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Grand Challenges for Life-Cycle Assessment of Biofuels

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INTRODUCTION

To address energy security and climate-change concerns, substitutes are needed for petroleum-based transportation fuels. In addition to electricity and natural gas, biofuels are emerging as an important class of substitutes, today dominated by ethanol that is produced from corn and sugar cane. For the future, many alternative pathways are being explored. Features of these alternatives include diversity in feedstocks, fuel composition, and byproducts. Decision-making tools are needed to support choices among these alternatives.

Addressing the world's need for near-term, cost-effective, and reliable production systems for biofuels requires research to overcome technological barriers[1] but must also address social, economic, and environmental challenges in parallel. These challenges include constraints imposed by economics and markets, resource limitations, health risks, climate forcing, nutrient-cycle disruption, water demand, and land use.[2] Responding to these challenges effectively requires a life-cycle perspective. Here we summarize seven grand challenges that must be confronted to enable life-cycle assessment (LCA) to effectively evaluate the environmental "footprint" of biofuel alternatives. These challenges may be relevant to many LCA efforts; our focus here is what we have learned in applying LCA to crop/plant-based biofuels.

LCA follows internationally accepted methods (ISO 14040 and ISO 14044) and practices to evaluate requirements and impacts of technologies, processes, and products so as to determine their propensity to consume resources and generate pollution. "Life cycle" refers to all stages of a process: from raw material extraction through manufacturing, distribution, and use to ultimate disposal, including all intervening transportation steps. Conducting an LCA entails four types of activities: (1) defining the goal and scope of the analysis; (2) collecting life-cycle inventory data on materials and energy flows, emissions, and wastes; (3) conducting a life-cycle impact assessment that characterizes the impacts of constituent processes; and (4) interpretation, which provides an analysis of the major findings, along with sensitivity and uncertainty analyses, to support decision-making.[3]

This paper emerged from research planning and progress meetings of the Life-Cycle Program of the Energy Biosciences Institute at the University of California, Berkeley. In developing and applying LCA to assess the environmental sustainability of transportation fuels, LCA practitioners commonly address the following impact categories: climate forcing, other pollutant emissions and impacts, water-resource impacts, land-use changes, nutrient needs, human and ecological health impacts, and other external costs. LCA practitioners may also consider social impacts and economic factors, which are not addressed here. In selecting the impact categories, we aimed for balance between being comprehensive and being parsimonious, noting that failure to address a key impact can lead to choices based on incomplete or unreliable information. Through our discussions, we identified seven issues as grand challenges for applying LCA to biofuels (Table 1). In the subsequent sections of this paper, we elaborate on each of these challenges and, where possible, note how progress might be made toward effectively addressing them.

UNDERSTANDING FARMERS, FEEDSTOCK OPTIONS, AND LAND USE

Biofuels begin with feedstocks. The current feedstocks for bioethanol, corn and sugar cane, are farm grown. Alternative future feedstocks may come from farms, rangelands, or forests.[4] Because of transportation costs, harvested feedstocks are likely to

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Table 1. Grand Challenges for Applying Life-Cycle Assessment to Biofuels

- *understanding farmers, feedstock options, and land use*
- *predicting biofuel production technologies and practices*
- *characterizing tailpipe emissions and their health consequences*
- *incorporating spatial heterogeneity in inventories and assessments*
- *accounting for time in impact assessments*
- *assessing transitions as well as end states*
- *confronting uncertainty and variability*

be stored and processed at small- to intermediate-scale facilities. Unlike oil companies and government agencies that have a hierarchical structure for decision-making, the first stages of biomass production might involve hundreds to thousands of decision-makers. Using LCA to influence policies that would alter the behaviors of these distributed decision-makers poses different challenges than when the decision-making authority is more highly concentrated. One expects that farmers utilize land to maximize profits. Pricing and tax policies can influence farmers to act in ways that may be difficult to predict, especially in light of imperfect information, uncertain weather and climate conditions, and complex markets.

Although numerous biofuel feedstocks have been proposed, information is limited about their ultimate potential for market success. Broad categories include herbaceous, woody, and green-waste feedstocks.[4] Specific examples include sugar cane and cane residue; corn grain, stover, and residues; miscanthus; switchgrass; soy, rapeseed, jatropha, and other oilseeds; poplar, pine, and willow trees; wood wastes; municipal waste; and crop residues. Algae and related organisms are also being considered as biofuels feedstocks, but have characteristics that put them out of the scope of the crop/plant-based issues addressed here. Having a large number of potential feedstocks with different characteristics in a system of distributed decision-making presents substantial challenges for current LCA approaches because of the vast scope of information needed to address so many alternatives. Many feedstock options include mixed output systems (for example, producing both protein and fuel feedstock from the same crop).[5] Multiple output streams necessitate allocation of impacts and benefits.

Allocation involves apportioning impacts among primary products, byproducts, coproducts, and residues. Because of their heavy influence on LCA outcomes, allocation decisions need to have a clear, rational basis. For impact metrics such as carbon, health, and water footprints, results for systems with mixed outputs are sensitive to whether one uses a no-allocation, allocation-by-energy, or allocation-by-economic-value approach, or some other allocation. The sensitivity of impacts to allocation choice has been an issue for the U.S. EPA's renewable fuel standard assessment.[6] Using allocation by energy content, Thamsiriroj and Murphy[7] found that rape-seed-based biodiesel fuels could meet the European Union Renewable Energy Directive (60% greenhouse gas emission savings) only by taking credit for rape cake (a coproduct) together with use of glycerol as a heat source.

Understanding Decision-Making in the Feedstock Production Community. Farmers and foresters may be reluctant to make long-term land and resource commitments to perennial feedstocks, such as miscanthus, switchgrass, and tree crops, even where land is suitable, until there are clear market signals and adequate financial security. Currently, the amount of ethanol produced from corn is nearly sufficient to saturate the U.S. gasoline market up to EPA's "E10" blend wall (i.e., the 10% maximum level of ethanol blended in gasoline for use in vehicles that are not flex-fuel). Without demand growth for biofuels, feedstock suppliers would need a strong incentive to substitute miscanthus or other cellulosic crops for existing corn plots.

How Does Land Use Really Work? The issue of indirect land-use change (ILUC) has received considerable attention in recent biofuels appraisals.[8−11] Briefly, the key concern is that globally, and in many regions, land available for crops (both for food and fuel) is already heavily used. Biomass production for biofuels could induce deforestation or could displace existing products from land currently used for food, forage, and fiber. Repurposing land otherwise productively used could increase the price of the goods in global markets, which could trigger land use conversion elsewhere. Deforestation is accompanied by large and immediate releases of carbon to the atmosphere, causing a climate-impact debt that could take decades to repay relative to fossil fuel or other transportation energy alternatives. But the magnitude of the climate impact from this working hypothesis remains uncertain and possesses high geographic variability.[9]

Society may be able to mitigate the ILUC penalty by producing biofuels on marginal or degraded lands. However, this possibility raises questions that have not yet been answered. How much marginal land is available and is it suitable for biofuel crops? What levels of nutrients, water, and other production inputs would be needed to produce biofuels in a sustainable way, economically, environmentally, and socially? How much additional biomass production can be achieved by intensification of land use, without interfering with other commodity production? To what extent does water availability constrain land-use choices? How will shifts in diet and food consumption affect the amount of land available for biofuel production? Case in point: a significant reduction in the consumption of grain-fed animal products would have major impacts on land demand, suggesting that future dietary policies and practices could influence the life-cycle impacts of biofuel systems. What are the consequences of land-use change on soil organic carbon sequestration or release rates? Few empirical data exist with which to answer these questions, so existing assessments must rely on assumptions and models, some of which lack a robust empirical or theoretical foundation.

Eventually, LCA must be able to address agriculture as a system integrated within an imperfect economy that can produce both food and fuels on the same parcels of land, in the presence of distributed decision-makers who are strongly influenced by markets and market-related public policies.[5] Because of the unpredictable interplay among multinational markets, national land-use policies, and heterogeneity in carbon emissions from land use change, ILUC will also continue to contribute substantial uncertainty, some irreducible, to biofuels LCA.

PREDICTING BIOFUEL PRODUCTION TECHNOLOGIES AND PRACTICES

Much of the variability among LCA results for biofuels arises from lack of knowledge about how biomass production operations and fuel production from biomass will evolve. Many alternatives exist both for production processes and for final products. For LCA, the plethora of options creates challenges. Does an analyst (a) choose the process/fuel combination that is likely and representative, (b) apply LCA to the full range of

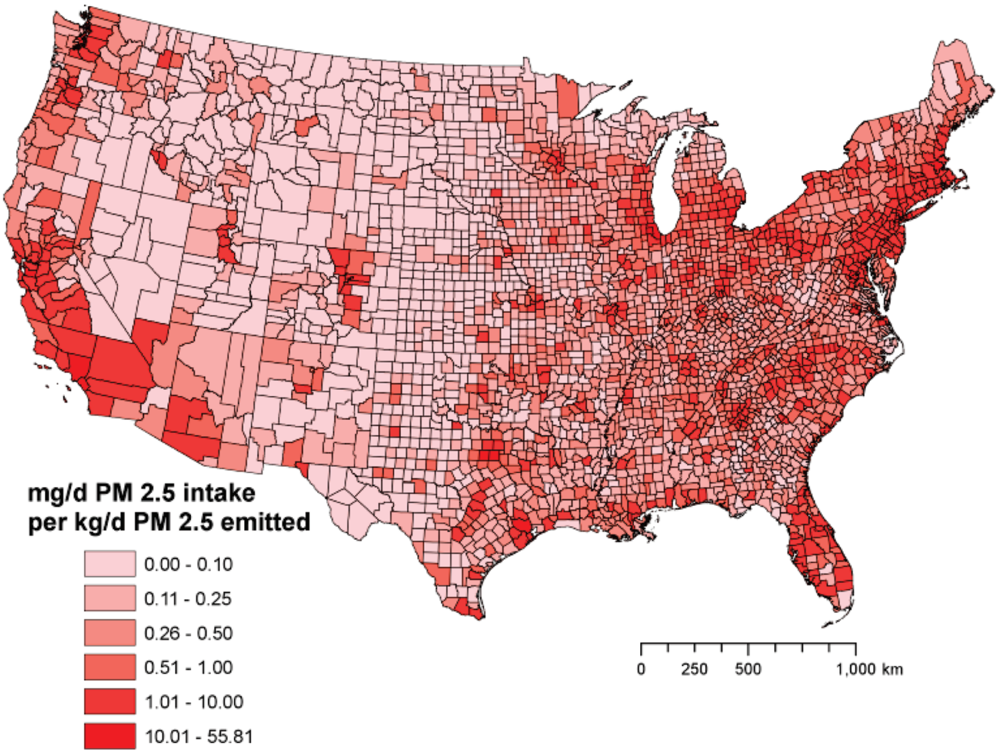

Figure 1. Variation in the population intake-to-emission ratio for primary fine particulate matter (PM2.5). The diagram shows cumulative population PM2.5 intake in mg/d from PM2.5 emissions in kg/d for each US county.

process/fuel combinations, or (c) apply LCA to a subset of process/fuel combinations that illustrate a range of outcomes informative to decision-makers?

An important challenge is to understand the energy, biomass, pollutant, and product mass balances of production facilities: To what extent will they be self-sufficient or even net producers of electricity? Will the facilities deliver a single product (fuel) or have multiple product streams (fuel, food, electricity, chemical commodities)? What are their waste products, air emissions, and water demands? A related challenge is accurately predicting scales of future biofuel production. For biofuels, the feedstocks are more dispersed and less dense than petroleum, which will induce biorefineries to be smaller than petroleum refineries. Ultimately, the scale of biorefining will depend on feedstock and production process choices, technological efficiency in converting feedstock to fuel, productivity of local land for feedstock production, and costs associated with feedstock production and transport, and biorefinery construction and operation. Much is unknown about this system at large scale and will remain uncertain until the system is created. Larger biorefineries may economize on refining-related impacts, but will increase transport-related impacts. Biorefinery scale has important ramifications for life-cycle impacts including the nature and the location of impacts.

■ CHARACTERIZING TAILPIPE EMISSIONS AND THEIR HEALTH CONSEQUENCES

Transportation is a major cause of urban air pollution.[12] LCAs of transportation fuel systems report that the fuel combustion stage makes the largest contributions to pollutant emissions and associated disease burdens.[2,6] Credible and reliable impact estimates for biofuel combustion are needed, yet provide challenges for LCA. Few studies of the health impacts of emissions from transportation fuel use have extended beyond criteria air pollutants. Those that have included an explicit metric for health damages have emphasized mortality rather than morbidity and the overall disease burden. When the assessment includes both primary PM emissions and secondary PM formation associated with gaseous precursors, fine particulate matter (PM2.5) dominates disease burden results. However, in addition to criteria air pollutants, there are 187 regulated hazardous air pollutants or HAPs[13] that include many compounds (e.g., benzene, aldehydes, butadiene, acrolein, and polycyclic aromatic compounds) associated with transportation-fuel combustion. Exposure to HAPs is associated with mortality owing to chronic diseases such as cancer and with morbidity due to acute and chronic diseases such as asthma. Other pollutants, such as ultrafine particles, are strongly linked to transportation fuel use but are not well characterized in terms of emissions, exposures, and related health risks. In recent decades, as new research has emerged from the environmental epidemiology and exposure science communities, burdens of disease estimates associated with air pollution have tended to become larger.

Another aspect of LCA's tailpipe challenge is the need for accurate emission factors for future fleets that cover a range of fuel alternatives and vehicle technologies.[2] Enormous technological progress has been made in controlling motor vehicle emissions, and there is strong momentum for continuing progress.[14] In what ways and to what extent will shifts from petroleum-based fuels to biofuels affect the combustion-phase emissions of air pollutants? One historical approach to answer analogous questions has been to conduct laboratory-based emissions testing. This approach is relatively expensive and lacks reliability for characterizing fleet-wide emissions from real drivers on real roads, and so is unlikely to provide accurate information in a timely manner. An alternative approach, used in LCA tools such as GREET,[15] assumes that vehicle emissions meet federal and state emissions standards regardless of the fuel used, and that emissions targets are the best estimate of what will happen in future years. However, standards only address a portion of the air pollutants of potential health concern. Furthermore, standards specify requirements for emissions from new cars, which have tended to be considerably lower than the fleet-wide average on-road pollutant emission rates.

■ INCORPORATING SPATIAL HETEROGENEITY IN INVENTORIES AND ASSESSMENTS

The health consequences of pollutant emissions are sensitive to release location. Proximity between air pollutant emissions and populations strongly influences the proportion of emissions inhaled by exposed populations, a concept parametrized as the *intake fraction*.[16] Figure 1 illustrates the variability in intake fractions among all counties in the conterminous United States for primary PM2.5. Depending on where pollutants are emitted, the exposure (and health-risk) consequences per unit emitted can vary by orders of magnitude.

Significant geographical variability among locations is an important feature influencing not only the health impacts of air pollutant emissions, but also soil carbon impacts and water demand consequences, among other factors. This issue is of concern for LCA methods in general as well as a challenge specific to biofuels. A key challenge for applying LCA to a broadly distributed system such as biofuels is to rationally select appropriate spatial scales for different impact categories without adding unnecessary complexity and data management challenges. LCA can address net changes across large geographic areas, or, alternatively, for generic urban and rural scales. But it must also address how the impacts will be experienced at local or regional scales. Accurate assessments must not only capture spatial variation at appropriate scales (from global to farm-level), but also provide a process to aggregate spatial variability into impact metrics that can be applied at all geographical scales.

■ ACCOUNTING FOR TIME IN IMPACT ASSESSMENTS

Similar to spatial resolution, selecting appropriate time scales poses challenges for biofuels LCA as well as for other LCA efforts.[17] Time allocations are important for comparing impacts, yet the time distribution of impacts is rarely made clear in LCA. We note briefly two examples of specific concern for biofuels: tracking fuel and transportation system changes in time and allocating impacts that accrue over time.

Time-Based Assumptions about System Parameters. Many factors in LCA vary significantly in time. Therefore, time-based assumptions must be clearly noted and evaluated. Among these "moving targets" are population distributions, vehicle fleet composition, technology options, regulatory requirements, and the degree of biofuel penetration in the overall energy mix. Moreover, the inputs one uses in LCA to characterize biomass and fuel production technologies as well as transportation infrastructure must capture how these systems are evolving.

Time Scales for Impacts. Different natural time scales associated with different impacts pose challenges for effective comparisons among climate-change, human health, and water use consequences. The impacts of air emissions from tailpipes and production facilities accrue within years and are typically allocated to the year of emissions without discounting. In contrast, the impacts of GHG emissions are distributed over decades using integrated assessment models and are commonly discounted.[2] Assumptions about the rate of discounting influence judgments about the relative importance of current year versus future year emissions. Similarly, impacts on water resources and soil can play out over decades. The ILUC question is also strongly linked to temporal allocation when selecting the period for which converted land will stay in biofuels production and assumedly compensate for some or all of the carbon loss associated with land-use conversion.[18]

■ ASSESSING TRANSITIONS AS WELL AS END STATES

Both advocates and critics of biofuels often focus on a restricted set of scenarios that appear to reinforce their *a priori* beliefs about how biofuel production and use might function. Even accomplished practitioners of LCA tend to focus attention on system end-states, i.e., what biofuel production and use will be like 20 or 30 years hence, when a proposed combination of fuels and vehicles has matured and is thoroughly deployed. This perspective ignores potentially important effects that accrue during the transition phase; the impacts from building new infrastructure, new vehicles, and integrating a new fuel into a mature and, in many respects, inelastic transportation system. Common LCA approaches also ignore the potential of emerging technologies to render many of the assumptions underlying the analysis obsolete.

Since less than ten percent of liquid transportation fuels in the United States now come from biomass,[1] major future infrastructure changes are needed if biofuels are to become a major alternative to petroleum. LCA to account for transitions will require much stronger integration between economists and systems engineers to address what happens during the transition phase when large-scale changes occur in many components of a complex, market-driven, technological system. For example, one of many key issues is whether fuel changes will affect the performance and lifetime of vehicles or the infrastructure transporting that fuel in ways that significantly increase climate forcing, water, health, and other externalities during transition. Consider climate forcing as an example. Technology investments are needed now, and these activities could cause GHG emissions to rise in the near-term as part of a longer-term effort to attain a more carbon-efficient end state. Under what circumstances and to what extent are "carbon investments" warranted now to gain "carbon benefits" in the longer term?

In addressing transitions, there should be recognition that emerging technologies could profoundly change the assumptions that underlie biofuel LCAs. Consider, for example, changes in protein production/consumption patterns or in urban land-use policies. These efforts could remove a significant number of livestock from pasture, reduce other impacts of agriculture, and open up substantial agricultural land for biofuel production; actions that would fundamentally change a biofuel LCA. In an era of rapid innovation, modifying LCAs to address emerging technologies applies to virtually all economic systems of consequence. This issue makes clear the need to support LCA as a contingent process, building scenarios from which one should learn, rather than as a tool designed to make firm predictions.

■ CONFRONTING UNCERTAINTY AND VARIABILITY

Addressing uncertainty is among the greatest of the grand challenges, not only for biofuels LCA, but for other LCA efforts as well.[19] Many sources of uncertainty and variability, both inherent and epistemic, are encountered in climate-change, human-health, environmental, and economic impact assessments. Some of the uncertainty and variability cannot be reduced with current knowledge (i.e., through improvements in data collection or model formulation) because of their spatial and temporal scale and complexity. Effective policies are possible, but such policies must explicitly take account of uncertainty. A well-developed theory of decision-making under uncertainty has evolved over the last several decades[20,21] emphasizing the need for flexibility to address margins of error; incorporate separate treatment of reducible versus irreducible uncertainty; recognize differences between variability and true scientific uncertainty; and consider benefits, costs, and comparable risks in the decision-making process. Among those commenting on how to formally address uncertainty in impact assessments, it has been established that there are "tiers" of sophistication in addressing uncertainty. In its recommendations for addressing uncertainty in risk assessment, the International Program on Chemical Safety[22] proposed four tiers, ranging from the use of default assumptions to sophisticated probabilistic assessment:

Tier 0: Default assumptions; single value of result;

Tier 1: Qualitative but systematic identification and characterization of uncertainties;

Tier 2: Quantitative evaluation of uncertainty making use of bounding values, interval analysis, and sensitivity analysis; and

Tier 3: Probabilistic assessments with single or multiple outcome distributions reflecting uncertainty and variability.

An LCA depends on a large number of input elements, and these elements are often based on data of varying quality. How the variable quality of inputs in turn influences the quality and robustness of outcome estimates is an important issue that deserves more attention in LCA. In the fields of decision science and risk assessment, protocols for addressing the problem have been developed that might help inform parallel efforts in the LCA community.

In confronting uncertainty and variability, we need to separate the "doable" and "knowable" from assumptions that are conditional components of the LCA. An informative LCA should sort out the data gaps that can be addressed with modest effort from those that would require a major undertaking. All LCA efforts require tools, such as sensitivity analysis, variance propagation methods, and decision/event trees for tracking the impact of data quality and model uncertainty through all components of an assessment. A strong challenge for LCA in addressing uncertainty is to provide and track metrics of data quality with respect to how data were acquired (measurements, assumptions, expert judgment, etc.), to what extent the data have been validated or corroborated, and how well the data capture technological, spatial, and temporal variations. Similar to the field of risk assessment, LCA needs an active and visible effort to provide guidance and "best practice" in addressing uncertainty and variability.

■ DISCUSSION

Confronting these seven grand challenges means recognizing some issues that have not been well articulated among practitioners of LCA. In particular, a good balance must be attained between the needs of technology momentum and adaptive decision-making. Most importantly, we must recognize that LCA is a process and not a product. Technology momentum refers to the difficulties encountered in backing away from fixed costs (financial, institutional, and environmental) that have been sunk into one alternative pathway. It is tempting to pick a winner in the face of uncertainty to get the system moving in the "right" direction, but then one may have to live with a suboptimal choice because the cost of scrapping the investment is too high. Adaptive decision-making refers to learning by doing, recognizing that commodity costs and impacts can diminish as a system scales up. These concepts live in tension. For biofuels we need technology momentum, but we must simultaneously maintain options for adaptive decision-making.

Technology Momentum. Although LCA can provide insight on options with the lowest impacts, it has not been designed to address technology momentum. LCA results are often burdened by uncertainty such that they become more informative as technologies are deployed, making it difficult to apply LCA during the early phases of a major technology shift. One example is the momentum of liquid fuels in terms of existing vehicle fleet, engines, and service stations. The large existing infrastructure constitutes a significant barrier to gaseous fuel alternatives such as hydrogen and methane. Another example is the important decision that must be confronted in a transition to cellulose-based biofuels; what end-product should be targeted among choices such as alcohols, alkanes, or a specific chemical compound such as dimethyl furan? This type of decision hinges on issues of timing, technical feasibility, and competitive advantage. The LCA practitioner requires knowledge about how the target choice will play out, but the decision-maker looks to the LCA practitioner to provide key insights. Once an initial decision is made, large investments ensue; facilities are built, infrastructures are deployed, and new vehicles are modified for fuel compatibility. An alcohol, such as ethanol, may be the more technologically facile fuel to achieve better cost, health, and climate footprint for short time scales; but an alkane fuel, although more technically challenging in the short term, may have a better impact profile in the long term. Nevertheless, once a commitment is made to adopt ethanol, even if it is considered a "bridge" or short-term option, technology momentum will impede opportunities to move to any other alternative.

The Use of LCA in Adaptive Decision Making. More collaboration and dialogue between basic scientists and LCA practitioners is important for incorporating LCA concepts into early phases of technology evaluation. Overall, approaches are needed to create more cross-talk among all members of the biofuel enterprise. Ideally, efforts toward developing the science and technology of biofuels will be continuously informed by those who are expert in impact assessment. In this way, the biofuels community has the best opportunity to attain the overarching sustainability goals they seek. In biofuels LCA, one must recognize that no large-scale industrial product can be developed in isolation. Resources such as food, energy, water, and land are all intimately interconnected.

The inherent magnitude of uncertainty associated with biofuels LCA, combined with the irreducibility of many uncertainties, poses clear challenges. To confront these challenges, planners and policy makers must consider their role in managing uncertainty as well as managing impacts. Managing uncertainty requires addressing different aspects of the overall decision-making process in the context of uncertainty. For example, decisions must be made that allocate resources among (i) investments to collect, store, and manage information; (ii) investments to improve the knowledge base (i.e., to generate new knowledge); (iii) formalization of the processes used to collect, use, and process information; (iv) formalization of processes to evaluate and communicate uncertainty; and (v) adjustment of the risk assessment process to mitigate the practical impact of the uncertainty on the analysis process.[23]

LCA as a Process. Barriers to LCA arise because many stakeholders want a final answer, to be "cleared for take off, with no call-backs. These stakeholders see LCA as a final exam; pass it and you are done being concerned with impacts and can proceed to technology deployment. This conceptualization serves only to highlight the flaws and uncertainties of LCA and fails to take advantage of the true power of LCA. At its best, LCA contributes to an ongoing process that organizes both information and the process of prioritizing information needs. We do not see these grand challenges as hurdles to be cleared, but rather as opportunities for the practitioner to focus attention and effort on making LCA more useful to decision makers. LCA coevolves with a technology and provides the basis for adaptive planning. Decision makers who work in real time and often cannot wait for precise results must recognize that LCA can provide valuable insight but it is not necessarily a "truth-generating machine".[24] Effective LCA can guide and inform decisions, but it cannot replace the wisdom, balance, and responsibility exhibited by effective decision-makers.

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