Review

Life-cycle analysis and the ecology of biofuels

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Biofuels have been proposed as an ecologically benign alternative to fossil fuels. There is, however, considerable uncertainty in the scientific literature about their ecological benefit. Here, we review studies that apply life-cycle analysis (LCA), a computational tool for assessing the efficiency and greenhouse gas (GHG) impact of energy systems, to biofuel feedstocks. Published values for energy efficiency and GHG differ significantly even for an individual species, and we identify three major sources of variation in these LCA results. By providing new information on biogeochemistry and plant physiology, ecologists and plant scientists can increase the accuracy of LCA for biofuel production systems.

Plant science in the energy industry

Plant biomass as a source of liquid fuel for transportation (i.e. biofuels) has been widely touted as a path to national energy independence and mitigation of global climate change [1,2]. However, the potential for widespread adoption of biofuels to reduce net carbon dioxide (CO_2) fluxes to the atmosphere has come under intense scrutiny (e.g. Refs [3,4]). Future research relating to the genetics of biofuel crops and changes in nutrient cycling as a result of land conversion to biofuel crops will strongly influence the sustainability of plants as energy sources. The integration of plant science into energy industry research is crucial for the success and sustainability of biofuels. This integration will only be effective if the plant scientists and ecologists who work with biofuels can communicate new findings in a way that is useful to the larger interdisciplinary community.

Life cycle analysis (LCA) is a computational tool used to evaluate the sustainability of a future biofuel industry. Here, we introduce the plant science community to LCA and review previously published LCA results for greenhouse gas (GHG) balances and energy efficiency of temperate grass species that are proposed as alternatives to corn for ethanol production in the major agricultural landscapes of the Midwestern USA. We explore factors that drive differences in estimates of the net benefits of biofuels relative to fossil fuels and examine variation in key assumptions that have been identified as sources of debate about the accuracy of energy LCA [5–8]. We also review how terminology, life-cycle inventories and system boundaries define the framework of an LCA and cause variation in their results. In addition, we examine how this variation relates to the inherent assumptions of LCA and clarify the roles that plant scientists and ecologists have in refining LCA results. Transparent and accurate LCA of biofuel crops provides the scientific foundation for evaluating their ecological and economic sustainability.

To improve current projections of biofuel sustainability, there is a need to reconcile the differences in methods that have thus far been used for bioenergy LCA [5,9]. We conducted a literature search of published studies that investigated temperate grass species as biofuel crops using LCA. We searched specifically for studies of corn (*Zea mays*), switchgrass (*Panicum virgatum*), miscanthus (*Miscanthus x giganteus*) and mixed temperate grasses (prairie or early successional communities after agricultural abandonment). We limited our review to these species because the latter three are the proposed alternatives to corn and corn is already grown for ethanol in large areas of the Midwestern USA. Criteria for studies that were included in this review were that they: (i) use an LCA to evaluate one of the previously mentioned crops; and (ii) include calculations of a GHG or energy balance through the biofuel production system. There are many other species that are considered for biofuel in other parts of the world (e.g. sugarcane, sugarbeets, palm, etc.), some of which are reviewed elsewhere (e.g. Ref. [8]); although we do not specifically address these alternative biofuel species, many of the concepts discussed here apply to any biofuel crop.

Background on biofuels

Biofuels are plant-derived energy sources that can either be burned directly for heat or converted to a liquid fuel such as ethanol or biodiesel. Domestic uses of biofuels, such as wood, have always been globally important, but industrial uses of biofuels, particularly in North America and Latin America, have been expanding over the past century [10]. The demand for liquid fuels is beginning to exceed supply [11] and there is increasing interest in the use of ethanol and biodiesel derived from plant matter. Here, we focus on ethanol as a liquid fuel, the most common sources of which currently are fermented corn (produced in the Midwestern USA) and sugarcane (widely used in Brazil). The fermentation process converts plant starches and sugars into so-called 'first-generation' biofuel [12]. Ethanol also can be produced from cellulosic and ligno-cellulosic (lignin-derived) plant biomass ('second-generation' biofuels), but the high pressure and temperature requirements of the conversion process incur high energy costs [13]. There is a surge of scientific initiatives to develop new technology

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that will improve the efficiency of second-generation biofuel production [1,13]. The desired outcome of these initiatives is to develop biofuels that: (i) have greater energy efficiency than corn grain ethanol; (ii) have positive effects on nutrient cycling in crop ecosystems; and (iii) require minimal land conversion [1,4,13–15].

LCA is an all-inclusive account of the inputs and outputs of a production system. The inputs and outputs for biofuel production are characterized in terms of energy requirements and yields, economic costs and benefits, and environmental costs and values. LCA is used for informing policies that govern the use of energy alternatives, but it is more commonplace in engineering and economic applications than in ecological and plant systems. Ecologists might equate an LCA to a foodweb or ecosystem model that traces the fluxes of energy through a system. In these examples, the system limits can be defined by geographical boundaries, time or the number of trophic levels considered. The energy and GHG balances of an agricultural corn ecosystem do not scale directly from the energy balance of a single corn plant to a farm or larger region because physiology, climate, herbivory and soil characteristics change across these scales. In other words, the inputs and outputs of a system differ depending on the scale under consideration, just as the inputs and outputs differ with a changing system boundary of an LCA.

Ecological impacts associated with land conversion and the establishment of new crop species for biofuel production are important determinates of the overall sustainability of biofuels as an energy source. Genetic modifications of plants grown for biofuel could reduce the ecological impact that biofuel agricultural systems currently incur [13]. It is, therefore, important that new ecological process descriptions for biofuels are complementary to the LCA framework that has been established in disciplines that are more closely aligned with the energy industry (e.g. engineering or economics). Inclusion of interactive climate, plant, soil and microbial controls over nutrient cycling in an LCA will provide a more realistic assessment of biofuel costs and benefits.

Anatomy of an LCA

The framework of an LCA is defined by a system boundary and a life-cycle inventory that can vary according to the goals of a particular research project. The system boundary is defined by the spatial, temporal and production chain limits (start and end points) of the process that is being analyzed. For example, the GHG balance of a crop grown for biofuel depends on the size and location of the cultivation area (space boundary), the number of growing seasons considered (time boundary), and whether fertilizer inputs and post-harvest transport are considered (start- and end-point boundaries). Each step of the biofuel production process involves energy and GHG uptake (inputs, e.g. uptake by plants and by soil) as well as energy use and GHG emissions (outputs; Figure 1). From a plant ecology perspective, the smallest possible system boundary would include only the ‘biofuel crop yield,’ where inputs of GHG would include the CO_2 required for photosynthesis and outputs of GHG would include CO_2 from autotrophic and heterotrophic respiration, as well as nitrogen oxide (NO_x, N_2O) and methane (CH_4) fluxes from the soil. Alternatively, the system boundary can be enlarged to include upstream GHG emissions from machinery used on the farm where the crop was grown or downstream GHG emissions from conversion of biomass to ethanol. The LCA thus becomes increasingly complicated as system boundaries are expanded (Figure 1).

A life-cycle inventory is a list of components that are included as a part of the system that is assessed in an LCA. Within a system boundary, a life-cycle inventory must be defined to clarify the required inputs and outputs to be calculated in each step of the biofuel production chain. For example, manufacture and transport of fertilizers, pesticides, herbicides and seeds represent the inventory of components used in calculating a GHG balance for farm inputs (Figure 1). Not all life-cycle inventories include all four of these components, and others can include more components, such as irrigation equipment or farm construction, even though the system boundary is theoretically the same. The life-cycle inventory thereby influences the outcome of an LCA and can be used to understand which components have the greatest effect on GHG balances.

Functional units are a metric for inputs and outputs of an LCA. Functional units vary among disciplines and research objectives and thus are important to consider when comparing LCAs, especially in cases where efficiency terms are calculated [5,16]. Two principal functional units that we explore for biofuel LCA are GHG and energy. GHG inputs and outputs occur throughout the process chain described earlier (Figure 1); typically, the atmospheric warming potential of these gases (e.g. NO_x and CH_4) is expressed as the equivalent GHG potential of a megagram of CO_2 (Mg CO_{2eq}). GHG units are important functional units for assessing the environmental benefits of biofuels relative to fossil fuels. The definition (e.g. in megajoules) of energy inputs and outputs through the process chain (Figure 1) is important in a biofuel LCA because these units translate directly to anthropogenic energy requirements.

Overview of biofuel LCA results

Our review revealed significant variation in the estimates for both the energy yields and the GHGs associated with biofuel production. Energy efficiency of the biofuel production chain is calculated using different assumptions in many studies that use LCA. Net energy value (NEV) is a commonly reported efficiency term that is calculated as the difference between the usable energy produced from a biofuel crop and the amount of energy required in the production of that fuel for energy. A negative NEV suggests that more energy is required to produce the biofuel than the amount of energy that can be used for fuel (a net energy loss), whereas a positive NEV is an estimate of the energy gained for fuel use in the production process (a net energy gain). In our review, NEV ranged from -2.63 MJ m^{-2} to 12.85 MJ m^{-2} (Table 1). Controversy in recent literature about the use of NEV [16,17] centers on the fact that not all kinds of energy are the same: different forms incur different costs and benefits. The upstream energy inputs incur an environmental and economic cost that depends on the

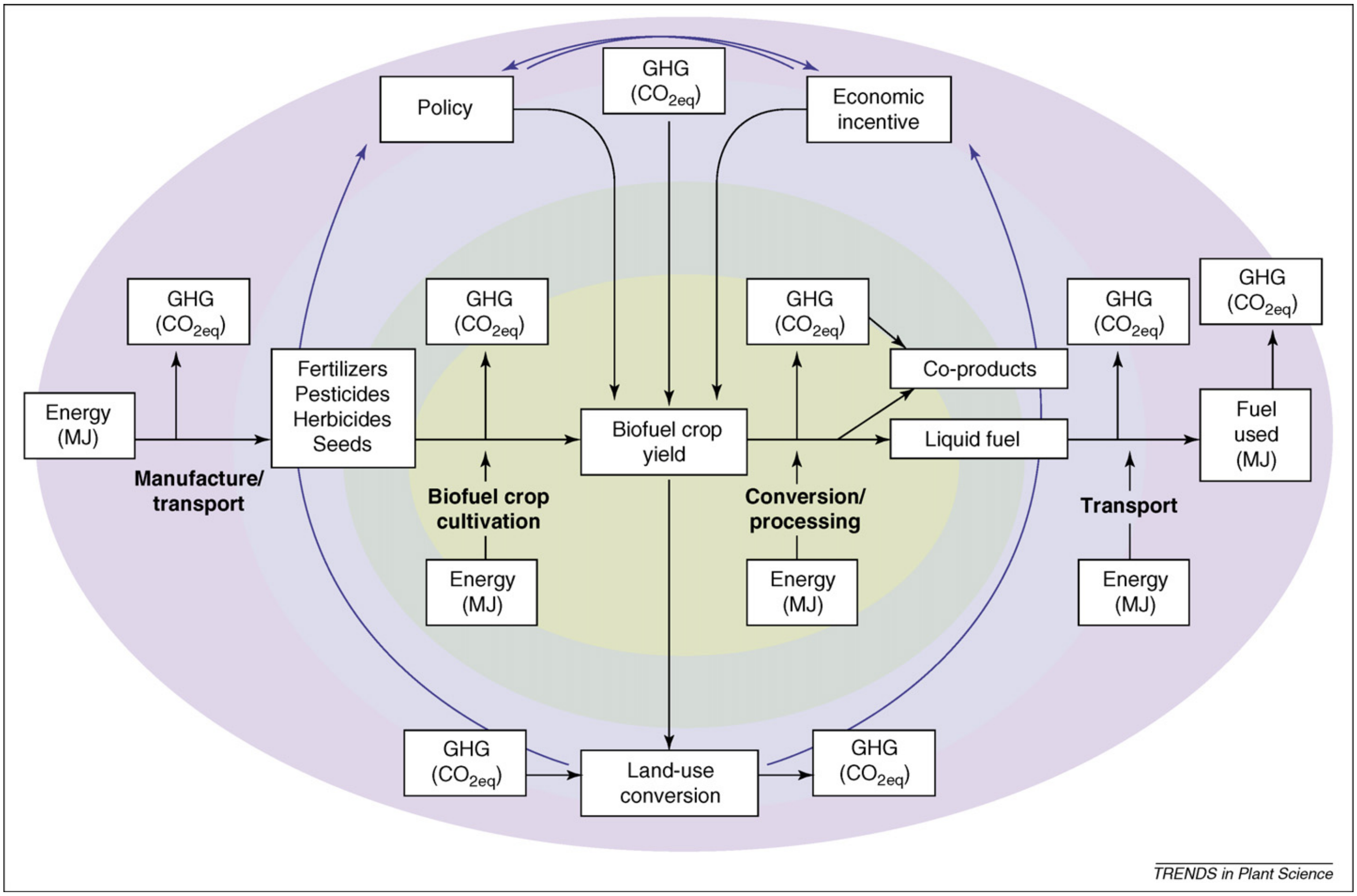

Figure 1. A chain of production for biofuels with energy and GHG requirements (inputs) and emissions (outputs) defined at each step in the production process. The smallest possible system boundary in this case would include only the center box, labeled 'Biofuel crop yield', where inputs of GHG would include the CO_2 required for photosynthesis and outputs of GHG would include CO_2 from autotrophic and heterotrophic respiration, as well as NO_x and CH_4 fluxes from the soil. The background colors represent different system boundaries that become increasingly complicated with size. The outer region defines a system boundary that includes interdisciplinary feedbacks between the GHG fluxes from land use and the policies and economic incentives that are both influenced by and effect changes to GHG balances associated with land-use change and fuel production.

Table 1. NEV of potential biofuels as estimated in previous literature[a]

Biofuel crop	NEV (MJ m^{-2})	Refs
Corn with stover	12.85	[25]
Switchgrass	6.96	[18]
Corn-soy	6.05	[18]
Switchgrass	6.00	[30]
Reed canarygrass	4.88	[18]
Cellulosic crop species (generalized)	4.52	[33]
Prairie planted with low input	3.00	[30]
Corn	2.30	[9]
	2.24	[9]
	1.69	[9]
	1.59	[9]
	1.59	[33]
	1.38	[31]
	1.37	[9]
	1.27	[17]
	1.16	[9]
Switchgrass (small low-input plot)	1.00	[30]
Corn	0.51	[9]
Corn	−0.30	[9]
	−0.63	[9]
	−2.52	[9]
	−2.52	[9]
Switchgrass	−2.63	[29]

[a]Shaded rows indicate negative values.

source of energy. Practically, the service gained from fuel energy is what really matters (e.g. the number of miles driven per unit of energy), so it might be more appropriate to compare biofuel energy balances directly to the fossil fuel energy equivalent that can be displaced.

The energy efficiency of biofuels can be reported as a ratio of the amount of fuel energy produced to the amount of fossil fuel energy required through the production process, termed the fuel energy ratio (FER). An FER <1 suggests a net energy loss, whereas an FER >1 suggests a net energy gain. The variation in FER values reported in the literature is surprisingly large, ranging from 0.44 to 5.60 (Table 2). There is no consistency among LCA estimates of biofuel energy efficiency.

We also compared literature LCA estimates of GHG balances that result from biofuel crop production. Total GHG fluxes from crops ranged from -89 Mg CO_{2eq} ha^{-1} to 9.60 Mg CO_{2eq} ha^{-1}, with negative values indicating a net uptake of GHG (i.e. removal from the atmosphere) and positive values indicating a net emission of GHG (i.e. added to atmospheric concentrations; Table 3). Some studies reported the amount of GHG that is replaced by the use of biofuels in place of fossil fuels (Table 4). Again, the variation is large and ranges from −114% displacement [18], meaning that all of the fossil fuel emissions would be

Table 2. FER as estimated in previous literature[a]

Biofuel crop	FER	Refs
Lignocellulosic crops (generalized)	5.60	[34]
Switchgrass	4.43	[35]
Lignocellulosic crops (generalized)	4.30	[34]
	3.51	[34]
	2.62	[34]
	2.19	[34]
Corn	1.95	[34]
Lignocellulosic crops (generalized)	1.80	[34]
Corn	1.76	[34]
	1.67	[34]
	1.64	[34]
	1.62	[34]
	1.60	[34]
	1.52	[36]
	1.51	[34]
	1.39	[34]
	1.34	[9]
	1.32	[31]
	1.28	[34]
	1.27	[17]
	1.25	[28]
	1.22	[34]
	1.21	[22]
	1.21	[35]
Miscanthus (combustion)	1.16	[7]
Corn	1.08	[9]
Miscanthus (gasification)	0.99	[7]
Corn	0.99	[34]
	0.95	[34]
	0.92	[34]
	0.80	[37]
	0.78	[34]
	0.69	[34]
Switchgrass	0.44	[22]

[a]Shaded rows indicate values where the energy required for production is greater than the energy in the fuel produced.

replaced plus an additional 14% would be sequestered by the biofuel crop (switchgrass in this case), to the opposite extreme reported as a 93% displacement [19], which indicates that 93% more GHG would be emitted to the atmosphere with the production of biofuel (corn in this case). Variation in overall net energy and GHG balances of biofuel production is high even within a single species; currently there is no clear consensus about the benefits or

Table 3. GHG fluxes, expressed as the equivalent GHG potential of a megagram of CO_2 (Mg CO_{2eq}), on a crop area basis as estimated in previous literature[a]

Biofuel crop	GHG Mg CO_2eq $ha^{-1}yr^{-1}$	Refs
Corn	−89	[17]
Sugarcane	−9.8	[14]
Prairie on marginal crop land	−7.8	[14]
Prairie on abandoned crop land	−4.3	[14]
Early successional species	−2.11	[38]
Switchgrass	−1.66	[18]
Corn	−1.2	[14]
Reed canarygrass	−0.85	[18]
Corn-soy	−0.49	[18]
Corn stover	0.84	[27]
Corn–soy–wheat rotation	1.14	[38]
Switchgrass	1.32	[27]
	2.28	[22]
Corn	5.14	[22]
	8.71	[19]
Switchgrass	9.60	[19]

[a]Shaded rows indicate an increase in GHG emissions to the atmosphere.

Table 4. GHG displacement, as reported in previous literature[a]

Biofuel crop	GHG displacement (%)	Refs
Switchgrass	−114	[18]
Switchgrass combustion compared with coal combustion	−109	[26]
Miscanthus (gasification)	−98	[7]
Switchgrass	−93	[30]
Corn	−86	[36]
Reed canarygrass	−84	[18]
Cellulosic	−80	[33]
Switchgrass	−73	[39]
Corn-soy	−38	[18]
Corn	−25	[33]
	−24	[39]
Switchgrass	−11	[40]
Corn	−3	[37]
Switchgrass	43	[22]
	50	[19]
Corn	66	[22]
	93	[19]

[a]Shaded rows indicate an increase in GHG emissions to the atmosphere.

ecological consequences of using biofuels relative to fossil fuels (Tables 3,4).

What causes variation in LCA estimates?

Inconsistencies in the assumptions applied to biofuel LCA lead to variable and, in some cases, conflicting results about their GHG and energy mitigation potential. There have been a few attempts to standardize LCA methods [1,20–22] but, to date, there is little consistency in the methods used. Differences in LCA assumptions about efficiency terms, life-cycle inventory components and system boundaries are the main factors generating variation in LCA results.

Efficiency terms and functional units

The terms and units used to describe energy and GHG balances are currently not defined consistently among bioenergy research disciplines, causing enormous variation in LCA results. The values reported in Tables 1–4 were converted to common units, but some studies did not report results in a way that could be directly compared. Examples of unique terminology that are important for biofuel descriptions but not directly comparable to GHG or energy balances are ‘carbon closure’ [23] and nutrient balances that are not summarized as gaseous fluxes (e.g. Ref. [24]). In an effort to make more comprehensive economic and ecological assessments of losses or gains in energy from biofuels, another new term, ‘eco-efficiency’, was introduced to summarize the ratio of economic efficiency to environmental impact [25]. These examples introduce important ecological considerations for bioenergy LCA, but the obscurity of the language limits the readership and strikes these analyses from inclusion in broader reviews of biofuel energy sustainability. An energy LCA is, by its very nature, interdisciplinary and requires the cultivation of a dialogue that transcends the specialized terminology of individual fields. There is a need to establish standardized, unbiased terminology that is easily interpreted by a wide audience. Published standards for LCA are few and not widely adhered to [1,20–22]. In addition to consistently applying common standards, these standards need to be updated and informed by research that describes plant, soil and microbial mediation of feedstock carbon and energy production. Standard terminology and interdisciplinary agreement about carbon currency at this ecological level will be important for refining assessments of alternative fuel options.

Life-cycle inventories

Variation in life-cycle inventories (the components used to calculate inputs and outputs) produces different LCA results [6,7], and the uncertainty associated with each item in a life-cycle inventory contributes to the variation in final LCA estimates [17,26,27]. The studies included in Tables 1–4 provided some description, albeit incomplete in some cases, of the items included in the life-cycle inventory. Of these 24 studies, only 13 included the quantities of each inventory item that were used to calculate the energy or GHG balance. Only three studies include uncertainty estimates of inventory item values. Although uncertainty estimation is a challenge in all fields that use complex modeling, inventory lists with component estimates and uncertainties could easily be provided in any LCA.

To reveal inventory items that drive variation in the final energy and GHG balances (Tables 1–4), we identified a simplified life-cycle inventory that would enable direct comparison of each item estimated from different studies. By reducing the inventory to three general categories (crop cultivation, crop transport and fuel processing), we provide examples of how life-cycle inventory estimates vary among studies. In LCA of corn ethanol, the estimated energy requirements for crop cultivation, crop transport and fuel processing were 46%, 12% and 48% lower, respectively, in the analysis of Ref. [28] than in that of Ref. [29]. For switchgrass ethanol [30], crop cultivation, crop transport and fuel processing were each estimated at only a fraction (92%, 98% and 97% lower, respectively) of the values estimated in Ref. [29]. Such differences in the life-cycle inventory help to explain the disagreement in GHG and energy balances of these studies. Standardized and transparent life-cycle inventories would facilitate comparisons among LCA estimates.

Many life-cycle inventories are also incomplete, neglecting components of the production chain that are important for assessing biofuel sustainability. For example, although changes in carbon storage in soil and biomass are crucial to the outcome of GHG balances [14,26,31], they were not included in every LCA that estimated a GHG balance. Inclusion of plant, soil and microbial processes that determine carbon balances are limited, and there is an urgent need for new research findings from plant and soil sciences to be integrated into the biofuel production chain.

System boundaries

Different system boundaries among studies are perhaps the most complex and influential cause of variation in LCA estimates of energy and GHG balances. System boundaries vary not only according to start and end points in the process chain for biofuel production (Figure 1) but also over space and time in a way that can dramatically affect energy and GHG balances. For example, estimates of GHG balances for switchgrass using three different system boundaries revealed that fertilizer GHG costs varied by up to 75% depending on how many upstream processes were included [26]. Temporal boundaries in the reviewed studies varied from one establishment year [29] to a 100-year time period [7], and geographical boundaries range from isolated regions, such as Belgium or the state of Iowa [7,24], to global boundaries that included international land-use feedbacks [14,19]. Topography, soil and climate variability within a region prevent direct scaling of LCA balances to larger areas [7,30], but economic and political interactions that influence land use introduce more variation as the system boundary expands across ecosystem and political borders [15,22]. Because fuel energy production is so closely influenced by, and is important for, economics at all scales, some studies include economic feedbacks in the production chain of a biofuel LCA (e.g. Refs [25,32]). A holistic view is necessary to accurately assess costs and benefits of alternative fuel systems, so feedbacks between policy, economics and land-use changes are required for a truly complete LCA (Figure 1).

The appropriate system boundary for a bioenergy LCA is often decided by the particular research question. For example, transportation fuels conventionally are assessed from fuel acquisition to combustion in automobiles [1,20]. The comparison of biofuel production against fossil fuel distribution and combustion in an automobile is a practical way to address a policy question that asks, 'What will it cost to convert the transportation fuel infrastructure to one that could distribute biofuel?' Unfortunately, this is not necessarily a fair comparison of the full life-cycle impacts on the environment. When we introduce a true cradle-to-grave life-cycle perspective that considers all of the upstream costs for growing a biofuel crop (fertilizer, crop establishment, etc.), a fair comparison against fossil fuels would require the upstream costs of fossil fuel production (exploration, drilling, etc.). The holistic LCA approach to biofuels is often not compared with an equally holistic view of the fossil fuels that they would replace. For example, LCA research that more broadly addresses system impacts (including acidification, human toxicity, etc.) leads to more negative results relative to fossil fuels [8] because these impacts were not as thoroughly assessed for the fossil fuels. Such oversight drives substantial differences in the overall efficiency estimates for biofuels and can be addressed by carefully considering system boundaries as well as the efficiency terms that embody the reference (i.e. fossil fuels) against which life-cycle impacts of biofuels are evaluated [17]. In effect, the choice of efficiency terms, life-cycle inventories and system boundaries determines the outcome of an LCA. An LCA must therefore be evaluated with a clear awareness of how each of these components could impact resulting estimates of GHG, energy or economics.

Conclusions and implications for plant scientists

Assessment of the sustainability of biofuels is challenged by the varied perspectives of diverse disciplines that contribute to biofuel research. Although LCA is a holistic approach to biofuel energy systems, much of the LCA work published so far has been isolated from the plant science and ecology communities, whose members study processes, such as the biogeochemical cycles of carbon, nitrogen and water, that underlie the sustainability of biofuel crops. The literature that reports environmental and energy benefits of biofuels is controversial owing to the lack of adherence to proposed LCA standards, and these standards are not well informed by ecological theory. Most LCA results for perennial and ligno-cellulosic crops conclude that biofuels can supplement anthropogenic energy demands and mitigate GHG emissions to the atmosphere. Wide-ranging estimates of biofuel GHG balances can be refined by identifying plant-mediated processes that should be included in LCA. Nutrient cycling and pollution mitigation, processes controlled by ecological systems, are currently not well integrated into LCA studies. A clear assessment of the environmental consequences of producing biofuels is essential for determining their sustainability relative to fossil fuels. Standardized and equally holistic assessments of biofuel and fossil fuel production systems must be made to acquire a scientific consensus about the benefits of biofuels. Of the studies reviewed here, the most complete side-by-side LCA of biofuel production relative to fossil fuel production resulted in the largest estimated reduction of GHG with biofuels [17].

Plant scientists and ecologists must place new discoveries of genetically modified biofuel crop species and their interactions with climate, soil and microbial communities in the context of clearly defined spatial and temporal boundaries. Furthermore, these discoveries must be communicated in a common terminology to engineers, economists and policy-makers who work on other aspects of the biofuel production system. Biogeochemical processes that are mediated by biofuel crops must be fully integrated with the economic costs and benefits of the biofuel production chain and compared with parallel holistic descriptions of the fossil fuel production chain. Second-generation biofuels hold great promise for supplementing the energy supply, but the ecological and environmental consequences of increasing our use of biofuels will not be fully understood without a transparent and standardized approach to LCA, based on new collaborations among ecologists, economists and engineers.

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