SUSTAINABLE TRANSPORTATION ENERGY PATHWAYS

A Research Summary for Decision Makers

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Chapter 13:
Beyond Life-Cycle Analysis: Developing a Better Tool for Simulating Policy Impacts

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As mentioned in this book's introduction and illustrated in various chapters, life-cycle analysis (LCA) is a powerful method for evaluating and comparing fuel/vehicle pathways with respect to a set of sustainability metrics. For more than twenty years, analysts have used LCA to estimate emissions of greenhouse gases (GHGs) from the use of a wide range of transportation fuels. The distinguishing feature of LCA is that it considers all of the activities involved in producing, distributing, and using a product.

However, as commonly employed, LCA cannot accurately represent the impacts of complex systems, such as those involved in making and using biofuels for transportation. LCA generally is linear, static, highly simplified, and tightly circumscribed, and the real world, which LCA attempts to represent, is none of these. In order to better represent the impacts of complex systems such as those surrounding biofuels, we need a different tool, one that has the central features of LCA but not the limitations. If this tool is to be relevant to policy making, it must start with the specification of a policy or action and end with the impacts on environmental systems.

We propose as a successor to LCA a method of analysis that combines integrated assessment modeling, life-cycle analysis, and scenario analysis. We call this method integrated modeling systems and scenario analysis (IMSSA). This chapter describes the key features of IMSSA for transportation fuels. Because IMSSA is meant to be a better model of reality than is conventional LCA, our discussion of IMSSA is a discussion of what an ideal model of reality looks like and how this differs from conventional LCA. We frame our discussion around the climate impact of biofuels because this is a particularly complex problem that nicely illustrates the deficiencies of conventional LCA.

Background and General Critique of LCA

Current LCAs of transportation and climate change can be traced back to "net energy" analyses done in the late 1970s and early 1980s in response to the energy crises of the 1970s, which had motivated a search for alternatives to petroleum. These were relatively straightforward, generic, partial engineering analyses of the amount of energy required to produce and distribute energy feedstocks and finished fuels. Their objective was to compare alternatives to conventional gasoline and diesel fuel according to total life-cycle use of energy, fossil fuels, or petroleum.

In the late 1980s, analysts, policy makers, and the public began to worry that burning coal, oil, and gas would affect the global climate. Interest in alternative transportation fuels, which had subsided with the low oil prices of the mid-1980s, was renewed. Motivated now by global (and also local) environmental concerns, engineers again analyzed alternative transportation life cycles. Unsurprisingly, they adopted the methods of their net-energy engineering predecessors, except that they took the additional step of estimating net carbon dioxide (CO_2) emissions based on the carbon content of fuels.

By the early 1990s, analysts had added two other GHGs, methane (CH_4) and nitrous oxide (N_2O), weighted by their "global warming potential" (GWP), to come up with life-cycle CO_2-equivalent emissions for alternative transportation fuels. Today, most LCAs of transportation and global climate are not appreciably different in general method from those analyses done in the early 1990s.[1] And although different analysts have made different assumptions and used slightly different specific estimation methods, and as a result have come up with different answers, only recently have some analysts begun to question the validity of the general method that has been handed down to them.

In principle, LCAs of transportation and climate are much broader than the net-energy analyses from which they were derived, and hence they have all of the shortcomings of net-energy analyses plus many more. For example, if the original net-energy analyses of the 1970s and 1980s could be criticized for failing to include economic variables on the grounds that any alternative-energy policy would affect prices and hence uses of all major sources of energy, the life-cycle GHG analyses that followed can be criticized on the same grounds but even more deeply because in the case of life-cycle GHG analyses we care about any economic effect anywhere in the world, whereas in the case of net-energy analyses we care about economic effects only insofar as they affect the country of interest. Beyond this, life-cycle GHG analysis in principle encompasses additional areas of data (such as emission factors) and, more importantly, additional large and complex systems (such as the nitrogen cycle, the hydrologic cycle, and global climate), all of which introduce considerable additional uncertainty.

The upshot is that traditional or conventional LCAs of transportation and climate are *not* built on a carefully derived, broad, theoretically solid foundation but rather are an ad-hoc extension of a method—net-energy analysis—that was itself too incomplete and theoretically ungrounded to be valid on its own terms and that could not reasonably be extended to the considerably broader and more complex problem of global climate change. And although recent LCAs of transportation and climate have been made to be consistent with LCA guidelines established by the International Organization for Standardization (ISO),[2] the ISO guidelines have only recently properly addressed a few of the issues discussed here and have not yet developed a proper policy/economic conceptual framework.

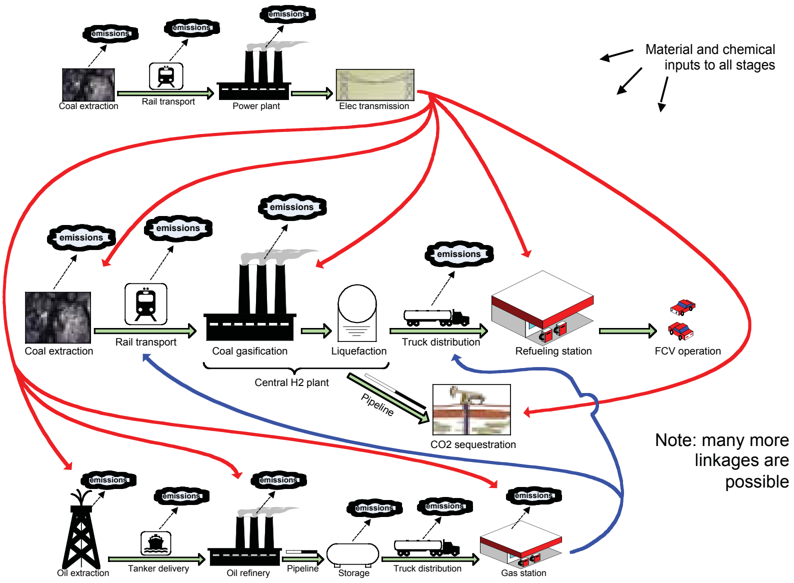
The broader LCA community is beginning to recognize this need for a more comprehensive, integrated modeling approach to traditional LCA problems. In this respect, researchers have discussed "system-wide accounting,"[3] "consequential environmental systems analysis,"[4] and "environmental systems analysis using life cycle methodology."[5] At a general conceptual level, all of these approaches, and our own, are a version of the well-established field of integrated assessment modeling (IAM).[6] We are proposing something similar to IAM but with more emphasis on the systems integration and scenario analysis; hence, we suggest the term *integrated modeling systems scenario analysis* (IMSSA).

Comparison of Conventional LCA with an Ideal Model

When we begin to examine the development and application of conventional life-cycle models for transportation we immediately run into a major problem: it is not clear what precise questions the models are supposed to answer. This is a serious flaw, because if we don't know what question a model is meant to answer, we cannot comprehend the answers (outputs) the model provides. In the case of conventional LCAs of transportation and global climate, we are forced often to infer a question from the nature of the outputs and the methods used. What we find, generally, is an unrealistic and irrelevant research question and a limited modeling method.

The weaknesses of conventional LCAs applied to transportation can best be seen by comparing current practice with an ideal model, which would replicate reality. In conventional LCA, a series of production and consumption activities are linked in fixed input-to-output ratios, with emissions per unit of input or output quantified for each activity. The total emissions are added up and expressed per unit of final product or service output. The linkages can be extensive and interrelated, but conventional LCA cannot be made to adequately represent reality simply by multiplying the number of linkages within the same static, circumscribed, linear framework. To see this better, we turn now to an ideal model of reality and compare this with conventional LCA.

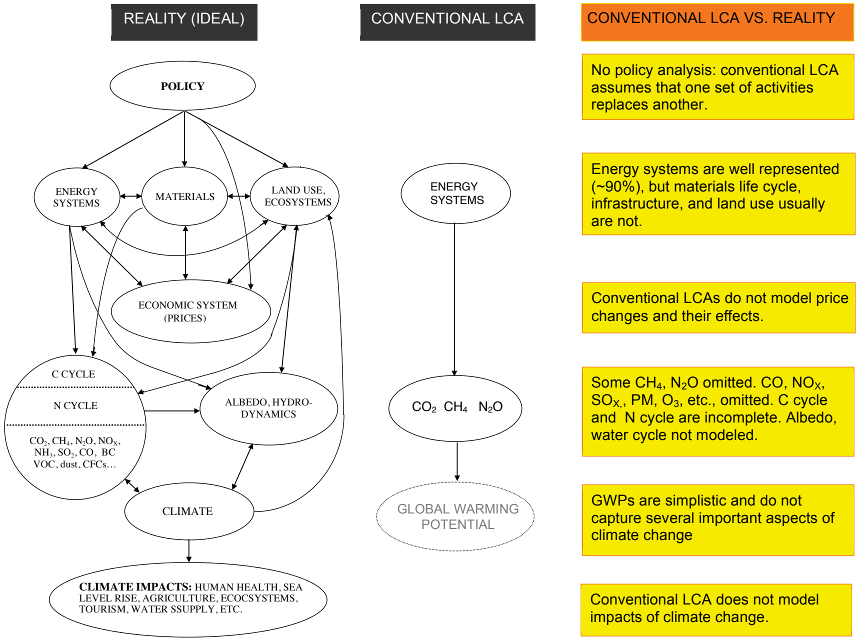
HOW CONVENTIONAL LCA IS APPLIED TO TRANSPORTATION



A conventional life-cycle analysis (LCA) links a series of production and consumption activities in fixed input-to-output ratios, with emissions per unit of input or output quantified for each activity. The total emissions are added up and expressed per unit of final product or service output. The linkages can be extensive. Here, for example, the coal life cycle is connected to the electricity life cycle, which is connected to the petroleum life cycle, which is connected back to the coal life cycle.

In principle, LCAs of transportation and climate change are meant to help us understand the impact on global climate of some proposed transportation action. Let us call this a policy/action and refer generally to the impacts of the policy/action on environmental systems. Hence, the ideal model starts with the specification of a policy/action and ends with the impacts on environmental systems. In between are a series of steps that constitute the conceptual components of our model of reality.

HOW CONVENTIONAL LCA COMPARES WITH AN IDEAL MODEL



No policy analysis: conventional LCA assumes that one set of activities replaces another.

Energy systems are well represented (~90%), but materials life cycle, infrastructure, and land use usually are not.

Conventional LCAs do not model price changes and their effects.

Some CH_4, N_2O omitted. CO, NO_X, SO_X,, PM, O_3, etc., omitted. C cycle and N cycle are incomplete. Albedo, water cycle not modeled.

GWPs are simplistic and do not capture several important aspects of climate change

Conventional LCA does not model impacts of climate change.

This conceptual flowchart of an ideal model, on the left, shows that it replicates reality as well as possible. Arrows show the relationships between various components. Next to the ideal model is a comparable conceptualization of conventional LCA. Across from each component, on the right side, is a yellow box that discusses whether and how the component is treated in conventional LCA.

In reviewing these components, it is easiest to work backward from the output of interest, the impact on environmental systems. The impact of climate change—the ultimate output of interest—is determined by the dynamic state of the climate system. The climate system is influenced by a wide range of emissions other than the three commonly considered in transportation LCAs (CO_2, CH_4, and N_2O) and by other factors, such as albedo. Emissions and nonemission factors, in turn, are affected by energy systems, material systems, and land use and ecosystems. All of these are affected by, and in some cases in turn affect, policies and economic systems. Indeed, in reality and hence in an ideal model, there are many important feedbacks, especially among energy systems, material systems, land use and ecosystems, economic systems, nonemission factors, and climate systems.

By contrast, conventional LCA generally represents a simplistic, one-way system from energy use to emissions of three GHGs to a simplified measure of climate, the global warming potential (GWP). Some LCAs also include the life cycle of materials, and recently many LCAs have added a simple, partial treatment of land-use change (LUC). Thus, conventional LCA lacks altogether explicit representations of policy, economic systems, and climate impacts, and offers simplified or incomplete treatments of the nitrogen cycle, land use and ecosystems, the climate system, and GHGs other than CO_2, CH_4, and N_2O.[7]

We will now examine in more detail the major deficiencies of conventional LCA compared with an ideal model (our integrated modeling systems and scenario analysis or IMSSA).

LCA Deficiency 1: Inability to Analyze a Specific Policy/Action

Conventional LCAs of transportation and climate change typically do not analyze a specific policy. Indeed, conventional LCAs typically do not even posit a specific question for analysis. The implicit questions of conventional LCA must be inferred from the conclusory statements and the methods of analysis. In transportation, the *conclusory statements* of life-cycle analysis typically are of this sort: "The use of fuel F in light-duty vehicles results in x% greater [or fewer] emissions of CO_2-equivalent GHGs per mile than does the use of gasoline in light-duty vehicles." The *method of analysis* is usually a limited input-output representation of energy use and emissions for a relatively small number of activities linked together to make a life cycle, with no parameters for policies or the function of markets, and no or limited representation of environmental and climate systems.

Given that CO_2-equivalent emissions (which typically are part of the conclusory statements) are equal to emissions of CO_2 plus equivalency-weighted emissions of non-CO_2 gases, where the equivalency weighting usually is done with respect to radiative forcing over a 100-year time period, we can infer that the question being addressed by most conventional LCAs of GHG emissions in transportation is something like this:

> ***What would happen to radiative forcing over the next 100 years if we simply replaced the set of activities that we have defined to be the gasoline life cycle with the set of activities that we have defined to be the fuel-F life cycle, with no other changes occurring in the world?***

The problem here is that this question is irrelevant, because we don't care about radiative forcing per se, and because no action that anyone can take in the real world will have the net effect of just replacing the narrowly defined set of gasoline activities with the narrowly defined set of fuel-F activities. Any policy/action that involves fuel F will have complex effects on production and consumption activities throughout the world via global political and economic linkages. These effects *will* occur and a priori cannot be dismissed as insignificant. Because conventional LCAs do not evaluate specific policies but rather evaluate implicit, unrealistic questions, it is difficult if not impossible to relate the results of conventional LCAs to any actual policies/actions in the real world.

The details of the specification of the policy/action are important because different policies will have different climate-change impacts. For example, considering the case of ethanol from corn, a policy to increase (or eliminate) the ethanol subsidy will have a different impact on climate than will a policy to mandate ethanol vehicles, mainly because different policies affect people, prices, and choices differently. In order to analyze the impacts of a particular policy, or indeed of any conceivable policy, one must include all of the variables affected directly by the policy. Many of these are economic variables, which are conspicuously absent from virtually all conventional transportation LCAs.

A related deficiency of conventional LCA is the failure to specify clearly the alternative world with which a specific policy scenario (say, a specific policy regarding ethanol) is being compared. It is conceptually impossible to evaluate a fuel such as ethanol by itself; rather, we must estimate the difference between one course of action involving ethanol and another course of action. These differences between alternative worlds are a function of the initial conditions in each world, the initial perturbations (or changes), and dynamic economic, political, social, and physical/environmental forces. Yet very few transportation life-cycle studies, old or new, have any sort of serviceably modeled alternative world—most likely because such a model requires something like general economic equilibrium analysis and integrated assessment modeling, and most life-cycle analysts are not familiar with these.

LCA Deficiency 2: Failure to Account for Price Effects

All energy and environmental policies affect prices. Changes in prices affect consumption and hence output. Changes in consumption and output change emissions. In the real world, price effects are ubiquitous and often important. They occur in every market affected directly or indirectly by transportation fuels—the markets for agricultural commodities, fertilizer, oil, steel, electricity, and new cars. An ideal model should account for them.

The LCA community is beginning to incorporate economic modeling into LCAs in order to account for price effects. As discussed below, a few LCAs have estimated how changes in biofuel production change the prices of agricultural commodities and thereby change the use of land, which leads to emission or sequestration of carbon. Researchers have also begun to examine some aspects of one of the most important potential price effects: the impact of any nonpetroleum alternative on the price of oil.

Price effects related to oil use

In general, the substitution of any nonpetroleum fuel for gasoline will contract demand for gasoline, which in turn will contract demand for crude oil, which will probably reduce the price of crude oil. This reduction in the world price of oil will stimulate increased consumption of petroleum products, for *all* end uses, *worldwide*. The increased use of petroleum products will increase all of the energy and environmental impacts of petroleum use, including climate change impacts. Hence, the use of nonpetroleum alternative fuels can cause increases in GHG emissions in the petroleum sector via price feedback effects.

Economic theory suggests that the web is even more complex. For example, a large price subsidy, such as corn ethanol enjoys, ultimately causes a deadweight loss of social welfare because output is suppressed below optimal levels by the inefficient use of (tax) resources. This loss of output probably is associated ultimately with lower GHG emissions. Thus, in this case, a subsidy policy may have countervailing effects: on the one hand, there will be an increase in GHG emissions caused by increased use of petroleum due to the lower price of oil due to the substitution of ethanol, but on the other, there will be a decrease in GHG emissions due to the reduction in output caused by the economic deadweight loss from the subsidy. By contrast, a research-and-development policy that succeeds in bringing to market a new low-social-cost fuel will because of the more efficient use of energy resources unambiguously improve social welfare.

Research on price effects related to oil use is relatively recent. Elsewhere I have detailed a formal scheme for incorporating price effects into existing conventional LCA models.[8] Dixon et al. use a dynamic computable-general-equilibrium (CGE) model of the U.S. economy to quantify the economy-wide effects of partial replacement of crude petroleum with biomass and conclude that there is "a noticeable damping effect on world demand for crude petroleum, generating a reduction in its price" (p. 716).[9] Kretschmer and Peterson survey approaches to incorporating biofuels into CGEs.[10] Zhang et al. use a theoretical model to examine the effects on fossil-fuel use of increased use of ethanol as a blend fuel and find that "making higher ethanol fuel blends available for all vehicles potentially has the adverse spillover effect of reducing the demand for flex-fuel vehicles [using 85 percent ethanol]" (p. 3429), thereby increasing the use of fossil fuels.[11] Rajagopal et al. estimate the "indirect fuel use change" (IFUC) effect of biofuel policies on petroleum consumption, where IFUC is the fuel-use analog of indirect land-use change (ILUC). They note that "the adoption of renewable fuels will affect the price of fuel and therefore affect total fuel consumption, which may increase or decrease depending on the policy regime and market conditions" (p. 228).[12] Finally, and most pertinently, Hochman et al. quantify the effects of biofuels on global crude oil markets and find that the introduction of biofuel reduces international fuel prices by between 1.07 and 1.10 percent and increases global fuel consumption by 1.5 to 1.6 percent (p. 112).[13]

Prices in the context of "joint production"

Price effects also are likely to be important in cases of joint production, where one process and one set of inputs inseparably produce more than one marketed output. It is well known that corn-ethanol plants, for example, produce commodities other than ethanol. A policy promoting ethanol therefore is likely to result in more output of these other goods as well as more production of ethanol. What is the impact on climate of the production of the other goods? The only way to answer this question is to model the market for the other goods to see, in the final equilibrium, what changes in consumption and production, mediated by price changes, occur in the world with the ethanol policy. The same issue of joint production also arises in petroleum refineries and in other processes in fuel life cycles. Economic models are needed to analyze these effects.

Other price effects

As mentioned earlier, price effects occur in every market, from the market for steel to the market for new fuels. For example, an economist might argue that price effects might eliminate and even reverse the environmental benefits of electric vehicles (EVs) as estimated in simple life-cycle analyses because if EVs are mandated but are quite costly, car buyers might delay purchase of new, clean, efficient vehicles to the possible detriment of the local and global environment.

Price changes can have a practically infinite number of what are likely to be relatively minor effects. For example, different life cycles use different amounts of steel and hence have different effects on the price and thereby the use of steel in other sectors. The same can be said of any material, or of any process fuel, such as coal used to generate electricity used anywhere in a life cycle. It might be reasonable to presume that in these cases the associated differences in emissions of GHGs are a second-order effect on a second-order process (for example, that the price effect of steel use is no more than 10 percent of the first-order or direct effect of using steel, which itself probably is much less than 10 percent of life-cycle CO_2-equivalent emissions) and hence relatively small. On the other hand, we might be surprised, and sometimes many individually quite small effects add up (rather than cancel each other). For these reasons, it would be ideal for life-cycle analysts to investigate a few classes of these apparently minor price effects.

LCA Deficiency 3: Incomplete Treatment of Land-Use Change (LUC)

Changes in land use and associated changes in climate impacts are another part of the complex web that links bioenergy policies with climate change. As touched on in Chapters 7 and 12, changes in land use can affect climate in several ways:

- by affecting the flows of carbon between the atmosphere and soil and plants
- by affecting climate-relevant physical properties of land, such as its albedo
- by affecting the nitrogen cycle, which in turn can affect climate in several ways—for example, via production of N_2O or by affecting the growth of plants, which in turn affects carbon-CO_2 removal from the atmosphere via photosynthesis
- by affecting the hydrologic cycle, which again affects climate in several ways—for example, via the direct radiative forcing of water vapor, via evapotranspirative cooling, via cloud formation, or via rainfall and thus the growth of and hence carbon sequestration in plants[14]
- by affecting the fluxes of other pollutants that can affect climate, such as CH_4, volatile organic compounds, and aerosols

CO_2 emissions from land-use change

As just indicated, CO_2 emissions from plants and soils due to LUC is just one of several ways that LUC can affect climate, and LUC, in turn, is just one of several consequences of bioenergy policies that can affect climate. However, this does not mean that the climate impact of CO_2 emissions from LUC is small; indeed, several analyses have suggested that CO_2 emissions from LUC could be a large fraction of total CO_2-equivalent GHG emissions from the entire life cycle of biofuels.[15]

Conceptually, an ideal model of the climate impact of changes in carbon emissions due to LUC caused by bioenergy policies would have several components. Emissions of CO_2 from LUC would be estimated based on the difference, over time, between ecosystem carbon content in a “no bioenergy program” baseline case compared with ecosystem carbon content in a “with bioenergy program” case, where “bionenergy program” refers to a specific program and need not encompass all bioenergy in the world. To represent this, one would create an economic/land-use model with dynamic, price-endogenous supply and demand functions, with land supply treated explicitly, and with yields determined as a function of endogenous parameters (such as price) and exogenous parameters (such as government R&D policy). One would run this model once with no bioenergy program to establish a dynamic “no bioenergy program” land-use baseline (that is, one in which prices, yields, supply curves, and land uses change year by year) and then run it again for a “with bioenergy program” case, simulated by an outward shift of demand at time zero and then demand contractions following the end of the program.

One would then compare land uses between the two cases year by year for as long as differences remain between the two cases (stream #1). For each year that there was a difference in land use, one would estimate the change in carbon stocks and emissions (stream #2) and then the change in atmospheric CO_2 (stream #3), the change in radiative forcing and climate (stream #4), and the change in climate impacts (stream #5). One would then track these changes in carbon stocks and climate for every land-use category every year. The *impacts* of climate change in each year would then be expressed in the values of a reference year (stream #6); in any cost-benefit or economic framework, this would be done by discounting the impacts to their present value. The sum of the reference-year values of each stream of the impacts of climate change—associated ultimately with the year-by-year differences in land uses between the "no bioenergy program" and "with bioenergy program" cases—would represent the climate-change impact of CO_2 emissions from LUC resulting from a bioenergy program.

HOW STREAMS IN THE REAL WORLD ARE TREATED IN AN IDEAL MODEL

An ideal model of the climate impact of changes in carbon emissions due to LUC caused by bioenergy policies would have several components. This table shows the hierarchy of streams in the real world that would be represented.

Stream in the Real World	**Treatment in an Ideal Model (IMSSA)**
1. Program actions. Prices, yields, supply curves, and land uses can change over time, year by year, in the "with bioenergy program" case compared to the "no bioenergy program" case. These changes occur at the end of the program as well as at the beginning.	Socioeconomic model of the relationship between changes in bioenergy production and changes in land use
2. **Emissions**. Then, each change in land use (in each year) generates its own time series of changes in carbon emissions; for example, a change in land use in any year T initiates a process of carbon emission or sequestration that can continue for many years after T. These emission streams occur at the end of the program as well as at the beginning.	Soil and plant carbon database; explicit representation of duration and shape of soil-carbon and plant-carbon emission streams, including post-program ("reversion") streams
3. **Concentration and radiative forcing**. Next, each change in carbon emission or sequestration (in each year) generates its own time series of changes in CO_2 concentration (atmospheric carbon stocks) and radiative forcing; for example, an emission of carbon from soils in year T+x (due ultimately to LUC in year T) will generate an atmospheric CO_2 concentration and decay profile and associated radiative-forcing effects that extend for many decades beyond T+x.	Simplified but realistic climate model showing CO_2 decay and radiative forcing
4. **Climate (temperature) change**. Next, any change in radiative forcing in any year will generate a stream of climate changes, with the lag between radiative forcing (stream #3) and climate change (stream #4) being due mainly to the thermal inertia of the oceans.	Explicit representation of the thermal inertia lag between radiative forcing and climate change
5. **Impacts**. Finally, any change in climate in any year (stream #4) can impact people and ecosystems for many years (for example, by changing the incidence of chronic diseases).	Comprehensive assessment of damages of climate change in a present-value/ annualization framework

Ideally, this modeling would be part of a comprehensive analysis of the climate impacts of bioenergy programs, which would include, in addition to the impacts of CO_2 emissions from LUC just described, two other general kinds of impacts: the climate impacts of LUC *other* than those resulting from CO_2 emissions (for example, changes in albedo) and the climate impacts from the rest of the bioenergy production-and-use chain. The value of all of these other impacts would be added to the value of the impacts of the CO_2 emissions from LUC to produce a comprehensive measure of the climate impact of a bioenergy program.

Note that reality and hence the ideal representation comprise a hierarchy of several separate streams over time: policy/action streams generate LUC streams, which generate soil-carbon and plant-carbon change streams, which generate CO_2-concentration-change streams, which generate climate-change streams, which finally generate climate-impact-change streams. An accurate representation of the climate impacts of a bioenergy program should have an explicit treatment of these streams and a method for making impact streams with different time profiles commensurate.

My 2011 review of the literature[16] shows that while a few recent LCA studies have addressed economic modeling of LUC,[17] the treatment of this component is incomplete, and no published, peer-reviewed LCA study has addressed the other four components properly or at all. Most important, no LCA work apart from my 2011 review has a conceptual framework that properly represents the reversion of land uses at the end of the biofuels program, the actual behavior of emissions and climate over time, and the treatment of future climate-change impacts relative to present impacts.

Biogeophysical impacts of land-use change

Changes in land use and vegetation can change physical parameters, such as albedo (reflectivity) and evapotranspiration rates, that directly affect the absorption and disposition of energy at the surface of the earth and thereby affect local and regional temperatures.[18] Changes in temperature and evapotranspiration can affect the hydrologic cycle,[19] which in turn can affect ecosystems and climate in several ways—for example, via the direct radiative forcing of water vapor, via evapotranspirative cooling, via cloud formation, or via rainfall, affecting the growth and hence carbon sequestration by plants.

In some cases, the climate impacts of changes in albedo and evapotranspiration due to LUC appear to be of the same order of magnitude but of the opposite sign as the climate impacts that result from the associated changes in carbon stocks in soil and biomass due to LUC. For example, Bala et al. find that "the climate effects of CO_2 storage in forests are offset by albedo changes at high latitudes, so that from a climate change mitigation perspective, projects promoting large-scale afforestation projects are likely to be counterproductive in these regions" (p. 6553).[20] This suggests that the incorporation of these biogeophysical impacts into biofuel LCAs could significantly change the estimated climate impact of biofuel policies.

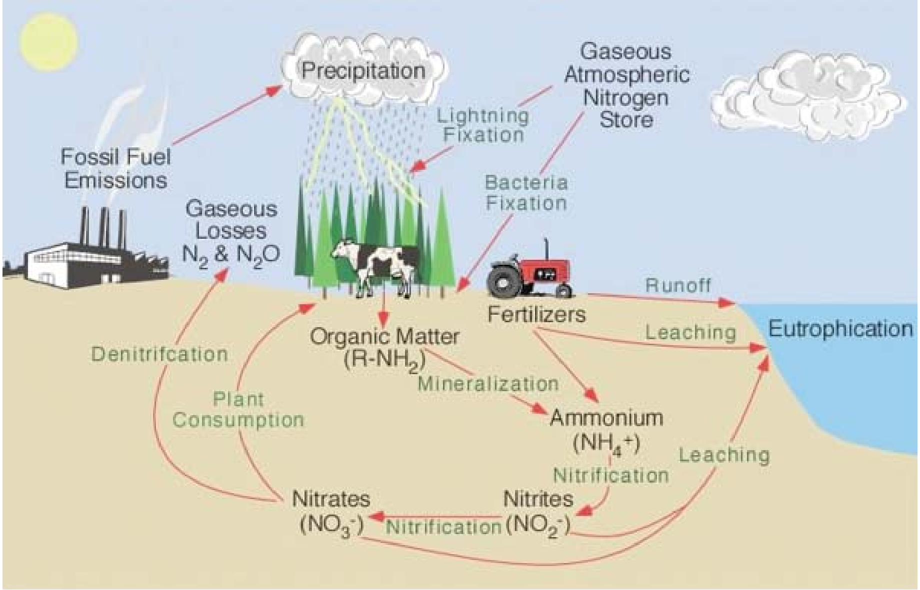
Interactive and feedback effects between climate change, land use, and water use

Climate change can affect water use and land use. For example, changes in precipitation and evapotranspiration (due to climate change) will affect groundwater levels[21] and cropping patterns, which in turn will give rise to other environmental impacts, including feedback effects on climate change. People in less wealthy countries may be most vulnerable to these changes because they have less capacity to mitigate or adapt to impacts on groundwater. These sorts of feedback interrelationships further complicate analyses of the impacts of biofuels on climate change, water use, and land use.

LCA Deficiency 4: Neglect of the Nitrogen Cycle

Anthropogenic inputs of nitrogen to the environment, such as from the use of fertilizer or the combustion of fuels, can disturb aspects of the global nitrogen cycle. These disturbances ultimately have a wide range of environmental impacts, including eutrophication of lakes and coastal regions, fertilization of terrestrial ecosystems, acidification of soils and water bodies, changes in biodiversity, respiratory disease in humans, ozone damages to crops, and changes to global climate.[22] Galloway et al. depict this as a "nitrogen cascade," in which "the same atom of Nr [reactive N, such as in NO_X, NH_3, or NH_4+] can cause multiple effects in the atmosphere, in terrestrial ecosystems, in freshwater and marine systems, and on human health" (p. 341).[23]

THE NITROGEN CASCADE



In what has been termed a nitrogen cascade, the same atom of reactive nitrogen can cause multiple effects in the atmosphere, in terrestrial ecosystems, in freshwater and marine systems, and on human health.

Nitrogen emissions to the atmosphere—as nitrogen oxide (NO_X), ammonia (NH_3), ammonium (NH_4+), or N_2O—can contribute to climate change through a number of complex physical and chemical pathways that affect the concentration of ozone, methane, nitrous oxide, carbon dioxide, and aerosols:

1. NO_X participates in a series of atmospheric chemical reactions involving CO, nonmethane hydrocarbons (NMHCs), H_2O, OH-, O_2, and other species that affect the production of tropospheric ozone, a powerful GHG as well as an urban air pollutant.
2. In the atmospheric chemistry mentioned in (1), NO_X affects the production of the hydroxyl radical, OH, which oxidizes and thereby affects the lifetime of methane, another powerful GHG.
3. In the atmospheric chemistry mentioned in (1), NO_X affects the production of sulfate aerosol, which as an aerosol has, on the one hand, a net *negative* radiative forcing (and thereby a beneficial effect on climate[24]) but on the other hand adversely affects human health.
4. NH_Y (NH_3 or NH_4+) and nitrate from NO_X deposit onto soils and oceans and then eventually re-emit N as N_2O, NO_X, or NH_Y. Nitrate deposition also affects soil emissions of CH_4.
5. NH_Y and nitrate from NO_X fertilize terrestrial and marine ecosystems and thereby stimulate plant growth and sequester carbon in nitrogen-limited ecosystems.
6. NH_Y and nitrate from NO_X form ammonium nitrate, which as an aerosol has, on the one hand, a net *negative* radiative forcing (and thereby a beneficial effect on climate[25]) but on the other hand adversely affects human health.
7. As deposited nitrate, N from NO_X can increase acidity and harm plants and thereby reduce C-CO_2 sequestration.

Even though the development of many kinds of biofuels will lead to large emissions of NO_X, N_2O, and NH_Y, virtually all LCAs of CO_2-equivalent GHG emissions from biofuels ignore all N emissions and the associated climate effects except for the effect of N fertilizer on N_2O emissions. Some preliminary, more comprehensive estimates are provided in work I published in 2003 and 2006.[26] Even in the broader literature on climate change, relatively little analysis of the climate impacts of N emissions has been done, because as Fuglestvedt et al. note, "GWPs for nitrogen oxides (NO_X) are amongst the most challenging and controversial" (p. 324).[27] Shine et al. estimate the global warming impacts of the effect of NO_X on O_3 and CH_4, focusing on regional differences (1 and 2 above), but they merely mention and do not quantify the effect of NO_X on nitrate aerosols (6 above) and do not mention the other impacts.[28] Prinn et al. and Brakkee et al. estimate effects 1 and 2.[29] These studies, along with my preliminary work, suggest that the climate impacts of perturbations to the N cycle by the production and use of biofuels could be comparable to the impacts of LUC.

LCA Deficiency 5: Omission of Climate-Impact Modeling Steps and Climate-Relevant Pollutants

The ultimate objective of LCAs of GHG emissions in transportation is to determine the effect of a particular policy on global climate and the impact of global climate change on quantities of interest (such as human welfare). This requires a number of modeling steps beyond the economic and environmental modeling discussed above. These steps involve estimating relationships between policies and emissions, emissions and concentration, concentration and radiative forcing, radiative forcing and temperature change, and temperature change and climate impacts for all climate-relevant pollutants. Conventional LCAs omit or characterize poorly most of these steps and omit most climate-relevant pollutants.

Conventional LCAs do not estimate the climate-change impacts of emissions of GHGs from transportation fuels but rather use a quantity called the global warming potential (GWP) to convert emissions of CH_4, N_2O, and CO_2 into a common index of temperature change. GWPs tell us the grams of CH_4 or N_2O that produce the same integrated radiative forcing, over a specified period of time, as one gram of CO_2, given a single pulse of emissions of each gas.[30] Typically, analysts use GWPs for a 100-year time horizon.

There are several problems with this method.[31] First, we care about the impacts of climate change, not about radiative forcing per se, and changes in radiative forcing are not simply (linearly) correlated with changes in climate impacts. Second, the method for calculating the GWPs involves several unrealistic simplifying assumptions, which can be avoided relatively easily in a more realistic, comprehensive CO_2-equivalency factor (CEF). Third, by integrating radiative forcing from the present day to 100 years hence, the GWPs in effect give a weight of 1.0 to every year between now and 100 and a weight of 0.0 to every year beyond 100, which certainly does not reflect how society makes trade-offs over time (a more realistic treatment would use continuous discounting[32]). Fourth, the conventional method omits several gases and aerosols that are emitted in significant quantities from biofuel life cycles and can have a significant impact on climate, such as ozone precursors—(for example, volatile organic compounds (VOCs), carbon monoxide and nitrogen oxides), ammonia, sulfur oxides, black carbon, and other aerosols.

A better approach is to use CEFs that equilibrate the present-dollar value of the impacts of climate change from a unit emission of gas X with the present-dollar value of the impacts of climate change from a unit emission of CO_2. Ideally, these present-value CEFs would be derived from runs of climate-change models for generic but explicitly delineated policy scenarios.

Toward a More Comprehensive Model: IMSSA

Thus far this chapter has identified major deficiencies in the development and application of conventional LCAs of transportation and climate. This concluding section briefly synthesizes the findings and delineates a more comprehensive and accurate model. Such a model can be built from scratch or developed by expanding an existing LCA model or IAM. At ITS-Davis we are currently exploring all of these options.

If we want the results of analysis of the climate-change impacts of transportation policies to be interpretable and relevant, our models must be designed to address clear and realistic questions. In the case of LCA comparing the energy and environmental impacts of different transportation fuels and vehicles, the questions must be of the sort "What would happen to [some measure of energy-use or environmental impacts] if somebody did X instead of Y?" where X and Y are specific and realistic alternative courses of action. These alternative courses of action may be related to public policies or to private-sector market decisions, or to both. Then the model must be able to properly trace out all of the differences—political, economic, technological, environmental—between the world with X and the world with Y. So rather than ask what would happen (to some marginally relevant metric such as radiative forcing) if we replaced one very narrowly defined set of activities with another and then use a technology life-cycle model to answer this (misplaced) question, we instead should ask what would happen in the world were we to take one realistic course of action rather than another, and then we should use an integrated economic, environmental, and engineering model—IMSSA—to answer the question.

Given the tremendous uncertainty in data, methods, and model scope and structure, IMSSA emphasizes *scenario analysis* rather than simple point estimates. IMSSA results thus would be described with nuanced statements of this sort: "Under conditions A, B, and C, the distribution of climate-impact damages for policy option 1 tends to be shifted toward lower values than the distribution for policy option 2, but option 1 also tends to result in fewer vehicle miles of travel and lower GNP."

SUMMARY OF THE DIFFERENCES BETWEEN CONVENTIONAL LCA AND AN IDEAL MODEL (IMSSA)

	Ideal Modeling Approach (IMSSA)	**Conventional LCA Approach**
Aim of the analysis	Evaluate impacts (worldwide if necessary) of one realistic action compared with another	Evaluate impacts of replacing one limited set of "engineering" activities with another
Scope of the analysis	All energy, materials, and economic, social, technological, ecological, and climate systems, globally	Narrowly defined chain of energy and material production and use activities Simplified, static, often linear energy-and-
Method of analysis	Dynamic, nonlinear, interrelated, feedback-modulated representations of all relevant systems	materials-in/emissions-out representation of technology
What is evaluated	Ideally, physical and economic impacts of direct interest to society (for example, damages from climate change)	Emissions aggregated by some relatively simple weighting factors (for example, global warming potentials, ozone-forming potential)
How results are expressed	Distribution of results for a range of scenarios	Point estimates

As mentioned above, I have framed the discussion of IMSSA around the climate impact of biofuels because this is a particularly complex problem that nicely illustrates the deficiencies of conventional LCA. But might conventional LCA be acceptable for much less complex problems? In general, the more an energy alternative perturbs technological, economic, and environmental systems, the less suitable is conventional LCA. This suggests that, in principle, conventional LCA might be almost as accurate as IMSSA in estimating the impacts of alternatives that do not appreciably affect technological, economic, and environmental systems. The problem, however, is that often it is difficult to identify low-perturbation alternatives without using relatively complex models to determine the impacts. This difficulty is compounded by our experience that the harder we look, the more impacts we find, for any system. Even alternatives that at first glance seem to have very small impacts (e.g., wind, water, and solar power) can, upon further inspection, turn out to have potentially nontrivial impacts not covered by conventional LCA. For example, the deployment of wind turbines over the ocean may cause local surface cooling due to enhanced heat latent flux driven by an increase in turbulent mixing caused by the turbines.[33] Large-scale photovoltaic arrays in deserts can alter surface albedo, affecting local temperature and wind patterns, with the sign of the temperature effect depending on the efficiency of the photovoltaic system relative to the background albedo (very efficient PV systems will cause local cooling).[34]

Nevertheless, resources for research are limited, and we cannot research everything forever. Ideally we want to concentrate our efforts on problems that are important, uncertain, and tractable. (If a problem is unimportant, or well understood, or intractable, it is not worth a great deal of attention. Thus, it is beside the point to argue that conventional LCA might be suitable for analyzing the impacts of policies that are intended to make only inconsequential changes in energy use, because there is no need to analyze such policies in the first place.) Given this, the most sensible approach is to evaluate periodically the state of our knowledge so that we can continue to target important, uncertain, and tractable problems. Unfortunately, at the beginning of this process, we need fairly comprehensive tools in order to do any kind of screening at all. Thus, we should develop at least rudimentary IMSSA as quickly as possible in order to guide the evolution of our analyses.

Summary and Conclusions

- As commonly employed, life-cycle analysis (LCA) cannot accurately represent the impacts of complex systems, such as those involved in making and using biofuels for transportation. LCA generally is linear, static, highly simplified, and tightly circumscribed, and the real world, which LCA attempts to represent, is none of these.

- Among LCA's major deficiencies are its inability to analyze a specific policy or action, its failure to account for price effects, its incomplete treatment of land-use change, its neglect of the nitrogen cycle, and its omission of climate-impact modeling steps and climate-relevant pollutants.

- In order to better represent the impacts of complex systems such as those surrounding biofuels, we need a different tool, one that has the central features of LCA but not the limitations. We propose as a successor to LCA a method of analysis that combines integrated assessment modeling, life-cycle analysis, and scenario analysis. We call this method integrated modeling systems and scenario analysis (IMSSA).

- IMSSA uses dynamic, nonlinear, feedback-modulated representations of energy, economic, ecological, and technological systems in order to estimate the physical and economic impacts of particular policies or actions. IMSSA can be built from scratch or developed by expanding an existing LCA model or IAM. We are currently exploring all of these options.

Notes

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