two major assessment issues in the new US *Renewable Fuel Standard*

On 1 July 2010, the second *Renewable Fuel Standard* (RFS 2) entered into effect in the United States. It builds on previous commitments and mandates 36 billion gallons of biofuel annually by 2022, with an additional requirement that the GHG emissions of qualifying renewable fuel must be 20% less than an average gasoline fuel. Even greater GHG savings are required for cellulose-based or sugarcane-based fuels. 'Compliance with the threshold requires a comprehensive evaluation of renewable fuels, as well the baseline for gasoline and diesel, on the basis of their life cycle emissions' states Environmental Protection Agency (EPA, 2010a).

Despite the focus on a precise 20% target, individual producers are not required to submit specific LCA results for emissions. Instead EPA conducted its own global LCA and has concluded that all corn-ethanol meets the 20% threshold as long as it is made in a natural gas-fired ethanol production facility. Since regulatory compliance comes down to this specific LCA carried out by EPA, this assessment deserves some detailed attention. In the discussion that follows we focus on the EPA corn-ethanol assessment.

Issue 1: National treatment of biomass production variables

Thousands of farms across the United States supply corn to ethanol refineries. While EPA recognizes 'there are regional differences in soil types, weather conditions and other factors which could affect, for example, the amount of fertilizer applied and thus the GHG impact of corn production' (EPA, 2009b; p. 25022), it has chosen to give biofuel production a 'national treatment'. In other words, the range of values for corn yields, for fuel used in tillage, planting and harvesting, for fertilizer rates, for energy used to dry grain, and for all other GHG emitting activities are collapsed into a single national corn sector variable. The rationale given is that corn is a well-traded commodity: 'for example, if corn from a certain location in Iowa is used to produce ethanol, corn from all other regions will be used to replace that corn' (EPA, 2009b, p. 25023). As we describe below, farming practices vary widely over short distances and the use of single national average treatment for corn farming obscures considerable differences in corn-ethanol GHG emissions. This decision is in stark contrast with the choice to model 34 different possible ethanol refinery configurations in the EPA LCA. The EPA seems to argue that a national treatment of only farming operations, but not of refinery operations, is meaningful in the GHG assessment context.

Issue 2: Consequential LCA

The EPA LCA is a forward-looking 'consequential LCA' instead of a traditional 'attributional LCA'. That is to say, instead of attributing GHG emissions specifically to production of a given unit of biofuel, assessors attempt to document the GHG emissions arising from the consequences of a decision to increase biofuel production. The consequential LCA relies on marginal changes in the economic relationships surrounding the product. So for example, while an attributional LCA assigns the GHG emissions arising from fertilizer use for corn production directly to a unit of corn-ethanol, a consequential LCA looks to include the possibility that increased corn production is offset by decreased soybean production and overall marginal changes in total fertilizer use.

The consequential approach also means that the LCA results are for the volume of ethanol that is produced above and beyond what might occur without the renewable fuel mandate policy (2.6 billion gallons according to EPA). Furthermore, the results are projected for GHG emissions resulting from the policy in the year 2022. For corn farming emissions this future modeling approach is heavily dependent on assumptions of projected yield improvements with constant fertilizer use and fuel inputs (EPA, 2010b, p. 876).

The two issues, consequential LCA plus 'national treatment' of corn production, combine to obscure the geographic differences in GHG profiles of corn grown throughout the United States. While the EPA approach gains a measurement of the larger market context for corn-ethanol production; it loses sensitivity to the reality that corn is farmed across diverse landscapes. The scoping statement for the EPA LCA suggests that 'a gallon of ethanol produced using corn grown in Iowa may have different direct life cycle emissions impacts than a gallon of ethanol produced at an identical facility in Nebraska using corn grown in Nebraska due to regional differences in agricultural practices. However, on a life cycle basis, considering the indirect impacts in the context of the entire corn market they are not different.'(EPA, 2010b, p. 309). We suggest that life cycle emissions from corn production are grossly misestimated by future (and inherently uncertain) assumptions about constant yield improvements and product substitution in the consequential approach and these concerns may well undermine the evidence used to support biofuel policies and regulations. When current field data are examined, as we do in the next section of the article, the evidence suggests that ignoring geographic differences can misrepresent the potential GHG reductions from corn-ethanol compared to gasoline.

Aggregate data and hopeful projections vs. real-world measurements

Empirical data from eight US counties

Not surprisingly, reviews of corn-ethanol LCAs have observed that with differences in geographic location of biomass production comes differences in GHG emissions of the end biofuel product (Farell *et al*., 2006; Larson, 2006; von Blottnitz & Curran, 2007). Kim *et al*. (2009) attempt to assess this issue in their LCA which estimates GHG emissions from corn production in eight counties across a 1400 km long swath of the corn belt of the United States (Fig. 1).

Their results show a range of 254 g CO_2 eq kg^{-1} of corn produced in Hardin County Idaho to 825 g CO_2 eq kg^{-1} of corn produced in Macon County Missouri. This threefold difference in emissions among major corn producing counties led the authors to recommend collecting site-specific agronomic data wherever possible. To put this in terms of the regulatory target set by US EPA for a 20% reduction in GHG for corn-ethanol we plugged the corn production emission data from Kim *et al.* (2009) into a comparison of GHG emissions for gasoline using the same emission values used by EPA for gasoline and for natural gas-fired ethanol refineries (see Appendix S1 for conversion factors). The percentage increase or decrease in emissions for corn-ethanol produced from corn in each county compared to gasoline is shown below (bars in Fig. 1). Only corn grown in two of the counties allow for corn-ethanol to meet a 20% reduction in GHG emissions vs. gasoline.

Our calculation accounts only for GHG emission stemming from grain corn production and does not include emissions from transportation of corn to the refinery or emissions from land-use change. Doing so only increases the total corn-ethanol emissions (von Blottnitz & Curran, 2007) and moves the end fuel further away from the 20% target. The key point is that data from Kim *et al.* (2009) show that when the LCA drills down to the subregional level we find that a national average corn production assumption conceals a range of variability of an extent that suggests some locations will meet a GHG balance target and that some will not. While *on average* corn-ethanol may meet a GHG emission target, this subregional variability suggests

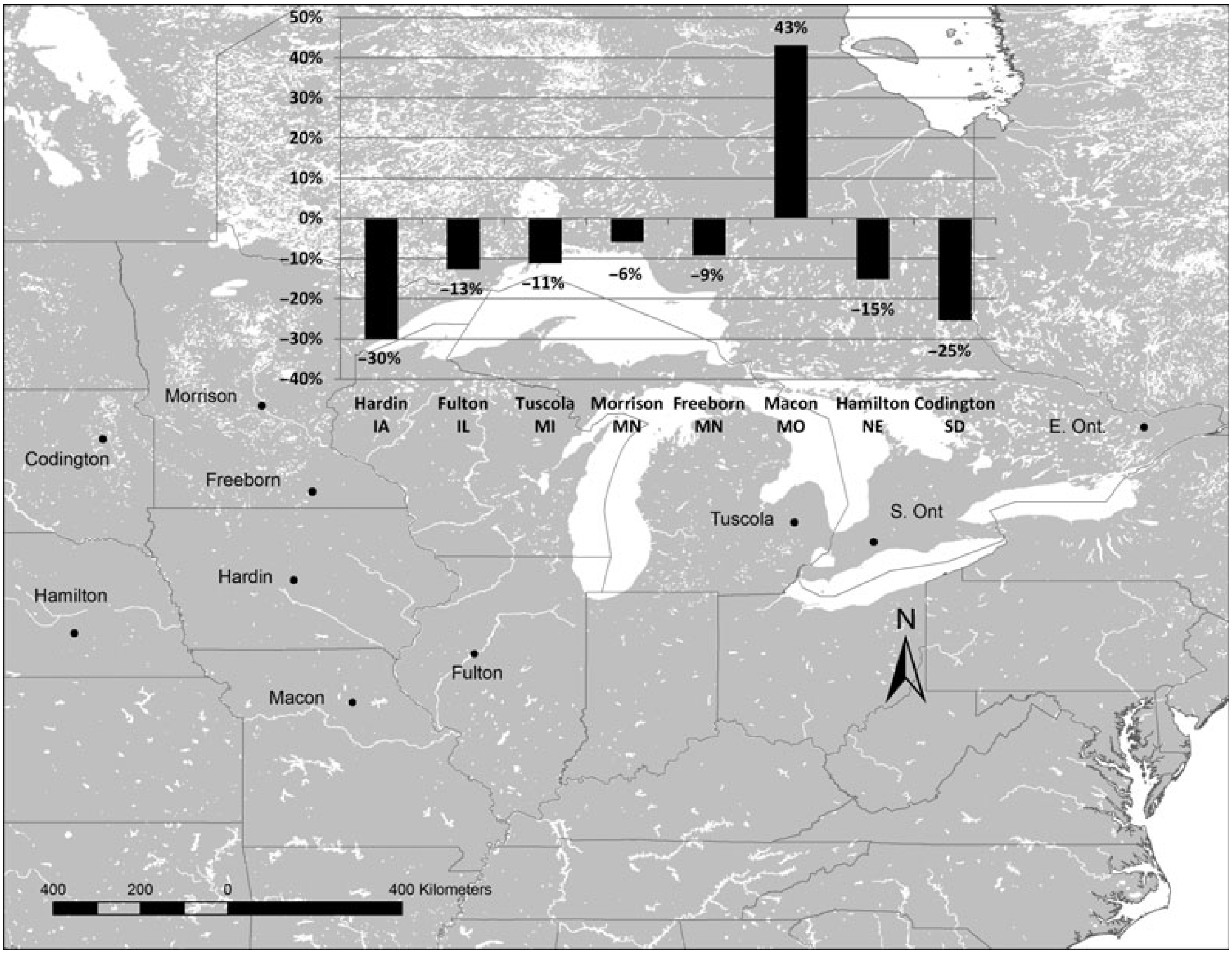

Fig. 1 Ethanol vs. gasoline greenhouse gas emissions using county-specific corn production data (data adapted from Kim *et al.*, 2009).

significant challenges for evidence-based regulation and decision making for two reasons: first, the EPA approach fails to disqualify corn-ethanol that very likely does not meet the 20% emission reduction threshold and second, when one sees that the United States corn belt is so highly variable in GHG emissions what confidence can the EPA have in its prediction that corn farming emissions will be negligible in 2022 and can be captured by a single sector value without attention to evidence of a range of current and future uncertainty? Farming practices have changed considerably over the past 20 years and, as we show in the next set of data, it is misleading to represent each farm as a homogenous entity.

Disaggregating down to the farm level

As a means of validating the data from Kim *et al.* (2009) and to investigate further disaggregation of agricultural data, we analyzed data sampled by the first author from two corn farms in Ontario, Canada. The two farms located 600 km apart capture the diversity of corn production in Ontario. The 'southern Ontario' (S.Ont) site is a more southern location with a longer and warmer growing season than the more northern and 'eastern Ontario' (E.Ont) site (Fig. 1). Both farms provide corn to local ethanol biorefineries and produce corn yields within 10% of the average in their respective counties. Ontario was one of the first jurisdictions in Canada to mandate a minimum 5% fuel ethanol content in gasoline and now accounts for more than half of Canada's production of ethanol (CRFA, 2011). Corn production techniques follow those of the United States corn belt with the exception of minimal use of irrigation in Ontario. Field data were collected by interview with farmers for crop years 2006–2008 (Table 1a), factors for converting field inputs to GHG emission estimates are found in Appendix S1.

Emissions from the S.Ont site are lower than those from the E.Ont (145 vs. 307 g CO_2 eq kg^{-1} corn; Table 1b). Differences in yield due largely to a warmer growing season in the southern site translate into lower GHG emissions per kg of grain corn produced but our data also show a number of farming practices from the S.Ont site that lead to lower emissions: (i) lower rates of synthetic fertilizer application, in particular potassium fertilizer needs met from manure, (ii) more targeted nitrogen application emissions due to Geographic Information System guided application, (iii) lower overall diesel obtained from fewer tillage passes and (iv) shorter distance to ethanol plant. The picture that emerges from our own study of current grain corn production and from Kim *et al.* (2009) is that emissions vary due to yield differences (linked to climate and soil conditions) *and* diversity in farming practices.

The diversity in farming practices shown in Table 1a means individual production steps are contingent on specific farms. Some of the differences seen between the Ontario sites are minor (e.g., propane gas burning dryers instead of natural gas burning ones) but several production activities (primary and secondary tillage, fungicidal treatment of seed) are found only on one of the sites (and by extension on some, but not all, farms). With no consistent set of emission-generating activities across farms, any single 'national treatment' type approach inevitably constructs a generic farm with physical processes that are entirely absent from some of the production systems that it claims to represent. While it is common practice to weigh the average for the proportion of land that is tilled (or any of the other contingent processes found here), the physical system that forms the basis of the LCA is conditional, and in that sense, flawed. For example, the national treatment approach will lead to the impression that potash fertilizing activities are significant GHG emitters in corn production, yet in the S.Ont site of our study these activities are unimportant. This problem goes beyond the obscuring of variability in field inputs by use of single average national corn sector value. Herein, we see that production practices that are used locally are undetected when represented at the national level and *vice versa*. To put it another way, a national treatment misses the realities of grain corn production evidence in two ways; first, by missing the wide range in quantities of field inputs and second, by missing the frequencies of production practices.

Biorefineries

Technological differences in the ways that refineries ferment corn to ethanol are additional sources of variance in the data for calculating corn-ethanol GHG emissions. Biorefineries differ from each other depending on process fuels used (natural gas, coal, or biomass), and presence or absence of various processes – for example a 'fractionation' technique to separate the corn kernel into component parts. This technological variability is unlike corn farming data for which much of the variance is linked to spatial variation in the natural environment. Biorefineries can be constructed with close to identical processes and close to identical emissions no matter their geographic location.

EPA has chosen to use ethanol refinery differences as the basis for judging compliance with the 20% reduction target. EPA considers 34 different types of refineries in their LCA with a sixfold difference in emissions. Their

Table 1 Grain corn production in southern Ontario (S Ont) and eastern Ontario (E Ont)

(a) Field processes, inputs, and greenhouse gas (GHG) emissions

		S.Ont	E.Ont	S.Ont	E.Ont
Input	Process	Input per 1000 kg corn (L, kg, m^3, or kWh)		GHG emissions (g CO_2 eq kg^{-1} corn)	
Fuels					
Diesel (L)	1° tillage	–	2.85E+00	–	9.38 E+00
	2° tillage	–	2.00E+00	–	6.91E+00
	Preplant fertilizer	2.36E−02	1.32E−01	8.14E−02	4.55E−01
	Preplant manure	4.67E−02	–	1.61E−01	–
	Planting	6.72E−01	9.05E−01	2.32E+00	3.12 E+00
	Herbicide burn down	5.19E−02	–	1.79E−01	–
	Herbicide postemergence	5.19E−02	1.32E−01	1.79E−01	4.55E+01
	Harvest	1.34E+00	5.24E+00	4.64E+00	1.81E+01
	Hauling grain carts	3.54E−01	6.60E−01	1.22E+00	2.2.8E+00
	Circulating grain for drying	–	2.20E+00	–	7.61E+00
	Move seed, fertilizer, pesticide	6.84E−02	6.02E−02	2.36E−01	2.08E−01
	Corn to ethanol plant	7.28E+01	1.49E+2	5.98E+00	1.23E+00
Natural gas (m^3)	Drying grain	1.59E+01	–	3.51E+01	–
Propane (L)	Drying grain	–	3.11E+01	–	6.47E+01
Electricity (kWh)	Circulating grain for drying	1.66E+01	–	3.66E+00	–
Fertilizer, seeds, and pesticides					
Nitrogen (kg)	Applied to field pre planting	5.35E−02	1.48E+00	3.57E−01	9.91E+00
	Applied to field at planting	1.27E+01	1.81E+01	8.46E+01	1.21E+02
Phosphate (kg)	Preplant	2.78E−01	7.09E+00	2.86E−01	7.28E+00
	Pre-emergence	1.38E+00	–	1.41E+00	–
Potassium (kg)	Preplant	3.21E−01	1.65E+00	8.91E−01	1.85E+00
	Pre-emergence	–	4.76E+00	–	1.32E+01
Manure (kg)	Applied to field pre planting	7.78E−02	–	2.87E−01	–
Seeds (kg)	Planting	1.53E+00	1.79E+00	5.56E−01	6.49E−01
Herbicide (kg)	Preplant	4.20E−02	–	1.05E+00	–
	Postemergence	1.01E−01	3.41E−01	2.53E+00	8.53E+00
Insecticide (kg)	Applied by seed supplier	7.67E−04	4.47E−03	1.92E−02	1.1.2E−01

(b) Yields and GHG emissions

	S.Ont	E.Ont
Grain corn (kg ha^{-1})	10 470	8850
GHG emissions (g CO_2 eq kg^{-1} corn)	145	307

LCA projects that emissions from individual ethanol facilities in 2022 will range from a minimum of 9.18 g CO_2 eq MJ^{-1} (9688 g CO_2 eq $MMBTU^{-1}$) for biomass fired plants to 57.1 g CO_2 eq MJ^{-1} (60 781 g CO_2 eq $MMBTU^{-1}$) for coal-fired plants and that 'clearly the choice of fuel production technology can be used as a measure to reduce the impact of corn-ethanol production' (EPA, 2009a, p. 281). Ultimately to comply with the regulations ethanol now has to be produced at a natural gas-fired ethanol plant (to which EPA ascribes 30.8 g CO_2 eq MJ^{-1} or 32 579 g CO_2 eq $MMBTU^{-1}$). We agree that ethanol refinery differences are an important basis for assessing which fuels meet the 20% reduction threshold, but argue that this should not preclude simultaneous use of corn production differences to encourage emission reductions.

Summary of 'Aggregate data and hopeful projections vs. real-world measurements'

In Table 2, we compare the EPA results for corn farming emissions with those from the Kim *et al.* (2009) study of farming in eight major corn producing counties reviewed above, and our own data from two Ontario farms. Note, the upper range of estimated GHG emissions for the Ontario examples fall within the lower end of the US studies from Kim *et al.* (2009). This validates the wide range seen by Kim *et al.* (2009) and bolsters arguments that capturing corn farming emissions in a single sector value as EPA does should be done with caution. *A priori* evaluations may be a good way to avoid burdening individual producers with the chore of completing individual GHG emission reduction assessments, but the variability in the emission profiles of fuels produced cannot be ignored and demands a new approach.

EPA arrives at a single value of 9.78 g CO_2 eq MJ^{-1} for corn farming emissions, a value that is between 2× and 10× *less* than values calculated from observed data at corn farms. Again, the EPA LCA is a *predicted* outcome of the consequences of the renewable fuel mandate. For corn farming emissions, this projection is heavily dependent on assumed increases in yields of grain corn driven by higher demand for ethanol that are achieved without increases in fertilizer and other field inputs. This approach can lead to extremely counterintuitive results, for example, earlier versions of the EPA LCA had corn farming emissions in 2022 as a *negative* value (EPA, 2009a,c). The low value for corn production emissions used in the EPA LCA is opposed not only by the data presented above but also by dozens of corn-ethanol LCAs (see reviews by Farell *et al.*, 2006; Larson, 2006; von Blottnitz & Curran, 2007). While the data sets of previous studies have differed, some using national corn farming data, some state data and others single farm specific data, fuel and fertilizer inputs for growing the corn in corn-ethanol are consistently estimated to emit approximately half as many emissions as burning an energy equivalent amount of gasoline (Farell *et al.*, 2006; Larson, 2006; von Blottnitz & Curran, 2007). When one considers that gasoline GHG emissions are 93.2 g CO_2 eq MJ^{-1}, and that other activities related to corn-ethanol production (e.g., soil carbon release from land-use change, biorefinery emissions, transportation of the biofuel) total ca. 70 g CO_2 eq MJ^{-1} in the EPA calculations (see table V.C-1 of EPA, 2010c and 'results 2022' of EPA, 2009c), it is apparent that only by considering grain corn production as a negligible carbon sink can the 20% GHG emission reduction target be reached in the EPA assessment. If corn farming emissions from observed current data are used the target is much less likely to be met.

What advice from LCA theory?

In this section we position biofuel LCA study within the methodological insights gained by use of the LCA method in other settings to see what advice is available for dealing with highly variable production systems.

The use of LCA to evaluate biofuels has a unique history (see Table 3). In the last decade, many dozens of GHG assessments of various biofuels have been completed (for a review, see Larson, 2006; Rowe *et al.*, 2008). A key question has long been whether it takes more energy or emits more GHG to make corn-ethanol than is reduced by its use. For a period of time a consensus began to emerge based on the meta-analysis of biofuel LCAs that ethanol promised modest GHG benefits but that cellulose-based ethanol would be a much better option.

Wider economic effects of biofuel incentive policies were brought into GHG assessments in the literature in 2008 (Fargione *et al.*, 2008; Searchinger *et al.*, 2008). These forward-looking modeling exercises predicted land-use change from increased demand for crops. These authors estimated release of soil-bound carbon and of carbon in standing biomass to dwarf any potential reduction in GHG emission from the fuel cycle savings of using a plant-based fuel over a fossil fuel. This issue dominated concerns about the data quality of LCA models during the development of updated biofuel regulation in both the United States and EU (EPA, 2009a,b; EU, 2009).

In concurrent work on various agricultural products, LCA practitioners have learned that the industrial production origins of LCA do not easily translate to agricultural production based on biological flows. Sleeswijk *et al.* (1996) list a number of methodological challenges in applying LCA to agriculture. Their findings have been supplemented by similar reviews (Cowell & Clift, 1997; Weidema & Meeusen, 2000; Hayashi *et al.*, 2005). Challenges include: setting system boundaries, including new impact categories (particularly biodiversity and esthetics), measuring soil quality, modeling the degradation profiles of pesticides and carefully aligning data sources and inventories with the goal of the study to

Table 2 GHG emissions due to production of grain corn for corn-ethanol as projected by EPA (2010b) and as observed and calculated by Kim *et al.* (2009) and by our own study

	Projected emissions for the year 2022 (EPA, 2010b)	Observed emissions for eight corn belt counties for years 2000–2003 (Kim *et al.*, 2009)	Observed emissions for S.Ont and E.Ont sites for years 2006–2008 (this study)
GHG emissions in g CO_2 eq MJ^{-1} corn-ethanol	9.78	30.2–98.2	17.3–36.5

GHG, greenhouse gas; S.Ont, southern Ontario; E.Ont, eastern Ontario.

Table 3 A timeline of key events in application of LCA to biofuels

1969–1980	1980–1995	1995–2004	2005–2008	2008–present
First 'proto-LCA' in 1969	Development of LCA code of practice under SETAC	Increasing number of biofuel LCAs	Short-lived consensus on modest GHG benefits of corn-ethanol	Indirect land-use expands scope of biofuel system boundary (Searchinger *et al.*, 2008) and introduces use of consequential LCA
First energy balances of corn-ethanol vs. gasoline (Chambers *et al.*, 1979)	First studies incorporating GHG emissions of biofuels (Marland & Turnhollo, 1991)	LCA begins to be applied to agriculture systems with consequent methodological developments (Sleeswijk *et al.*, 1996; Weidema, 1998)	US target for 7 billion gallons of biofuel by 2012 under RFS #1	LCA based GHG reductions regulation in EU and United States
			EU directive targets 10% biofuel	Biomass production variability concerns

GHG, greenhouse gas; LCA, life cycle assessment.

avoid unrealistic extrapolations. This last challenge covers the focus of our present article; in the language of LCA analysts the 'national treatment' issue we identify herein is part of the 'inventory' step of the LCA. Agricultural inventories are particularly hard to develop for two reasons.

First, agricultural production systems are carried out in *highly variable physical environments*. This can be contrasted with other natural resource production systems such as that for mining where sites of extraction are fewer and more concentrated. For example, in Canada over 3500 farms produce corn (Statistics Canada, 2006); compared with only six iron mines (Atlas of Canada, 2004). This spatial characteristic makes it much more difficult to build representative databases. Within small geographic areas, large numbers of farms may produce the same crop or livestock potentially requiring hundreds of sampling points to obtain statistically valid figures (Pfefferli & Gaillard, 2000).

The second barrier to developing reliable agricultural life cycle inventory data is that farming is carried out using *highly variable production methods*. Unlike an industrial facility characterized by closely monitored conditions and calibrated machinery (e.g., *an ethanol refinery*), agriculture production has multiple uncontrollable variables. Production is routinely affected by unpredictable changes in weather and pest presence and other aspects of natural systems (Nemecek & Erzinger, 2005). While agricultural inventories can be derived from stoichiometric relationship between inputs and outputs (Mourad *et al.*, 2007), each farm has a unique combination of soil fertility, topography, microclimate and farming techniques which make cross farm generalizations difficult.

Given the above limitations, LCA theory warns that the use of average and highly aggregated data in an inventory cannot deliver precise estimates of environmental impacts just as use of site-specific data is precise but cannot deliver estimates that are meaningful for other sites (Sleeswijk *et al.*, 1996; Weidema, 1998). Some form of data averaging is an acceptable way to scale results to a meaningful geographic area (e.g., the size of the territory for which governments are responsible), but the crucial point is that the LCA conclusion should correspond to the limitations of the data. We contend that spatial variation in crop production is a particular type of data limitation that has been overlooked in the LCA conducted for RFS 2. The use of average national projected data for corn farming provides an unsuitable basis on which to conclude all corn-ethanol produced in natural gas refineries meets a 20% GHG reduction target.

Recent work suggests that the high level of variance in natural environments and production techniques that are part of growing crops can be addressed by focusing on a suite of representative farms selected for a given region with regular checks to ensure that inputs and production are within 5–10% of the larger geographic area (Weidema & Meeusen, 2000). This approach offers both broad geographic representation and a better degree of precision. The Swiss 300 farm LCA-FADN project in which farms have been selected to represent types of terrain and management styles (Gaillard *et al.*, 2007) appears to be a good example of this approach.

Does the EU approach solve the issues?

Both the US RFS 2 and the EU Renewable Energy Directive (EU, 2009) set precise GHG emission reduction requirements for biofuels and both use LCA to establish compliance with the requirements. Both distinguish between conventional first generation biofuels such as corn-ethanol and advanced future fuels from cellulose or waste-wood. However, while the US approach sets specific emission reduction levels for 'advanced' and 'cellulosic' biofuels, the EU Directive bundles these together with conventional biofuels and requires 35% fewer GHG emissions from all biofuels with the target rising to 60% by 2018. Much like the US approach, the EU has performed its own LCA calculations for a variety of feedstocks to help with determining compliance with the emission reduction requirement. For corn-ethanol processed in a modern natural gas-fired facility, the default GHG savings are 49% (EU, 2009, annex V, table A), a value that is much more optimistic than the 20% savings calculated in the EPA's assessment for the same biofuel category.

Part of the reason for the different values is the EU's uncertainty over including indirect carbon emissions that could occur with relocation of agricultural production to forest or grassland to cropland for biofuel. Both the EU and the EPA track and incorporate emissions from conversion of previously uncultivated land to biofuel crops but the EU does not yet require a generic allocation of indirect emissions for predicted overall expansion of cultivated area around the globe. In other words, corn-ethanol incurs an indirect land-use emissions 'penalty' in the US approach but not in the EU approach. The EU is currently reviewing their approach (EC, 2010).

The main difference in the LCA technique of the EU compared to the EPA is that the traditional attributional approach is used by the EU instead of the forward-looking marginal modeling of the EPA consequential approach (Brander *et al.*, 2010). Despite this methodological difference the EU approach also appears to obscure geographic differences in biomass production emissions. The Directive requires member countries to submit lists of areas for which 'typical' agricultural GHG emissions meet, or are lower, than those shown in the EU default LCA calculations. Presumably, this is how the geographic differences in biomass production will be accommodated if at all. Chiaramonti & Recchia (2010) have critiqued the default LCA calculations in their work on sunflower crops in North-Central Italy. They show that within this relatively small area, GHG farming emission could vary by as much as 300%. They conclude that the GHG emissions reduction target set by the EU directive will not always be met in this region. They suspect that other biofuel chains are also location-dependent and advocate biofuel producers should submit production data to a streamlined LCA assessment before qualifying to receive incentives under the biofuel policy.

Discussion and recommendations

Environmental scientists and policy makers have turned to LCA as a method able to account for the long biofuel production chains and multiple occasions of GHG emissions. This method provides a useful estimate of the quantity of GHG reductions possible from biofuel, but real-world data and LCA theory tell us that treating farming as a homogenous sector with one set of emission values is insufficient to measuring compliance of biofuels with a 20% (United States) and 35% (EU) reduction target. The differences across space in biomass growing conditions and farming practices are too large and introduce uncertainties that ultimately cloud the reliability of LCA assessments of GHG emissions. Yet, governments in the United States (and EU) have chosen to use LCA in this way to assess compliance of specific biofuels. What needs to happen to ensure that application of LCA is evidence-based? We offer the following points for consideration.

We believe that the approach chosen for biofuel refineries should be applied equally to corn production: currently the US RFS 2 takes seriously the existence of technological differences in biofuel production (i.e., refineries), but glosses over the existence of geographic differences in biomass growing conditions. RFS 2 established 34 variations in biorefinery types in its corn-ethanol LCA but gives corn production a single national treatment. This approach is counter to evidence of a threefold range in corn production emissions between major corn producing counties. It also constructs a generic farming situation with physical processes that are entirely absent from some of the production systems that it claims to represent. This hinders any attempt to distinguish between farming practices that can reduce the overall GHG emissions of biofuel and prevents the creation of regulatory incentives to improve farming practices.

The LCA studies of corn (Kim *et al.*, 2009 and original data presented in Table 1) and sunflowers (Chiaramonti

& Recchia, 2010) reviewed in this article show that compliance with GHG emission thresholds is highly location-dependent. Some of the produced renewable fuels simply will not meet the 20% or 35% emission reduction thresholds. The assumption of a generic average set of emissions is even more troubling for novel crops such as switchgrass for which agronomic data are scant and likely to change as more experience is gained in production (Larson, 2006).

If bioenergy is to be realized as a sound solution to climate change we agree with other comments made in this journal (Long, 2009) that improved data and analysis and better interplay between science, economics, and policy are needed. In applying LCA to biofuels, as with many issues concerning climate change, there is a gap between the data that are available and the information required to make evidence-based regulations. The reality is that once corn is produced it is commingled with corn from many sites. Disaggregation may be the best science, but it would be more difficult and expensive to regulate on this basis. We realize that giving biomass production a 'national treatment' is the simplest approach particularly when regulators are under pressure to consider the impact of increased corn for ethanol production on global land cover change, soil carbon fluxes, and global food production. The EPA and EU approach is understandable but their communication of a single precise number as the regulatory standard is unsupported. We further realize that policies and regulations always balance potentially conflicting goals and interests such as energy security, climate change mitigation, and rural development. However, scientific tools, such as LCA, should not become rhetorical tools to provide the appearance that the policy goals are straightforward and reachable. If legislators and regulators wish to require compliance with specific emission reduction thresholds, the evidence dictates that compliance should focus not only on the technology used to convert biomass to fuel, but also on the inputs used to create the biomass. We suggest two options below.

One possibility is to have producers calculate a GHG emission value for each year's harvest. For corn-based ethanol a standard calculation could be employed that varies with specific information on yield, nitrogen fertilizer rate, and tillage practices. This information could be tracked along with the currently collected information on weight, and moisture content of each corn shipment made to ethanol refineries. This is akin to the recommendation made by Chiaramonti & Recchia (2010) in their study of sunflower biodiesel production discussed earlier. Mandatory calculation and reporting of farm emissions would provide a solid basis for regulators to be sure that GHG emission targets are being met but it would be onerous. Presently, some policy makers permit, but do not require, this kind of site-specific reporting. For example, both California's Low Carbon Fuel Standard and the United Kingdoms' Renewable Transport Fuel Obligation program permit fuel producers to propose alternate values to the default cultivation emissions values when reporting carbon intensity of biofuels (CARB, 2010; E4Tech, 2010).

A second option is to develop a suite of representative farms and perform LCA assessments on the corn produced at each farm as suggested by Weidema & Meeusen (2000). The data from these individual farms would need to be monitored against state or county level fertilizer and fuel inputs, data which are collected by national agencies such as USDA (NASS, 2011), to ensure that their inputs and practices were within a reasonable range of those in the surrounding region. Such an effort could incorporate and take advantage of core agricultural research on carbon fluxes and related research (e.g., Aitken, 2011), and perhaps farm data from nascent biofuel certification schemes, but predominantly, it would require knowledge of production trends and farming types. This knowledge rests with farmers themselves and to some extent with agricultural extension offices. For example, preliminary analysis of our own study suggests the S.Ont and E.Ont sites could be used in an effort to build LCIs for specific farm types in Ontario or North America. The S.Ont site could be characterized as no-till, high technology, ideal climate corn farm and the E.Ont site as reduced-tillage, slow technology adopter, marginal corn climate. Farms like these could be enrolled in a reporting program together with other representative farms to update LCA results and in so doing improve confidence in the projections made of biofuel policy in 2022 and further in the future.

In sum, what we suggest is realignment in the approach to regulating biofuel GHG emission reduction thresholds. The recent past has seen laudable attempts to model wider economic system impacts of biofuel production but, in doing so we are losing sight of the agro-biological foundation upon which this form of energy is based. We argue that biofuel regulatory approaches should acknowledge the spatially diffuse and variable realities of on-the-ground growing conditions and grower's choices. The goal of evidence-based decision making demands that much.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Conversion factors.