SUSTAINABLE TRANSPORTATION ENERGY PATHWAYS

A Research Summary for Decision Makers

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Chapter 12: Key Measurement Uncertainties for Biofuel Policy

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The previous chapter argued that a policy approach to reducing GHG emissions associated with transportation fuel use should, among other things, take account of all greenhouse gas emissions associated with the production, distribution, and use of a fuel. But as mentioned in that chapter, some areas of scientific uncertainty exist when it comes to quantifying the climate impacts of biofuels. This chapter explores four key measurement uncertainties that create challenges in accounting for such impacts—uncertainties that transportation policies designed to encourage low-carbon fuels should consider addressing. First, instead of treating emissions that occur at different times equally, an accounting of the climate impacts of GHG emissions should consider the effect of emissions over time. Second, there is a need to account for non-GHG global warming factors such as albedo, and the effect of non-Kyoto gases and pollutants such as aerosols and black carbon. Third, more work needs to be done on the question of how to account for indirect land-use effects, which can be large for crop-based feedstocks. And fourth, when forest wastes are used as feedstock for biofuel production, the impacts on forest systems, especially changes in the fire behaviors, forest sinks, soil emissions, and other forest carbon pools should be considered. The last two uncertainties relate to what are often called the leakage and indirect effects that occur when there are dynamic linkages between different carbon pools.

Accounting for GHG Emissions Over Time[1]

When land is cleared in order to grow biofuel crops, carbon that is sequestered in the roots and vegetation below and above ground is released. Although these emissions occur primarily at the outset of land-use change (LUC), current accounting methods typically allocate these emissions evenly over an assumed time horizon (e.g. 20 years).[2] This method underestimates the impact of early emissions and leads to a miscalculation of climate-change effects from LUC emissions. This is due to the fact that the cumulative radiative forcing of GHG emissions, a direct measure of climate warming potential, grows with the time it remains in the atmosphere. The earlier an emission occurs in a product life cycle, the larger its effect at a specific time in the future, unless that time is in the very distant future.

The difference between an earlier and later emission can, and should, be modeled based on the actual climate-change effects of gases. Two methods for doing this are the net present value (NPV) method presented by Delucchi in his lifecycle emissions model (LEM)[3] and the time correction factor (TCF) method proposed by Kendall et al.[4] Both methods aim to address one central question: How do we count the effects/costs of GHG emissions over time and how long do we count them? The two methods offer two distinct approaches, the NPV making an economic valuation of damages and the TCF making an approximation of physical damages over time.

The net present value (NPV) method

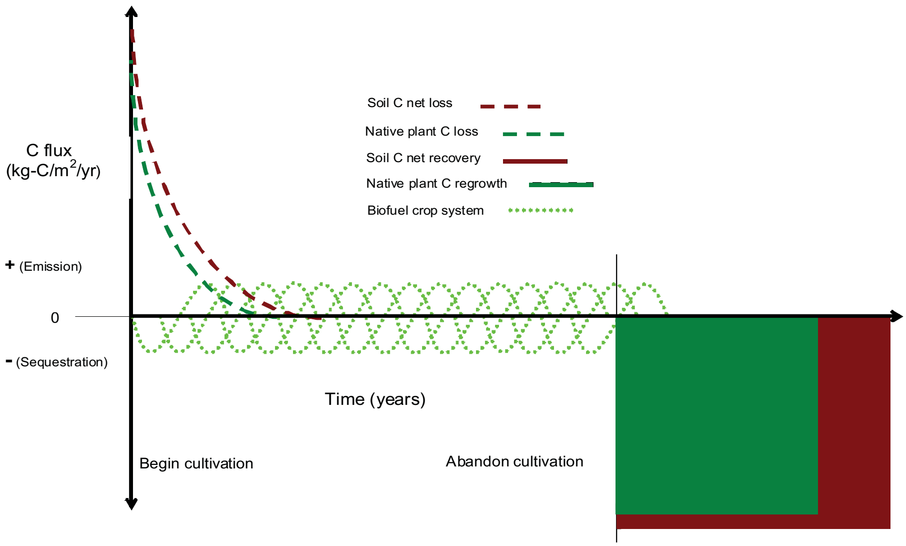
Delucchi's net present value (NPV) method for estimating CO_2 emissions from land-use change consists of two steps:

1. Estimate the net present value of the impacts of the actual changes in soil and plant CO_2 emissions, using a time-varying discount rate and accounting for the reversal of the LUC impacts and emissions at the end of the biofuel crop's life cycle.
2. Annualize the NPV—that is, convert it to an annuity—over the assumed life of the crop-to-energy program.

This economic approach is de rigueur in cost-benefit or cost-effectiveness analyses.

Delucchi applied the NPV method in a case study that describes bioenergy crops replacing an originally undisturbed native ecosystem such as a forest or grassland.[5] He laid out four general approaches to estimating LUC emission impacts in grams CO_2 equivalent per KJ of bioenergy (or ton of biomass) produced, depending on how we account for the value of emission impacts as a function of when they occur (with a continuous discounting function or with a discontinuous, threshold time horizon implying zero discounting in the near term and high discounting in the long term), and whether we include emissions that occur after cultivation ends.

CO_2 EMISSIONS FROM PLANTS AND SOILS DUE TO LAND-USE CHANGE



This shows how CO_2 stock and flux change when bioenergy crops replace an originally undisturbed native ecosystem such as a forest or grassland. The start of cultivation of a bioenergy crop creates three streams of CO_2 emission or sequestration: (1) the decay of the original, native ecosystem plant biomass (represented by the dark green dashed line), (2) a change in the CO_2 content of the soil (represented by the brown dashed line), and (3) the growth/harvest cycles of the bioenergy (represented by light green dotted line). Source: M. A. Delucchi, "A Conceptual Framework for Estimating the Climate Impacts of Land-Use Change Due to Energy-Crop Programs," Biomass and Bioenergy *35 (2011): 2337–60.*

The total emission impact at the end of cultivation is calculated based on a continuous discounting function to represent the valuation of emissions and impacts over time. The changes in CO_2 fluxes (as shown in the figure above) were converted to changes in CO_2 stocks assuming exponential decay of emission fluxes and atmospheric CO_2 stocks. The change in temperature follows the change in the atmospheric CO_2 stock, but with a time lag of about 50 years (following the FUND model as reported in Warren et al.[6]) that represents the thermal inertia of the system.

With this NPV method, CO_2 emissions impacts from the initial land-use change are at least partially offset by the CO_2 sequestration impacts that occur at the end of the bioenergy program when the land reverts to its original condition. As a result, the method arrives at significantly lower estimates of CO_2-equivalent emissions from land-use change than other models arrive at. Despite offering improvement, the NPV approach also has many uncertainties concerning the treatment of the discount rate (for example, whether the discount rate should be constant or change over time), emission profiles over time (for example, do CO_2 emissions from soil follow an exponential decay pattern, as assumed above), and the lag between changes in concentration and changes in temperature. It nevertheless offers an option to deal with social valuation of CO_2 stock changes as a function of time.

The time correction factor (TCF) method

Another method of accounting for GHG emissions timing, proposed by Kendall et al., is to apply a time correction factor (TCF) that scales the value of an amortized emission to equal the cumulative radiative forcing of the emission at the end of the amortization time horizon. As mentioned earlier, cumulative radiative forcing is a direct measurement of global warming potentials, whereas total cumulative GHG emission is a poor proxy. The cumulative radiative forcing of GHGs is the basis for both global warming potentials (GWPs) and TCF values: the Intergovernmental Panel on Climate Change (IPCC)[7] calculates the relative effects of different gases compared to CO_2 and calls them GWPs; the relative effect of CO_2 emitted at different points in time is captured via TCF.

Applying the TCF increases the relative importance of LUC-derived GHG emissions, which occur predominantly at the outset of the biofuel cultivation life cycle. For example, Searchinger et al. amortized their estimate of LUC emissions for U.S. corn ethanol over a 30-year time horizon[8] and estimated a total life-cycle GHG intensity of 177 g CO_2e/MJ. Applying the TCF to LUC emissions estimates in this case increases the life-cycle GHG estimate by 46 percent (from 177 to 258.6 g CO_2e/MJ) for the 30-year time horizon.

THE TCF APPLIED TO U.S. CORN ETHANOL LIFE-CYCLE EMISSIONS

This table shows how much the life-cycle GHG emissions profile for corn ethanol arrived at by Searchinger et al. changes when LUC emissions estimates are adjusted by the TCF. For the 30-year time horizon, the TCF increases the life-cycle GHG estimates by 46 percent. Source: Adapted from Table 2 in A. Kendall, B. Chang, and B. Sharpe, "Accounting for Time-Dependent Effects in Biofuel Life Cycle Greenhouse Gas Emissions Calculations," Environmental Science and Technology *43 (2009): 7142–47.*

Time Horizon (years)	Time Correction Factor (TCF)	% Increase over Non-TCF Calculation
10	1.730	246%
20	1.778	98%
30	1.785	46%
40	1.775	19%
50	1.769	4%

The TCF has other important applications in life-cycle GHG emissions intensity estimates for biofuels. Many life-cycle analyses of biofuel production omit capital investments required for production, such as factory construction and equipment manufacture, but when included they are straight-line amortized over a time horizon, just like LUC emissions. (For an example of this, see the Energy and Resources Group Biofuel Analysis Meta-Model, also known as EBAMM.[9]) While in many cases the emissions associated with capital investments are small compared to production-related emissions, their importance increases when GHG intensity calculations account for their timing. In addition, as lower-GHG-intensity fuels such as cellulosic ethanol are developed and commercialized, the influence of capital investments on life-cycle GHG intensity is more pronounced.

When EBAMM 1.1 and an average TCF factor of 1.77 are employed,[10] life-cycle GHG intensity estimates increase by slightly more than 1 percent for conventional ethanol (referred to as "ethanol today" in Farrell et al.[11]) and nearly 10 percent for cellulosic ethanol compared to straight-line amortization calculations. This finding suggests that for advanced, lower-carbon fuels, GHG intensity accounting for capital investments and their timing will affect the calculation of the climate change effects of a fuel.

Accounting for Other Non-GHG Climate-Forcing Attributes

Besides ignoring emissions timing, the conventional method of life-cycle analysis of GHG emissions has led to ignoring important climate-forcing effects of other gases and pollutants that are emitted in significant quantities during biofuel life cycles. These include ozone precursors, carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x), and black carbon (BC). Estimating climate impacts including these non-GHG gases and aerosols will produce comparative assessments that are appreciably different from those that use only the traditional GHGs.[12]

Conventional LCA also does not quantify the climate impact of biofuel-induced changes in biogeophysical characteristics. For example, changes in land use and vegetation as a result of biomass cultivation can change albedo (reflectivity) and evapotranspiration, and these directly affect the absorption and disposition of energy at the surface of the earth and thereby affect local and regional temperatures. Changes in temperature and evapotranspiration can affect the hydrologic cycle, 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 of and hence carbon sequestration by plants.

Because of the higher albedo and higher evapotranspiration of many crops, the conversion of mid-latitude (for example, North American) forests and grasslands to agriculture will generally reduce regional temperatures. On the other hand, the biogeophysical effects of a conversion of broadleaf tropical forests to agriculture will lead to a significant warming. In some cases, the climate impacts of changes in albedo and evapotranspiration due to LUC appear to bear an inverse relationship to 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."[13] This suggests that incorporation of these biogeophysical impacts into biofuel LCAs could significantly change estimates of the climate impact of biofuel policies.

Accounting for Indirect Land-Use Effects[14]

Accounting of the GHG effects of biofuels must also consider the indirect, or market-mediated, impacts of biofuel production, which can be large. To understand indirect impacts, we need to realize that when biofuel production from land-using feedstocks increases, prices change in feedstock, energy, and related markets to the extent that land is diverted from growing food crops. Indirect impacts of concern include food security for the poor due to higher food prices and a rebound of increased use of fossil fuels outside the area where the biofuel policy is being implemented due to lower fossil fuel prices caused by decreased fossil fuel consumption inside that policy area. For example, increased biofuel demand in the past 2 years due to U.S. biofuel policies led to lower gasoline consumption in the U.S. and some moderate effect on slowing down global oil price increases. Lower global oil prices can lead to higher demands in other countries, especially fast growing countries such as China.

Indirect land-use change (iLUC) and associated emissions have received the most policy attention thus far. The accounting of emissions associated with iLUC is controversial, since carbon emissions occur outside of the direct biofuel supply chain (including from other domestic agricultural sectors or elsewhere in the world) are counted within the lifecycle emissions of increased biofuel production. This reflects a policy approach counting all direct and indirect emission changes as a result of policy, the so-called consequential LCA. Biofuel-induced price changes cause some food production to be displaced elsewhere, bringing new land that might previously have been pastureland, wetlands, or perhaps even rain forest into agricultural production. When the new land is cleared for production, carbon sequestered in the roots and vegetation below and above ground is released. If rain forests are destroyed or peat is burned, the carbon releases are huge.[15] In the more extreme cases, these land-use shifts can result in each new gallon of biofuel releasing several times as much carbon on a life-cycle basis as the petroleum fuel it is replacing. In the case of corn ethanol, some analyses suggest that under some conditions, indirect land-use changes may increase GHG emissions by 40 percent or more per unit of energy in ethanol compared to the petroleum fuel it is replacing.[16] Cellulosic fuels are expected to have a much smaller effect (mostly because of less direct competition with food-based agricultural production if planted on degraded or marginal land, or derived from waste and residue without disrupting existing production).

Estimates of iLUC emissions associated with specific biofuel feedstocks—"iLUC factors"—have entered the regulatory arena as iLUC regulations have emerged as a way to address the urgent issue of land-use change due to biofuel policy. This consequential LCA GHG emission accounting for biofuels has been adopted in policies such as the California Low Carbon Fuel Standard (LCFS) and the U.S. Renewable Fuel Standard (RFS). Such a policy differs from the more familiar "polluter pays" principle for conventional environmental regulation because the land use emissions can happen far away from where the feedstock is produced. In the absence of systems in effect worldwide to control carbon accounting from land use change of *any* kind (which would eliminate iLUC), a policy that targets iLUC (and other significant indirect emissions) is necessary to address unintended policy consequences.[17]

Modeling systems used to derive regulatory figures have been subjected to scrutiny over their assumptions and readiness—in terms of accuracy and transparency—for a policy role. There are considerable differences in feedstock-specific results from the iLUC models being used by different regulatory bodies, due to the use of different modeling approaches and assumptions, different time frames for policy evaluation, and different methods for allocating effects to specific feedstocks. Results have also changed as the modeling systems themselves have evolved in response to critiques and cross-fertilization.

The piecemeal nature of sensitivity and uncertainty analysis conducted so far by existing iLUC studies means a plausible range of iLUC results has yet to be established. But even with the substantial variation in and uncertainty about results, both short-run and long-run studies find a potentially large impact from iLUC emissions, indicating a need for policy options to mitigate these impacts.

Models used for iLUC analysis

Three main types of models are used for iLUC analysis: economic equilibrium models, causal-descriptive models, and deterministic models. U.S. and California regulations have thus far been based on economic equilibrium models, with each regulatory agency relying on a single modeling system to generate results. Strengths of these types of models include history of policy analysis and theoretical underpinning, but there are drawbacks. Among these are uncertainty about certain model parameters, model transparency, and ease of use (the complicated representation of multi-market adjustments can make it difficult to glean pathways of causation, and the models themselves must be run by those trained in them).

Causal-descriptive and deterministic models stress transparency (making them more amenable to stakeholder input), fewer data requirements, and ease of implementation. By simplifying the characterization of market links, however, they risk missing some market feedbacks that drive iLUC.

TYPES OF MODELS FOR ANALYZING iLUC

Three main types of models are used for iLUC analysis: economic equilibrium models, causal-descriptive models, and deterministic models.

Model Type	**Description**	**Who Uses?**	**Pros and Cons**
Economic equilibrium models (general or partial)	Focus on regional supply and demand for biofuel feedstocks and related agricultural commodities; trade; links to energy market	California LCFS (GTAP model); U.S. Renewable Fuel Standard (RFS2) (FASOM and FAPRI models); European Commission (MIRAGE model)	Pros: History in policy analysis, captures actual economic behavior and linkages. Cons: Many data gaps and uncertainties, false sense of precision, lack of transparency.
Causal-descriptive models	Trace specific market pathways to iLUC change	Under development for UK's Renewable Transport Fuels Obligation (RTFO)	Pros: Transparency. Cons: Can miss complex market feedbacks; relies on historical trends and expert and stakeholder opinion to identify pathways.
Deterministic models	Use externally specified average land-use, trade patterns, land cover	Research institute (Öko-Institut)	Pros: Transparency, ease of implementation. Cons: Can miss complex market linkages and feedbacks; use of averages may not reflect most likely effects; some unsubstantiated assumptions regarding iLUC pathway potential.

Source: Adapted from Table 1 in S. Yeh and J. Witcover, "Indirect Land-Use Change from Biofuels: Recent Developments in Modeling and Policy Landscapes," International Food and Agricultural Trade Policy Council policy brief, 2010.

Some of the critical factors driving model results include the following:

- Yield trends for both crops and livestock—due to technological progress, productivity response to higher prices, and productivity of new areas
- Land competition, or type of land cover displaced by new cropping areas
- Co-products that can substitute for agricultural commodities, easing the need for additional land
- Trading relationships, or whether production flows, via trade, to lowest-cost regions
- Time frame for LUC emissions after clearing, and how to account for the time profile of emissions by methods such as the TCF and NPV, described earlier

Sources of uncertainty in iLUC model analyses

There are many sources of uncertainty in iLUC model analyses. These range from choice of model type, what to include in the model, and level of aggregation, to projections about future developments that provide the without-policy baseline against which the policy effects are measured. Key uncertainties across models of iLUC are as follows:[21]

- Feedstock demand—Fuel yield; co-product markets; price elasticity of demand
- Trade balance—Tariffs and other trade barriers (for example, subsidies); trade impacts of increased biofuel demand (altered trading patterns)
- Area and location of lands converted—Increases in crop yields; productivity of new land; bioenergy-induced additional productivity increase; land-use elasticities; supply of land across different uses; availability of idle, marginal, degraded, abandoned, and underutilized land and unmanaged forest; methodology of allocating converted land (for example, grassland vs. forests)
- GHG emissions from land use and land use change—Biofuel cultivation period; soil and biomass carbon stock data (especially peatlands); soil nitrogen emissions; time accounting of carbon emissions
- Other non-iLUC emissions and climate effects—GHG emissions from agriculture production changes such as cattle, methane emissions from rice cultivation and fertilizer inputs; albedo changes (for example, snow on former boreal or temperate forest land)

Behind the uncertainty and variation lies, in some cases, knowledge gaps due to the difficulty of modeling relationships with no historical track record—the case with various aspects of biofuel markets (market penetration and its dependence on new infrastructure, trade in biofuels or their feedstocks, substitutability between biofuels and petroleum fuels). In other cases, variation results from disagreements over or lack of clear empirical evidence about current patterns (for example, about how yields respond to output price changes, or what determines how and where agricultural land expands). The studies deal with the uncertainty by presenting alternative scenarios and/or undertaking systematic sensitivity analysis across many parameters to create a range of likely results.

POLICY OPTIONS FOR MITIGATING ILUC EMISSIONS

Even though GHG emissions from iLUC cannot be quantified exactly due to the nature of uncertainties in future projections, options for mitigating these emissions are being explored. In addition to the 'iLUC factor' already described, other complementary policy approaches that could be considered include the following:

- **Promoting biofuel feedstocks that avoid or minimize land and resource competition** (for example, agricultural wastes and residues, cellulosic energy crops on marginal land, and forest wastes). Biofuels produced from cellulosic energy crops grown on degraded lands can have lower iLUC effects due to less direct competition for land for food and other agricultural production. This pathway also tends to have better sustainability performance than food crops due to lower intensity of agricultural inputs (fertilizer, irrigation, and pesticides).
- **Improving the overall pool of agricultural resources for food and fuel by investing in higher yields or reducing losses throughout the supply chain.**
- **Linking into existing mechanisms designed to reduce or offset carbon emissions,** such as the Kyoto Protocol's Clean Development Mechanism (CDM) and the UN's Reducing Emissions from Deforestation and Forest Degradation (REDD) program, or generating new certification schemes, perhaps on a regional level (for example, accepting only biofuel feedstock from areas with forest protections in place). Some of these options face the same administrative and enforcement difficulties as other offset programs, including how to establish that the advances would not have taken place in the absence of the mitigation action (additionality) and do not prompt emissions elsewhere (leakage). Leakage could be dealt with most effectively by using an economy-wide carbon market across all potentially affected jurisdictions and sectors, but such policies may take a long time to implement, especially a globally implemented carbon market that reduces international leakage and iLUC emissions.
- **Finding situations where biofuel feedstock production can occur without displacing another land use** through, for example, changes or improvements in production system management. For example, a strengthened linkage between the biofuel and cattle-ranching production systems in Brazil could significantly reduce the risk of indirect land-use changes caused by biofuels.

While commercial development of low-iLUC biofuels lies largely in the future, there are indications the United States could produce large quantities at a reasonable cost given sustained and aggressive efforts to accelerate the development and penetration of low-carbon alternative fuels and technologies. To prevent iLUC and other unintended consequences, governments should also adopt enforceable, effective sustainability policies to prevent conversion of ecologically sensitive and high-carbon areas for biofuels or any other purpose; encourage appropriate use of fertilizers and other inputs for biofuels and other crops to reduce harmful environmental impacts from excess run-off; and work to improve access to food by the poor, especially if prices rise. These policies, not specifically aimed at biofuels, target the sweeping economy-wide changes needed to reduce the unwanted "leakage" effects from biofuel (or other) policies aiming to reduce GHG emissions.

Modeling Climate Impacts of Forest Management[22]

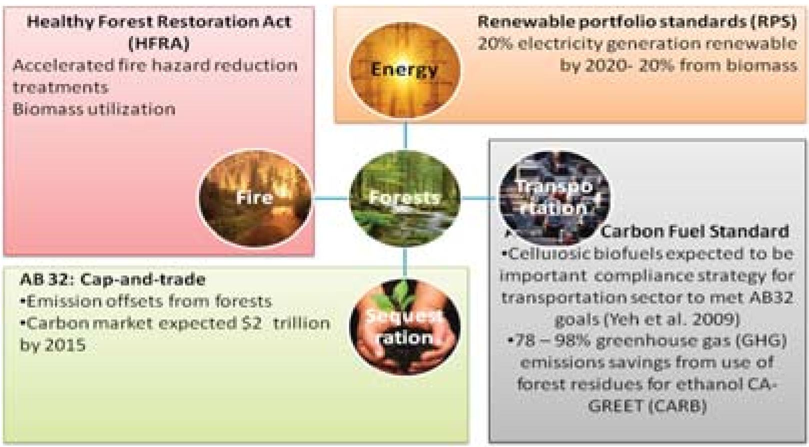
One way to reduce GHG emissions from iLUC is to use biofuel feedstocks that avoid or minimize land and resource competition, such as agricultural and forest wastes. However, the proposal to drastically increase the utilization of forest wastes for biofuel production has been met with strong criticisms and doubts about its actual climate benefits and sustainability impacts.

The use of wood biomass from forests has multiple effects on GHG balances. Biomass from forests can be used to produce energy and materials that offset the use of products derived from fossil sources, thereby reducing anthropogenic emissions. Forests sequester carbon through photosynthesis at varying rates influenced by tree age, stand conditions, rainfall, and other factors. Ecological disturbances such as wildfire, severe weather, pests, and disease have the potential to catastrophically alter the carbon dynamics of forests. Some studies suggest that producing biofuel and bioenergy from forest waste products considered to be uneconomical to harvest displaces significant well-to-tank GHG emissions from fossil resources. But comprehensive life-cycle modeling has not yet been done that would enable forest management decisions to be made based on maximizing GHG benefits.

Policies in California intended to increase the rate of sequestration in managed forests have resulted in changes to forestry practices on private lands in California. The Climate Action Reserve (http://www.climateactionreserve.org/) has registered 1.4 million tons of additional GHG sequestration by forests in California resulting from changes in forest practices. In parallel, several energy policy initiatives in California promote renewable energy by requiring more use of renewable sources including biomass produced from forests. These policies, though targeted at the electricity and transportation fuel sectors, will directly impact California's forests, which are already managed for a broad range of environmental, public interest, and market-driven objectives. As such, these new policies challenge the capacity of traditionally disparate research and policy communities to develop analysis and tools that address tightly coupled environmental, climate, and industrial wood and energy production systems.

There is also the fact that forests are valued for a range of public and economic products and services, and managing forests for maximal GHG benefit can have adverse impacts on other forest values. For example, in regions of high growth rate and where an efficient multi-product supply chain is in place, short-return, even-aged management may produce the greatest climate benefit. But silviculture of this type can reduce habitat diversity, alter hydrologic systems, and reduce the scenic and cultural value of forest ecosystems. In other regions, GHG management may be more in harmony with other forest values. Reconciling the range of environmental, ecological, social, and climate values present in forests while significantly increasing sequestration and offset of fossil energy sources through management is a significant policy and political challenge.

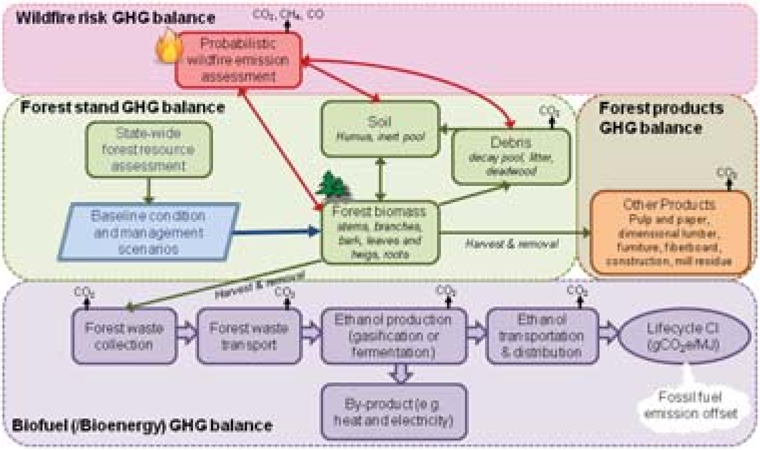
OBJECTIVES OF FOREST MANAGEMENT IN CALIFORNIA



California's forests are already managed for a broad range of environmental, public interest, and market-driven objectives.

Tittmann and Yeh have proposed an integrated accounting framework that encompasses the dynamic interactions between carbon pools taking into account forest management practices, forest fire behavior, and the fate of forest biomass in debris, forest products, and energy production. Using a consistent framework like this for policy planning would maximize the overall benefits of GHG policy and would have a better chance of balancing the trade-offs and maximizing synergies between carbon management and sustainability goals.

A PROPOSED GHG ACCOUNTING FRAMEWORK FOR FOREST MANAGEMENT



Tittmann and Yeh propose this GHG accounting framework. The biofuel/bioenergy GHG balance system illustrates a biofuel production pathway, though a similar (but slightly more complex) flow diagram can also apply to bioenergy production. Because biofuel production affects the forest system, an accounting of the GHG impacts of utilizing forest wastes for biofuel/bioenergy production should also consider the impacts of GHG balance within an integrated forest system, especially changes in the fire behaviors, forest sinks, soil emissions, and other forest carbon pools.

Tittmann and Yeh suggest that in comparison with a no-action alternative, utilizing material from treated stands to offset the use of gasoline and diesel in the transportation sector could result in substantial systemwide GHG reduction. This initial analysis points to the need for more comprehensive statewide and regional modeling of risk-based forest management in order to maximize the net life-cycle carbon balance over the long term. A 2005 study commissioned by the California Energy Commission (CEC) estimated that 11.7 million bone-dry tons (BDT)/y of forest residue are available accounting for technical and administrative constraints and 2.7 million BDT/y could be generated from treating forests determined to be in critical need of Fire Threat reduction. Annual electricity generation from 11.7 million BDT/yr can reach 2,048 MWe and 15 million MWh/yr.[23]

Summary and Conclusions

- Key areas of scientific uncertainty exist about how to quantify the climate impacts of biofuel production. Policy makers need to acknowledge this and to create a robust policy framework that reflects evolving scientific understanding and provides a stable compliance environment while work is done to better understand and quantify these areas of uncertainty.

- More needs to be known about how to account for GHG emissions timing and other factors affecting measurement of GHG impacts. The NPV and TCF methods offer differing approaches. Policy makers may not be in the best position to decide between these approaches. Instead, conducting sensitivity analysis and testing the robustness of the results of different approaches may be the best way to ensure the policy choices are robust given uncertainties.

- Recent work reviewing iLUC modeling has highlighted the data uncertainties, modeling choices, and scenario dependencies inherent in iLUC modeling. These make it more difficult to argue that a single model or scenario of the future has sufficient scientific grounding to generate a single iLUC factor to serve as the basis for a policy decision with large social, economic, and technology implications. One approach to the uncertainty about iLUC emissions would be to establish the *range* of likely emissions consequences based on best scientific information (such as peer-reviewed modelling outcomes published to date) as an input for policymakers, to be updated as new scientific estimates become available.

- Policies should adopt, as much as possible, integrated frameworks for evaluating the GHG benefits of alternative fuels and should consider balancing the trade-offs and maximizing synergies between carbon management and sustainability goals of different policies. In the case of utilizing forest waste for biofuel production, conducting integrated analysis that takes into account the dynamic interactions between carbon pools and sustainability outcomes can maximize the overall benefits of GHG policy and sustainability goals.

Notes

1. This section and the next ("Accounting for Other Non-GHG Climate-Forcing Attributes") are condensed from M. A. Delucchi, *A Lifecycle Emissions Model (LEM): Lifecycle Emissions from Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity Use, Heating and Cooking Fuels, and Materials*, UCD-ITS-RR-03-17 (Institute of Transportation Studies, University of California, Davis, 2003); M. A. Delucchi, *Lifecycle Analysis of Biofuels*, UCD-ITS-RR-06-08 (Institute of Transportation Studies, UC Davis, 2006); M. A. Delucchi, "Impacts of Biofuels on Climate, Land, and Water," *Annals of the New York Academy of Sciences* 1195 (2010): 28–45 (issue *The Year in Ecology and Conservation Biology*, ed. R. S. Ostfeld and W. H. Schlesinger); M. A. Delucchi, "A Conceptual Framework for Estimating Bioenergy-Related Land-Use Change and Its Impacts over Time," *Biomass and Bioenergy*, 35 (2011): 2337-2360; A. Kendall, B. Chang, and B. Sharpe, "Accounting for Time-Dependent Effects in Biofuel Life Cycle Greenhouse Gas Emissions Calculations," *Environmental Science and Technology* 43 (2009): 7142–47.
2. T. Searchinger, R. Heimlich, R. A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T. H Yu, "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change," *Science* 319 (2008): 1238. Accounting for emissions from advanced fuels and vehicles has historically been narrowly focused on summing the major GHGs identified by the Intergovernmental Panel on Climate Change (IPCC) in CO_2 equivalents averaged over 100 years.
3. Delucchi, *Lifecycle Emissions Model*.
4. A. Kendall, B. Chang, and B. Sharpe, "Accounting for Time-Dependent Effects in Biofuel Life Cycle Greenhouse Gas Emissions Calculations," *Environmental Science and Technology* 43 (2009): 7142–47.
5. Delucchi, "Conceptual Framework for Estimating Bioenergy-Related Land-Use Change."
6. R. Warren, C. Hope, M. Mastrandrea, R. Tol, N. Adger, and I. Lorenzoni, "Spotlighting Impacts Functions in Integrated Assessment; Research Report Prepared for the Stern Review on the Economics of Climate Change," Working Paper 91 (Tyndall Centre for Climate Change Research, University of East Anglia, United Kingdom, September 2006).
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8. Searchinger et al., "Use of U.S. Croplands."
9. http://rael.berkeley.edu/sites/default/files/EBAMM.

10. EBAMM specifies the time horizon of amortization for farm equipment at 10 years; however, the time horizon for other capital investments is not clear. We use an average TCF of 1.77 (the mean of TCFs calculated for time horizons between 10 and 50 years) and apply it to all amortized emissions for capital equipment in EBAMM.
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