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Methodological Issues Regarding Biofuels and Carbon Uptake

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Abstract: Questions regarding the net effect of biofuels on carbon dioxide (CO_2) emissions have been difficult to resolve because of methodological uncertainties. One method of choice is lifecycle assessment (LCA), which takes a fuel product system as its object of analysis. LCA uses a static system model, with carbon flows averaged over a defined "lifecycle". Although it may evaluate some carbon stock changes, the LCA convention of treating biogenic CO_2 emissions as fully offset by the carbon embodied in a biofuel's feedstock renders its results independent of the dominant portion of carbon uptake on the land from which the feedstock is sourced. An application of material flow analysis termed annual basis carbon (ABC) accounting captures system dynamics and is fully sensitive to changes in carbon uptake. This paper compares the LCA and ABC methods, and contrasts their respective results for a case study of real-world biofuel production. It highlights the large impact of baseline carbon uptake, which can affect the sign of the results from either a likely decrease or a likely increase in net CO_2 emissions even before considering economically-induced effects. Implications include the need for further methodological work, new program-scale model development, an empirical re-analysis of biofuel systems, and a reconsideration of existing public policies and research priorities.

Keywords: carbon; emissions; biofuels; fuels; energy; climate; lifecycle analysis; methodology

1. Introduction

The use of liquid biofuels has grown rapidly over the past decade as a result of policies that promote their substitution for petroleum fuels [1]. Liquid fuels have long been the world's largest source of commercial energy, and are projected to remain so for several decades [2]. Transportation generates a tenacious demand for liquid fuels because their energy density, and the convenience of handling make them difficult to replace, even with extensive efforts to develop battery electric and hydrogen vehicles. Given concerns about the energy security, as well as the economic and environmental impacts of petroleum use, finding renewable liquid fuels has been a longstanding objective [3].

The main environmental rationale for biofuels is their potential role in climate change mitigation. Anthropogenic carbon dioxide (CO_2) emissions, which are now largely from fossil fuel combustion but also from terrestrial carbon stocks released by land-use change, have increased the atmospheric CO_2 concentration from under 280 parts per million (ppm) in pre-industrial times to over 410 ppm and rising [4]. Excess radiative forcing caused by rising CO_2 and other greenhouse gas (GHG) emissions is already disrupting the climate in many ways. The damages include ice cap and glacial melting, sea level rise, ocean acidification, extreme weather, greater variability in agricultural and forest production including risks of crop failure, harm to ecosystems, the spread of diseases, and other risks to humans and other life forms [5].

Carbon-based liquid energy carriers, which are now largely based on petroleum and used as transportation fuels, are (after coal) the world's second largest source of anthropogenic CO_2 emissions [6]. Addressing this portion of CO_2 emissions is therefore important for climate mitigation. In addition to reducing the demand for liquid fuels by limiting energy-intensive travel, raising vehicle efficiency and using non-carbon energy carriers such as electricity or hydrogen, biofuels have been considered an important mitigation option [7]. Emerging economies may include biofuels in their sustainable development plans, particularly if they face rising transportation fuel demand, but have limited domestic petroleum resources [3]. China considers the reduction of CO_2 along with smog, SO_2, and other pollutants among its sustainability goals and accounts for over one-third of global renewable energy investment, even though the investment efficiency of its new energy industries remains relatively low [8]. China has just expanded a biofuel (10% ethanol blending) requirement nationwide [9], which is an action that can affect energy and carbon emissions efficiency [10], and underscores the need to understand the impact of biofuels on net CO_2 emissions.

Methodologies for assessing the net effects of alternative (non-petroleum) fuels on CO_2 emissions are therefore necessary for both research and policy. Particularly important are tools for guiding programmatic decisions made at national, subnational, and corporate levels of governance. The scope can range from particular projects through to policies that are designed to leverage renewable fuel investments at sectoral scales. Program-level methods require a resolution that is different from that of global integrated assessment modeling (IAM), which examines renewable fuels among suites of global-scale options for meeting climate targets, and is highly dependent on inherently unverifiable techniques and assumptions [11,12]. Although many evaluations need to be forward-looking, the models that are used should be verified as much as possible using historical data. Even when a program's economic effects span beyond a fuel's supply chain so that an approach such as IAM is needed to project global impacts, it is important to empirically constrain the results as much as possible. This paper focuses on program-level methods for addressing the biofuels and climate questions by identifying the aspects of the analysis that can be constrained and for which confidence can be improved through the use of field data.

1.1. Established Use of LCA

To date, lifecycle assessment (LCA) has been widely used for project-scale and program-scale evaluations of transportation fuel alternatives. It is the method of choice for sectoral policy analysis and LCA findings provided the justification for renewable fuel programs in many jurisdictions. Such is the case for the United States (U.S.) Renewable Fuel Standard (RFS) [13], fuel quality provisions of the European Union (E.U.) Renewable Energy Directive (RED) [14], California's Low-Carbon Fuel Standard (LCFS) [15], and similar policies elsewhere.

Largely due to such programs, biofuel production has grown rapidly in recent years, rising from 0.7 exajoules (EJ, 10^{18} J) in 2005 to 3.1 EJ in 2015 globally [1]. The highest use is seen in the United States, where as of 2015, renewable motor fuel use reached 1.2 EJ of ethanol and 0.2 EJ of biodiesel, which were derived largely from corn and soybeans, respectively [16]. Biofuels depend on carbon uptake through photosynthesis, so their production is land-intensive. Ethanol production consumed 44% of the U.S. corn harvest, and biodiesel consumed 26% of the soybean harvest in 2015 on a gross basis (not net of coproducts), just to supply 5% of the nation's 28 EJ of liquid transportation fuel use [17]. It has been hoped that biofuels could be produced from cellulosic feedstocks that do not directly compete with food crops (although they would still impact land). However, cellulosic fuels have failed to become viable at a meaningful scale in spite of major subsidies and high expectations when renewable fuel mandates were established over a decade ago [18].

Although energy security and agribusiness income provide policy rationales for biofuels, the main sustainability rationale is the hope that they would reduce net CO_2 emissions. The amount of CO_2 emitted when biofuels are burned differs little from that of the petroleum fuels they replace [19]. However, because CO_2 is removed from the atmosphere during biomass feedstock growth, the belief has been that net emissions are reduced as long as production-related GHG emissions are low enough. This justification for biofuels reflects the presumption of biomass carbon neutrality, i.e., that "in a sustainable agricultural system, there is no net CO_2 flux to the atmosphere" from biomass combustion [20]. This assumption is embedded in the LCA models that are used to evaluate transportation fuels, which therefore tally only the CO_2 emitted by fossil fuels use during biofuel production and other production-related greenhouse gas (GHG) emissions; some versions also account for changes in carbon stocks, such as land-use or soil carbon changes tied to feedstock production.

1.2. Issues Raised

When assessing the net GHG emissions effects of biofuel use, LCA has come to suffer from a high level of uncertainty [21]. This shortcoming is not only one of parameter of choices that might be eventually resolved with better data, but also pertains to epistemic issues regarding how to implement the method. It also results from compounding uncertainties as system boundaries are expanded to account for effects whose significance was not appreciated when the method was first proposed for assessing transportation fuels [22–25].

A basic issue is that LCA methods are insensitive to changes in the rate of carbon uptake on the land from which a biomass feedstock is sourced, which comprises the largest carbon flow in a biofuel production and use system. Consistent with the carbon neutrality assumption, this biogenic carbon is assumed to be in a steady-flow equilibrium with the atmosphere and is not explicitly evaluated. This aspect of LCA is similar to the international carbon accounting convention of treating energy-sector biogenic CO_2 emissions as carbon neutral, with carbon stock changes tallied in the land-use sector [26]. Forest bioenergy models often do account for carbon uptake on the harvested land, which relates to how long it takes for regrowth to offset the CO_2 emitted when wood is burned. Many biofuel LCA studies now account for land-use change, leading to similar questions about carbon debt. Nevertheless, by invoking the biomass carbon neutrality assumption, LCA ignores the most certain data about a biofuel system's carbon exchanges with the atmosphere, namely the CO_2 from fuel combustion. It then incurs irreducible uncertainties about net overall emissions in light of the indirect effects of diverting biomass from its prior disposition [27].

Such shortcomings were pointed out as the LCA methodology was being adopted for fuel policy applications [22]. The severity of the problems became clear when considering the carbon stock releases from direct land-use change (DLUC) and indirect land-use change (ILUC) [28,29]. Nevertheless, the research community has continued to rely on LCA, increasing the method's complexity in order to model land-use change and other effects inadequately handled in the attributional (ALCA) methods originally used. The resulting consequential (CLCA) methods couple ALCA to global economic and land-use models [30–32]. Such modeling expands the boundary of a "lifecycle" from that of a circumscribed fuel production system to one that encompasses the entire globe and extends well into the future [25,27,33]. The results then become so uncertain that it may not be possible to estimate whether the net GHG emissions from biofuels are less than or greater than those of a petroleum fuel [34]. Some researchers therefore propose moving beyond LCA or expanding the scope of effects addressed by using IAM as a form of CLCA [25,35].

Even though the effects modeled by CLCA are dynamic, the method retains a static framework for the carbon embodied in a fuel. That carbon is still assumed to be in a steady-state flow, with biogenic CO_2 emissions fully balanced by feedstock carbon uptake. A few researchers have warned that biofuels require systems analysis methods designed to handle dynamic effects [22,36] and there has been some attempt to partially address carbon cycle dynamics in CLCA [37]. Some maintain that LCA is still the best approach for assessing the GHG emissions from biofuel use, and that CLCA remains suitable for fuels regulation [38]. Others acknowledge that neither ALCA nor CLCA can provide definitive estimates with the confidence needed for regulatory policies [25,39].

However, it is straightforward to evaluate the dynamics of carbon exchanges to and from a given physical system without LCA. Although economically-induced effects remain uncertain, the carbon flows that are directly tied to biofuel production and consumption can be evaluated empirically. A method termed annual basis carbon (ABC) accounting, which evaluates carbon exchanges in a temporally and spatially explicit manner, was proposed for this purpose [27]. Applying principles of material flow analysis [40], field data can then be used to constrain estimates of net emissions. Although it is suitable for tracking carbon, ABC accounting is not itself a modeling method. Nevertheless, it captures dynamic effects and can be used to verify the modeling of key carbon flows.

2. Methods

This paper compares LCA and ABC accounting by focusing on key carbon exchanges and highlighting the crucial role of terrestrial carbon uptake. The approach involves a structural comparison of the two methods and a numerical comparison based on a case study of substituting corn ethanol from a given biorefinery for petroleum gasoline. Since the objective is to address program-level evaluation needs as opposed to global-scale scenario analysis, this inquiry does not attempt to elaborate on all of the many challenges related to modeling biofuels.

The structural comparison focuses on *material* carbon flows, referring to the mass flows of carbon that originate in a feedstock (biological or fossil) and are processed into fuel molecules with some losses along the way. These material flows are crucial when considering how replacing fossil carbon with biogenic carbon affects atmospheric carbon. Material carbon flows are distinguished from the CO_2 and other GHG emissions associated with non-material inputs (such as electricity or natural gas used for production processes, or the fuel used for tractors or trucks that transport feedstocks, as well as other inputs and products), which are not at issue for the concerns addressed here.

To illustrate the quantitative implications of the different methods, a numerical comparison is presented based on the data and results from two previously published technical reports. One of these reports [41] used LCA and the other [42] used ABC accounting to evaluate corn ethanol from a particular biorefinery. To maximize transparency, this case study is deliberately simple, evaluating a single facility and its surrounding farm draw area over the time step of a single year. The analysis restricts itself to a fuel's physical supply chain (the same focus as ALCA) without including highly uncertain economic effects. However, by focusing on a core aspect of the issue, it shows why very different results are obtained when applying different methods to the same data.

2.1. Structural Features of the Methods

As commonly applied for evaluating the GHG emissions aspects of transportation fuel policies, LCA takes a fuel production and consumption system as its object of analysis [33]. Often termed a fuel *pathway*, this circumscribed vehicle-fuel system includes the supply chain and associated physical inputs that are evaluated when modeling GHG emissions from "well-to-wheels" for a fossil fuel, or "field-to-wheels" for a biofuel.

The system modeled includes the various processes within each fuel's physical supply chain, such as farm operations (tractor fuel, natural gas, electricity, etc.); petroleum refinery, biorefinery operations, and the associated upstream processes for natural gas, electricity, and other inputs; production of inputs (fertilizers and other materials); and the transportation of fuels, feedstocks, and other material inputs. LCA then attributes to a "fuel" (as defined by a particular pathway) the result of summing these emissions over the fuel's pre-defined lifecycle. The result is termed the fuel's carbon intensity (CI), e.g., in units of gCO_2e/MJ (grams of CO_2-equivalent GHG emissions per megajoule of a fuel's lower heating value). This attribution of a modeling result to a fuel as if it were a fuel property is done by both ALCA and CLCA, and is the basis for the method's claimed ability to discriminate among fuels—e.g., grain-based ethanol versus cellulosic ethanol or a given renewable fuel and the petroleum fuel it might replace—according to their net atmospheric impact.

In ABC accounting, the same physical components are analyzed, but the method abandons the notion of a pre-defined lifecycle over which dynamic effects are averaged. It instead records carbon exchanges and other GHG emissions one year at a time in a spatially explicit manner, not making abstract connections between distinct physical processes. Biogenic carbon, represented as a closed-loop flow in LCA, is treated as two separate flows: carbon uptake on cropland, and CO_2 emissions from vehicles. The method uses a single system boundary to enclose both the biofuel and fossil fuel pathways. GHG exchanges are therefore evaluated directly where and when they occur for different operating conditions of a unified physical system, as recommended by Schlamadinger et al. [43]. ABC accounting does not generate a unique CI value that can be attributed to a given fuel independently of time. Rather, it produces annual results for both positive and negative carbon exchanges with the atmosphere, including year-to-year changes in carbon uptake.

Figure 1 compares the structure of the LCA and ABC methods in terms of material carbon flows. For simplicity, all of the production processes are shown in a single box, even though multiple processes and locations are involved. As previously noted, purely process-related emissions are not at issue here in contrast to the material carbon embodied in the fuel itself, i.e., the biogenic carbon in a biomass feedstock and the fossil carbon in crude oil.

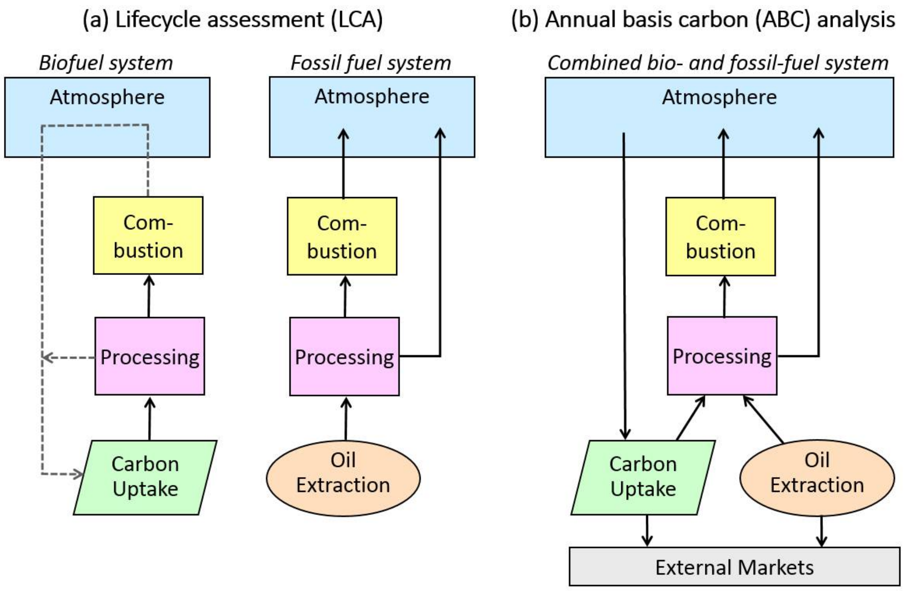

Figure 1. Structural comparison of material carbon flows when comparing CO_2 emissions for biofuels and fossil fuels. (**a**) Schematic diagram for standard fuels-oriented lifecycle assessment (LCA) methods. (**b**) Schematic diagram for annual basis carbon (ABC) analysis.

2.2. Fuels-Oriented LCA

Panel (a) of the figure depicts how these flows are represented in LCA. Leftmost is the biofuel pathway, which LCA models as a closed-loop flow. The biogenic CO_2 emissions from biofuel combustion, plus any biogenic processing emissions (such as the CO_2 released during ethanol fermentation), are presumed to be "recycled" back to carbon uptake on the land where the feedstock is grown. Unlike the physical flow of carbon fixed during feedstock growth, which is processed into biofuel and then combusted, this notionally recycled carbon is not a well-defined mass flow, but rather part of the global carbon cycle. It is therefore shown as a dashed gray line rather than a solid line as used for the carbon flowing in the feedstock-to-fuel segment of the lifecycle. For a petroleum fuel, which is shown as the right-hand pathway of panel (a), there is a straightforward flow of carbon from underground and into the atmosphere via oil extraction, refining, and combustion. (In principle, process CO_2 emissions from either biorefining or petroleum refining could be captured and sequestered, but that option is not salient for the issue at hand and would not fundamentally change this discussion.) For the most part, the traditional LCA method does not model interactions with external commodity markets, either for grains in the case of biofuels, or for crude oil in the case of petroleum fuels. An exception is a coproduct, such as distillers' grains in the case of corn ethanol, for which LCA models commonly compute a credit. The coproduct credit is often based on a selective expansion of the biofuel system boundary, e.g., to model changes in livestock feeding operations. This nuance also does not change the key issues at hand, and so such flows are not shown in Figure 1a.

Because the LCA tally for a biofuel excludes biogenic CO_2 emissions, a biofuel's atmospheric impact is modeled only on the basis of non-biogenic processing emissions. For the fossil fuel system (reference pathway), all of the CO_2 emissions (both processing and combustion) are tallied. LCA then compares a biofuel to a fossil fuel on the basis of the separate GHG emission tallies, which is equivalent to computing the difference between two distinct steady-flow systems.

2.3. ABC Analysis

Figure 1b shows how the biofuel and fossil fuel carbon flows are represented in ABC accounting. In this case, a unified system contains all of the production processes for both the biofuel and fossil fuel pathways. The method then evaluates the carbon flows and processing emissions for the unified system under different operating conditions. A reference fossil fuel case would include all of the biofuel production components, but not all of them are always active. However, terrestrial carbon uptake is always active, regardless of the use of whatever harvest might be taken from the land. This logic is crucial, because what matters for atmospheric CO_2 concentrations is how this net downward carbon flow changes. ABC accounting treats the atmosphere as a well-mixed carbon stock without assuming that any particular carbon is "recycled". Panel (b) therefore uses a solid black line for carbon uptake, which is always explicitly evaluated, and for the CO_2 emitted from processing and combustion. Rather than presuming that biofuels are inherently carbon neutral, the extent to which carbon uptake offsets biogenic CO_2 emissions is treated as an open question.

ABC analysis yields estimates of GHG exchange rates between the defined vehicle-fuel system and the atmosphere, e.g., in metric tons of carbon-equivalent per year (t_c/yr). Such results are not lifecycle estimates, and cannot be reduced to CI values as generated by LCA models. Rather, they reflect the net direct GHG emissions impact of a biofuel and fossil-fuel production and consumption system that operates differently from one year to the next.

2.4. Carbon Displacement Effects

As also shown in Figure 1b, carbon moves across the system boundary in biomass (crops and other agricultural products or coproducts) and fossil (petroleum) forms that are exchanged with commodity markets. Changes in these carbon flows with external systems cause displacement effects, which lead in turn to changes in GHG emissions (positive or negative) that occur outside the system boundary. Since these effects are economically mediated, it cannot be assumed that a decrease of one ton of carbon provided to external markets from the land within the system boundary leads to exactly one ton less carbon emitted by external systems. If the displaced carbon is not fully compensated by more intensive crop production and reduced food consumption due to higher grain prices, then new land may be brought into production in other locations. The resulting DLUC or ILUC can cause a terrestrial carbon stock release that exceeds the decrease in CO_2 emissions from the other effects. Similarly, it cannot be assumed that one ton of carbon in crude oil not used for fuel leads to one ton of carbon left in the ground. In this case, a rebound effect can occur as lower oil prices induce higher petroleum demand in other locations.

Prior studies show that, although highly uncertain, these consequential effects ultimately increase net GHG emissions for biofuels sourced from productive land [24,44–46]. Therefore, both ALCA and ABC analyses of fuel pathways as depicted in Figure 1 yield lower bounds on the overall GHG impact of using a biofuel rather than a fossil fuel.

3. Analysis

Data from a particular corn ethanol biorefinery are used to illustrate the quantitative implications of the different methods. The Illinois River Energy (IRE) facility began operating in 2007, and was analyzed in a well-documented technical report [41]. During its first year of operation, it supplied 56 million gallons (4.5 × 10^9 MJ) of anhydrous ethanol, which was blended into retail gasoline to displace 37 million gallons of petroleum fuel components. LCA and ABC accounting offer two different ways to estimate the direct change in the net flow of CO_2 into the atmosphere when ethanol displaced gasoline during the facility's first year of operation.

The LCA study used GREET [47], an LCA model sponsored by the U.S. Department of Energy (DOE) that has been used for many biofuel studies [48–50] and is also used by the California Air Resources Board (CARB) for administering the LCFS [15]. Entering IRE operations data into GREET resulted in an estimate that the corn ethanol had a CI of 55 gCO_2e/MJ, which was 40% lower than the 92 gCO_2e/MJ GREET-modeled value for petroleum gasoline [41]. Given the facility's fuel output, the implied GHG emissions reduction when burning ethanol instead of gasoline is 46 kt_c/yr (10^3 metric tons per year on a carbon-mass equivalent basis). For reference, the carbon mass flow embodied in the ethanol supplied was 87 kt_c/yr, which was slightly less than the 89 kt_c/yr embodied in gasoline that provides the same amount of energy. As customary for LCA and assumed in GREET, biogenic CO_2 emissions were not counted, and the analysis did not evaluate carbon uptake on the cropland serving the biorefinery.

The same data were re-analyzed using ABC accounting, as recounted in a later report [42], which found no significant reduction in net direct GHG emissions when the ethanol replaced gasoline. That study's nominal estimate of a net 4 kt_c/yr emissions increase was not considered significant given data uncertainties. As explained below, the reason for this large difference in findings is that the ABC method always evaluates the carbon uptake on the cropland serving the facility, reflecting the local flow of carbon out of the atmosphere on productive land, regardless of how its harvest is used. In the pre-operational year, that cropland supplied corn and soybeans to feed and food markets, while petroleum gasoline was used for fuel. In the facility's first operational year, the same cropland grew only corn, which was processed into ethanol and replaced an energy-equivalent amount of petroleum fuel. Note again that both the ABC and LCA estimates are for direct emissions only, excluding indirect and other economically-induced effects, which neither study sought to project, but would serve only to increase net CO_2 emissions.

3.1. Pathway Breakdowns

Table 1 provides a side-by-side comparison of the key numerical results when applying the two methods to the IRE data. It details how the different analytic structures yield very different answers. Values are tabulated for a biomass pathway, when corn ethanol is produced and consumed, and for a fossil fuel pathway, when petroleum gasoline is produced and used.

Table 1. Comparison of LCA and ABC methods for a case study of corn ethanol production. GHGs: greenhouse gases.

All Values in kt_c/yr	**LCA Method**		**ABC Method**			
	(Static Analysis)		**y_0 (Gasoline Use)**		**y_1 (Ethanol Use)**	
Exchanges with Atmosphere	**Biomass**	**Fossil**	**Biomass**	**Fossil**	**Biomass**	**Fossil**
Carbon uptake	*		(119)		(189)	
Processing						
Biogenic CO_2	*		-		44	
Other GHGs	66	22	17	22	72	-
Combustion	*	89	-	89	87	-
Pathway sum	66	111	(101)	111	14	-
Combined system sum			10		14	
Carbon to/from external commodity markets			119	(109)	65	-

* Carbon flows omitted from LCA tallies under the biomass carbon neutrality assumption.

3.1.1. LCA Estimates

The left section of the table summarizes the LCA results, with values given in units of kt_c/yr (on a carbon-mass equivalent basis, recalling that C:CO_2 = 12:44). These attributional LCA results are static in that they ignore material carbon flow dynamics. Year-to-year changes in carbon uptake are not evaluated, and so the LCA results reflect the behavior of a fuel product system averaged over its pre-defined lifecycle.

Since LCA tallies neither carbon uptake nor biogenic CO_2 emissions, those items have an asterisk (*) in this section of the table. The higher processing emissions that are shown for ethanol (66 kt_c/yr) compared with gasoline (22 kt_c/yr) are typical of dry-mill biorefineries such as the IRE facility. Adding the gasoline processing emissions to the combustion emissions of 89 kt_c/yr yields 111 kt_c/yr as the fossil pathway sum. Relative to this "well-to-wheels" estimate for gasoline, the biofuel pathway sum of 66 kt_c/yr represents a 40% decrease in net GHG emissions [41].

3.1.2. ABC Estimates

The other section of Table 1 tabulates the ABC results. Since the method reflects system dynamics, values are given for the pre-operational year (y_0) before ethanol production, and the facility's initial year of operation (y_1) when biofuel replaced fossil fuel. As noted in the initial IRE study [41], the cropland serving the facility was planted with soybeans (49%) and corn (51%) in y_0, and then 100% corn in y_1. The later study [42] used crop composition data to compute the *carbon harvest*, i.e., the mass of carbon embodied in the crops harvested from land. Although most U.S. cropland is depleted of soil carbon and little or no soil carbon accumulates under standard crop rotations, a small soil carbon gain in no-till portions of the cropland was calculated [41], and is reflected in the carbon uptake estimates. Net uptake is largely determined by the carbon harvest, giving estimates of 119 kt_c/yr in y_0 and 189 kt_c/yr in y_1. The y_1 value reflects that corn yields are much higher than soybean yields. Carbon uptake is tabulated as a negative number (in parenthesis) because it is a flow entering the vehicle-fuel system, in contrast to the emissions that are shown as positive numbers.

For processing emissions, farm operations on the cropland surrounding the facility emitted 17 kt_c/yr in y_0. Similar to the cropland, these farm operations are part of the combined physical system defined for ABC analysis, and so their emissions are part of the y_0 total, even though their harvest is not being used for ethanol that year. The fossil pathway emissions in y_0 are the same as they are under the LCA method. The biomass pathway has much higher processing emissions in y_1 because the biorefinery is then operational; the value of 72 kt_c/yr given in the table includes GHG emissions from both the farms and the biorefinery. These purely process-related emissions reflect energy use and processing inputs other than the material carbon embodied in the biomass feedstock itself. This column also shows 44 kt_c/yr of biogenic CO_2 emissions, reflecting the CO_2 released during ethanol fermentation. Finally, the carbon released by fuel combustion of 87 kt_c/yr for ethanol in y_1 is slightly less than the 89 kt_c/yr for gasoline, reflecting their respective combustion chemistries.

The ABC method computes an annual sum for the combined biomass and fossil fuel pathways. These sums are 10 kt_c/yr for y_0 (prior to ethanol production) and 14 kt_c/yr for y_1 (with ethanol being produced and burned instead of gasoline). The nominal 4 kt_c/yr increase when ethanol was used was not considered significant [42]. Therefore, in contrast to the LCA finding of a 40% reduction when the ethanol replaced gasoline, the ABC analysis found no significant GHG emissions reduction.

3.2. External Carbon Flows

Shifts in agricultural and energy commodity flows when substituting biofuels for fossil fuels cause displacement effects that impact GHG emissions beyond a fuel's physical supply chain [44,45]. Such effects fall outside the vehicle-fuel system boundary for both ALCA and ABC accounting.

These carbon displacements are largely neglected by GREET and similar LCA tools. The one exception that LCA models often make is applying a credit for coproducts, such as distillers' grains that displace other livestock feeds. The coproduct credit for the ethanol is the reason why the 66 kt_c/yr processing emissions value for LCA in Table 1 is lower than the corresponding 72 kt_c/yr for ABC accounting, which does not apply a coproduct credit. However, such selective inclusion of an external effect (coproduct credits) that lowers a biofuel's CI while omitting those that could raise the CI is questionable and likely to produce biased results, particularly if the omitted effects are large.

In ABC accounting, these external carbon flows are shown as balance terms. The lowest line in the ABC section of Table 1 shows a y_0 carbon flow to commodity markets of 119 kt_c/yr, which is equal in magnitude but opposite in sign to the cropland carbon uptake. This is the amount of carbon embodied in the grains supplied for food and feed before the harvest was diverted for biofuel production. The other external flow is the 109 kt_c/yr input of fossil carbon from the petroleum market, which is negative because it represents carbon entering the system. This value is lower than the 111 kt_c/yr fossil pathway sum because it excludes non-petroleum inputs and non-CO_2 GHGs such as CH_4 during fossil fuel processing [42]. In y_1, the biomass carbon supplied to external markets declines to 65 kt_c/yr, which is the amount of carbon in the biorefinery's coproducts. This lower y_1 value reflects a major displacement of carbon harvest from food and feed production to biofuel production. Also in y_1, no fossil material carbon enters the system (as opposed to fossil inputs used for processing that are not part of the biofuel's material carbon flow). Although the y_0-to-y_1 drop of 109 kt_c/yr flowing into the system represents a reduction of petroleum demand, it does not directly reduce the flow of carbon into the atmosphere from the vehicle-fuel system, because the vehicles are still burning carbon.

CLCA was developed to address such external effects and, depending on how it is structured, adds varying levels of dynamic analysis to LCA. To date, published CLCA studies have not evaluated the dynamics of terrestrial carbon uptake for biofuel feedstocks. IAM has been proposed as a platform for CLCA because it models many dynamic effects, including climatic influences that are not limited to GHG emissions, and provides a coherent framework for integrating biogeophysical and economic effects along with associated feedbacks [25]. Although ABC accounting is quite narrow by comparison, it quantifies the direct offset of biogenic CO_2 emissions due to feedstock carbon uptake, as opposed to indirect offsets due to displacement effects. Conversely, since the scope of CLCA is so broad and its results are so inherently uncertain, the method cannot empirically constrain the salient carbon offset. The quantitative significance of ABC results is highlighted by the sensitivity analysis below, which considers baseline carbon exchanges on cropland and resolves real-world carbon flows in a way that neither LCA nor IAM have done to date.

3.3. Sensitivity to Baseline Carbon Uptake

As seen in Table 1, the ABC results are greatly driven by the change in cropland carbon uptake, which for the IRE facility's first year of operation reflected a shift from growing soybeans on nearly half the land to growing only corn. General yield gains for both crops are also a factor. The ABC study therefore explored the effect of varying the baseline (y_0) carbon uptake, comparing four cases:

A The same values as used in Table 1 (base case as actually documented)
B Corn–corn rotation, i.e., with no soy planted in y_0
C Fixed yield but keeping the soy–corn rotation
D Both corn–corn rotation and fixed yield.

The results are shown in Table 2, with the y_1 values held constant as given above in Table 1, and differing assumptions made for the y_0 conditions.

The strong dependence on baseline carbon uptake is apparent, with the largest effect resulting from whether or not the cropland is planted with corn and soy in y_0 or planted with only corn, which produces a much higher carbon harvest than soybeans. If only corn were planted in y_0 (Case B), the carbon uptake would have been 176 kt_c/yr rather than 119 kt_c/yr. This higher baseline rate of carbon uptake implies less gain from y_0 to y_1, and therefore a lower offset of biogenic CO_2 emissions. Adjusting for corn's higher farm inputs then implies a 49 kt_c/yr increase in GHG emissions. That amounts to a significant increase in emissions when using ethanol instead of gasoline in contrast to the insignificant change of 4 kt_c/yr seen for Case A.

Table 2. Dependence of net change in GHG emissions on baseline carbon uptake.

All Values in kt_c/yr	Base Year (y_0) Carbon Flows by Case:			
	A	B	C	D
Carbon uptake	(119)	(176)	(122)	(188)
Farm processing	17	29	17	29
Fossil fuel pathway	111	111	111	111
Combined system total	10	(35)	6	(48)
Net change in emissions from system to atmosphere, $y_1 - y_0$	4	49	7	61

See text for case definitions; net changes are calculated relative to y_1 emissions of 14 kt_c/yr (Table 1); sums may not exactly match due to rounding. Source: derived from DeCicco & Krishnan [42].

Case C controls for yield while keeping the same soy–corn rotation as in Case A. This effect is much smaller than the crop rotation effect, implying a 7 kt_c/yr increase in emissions. Finally, Case D examines what would happen if there were no gain in carbon harvest from y_0 to y_1. In that case, net GHG emissions from the circumscribed vehicle-fuel system would rise by 61 kt_c/yr when using corn ethanol instead of petroleum gasoline. For perspective, that would be an increase of 55% relative to the gasoline pathway GHG emissions of 111 kt_c/yr given in Table 1. Again, this increase of direct GHG emissions is prior to considering economically-induced indirect effects.

4. Discussion

When analyzing the same physical system components and using the same real-world data, LCA and ABC accounting produce starkly different results. The main reason is the treatment (or lack thereof) of carbon uptake on the land from which biofuel feedstocks are sourced. This issue relates to two others. One is whether or not the method of analysis captures system dynamics, reflecting the stock-and-flow nature of the carbon cycle. The other is whether or not bioenergy is assumed to be inherently carbon neutral, which is an assumption aligned with the LCA worldview.

As seen in Figure 1a, analyzing a biofuel in terms of its lifecycle invokes a closed-loop model of biogenic carbon flows, rendering biofuels carbon neutral by construction. This assumption is made throughout the bioenergy literature and in many official policy documents. In addition to the earlier quote from Marland and Turhollow [20], examples include:

> Bioenergy is a renewable source of primary energy, and its sustainable use does not emit carbon dioxide. [51] (p. 151)

> Emissions from the fuel in use, e_u, shall be taken to be zero for biofuels and bioliquids. [14] (p. 55)

> ... over the full lifecycle of the fuel, the CO_2 emitted from biomass-based fuels combustion does not increase atmospheric CO_2 concentrations, assuming the biogenic carbon emitted is offset by the uptake of CO_2 resulting from the growth of new biomass. As a result, CO_2 emissions from biomass-based fuels combustion are not included in their lifecycle emissions results. [52] (p. 444)

In some LCA models, including GREET [47], biogenic CO_2 emissions are computed internally, but are then automatically credited by an equal amount of assumed carbon uptake, so that they are treated as fully carbon neutral in the results.

Although widely used, this assumption has been questioned in recent years [53]. A similar debate is playing out for forest bioenergy. Instead of the annual cropping cycles that are relevant for liquid biofuels as now produced, it faces the added complexity of multi-decade forest regrowth periods. The issue of baseline carbon uptake and the extent to which woody biomass CO_2 emissions are "neutralized" over time are well recognized in that context even though consensus is lacking about how to handle the matter [54–56].

An important issue is whether one conceptualizes the system as static in that carbon exchanges are modeled as being in a steady-flow equilibrium over the spatial and temporal extent of the system being analyzed. That view is implied when treating biofuels *a priori* as a "sustainable" system [20] or in "sustainable use" [51]. However, presuming a sustainable carbon flow begs the question of whether the *rate* of carbon uptake speeds up enough to offset the *rate* at which CO_2 is emitted during combustion, which is unchanged when a biofuel replaces a fossil fuel. The act of fuel substitution is itself a dynamic process. Mass flow analysis shows that an additional net carbon uptake (technically, an increase in net ecosystem production) is needed to offset biofuel CO_2 emissions [57]. The magnitude of the offset (i.e., the extent to which a gain in uptake "neutralizes" biogenic CO_2 emissions) is an empirical question, which ABC analysis addresses.

Interestingly, these issues of carbon dynamics were identified early on within the research community, notably in the "standard methodology" proposed by Schlamadinger et al. [43] as part of work undertaken by the International Energy Agency (IEA) on bioenergy analysis. However, as LCA methods were developed, it appears that these considerations were lost as researchers embraced a closed-loop model of biogenic carbon flows. The biomass and fossil-fuel pathways were then defined as separate systems, with their respective components enclosed in distinct system boundaries. This shift in thinking can be seen by comparing Figure 1 of Schlamadinger et al. [43] with similar diagrams developed in later IEA Bioenergy work, e.g., Figure 3 of Green & Byrne [58] and Figure 7 of IEA [59]. Those latter diagrams show a circular flow for biogenic carbon, while the earlier diagram [43] shows carbon flows to and from an explicitly defined biological carbon stock, and also clearly indicates both biogenic and fossil CO_2 emissions as flowing into the atmosphere.

Those diagrams are more complex than Figure 1 as given here, because they break out various processing steps and their associated GHG emissions. Figure 1 strips the issue to its bare essentials in terms of material carbon flows. The LCA diagram of Figure 1a has the same structure as the latter diagrams [58,59], which are also used in models such as GREET. In contrast, the ABC diagram of Figure 1b here has the same structure as Figure 1 of Schlamadinger et al. [43], which is consistent with the early paper's guidance that the bioenergy and fossil fuel pathways should be treated as subsystems of a unified system. The ABC method recognizes that "it is ... not sufficient to calculate average annual C balances, but rather the dynamic path of emission reductions over time must be taken into account" [43] (p. 363).

Annual average carbon balances also form the basis for the international carbon accounting convention of treating bioenergy as carbon neutral, with carbon stock changes being recorded in the land-use sector. However, merely comparing bioenergy to fossil energy on the basis of annual averages misses the time-varying effects as carbon is shifted from one use to another. The resulting bias is revealed when varying the baseline carbon uptake, as seen in Table 2. Mathematically, such results reflect that the behavior of a dynamic system depends on its initial condition. For a biofuel product system, the key initial condition is baseline carbon uptake.

To date, most published analyses of biofuel systems at the program level (as opposed to global scenario analyses) have relied on versions of LCA, and so this discussion calls those results into question. An ABC-based retrospective analysis of the U.S. biofuel expansion between 2005 and 2013 found much less than a full offset of biogenic CO_2 emissions [60]. However, that work did not build a dynamic model to enable the counterfactual analysis that is necessary for a full evaluation. ABC accounting is not itself a modeling tool. This analysis merely uses it to reveal the importance of a key dynamic effect that is neglected by LCA; it does not suggest that ABC accounting can replace LCA, but rather indicates that a dynamic method must be used.

The development of system dynamics models for bioenergy is an important task for future work. Also valuable would be retrospective studies of real-world biofuel production and methodological research on practical program-scale evaluation tools. Such ground-up, data-driven analysis would be a valuable complement to the extensive but generally not validated modeling that has been widely supported. Even though there is now real-world experience with biofuel programs implemented at regional and national scales, little existing research fully utilizes the available data to examine how current biofuel production actually affects the net amount of carbon in the atmosphere.

5. Conclusions

The premise of biofuels as a carbon mitigation option rests on the potential offset of combustion CO_2 emissions by carbon uptake during feedstock growth. For existing biofuel production, as well as the most currently feasible options being developed, the location of carbon uptake is ecologically productive land. Land is a finite resource, and it is already used in many ways, whether harvested for economic purposes or accumulating carbon in natural ecosystems. Baseline levels of terrestrial carbon uptake cannot be ignored when procuring biomass for fuel.

As widely applied to date, LCA neglects this critical issue. The magnitude of the resulting problem is illustrated when quantifying the directly measurable shifts in material carbon flows when ethanol replaces gasoline. Accounting for baseline carbon uptake changes the result from a LCA-based estimate of a substantial reduction in net CO_2 emissions to an ABC estimate of no significant reduction. Varying levels of baseline uptake can result in ethanol use having significantly higher net CO_2 emissions than gasoline use.

This analysis underscores the crucial importance of accounting for the initial conditions when evaluating dynamic systems, such as those that engage the terrestrial carbon cycle. Since bioenergy systems are dynamic, it is misleading to analyze them as if they were in steady-flow equilibrium with the atmosphere, that is, "sustainable" by assumption. Given the doubt that it casts on the LCA methods that are used to analyze renewable transportation fuels, this analysis suggests further investigation of the methodological issues raised here. It also suggests the need for re-evaluation of biofuel-related GHG impacts, the development of program-scale dynamic modeling and evaluation methods, and the reconsideration of public policies and research priorities for renewable fuels.

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