DO BIOFUELS LIFE CYCLE ANALYSES ACCURATELY QUANTIFY THE CLIMATE IMPACTS OF BIOFUELS-RELATED LAND USE CHANGE?†

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Land use change (LUC) may be the single most important factor in determining the sustainability of biofuels. To ensure that legal standards are effective in limiting climate change forcings, it is essential that LUC be given thorough and rigorous treatment. This Article examines the premise that the climate impacts of LUC—as characterized by biofuels life cycle analyses (LCAs)—are completely fungible with the climate impacts of greenhouse gas (GHG) emissions from other sources. LUC affects climate through both 'biogeochemical' and 'biophysical' forcings, or the climate impacts of LUC through alteration of atmospheric GHG concentrations and through perturbation of water and energy exchange between the land surface and the atmosphere, respectively. This Article presents a method for thoroughly quantifying the GHG effects of LUC and also provides quantitative estimates of the magnitude of biophysical forcings. The Article then assesses the comprehensiveness of the accounting systems used by major fuel standards. Biofuel LCAs are increasingly including the most important elements required to thoroughly quantify the

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GHG effects of LUC, yet they are not comprehensive in all aspects and generally use improper accounting for the timing of emissions. Biophysical forcings are sometimes more influential than biogeochemical forcings. However, they have never been included in assessments of the impacts of biofuels-related LUC. Thus, biofuels LCAs are not accurately quantifying the climate impacts of LUC.

I. INTRODUCTION

A primary goal of biofuel production is climate change mitigation. The potential for biofuel production systems to meet this objective is largely dependent on land use. Terrestrial ecosystems interact strongly with the climate system, and, therefore, land use decisions have important climate impacts.[1] Large-scale biofuel production would impact global patterns in land use,[2] and would therefore have significant climate implications. In fact, land use change (LUC) is emerging as the single most important factor in biofuels greenhouse gas (GHG) life cycle analyses (LCAs), often determining whether or not a biofuel meets GHG reduction thresholds.[3] Given the importance of LUC to biofuel sustainability, it is essential that the climate impacts of biofuels-related LUC be thoroughly and accurately quantified. Policies that do not reliably characterize the climate effects of LUC will fail to advance the best possible climate solutions or, worse yet, be counterproductive.[4]

Biofuels sustainability policies—and the LCAs upon which they are based—operate on the implicit assumption that the climate impacts of LUC are completely fungible with the climate impacts of GHG emissions from other sources. For this assumption to be logically true, the full climate costs or benefits of both LUC and other sources of emissions must be incorporated in the LCA. With regards to LUC, the key question then becomes whether LCAs consider the full suite of ecosystem climate services.

1. *See, e.g.*, Johannes J. Feddema et al., *The Importance of Land-Cover Change in Simulating Future Climates*, 310 SCIENCE 1674, 1678 (2005); R.A. Houghton, *Balancing the Global Carbon Budget*, 35 ANN. REV. EARTH & PLANETARY SCI. 313, 329 (2007); Pete Smith et al., *Agriculture*, *in* CLIMATE CHANGE 2007: MITIGATION OF CLIMATE CHANGE 497, 501–03 (Bert Metz et al. eds., 2007).

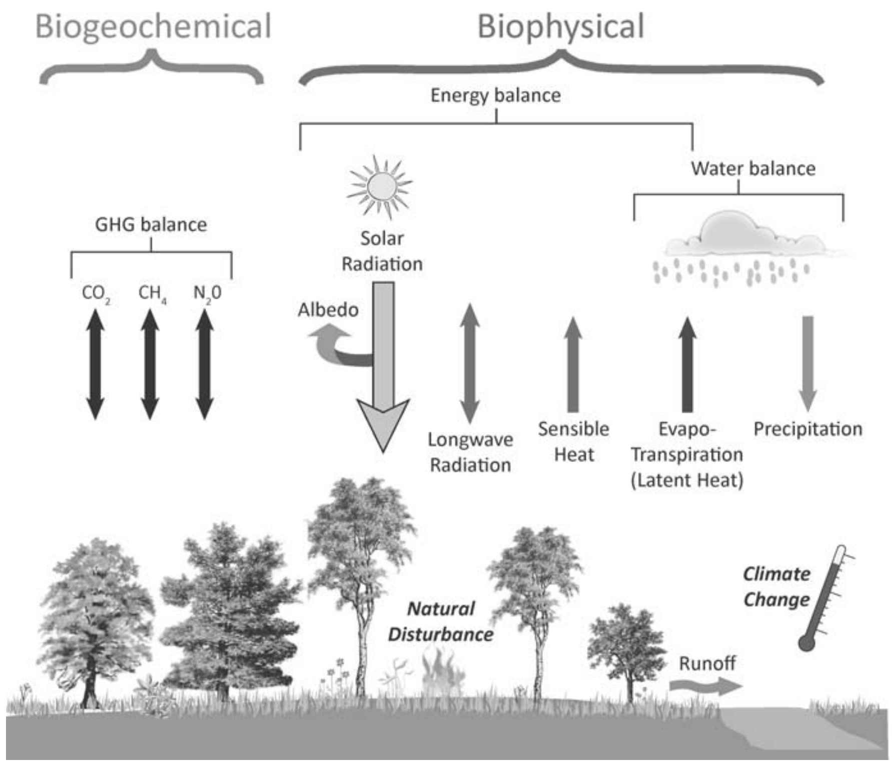
2. *See, e.g.*, Angelo Gurgel et al., *Potential Land Use Implications of a Global Biofuels Industry*, 5 J. AGRIC. & FOOD INDUS. ORG., no. 2, 2007 at 1, 22–23; Timothy Searchinger et al., *Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change*, 319 SCIENCE 1238, 1238 (2008).

3. *See, e.g.*, U.S. ENVTL. PROT. AGENCY, EPA-420-R-10-006, RENEWABLE FUEL STANDARD PROGRAM (RFS2) REGULATORY IMPACT ANALYSIS 3–6 (2010).

4. *See, e.g.*, Robert B. Jackson et al., *Protecting Climate with Forests*, 3 ENVTL. RES. LETTERS, Oct.–Dec. 2008, no. 044006, at 1, 3; Gregg Marland et al., *The Climatic Impacts of Land Surface Change and Carbon Management, and the Implications for Climate-Change Mitigation Policy*, 3 CLIMATE POL'Y 149, 154–56 (2003).

Ecosystems regulate climate through both *biogeochemical* and *biophysical* interactions with the atmosphere (Figure 1).[5] "*Biogeochemical* climate services" refers to the regulation of atmospheric GHG concentrations through ecosystem-atmosphere GHG exchange. "*Biophysical* climate services" refers to regulation of climate through water and energy exchange between the land surface and the atmosphere. LUC dramatically impacts the exchange of GHGs, water, and energy between the ecosystem and the atmosphere, resulting in both biogeochemical and biophysical climate forcings.

FIGURE 1
SCHEMATIC DIAGRAM OF ECOSYSTEM CLIMATE SERVICES



Ecosystem climate services include both biogeochemical and biophysical regulation of climate. These are broken down into various components of GHG, energy, and water balances (discussed in text), and are subject to perturbation through natural disturbance and climate change.

5. *See, e.g.*, Gordon B. Bonan, *Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests*, 320 SCIENCE 1444, 1447 (2008); Christopher B. Field et al., *Feedbacks of Terrestrial Ecosystems to Climate Change*, 32 ANN. REV. ENV'T & RESOURCES 1, 4–6 (2007).

The purpose of this Article is to examine, from a scientific standpoint, the premise that *climate impacts of LUC—as characterized by biofuels LCAs—are completely fungible with the climate impacts of GHG emissions from other sources*. To set the foundation, the Article begins by reviewing how terrestrial ecosystems regulate climate through both *biogeochemical* and *biophysical* interactions with the atmosphere (Figure 1) and how these climate services might best be quantified. Specifically, Part II discusses how *biogeochemical* climate services can be quantified using a metric of the greenhouse gas value (*GHGV*) of ecosystems,[6] delving into some issues beyond those currently considered in LCAs. Part III then reviews biophysical forcings associated with LUC and discusses how they compare in magnitude to biogeochemical forcings. Next, using these criteria for quantifying the climate services of ecosystems, Part IV evaluates the treatment of LUC in biofuels GHG LCAs and sustainability standards, discussing strengths and limitations of the current paradigms. Finally, Part V concludes with a discussion of some of the potential policy implications.

II. BIOGEOCHEMICAL CLIMATE SERVICES

'Biogeochemical climate services' refers to the regulation of atmospheric GHG levels by ecosystems. These services consist of both storage of organic matter, the disturbance of which would result in GHG release, and annual GHG exchange with the atmosphere.[7] The GHG value of maintaining an ecosystem over a multiple-year time frame can be quantified using the recently developed metric of the *GHGV* of terrestrial ecosystems.[8] *GHGV* can then be used to calculate the full GHG cost of LUC, which is simply the difference between the *GHGV*s of new and old ecosystems.

A. Description of GHGV

An ecosystem's *GHGV* is defined as "the total benefit of avoiding radiative forcing from GHGs through maintenance of one hectare of the ecosystem" over a multiple-year time frame.[9] *GHGV* incorporates potential GHG release upon clearing of stored organic matter, the annual flux of GHGs from the ecosystem to the atmosphere, and probable GHG exchange resulting from disturbance. *GHGV* measures ecosystem-atmosphere GHG exchanges and their effects over a multiple-year time

6. Kristina J. Anderson-Teixeira & Evan H. DeLucia, *The Greenhouse Gas Value of Ecosystems*, 17 GLOBAL CHANGE BIOLOGY 425 (2011).

7. *Id.*

8. The following section is based on Anderson-Teixeira & DeLucia, *supra* note 6.

9. *Id.*

span and is sensitive to the timing of emissions. Specifically, *GHGV* predicts ecosystem-atmosphere GHG exchange as a function of time following (hypothetical) land clearing, computes how this affects atmospheric GHG concentrations over time, and translates that into radiative forcing effects.[10] Treatment of time and its affect on *GHGV* are discussed below. Analogous to the Intergovernmental Panel on Climate Change's (IPCC's) global warming potential (GWP) metric[11] but differing in that it treats a multiple-year emissions time span, *GHGV* is expressed in carbon dioxide (CO_2)-equivalents (Mg CO_2e ha^{-1}) through comparison with the cumulative radiative forcing that would arise from a pulse emission of CO_2 at time zero.

B. GHGV*s of Various Ecosystems*

GHGV varies across ecosystem types. Figure 2 shows first-order estimates of *GHGV* for various native, aggrading,[12] and managed ecosystem types.

1. Contributions from Storage of Organic Material

Ecosystems store organic material, the disturbance of which results in GHG release—either immediately through combustion (if fire is used to clear the land) or over time through decomposition (Figure 2a). This comes primarily from storage of carbon, which contributes approximately half the dry weight of the organic compounds that make up vegetation, dead wood (standing or fallen dead trees), an organic layer of decomposing organic material ('litter' or peat), and soil organic matter, and is subject to release as CO_2 when the material decomposes or is burned. Storage of carbon that is vulnerable to release through disturbance varies dramatically across ecosystems, ranging from minimal storage of < 25 Mg CO_2e ha^{-1} in croplands and abandoned cropland up to > 2,000 Mg CO_2e ha^{-1} in tropical peat forests.[13] The high carbon storage of forests (generally, > 400 Mg CO_2e ha^{-1}) makes their preservation one of the most effective mechanisms of mitigating climate change[14] and, conversely, implies that any biofuels-driven deforestation would quickly negate the GHG benefits of fossil fuel displacement.[15]

10. For a thorough explanation, see *id.*

11. Piers Forster et al., *Changes in Atmospheric Constituents and in Radiative Forcing*, *in* CLIMATE CHANGE 2007: THE PHYSICAL SCIENCE BASIS 129, 210 (Susan Solomon et al. eds., 2007).

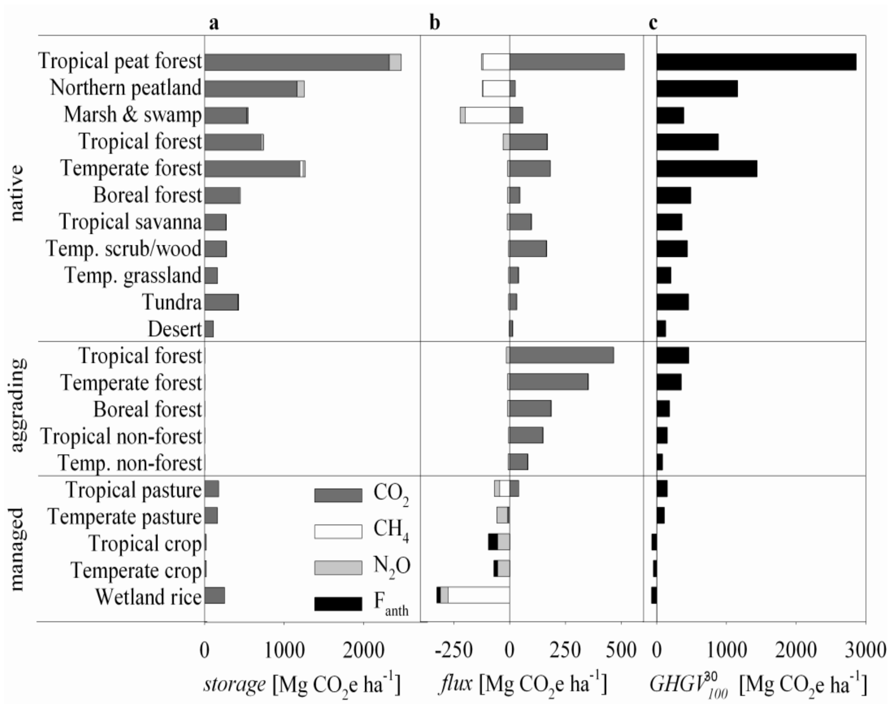
12. "Aggrading" signifies an ecosystem that is accumulating biomass such as abandoned farmland or a forest that is recovering from a fire.

13. Based on data and methodology of Anderson-Teixeira & DeLucia, *supra* note 6.

14. Raymond E. Gullison et al., *Tropical Forests and Climate Policy*, 316 SCIENCE 985, 985–86 (2007).

15. *See, e.g.*, Joseph Fargione et al., *Land Clearing and the Biofuel Carbon Debt*, 319 SCIENCE 1235, 1237 (2008); Searchinger et al., *supra* note 2, at 1240.

FIGURE 2
GREENHOUSE GAS VALUES OF VARIOUS ECOSYSTEM TYPES[16]



Contributions to *GHGV* from (a) storage of materials vulnerable to release as GHGs upon land clearing and (b) displaced flux of CO_2, CH_4, and N_2O, and anthropogenic emissions (F_{anth}). These are combined to yield (c) *GHGV* for a thirty-year ecosystem time span and 100-year analytical time span. Here, effects of disturbance are not included, and no discounting is applied. These values should not be used as off-the-shelf estimates for any particular ecosystem, as influential variables such as organic matter storage, burn characteristics, cattle density, and crop management practices can vary by orders of magnitude for some of the ecosystem categories presented here.

16. Based on data and methodology of Anderson-Teixeira & DeLucia, *supra* note 6.

The amount and timing of GHG release by disturbance depends, in part, on the type of disturbance. Mechanical clearing kills the vegetation and commits the carbon stored in organic material to release as CO_2 through decomposition. The rate of decomposition varies widely depending upon climate, type of material,[17] post-clearing land management, and possible diversion of harvested materials to various wood products, the lifetimes of which vary widely. If fire is used to clear the ecosystem, there will be an immediate release of CO_2, followed by decomposition of unburned material. In addition to this carbon release, a wide variety of trace GHGs (including methane (CH_4) and nitrous oxide (N_2O); Figure 2a) and aerosols are produced as the organic material burns.[18] Thus, the value of the ecosystem climate service of organic matter is somewhat dependent upon the type of disturbance that would be used to clear the ecosystem.

2. Contributions from Annual GHG Flux

In addition to the service provided by the storage of organic material, ecosystems exchange GHGs with the atmosphere on a continual basis, thereby contributing substantially to their *GHGV* (Figure 2b). Ecosystems may serve as either a GHG sink or source. The three most important long-lived GHGs exchanged between ecosystems and the atmosphere are CO_2, CH_4, and N_2O.[19]

The net flux of CO_2 is shaped most strongly by CO_2 release through respiration and CO_2 uptake through photosynthesis, but also includes nonrespiratory fluxes such as those arising from fire or ultraviolet oxidation of organic matter. It generally approximates, but is not identical to, the net change in ecosystem carbon storage.[20] Many native ecosystems tend to be carbon sinks (Figure 2b), albeit very high variability in annual CO_2 flux.[21] Aggrading ecosystems such as regrowing forests and abandoned agricultural land (including Conservation Reserve Program land in the United States) are consistently carbon sinks (Figure 2b), with sink strength generally increasing from cold to warm climates.[22] In crop eco-

17. For example, plant material would decompose more rapidly than soil organic material, and the decomposition rate of dead wood depends upon its size.

18. M.O. Andreae & P. Merlet, *Emission of Trace Gases and Aerosols from Biomass Burning*, 15 GLOBAL BIOGEOCHEMICAL CYCLES 955, 958–60 (2001).

19. Forster et al., *supra* note 11, at 135.

20. F.S. Chapin III et al., *Reconciling Carbon-Cycle Concepts, Terminology, and Methods*, 9 ECOSYSTEMS 1041, 1045–46 (2006).

21. B.E. Law et al., *Environmental Controls Over Carbon Dioxide and Water Vapor Exchange of Terrestrial Vegetation*, 113 AGRIC. & FOREST METEOROLOGY 97, 99 (2002); Sebastiaan Luyssaert et al., *CO_2 Balance of Boreal, Temperate, and Tropical Forests Derived from a Global Database*, 13 GLOBAL CHANGE BIOLOGY 2509, 2522 (2007).

22. Kristina J. Anderson et al., *Temperature-Dependence of Biomass Accumulation Rates During Secondary Succession*, 9 ECOLOGY LETTERS 673, 674–76 (2006).

systems, net flux of CO_2 is generally equal to changes in soil carbon and is minimal for ecosystems that have undergone consistent management for many years. Perennial grass biofuel crops, however, tend to be CO_2 sinks.[23]

Most natural ecosystems with unsaturated soils have minimal CH_4 fluxes (Figure 2b), with soils sequestering small amounts through the process of methanotrophy.[24] Important exchanges with the atmosphere occur in (1) wetlands, which produce methane; (2) pastures, where enteric fermentation of ruminants (e.g., cattle) releases methane; and (3) systems with high levels of termite-mediated decomposition. Recent scientific work has revealed that plants emit methane,[25] although the magnitude of these releases remains controversial.[26] In general, annual CH_4 flux is highly uncertain in most ecosystems; further scientific research will be important to understanding this aspect of ecosystem climate services.

N_2O emissions occur as a natural byproduct of nitrogen cycling in terrestrial ecosystems. In natural ecosystems, these emissions are minimal; however, in ecosystems with high nitrogen inputs through fertilizer or manure, N_2O fluxes can be much higher (Figure 2b).[27] Accurately quantifying annual N_2O emissions remains difficult, and controversy remains as to what fraction of the nitrogen in fertilizer is released as N_2O.[28]

In croplands, CO_2 emissions associated with fertilizer production, lime, and fuel use by farm machinery also contribute to total annual GHG flux (Figure 2b), depending strongly on crop management practices.

23. Kristina J. Anderson-Teixeira et al., *Changes in Soil Organic Carbon Under Biofuel Crops*, 1 GCB BIOENERGY 75, 83 (2009).

24. Jean Le Mer & Pierre Roger, *Production, Oxidation, Emission and Consumption of Methane by Soils: A Review*, 37 EUR. J. SOIL BIOLOGY 25, 28 (2001).

25. S. Houweling et al., *Atmospheric Constraints on Global Emissions of Methane from Plants*, 33 GEOPHYSICAL RES. LETTERS, Aug. 16, 2006, L15821, at 4; Frank Keppler et al., *Methane Emissions from Terrestrial Plants Under Aerobic Conditions*, 439 NATURE 187 (2006); Mirwais M. Qaderi & David M. Reid, *Methane Emissions from Six Crop Species Exposed to Three Components of Global Climate Change: Temperature, Ultraviolet-B Radiation and Water Stress*, 137 PHYSIOLOGIA PLANTARUM 139, 142 (2009).

26. *See, e.g.*, R.E.R. Nisbet et al., *Emission of Methane from Plants*, 276 PROC. ROYAL SOC'Y B: BIOLOGICAL SCI. 1347, 1352–53 (2009).

27. Elke Stehfest & Lex Bouwman, *N_2O and NO Emission from Agricultural Fields and Soils Under Natural Vegetation: Summarizing Available Measurement Data and Modeling of Global Annual Emissions*, 74 NUTRIENT CYCLING AGROECOSYSTEMS 207, 211 (2006).

28. Intergovernmental Panel on Climate Change, *Agriculture Forestry, and Other Land Use*, *in* 4 2006 IPCC GUIDELINES FOR NATIONAL GREENHOUSE GAS INVENTORIES §§ 10.52, 10.66 (Simon Eggleston et al. eds., 2006); P.J. Crutzen et al., *N_2O Release from Agro-Biofuel Production Negates Global Warming Reduction by Replacing Fossil Fuels*, 8 ATMOSPHERIC CHEMISTRY & PHYSICS 389, 389, 391–93 (2008).

3. *Total* GHGV

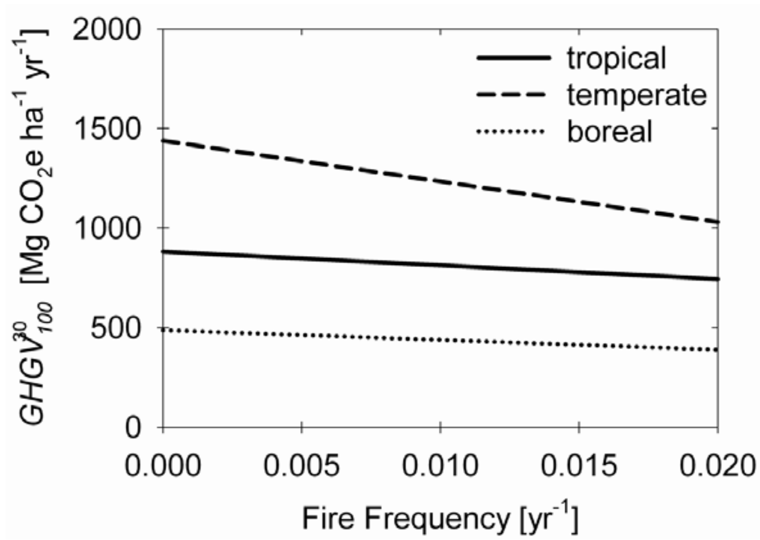
Contributions from storage and flux combine to determine *GHGV* (Figure 2c). Native ecosystems tend to have high *GHGV*s, deriving most of their value from storage of organic matter. Aggrading ecosystems such as regrowing forests and abandoned agricultural land (including conservation reserve program land in the United States) have modest but reliably positive *GHGV*s. Managed ecosystems tend to have low or negative *GHGV*s. In pastures, the benefits of relatively high soil carbon storage are counteracted by the negative effects of methane from cattle. In annually tilled croplands, carbon storage is minimal, and N_2O emissions—along with CO_2 emissions associated with fertilizer production, lime, and fuel use by farm machinery—make the ecosystem a GHG source, resulting in negative *GHGV*s. Perennial grass biofuel crops, in contrast, generally have modest but positive *GHGV*s.

C. *Effects of Disturbance on* GHGV

The *GHGV* of preserving an ecosystem depends on its *volatility*, or the probability that sequestered GHGs (e.g., carbon stored in trees) will be released through natural disturbance (e.g., a forest fire) or by disturbance related to agronomic management and harvest practices (i.e., for a biomass crop). For example, if a major forest fire were to occur during the time span of interest, there would be a large GHG release followed by continuing CO_2 release from the decomposition of dead trees. Counteracting this, however, would be the rapid CO_2 uptake by the regrowing forest. Overall, an increasing probability that a major fire will occur during the time span of interest reduces the *GHGV* of forests (Figure 3). The slope of this decline depends upon forest characteristics such as biomass storage and annual net CO_2 flux.[29]

29. Anderson-Teixeira & DeLucia, *supra* note 6, at 430.

FIGURE 3
INFLUENCE OF FIRE FREQUENCY ON *GHGV*[30]



Influence of the probability of a stand-clearing forest fire on the *GHGV* of tropical, temperate, and boreal forests. Values are based on a thirty-year ecosystem time span and 100-year analytical time span with no discounting.

D. Treatment of Time in GHGV

Unlike other metrics of the GHG services of ecosystems, *GHGV* gives explicit treatment to three aspects of the treatment of time that affect *any* metric of the potential of GHG emissions to affect climate: (1) the time frame over which the ecosystem's interaction with the atmosphere is evaluated ("ecosystem time frame"); (2) the time horizon over which climate effects are evaluated ("analytical time frame"); and (3) the timing of emissions, including potential weighting of climate effects over time. Treatment of time in *GHGV* differs from other metrics of the GHG services of ecosystems, leading to meaningful differences in estimates of the values of these services.

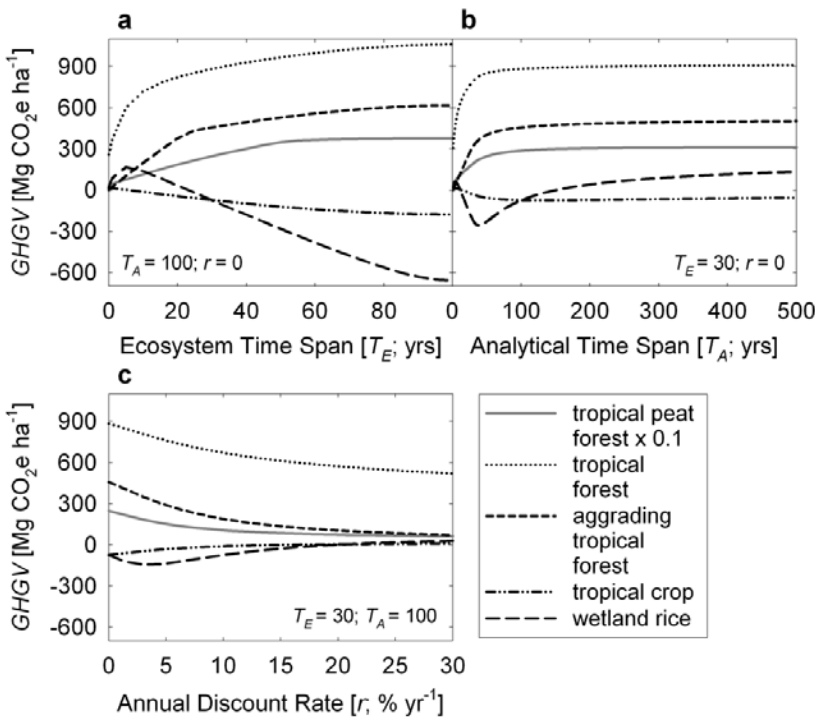
1. Ecosystem Time Frame

GHG exchange between the ecosystem and the atmosphere is counted over an "ecosystem" or "emissions" time frame[31] (T_E), or the

30. Based on data and methodology of Anderson-Teixeira & DeLucia, *supra* note 6, at 433.
31. Referred to as "emissions time frame" by Anderson-Teixeira & DeLucia, *supra* note 6, at 427.

number of years over which the ecosystem is presumed to affect the atmosphere. *GHGV* is dependent upon the choice of T_E (Figure 4a). Typically, *GHGV* grows in magnitude (positive or negative) with increasing T_E, although there are some cases in which *GHGV* first grows and then declines as T_E increases. Moreover, the response of *GHGV* to T_E varies across ecosystems. Specifically, ecosystems whose value is derived mainly from storage of organic matter are less sensitive to T_E than are those whose value is derived mainly from annual GHG flux. Therefore, the choice of T_E alone strongly shapes the perceived value of various types of ecosystems.

FIGURE 4
INFLUENCE OF TREATMENT OF TIME ON *GHGV*[32]



GHGV for five tropical ecosystem types as a function of (a) ecosystem time span, (b) analytical time span, and (c) annual discount rate. For display purposes, values for tropical peat forest are multiplied by 0.1.

32. Modified from Anderson-Teixeira & DeLucia, *supra* note 6, at 434.

2. *Analytical Time Frame*

Because GHGs remain in the atmosphere—and thereby impact the climate—for many years following their release, it is generally desirable to evaluate the climate impact of ecosystem-atmosphere GHG exchange (i.e., cumulative radiative forcing) over a longer "analytical" time frame (T_A), which is analogous to the "time horizon" for GWPs.[33]

GHGV is dependent upon the choice of T_A (Figure 4b). Whereas cumulative radiative forcing continues to increase over hundreds to thousands of years, normalization by a CO_2 pulse causes *GHGV* of most ecosystems to become relatively stable within about fifty years after the cessation of emissions. As is the case with T_E, choice of T_A has the strongest effect on ecosystems with high GHG exchange later during the time span of interest. Choice of T_A is also highly influential when contributions from CH_4 are substantial.[34]

3. *Timing of Emissions*

GHGV is sensitive to the timing of GHG exchange between the ecosystem and the atmosphere. There are several aspects to this. First, calculation of *GHGV* entails calculation of the expected timing of ecosystem-atmosphere GHG exchange; for example, the release of CO_2 from clearing a forest is modeled to occur over many years, and at different rates for wood products and soil organic matter. Second, emissions that occur over a multi-year time span are properly translated into radiative forcing impact.[35] Specifically, *GHGV* calculates the ecosystem's effects on atmospheric GHG concentrations throughout the analytical time frame and then translates these changes in concentration into radiative forcing.[36]

Finally, discounting—in other words, calculating the *net present value* (NPV)—may be used to weight radiative forcing impacts based on their timing. Discounting places greater weight on current than on future emissions. One justification for discounting is that earlier emissions may be more likely to determine the fate of climate change in that they could trigger feedback mechanisms or push the climate system past critical damage thresholds.[37] In addition, because society tends to place more

33. Forster et al., *supra* note 11, at 211.

34. Steven J. Smith, *The Evaluation of Greenhouse Gas Indices*, 58 CLIMATIC CHANGE 261, 262 (2003).

35. Anderson-Teixeira & DeLucia, *supra* note 6, at 427; M. O'Hare et al., *Proper Accounting for Time Increases Crop-Based Biofuels' Greenhouse Gas Deficit Versus Petroleum*, 4 ENVTL. RES. LETTERS, Apr.–June 2009, no. 024001, at 1, 6.

36. *See* Anderson-Teixeira & DeLucia, *supra* note 6, at 427.

37. *See, e.g.*, Timothy M. Lenton et al., *Tipping Elements in the Earth's Climate System*, 105 PROC. NAT'L ACAD. SCI. 1786, 1789 (2008).

value on near-term than on long-term costs and benefits, economic and policy applications often apply an annual discount rate to future emissions.[38] Unlike some LCAs that have discounted based on the time of emissions,[39] *GHGV* discounts by the time of climate effect (radiative forcing).

As with T_E and T_A, annual discounting has the strongest effect on ecosystems with high GHG flux or slow release of stored organic material following disturbance (Figure 4c). The importance of GHG exchange later in the ecosystem time period declines with increasing annual discount rate such that, at extremely high discount rates, *GHGV* approaches the value of initial GHG releases from land clearing.

4. *Relationship Between* GHGV *and Global Warming Potential*

Many analyses of the climate effects of emissions—most notably those of the IPCC[40]—use GWPs[41] to translate emissions of a variety of GHGs into CO_2-equivalents. The difference between *GHGV* and this approach is simply that GWP can only be appropriately applied to emissions time frames (our T_E) of one year, whereas *GHGV* is appropriate for a multi-year time frame.[42] GWP is designed to compare emissions that occur *at the same time* and has been appropriately applied for this purpose in annual reporting of GHG emissions under the U.N. Framework Convention on Climate Change (UNFCCC).[43] Analyses become skewed, however, when GWP is applied to emissions that occur over a multiple-year time frame, such as biofuel LCAs.[44] To understand the climate impacts of a land use decision that will affect the atmosphere for many (T_E) years into the future, it is necessary to perform more complex calculations.[45] *GHGV* does so, expressing the climate impact of a land use decision in terms of current CO_2 emissions.

When the timing of emissions is properly accounted for—as in *GHGV*—the impacts of emissions that occur later within the ecosystem time frame are reduced. As a result, *GHGV*s, whether positive or negative, are often reduced relative to values calculated using GWP (Figure 5). *GHGV* may be greater than values calculated using GWP if the ecosystem has positive contributions from organic matter storage and nega-

38. *See, e.g.*, Man-Keun Kim et al., *Permanence Discounting for Land-Based Carbon Sequestration*, 64 ECOLOGICAL ECONOMICS 763, 764 (2008).

39. *See, e.g.*, Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program, 74 Fed. Reg. 24904 (proposed May 26, 2009) (to be codified at 40 C.F.R. pt. 80).

40. Intergovernmental Panel on Climate Change, *supra* note 28, at § 1.11.

41. Forster et al., *supra* note 11, at 137.

42. *See* Anderson-Teixeira & DeLucia, *supra* note 6, at 427–28; O'Hare et al., *supra* note 35, at 1–2.

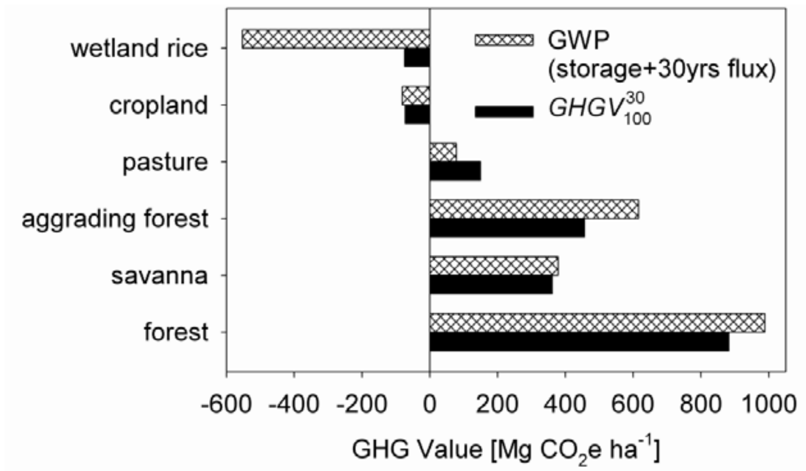
43. *See* O'Hare et al., *supra* note 35, at 1–2.

44. *Id.* at 2.

45. *Id.*

tive contributions from annual flux, as is the case with tropical pasture and wetland rice. Differences may be particularly pronounced with CH_4 emissions contributing strongly to the ecosystem's *GHGV*, as is the case with wetland rice.

FIGURE 5
COMPARISON OF VALUES CALCULATED USING GWP AND *GHGV*[46]



Comparison of the thirty-year costs of clearing an ecosystem (100-year analytical time frame) calculated using GWP and *GHGV* for six tropical ecosystem types.

E. Limitations of GHGV

There remain several challenges to accurately quantifying the biogeochemical climate services of ecosystems. First, accurately calculating *GHGV* requires knowledge of how GHG flux changes as a function of ecosystem age. This is closely tied to the issue of *saturation*, or reduction in GHG sink strength as ecosystems age. While *GHGV* provides an appropriate framework for quantifying the value of an ecosystem whose GHG sink saturates, appropriate data is methodologically difficult to obtain. Current estimates of *GHGV*[47] break the age spectrum into only two classes—"aggrading" and "mature"—which is an oversimplification. In reality, GHG flux changes continuously as ecosystems age.[48] The course of CO_2 flux as a function of ecosystem age, however, remains disputed

46. Modified from Anderson-Teixeira & DeLucia, *supra* note 6, at 435.
47. *Id.*
48. *See, e.g.*, Sebastiaan Luyssaert et al., *Old-Growth Forests as Global Carbon Sinks*, 455 NATURE 213, 214 (2008); G. Philip Robertson et al., *Greenhouse Gases in Intensive Agriculture: Contributions of Individual Gases to the Radiative Forcing of the Atmosphere*, 289 SCIENCE 1922, 1922–23 (2000).

for forests[49] and less resolved for other types of ecosystems. There has been little research on how CH_4 and N_2O flux change as a function of ecosystem age.[50] In some cases, resolving these dynamics will be key to producing reliable estimates of *GHGV*.

A second challenge will be improved treatment of the effects of probable disturbance. The current version of *GHGV* accounts for only one disturbance type and size and does not allow repeat disturbances in the time frame of interest. While valuable in quantifying the effects of infrequent stand-clearing disturbances, *GHGV* will require further development to capture the impacts of a full suite of possible disturbances.

These challenges are compounded by a third challenge: quantifying the effects of climate change on *GHGV*. Climate change will impact ecosystem properties that shape *GHGV*. GHG exchange in virtually every type of terrestrial ecosystem stands to be impacted by climate change.[51] For example, CO_2 sequestration may be reduced by drought[52] or enhanced by CO_2 fertilization,[53] CH_4 emissions may be impacted either way by altered hydrology,[54] N_2O emissions may be impacted by altered nitrogen cycles and hydrology,[55] and anthropogenic emissions from land management may change as management practices adapt to altered climatic conditions. Moreover, the frequency of natural disturbances such as wildfires, drought-related forest dieback, and hurricanes is likely to increase as a result of climate change,[56] thereby decreasing the stability of ecosystem climate services (lowering *GHGV*). High levels of uncertainty regarding the response of ecosystems to the full suite of climate change factors makes predicting the effects of climate change on *GHGV* particularly challenging.

49. *See, e.g.*, Ben Bond-Lamberty et al., *Net Primary Production and Net Ecosystem Production of a Boreal Black Spruce Wildfire Chronosequence*, 10 GLOBAL CHANGE BIOLOGY 473, 482 (2004); Luyssaert et al., *supra* note 48, at 213; Federico Magnani et al., *The Human Footprint in the Carbon Cycle of Temperate and Boreal Forests*, 447 NATURE 848, 848 (2007).

50. *But see* Matthias Peichl et al., *Carbon Dioxide, Methane, and Nitrous Oxide Exchanges in an Age-Sequence of Temperate Pine Forests*, 16 GLOBAL CHANGE BIOLOGY 2198, 2198–99 (2010); Anders Priemé et al., *Slow Increase in Rate of Methane Oxidation in Soils with Time Following Land Use Change from Arable Agriculture to Woodland*, 29 SOIL BIOLOGY & BIOCHEMISTRY 1269, 1269 (1997); Robertson et al., *supra* note 48, at 1922.

51. *See, e.g.*, Field et al., *supra* note 5, at 4–5.

52. *See, e.g.*, Kristina J. Anderson-Teixeira et al., *Differential Responses of Production and Respiration to Temperature and Moisture Drive the Carbon Balance Across a Climatic Gradient in New Mexico*, 17 GLOBAL CHANGE BIOLOGY 410, 421 (2011).

53. *See, e.g.*, Evan H. DeLucia et al., *Net Primary Production of a Forest Ecosystem with Experimental CO_2 Enrichment*, 284 SCIENCE 1177, 1177 (1999).

54. *See, e.g.*, Field et al., *supra* note 5, at 5.

55. *See, e.g.*, *id.*

56. *See, e.g.*, Craig D. Allen et al., *A Global Overview of Drought and Heat-Induced Tree Mortality Reveals Emerging Climate Change Risks for Forests*, 259 FOREST ECOLOGY & MGMT. 660, 661 (2010); M.E. Mann & K.A. Emanuel, *Atlantic Hurricane Trends Linked to Climate Change*, 87 EOS, TRANSACTIONS, AM. GEOPHYSICAL UNION 233, 233 (2006); A.L. Westerling et al., *Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity*, 313 SCIENCE 940, 943 (2006).

These challenges imply that, whereas *GHGV* can be calculated with reasonable accuracy for short ecosystem time frames, it becomes increasingly uncertain as T_E increases. Developing reasonable estimates of this uncertainty will be key to understanding the limits of the utility of *GHGV* (or any other metric of ecosystem climate services) for guiding land management decisions.

III. BIOPHYSICAL CLIMATE SERVICES

"Biophysical climate services" refers to the regulation of the climate through the exchange of water, energy, and momentum between the land surface and the atmosphere (Figure 1). The two dominant biophysical mechanisms through which ecosystems influence the climate are (1) reflection of solar radiation by the land surface (referred to as the *surface albedo*) and (2) the partitioning of absorbed energy into sensible heat loss and latent heat loss through evapotranspiration (ET).[57] These two mechanisms are responsible for biophysical climate regulation in all of Earth's biomes; however, which process dominates for a given location depends on the biome, the season, and environmental factors.[58]

In many biomes on Earth, the biophysical contributions to regulating the climate exceed the biogeochemical climate contributions. This has important consequences when one makes decisions as to how land will be used for purposes of climate change mitigation or to meet food and energy demands. For example, the conversion of a native forest stand to a row crop may lead to a significant change not only in the storage and flux of carbon, but also in the amount of energy absorbed by the land surface. To correctly assess the potential climate changes resulting from land use conversion, both biogeochemical and biophysical processes must be taken into account.

A. Surface Albedo

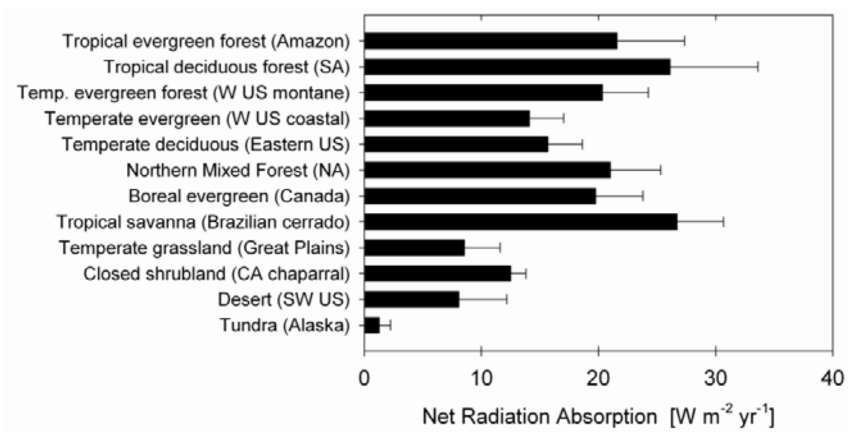
Solar radiation drives the energy and water cycles of ecosystems, heating the air and soil and fueling plant transpiration and evaporation (Figure 1). Not all solar radiation incident on the surface of the Earth is absorbed, however. Some of it is reflected back to the atmosphere. The reflectivity of the land surface has important implications for both the biosphere and the climate. The reflectivity of the land surface is termed the *surface albedo* and varies by land surface type. For example, a patch of dark, wet soil may have an albedo of 0.1, meaning that only ten per-

57. P.K. Snyder et al., *Evaluating the Influence of Different Vegetation Biomes on the Global Climate*, 23 CLIMATE DYNAMICS 279, 297 (2004).

58. *See* Jonathan A. Foley et al., *Global Consequences of Land Use*, 309 SCIENCE 570, 572–73 (2005); Snyder, *supra* note 57, at 297.

cent of the radiation incident on the soil surface will be reflected back to the atmosphere. The remaining ninety percent, therefore, is absorbed by the soil surface. The amount of energy absorbed by a surface also includes longwave radiation (thermal radiation or heat) gained from the atmosphere. Some of the energy absorbed by a surface will also be reradiated back to the atmosphere as longwave (terrestrial) radiation. The net longwave and solar radiation incident on a surface is called the net radiation and it is the energy available for photosynthesis, heating the surface and near-surface soil layers, and the evaporation of water. Depending on the type of LUC that occurs, the amount of net radiation absorbed by the surface may increase or decrease, resulting in a change in the surface air temperature.

FIGURE 6
REDUCTION IN ABSORBED RADIATION THROUGH CLEARING SELECT WESTERN HEMISPHERE ECOSYSTEMS



Integrated Biosphere Simulator (IBIS) model[59] estimates of the reduction in absorbed radiation through clearing of select pan-American ecosystems. The results presented here are based on ten years of climate data representing the 1991–2000 period and are meant to reflect an "average" climate period. The amount of net radiation absorbed by a given surface is calculated in the IBIS model by performing two simulations: (1) a simulation with vegetation in its present location, and (2) a

59. The Integrated Biosphere Simulator (IBIS) is a comprehensive process-based model of land surface and terrestrial ecosystem processes developed for the purpose of studying the response of natural vegetation and carbon, nitrogen, and water cycles (e.g., runoff) to various environmental drivers. IBIS simulates the energy, water, carbon, and momentum balance of the soil-vegetation-atmosphere system. For details, see Jonathan A. Foley et al., *An Integrated Biosphere Model of Land Surface Processes, Terrestrial Carbon Balance, and Vegetation Dynamics*, 10 GLOBAL BIOGEOCHEMICAL CYCLES 603, 605 (1996); Christopher J. Kucharik et al., *Testing the Performance of a Dynamic Global Ecosystem Model: Water Balance, Carbon Balance, and Vegetation Structure*, 14 GLOBAL BIOGEOCHEMICAL CYCLES 795, 796 (2000).

simulation with bare ground. The difference in the net radiation between the two simulations yields the amount of energy absorbed by the surface for that particular biome. Error bars represent one standard deviation of the spatial variation across the biome.

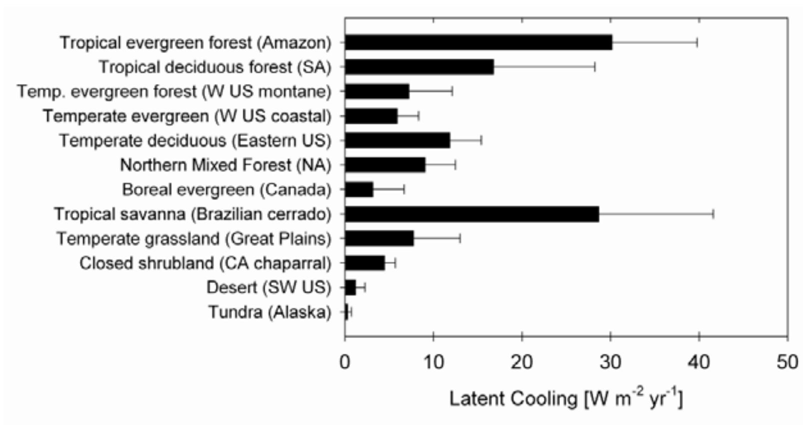
For any ecosystem type, the clearing of vegetation translates into a reduction in net radiation absorbed by the surface and a decrease in the surface air temperature (Figure 6). This is because the presence of vegetation generally lowers the albedo of a land surface (relative to bare ground), resulting in a greater amount of radiation absorbed. In general, ecosystems with more dense vegetation (e.g., forests) absorb more radiation than those with less vegetation (e.g., desert, shrubland, grassland, and tundra) (Figure 6). The direct effects of changes to the reflectivity of vegetation are confounded somewhat by indirect effects through changes in cloudiness, which also affects albedo.

B. Partitioning of Latent and Sensible Heating

Net radiation absorbed by an ecosystem is partitioned primarily into latent and sensible heat loss. *Latent heat loss* occurs through the process of cooling by ET, which consists of both transpiration (a byproduct of photosynthesis) and evaporation of water either from the vegetation surface (intercepted water), water on the ground, or water in the soil (i.e., soil moisture). Because energy is needed to change the phase of water from liquid to gas, ET has a cooling effect (i.e., *latent cooling*). Heat that is not lost through latent cooling is transferred to the atmosphere through *sensible heat loss*, or the cooling of a surface both by the temperature gradient between the surface and the atmosphere as well as the wind and roughness of a surface.

Although clearing of vegetation translates into a reduction in net radiation absorbed by the surface (Figure 6), this does not necessarily imply that removal of vegetation will contribute to global cooling. Depending on water availability and seasonal growth patterns of the vegetation, the cooling effect of ET (Figure 7) may outweigh the warming effect of vegetation's lower albedo relative to bare ground. For example, in tropical rainforests there is both ample water available and a long growing season, such that energy received at the surface is primarily partitioned into latent cooling through ET. The removal of the vegetation decreases evaporative cooling more than it decreases the absorption of radiation, such that deforestation has a net warming effect. In environments that are water limited or have short growing seasons, such as boreal forests or tundra, latent cooling is less significant both because of less energy received as well as a shorter growing season. In this case the albedo effect dominates and the surface cools with removal of the vegetation. In the temperate mid-latitudes, whether an ecosystem influences the atmosphere by way of the albedo effect or latent cooling depends on the time of year and whether snow cover is present.

FIGURE 7
REDUCTION IN EVAPOTRANSPIRATION THROUGH CLEARING OF SELECT WESTERN HEMISPHERE ECOSYSTEMS



IBIS model estimates of reduction in ET through clearing of various types of pan-American ecosystems. The results presented here are based on ten years of climate data representing the 1991–2000 period and are meant to reflect an "average" climate period. The amount of net radiation absorbed by a given surface that is partitioned into latent cooling can be determined for a specific biome by running two simulations: (1) a simulation with vegetation in its present location, and (2) a simulation with bare ground. The difference in the latent heat flux between the two simulations yields the amount of energy that is partitioned into latent cooling by that biome. Error bars represent one standard deviation of the spatial variation across the biome.

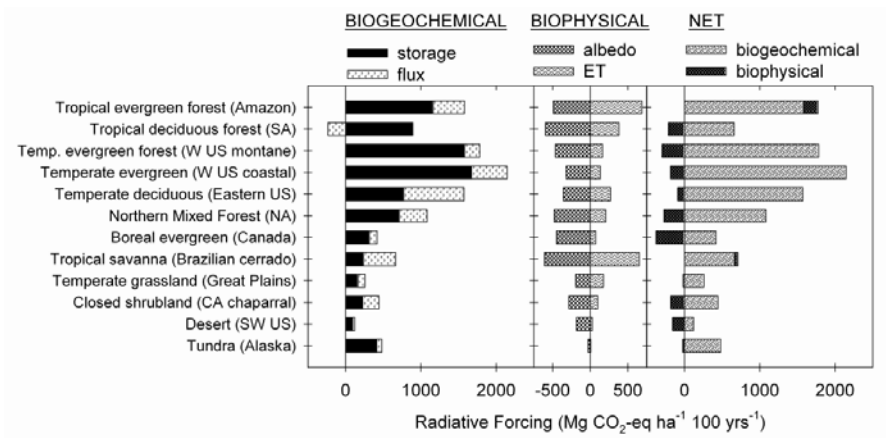
C. Magnitude of Biophysical Forcings Relative to Biogeochemical Forcings

Biophysical climate forcings may be translated into CO_2-equivalents by comparing their climate forcing effects with biogeochemical effects through changes in atmospheric CO_2 concentrations.[60] While there remains a number of challenges to this approach (see below), it allows for comparison of *GHGV*s with the effects of altered albedo and ET, thereby improving quantification of the net climate effects of different land use conversions.

60. *See* Richard A. Betts, *Offset of the Potential Carbon Sink from Boreal Forestation by Decreases in Surface Albedo*, 408 NATURE 187 (2000).

Figure 8 shows biogeochemical and biophysical forcings that would result from clearing various types of ecosystems (in Mg CO_2-equivalent per hectare; $T_E = 100$ years; $T_A = 100$ years). For all of these ecosystems, clearing results in positive biogeochemical forcings through increased atmospheric GHG concentrations, negative biophysical forcing (cooling) effects through increased albedo (Figure 6), and positive biophysical forcing (warming) effects through reduced ET (Figure 7). At this time scale, biogeochemical forcings generally outweigh biophysical forcings, although net biophysical effects rival biogeochemical forcings in Canadian boreal evergreen forests and Southwest North American deserts. In all cases, biophysical forcings have a meaningful influence on climate, highlighting the importance of considering biophysical effects when calculating the total climate impacts of LUC.

FIGURE 8
BIOGEOCHEMICAL AND BIOPHYSICAL RADIATIVE FORCING EFFECTS FROM CLEARING SELECT WESTERN HEMISPHERE ECOSYSTEMS



Comparison of the 100-year costs of clearing various Western hemisphere ecosystems ($T_E = T_A = 100$ years) with respect to (a) biogeochemical forcings (i.e., *GHGV*), (b) biophysical forcings from changes in albedo and ET, and (c) net changes in radiative forcing from biogeochemical and biophysical effects.

D. Challenges to Comparing Biogeochemical and Biophysical Effects

There are a number of challenges to producing a meaningful, objective metric of combined biogeochemical and biophysical radiative forcings. Of primary importance is the fact that these effects act over different temporal and spatial scales.

1. Time Scale

A major difference between biogeochemical and biophysical forcings from LUC is that biogeochemical forcings (changes in atmospheric GHG concentrations) persist over long time scales, even if the ecosystem reverts to its previous condition. In contrast, biophysical forcings could be reversed immediately if the ecosystem were to revert to its previous condition.[61] Therefore, for biophysical forcings, it makes no sense to use a T_A that differs from the T_E, whereas the nature of biogeochemical forcings often makes it desirable to have a T_A that is much greater than T_E. Thus, any metric that combines biogeochemical and biophysical forcings must give very careful attention to the treatment of time. Ideally, T_E and T_A should be equal and long-range (e.g., 100 years; Figure 8); however, this implies considerable uncertainty associated with high T_Es.

2. Spatial Scale

Biogeochemical and biophysical forcings act over very different spatial scales. Whereas biogeochemical forcings are generally assumed to be distributed evenly over the globe because of well-mixed distribution of GHGs in the atmosphere,[62] biophysical forcings affect temperature and precipitation most strongly on local to regional scales. Comparison of the two requires a single spatial scale and, therefore, biophysical radiative forcings are expressed according to their affect on the global atmosphere.[63] A further complication is that climatic forcings in one location may trigger changes in the opposite direction in another location, such that dramatic local climatic changes in various locations average out to minimal average changes on the global scale. Therefore, representing

61. In certain ecosystems extreme land cover change may result in a slow succession back to the original ecosystem assuming the local or regional climate can support it (e.g., northeastern U.S. temperate forests). In other ecosystems (e.g., the northern fringe of the African Sahel), however, the precipitation regime and other environmental factors may be irreparably altered such that return of the ecosystem is unlikely.

62. This assumption is not completely correct, as indicated by recent NASA AIRS data. M.T. Chahine, *Satellite Remote Sounding of Mid-Tropospheric CO_2*, 35 GEOPHYSICAL RES. LETTERS, Sept. 9, 2008, L17807, at 1.

63. *See, e.g.*, Betts, *supra* note 60, at 188; J.T. Randerson et al., *The Impact of Boreal Forest Fire on Climate Warming*, 314 SCIENCE 1130, 1130 (2006).

biogeochemical and biophysical forcings using a single metric presents an ongoing challenge.

IV. EVALUATION OF LUC TREATMENT IN BIOFUELS LCAS

Over the past several years, the theory underlying biofuels LCAs has been evolving rapidly. This Part assesses the treatment of GHG forcings, biophysical forcings, and time in biofuels LCAs; discusses remaining limitations; and provides some science-based guidelines for treatment of LUC in future LCAs.

A. GHG Forcings

1. Assessment of Treatment in LCAs

Biofuels LCAs have become increasingly comprehensive in their treatment of the GHG impacts of LUC. Over the past few years, biofuels LCAs have evolved rapidly from including only the GHG effects of the biofuel crop ecosystem, if even that, to including the GHG effects of both direct and indirect LUC (Table 1). Recent LCAs incorporate most of the terms included in *GHGV*, although none are comprehensive.

TABLE 1
TREATMENT OF GHGS FROM LAND USE CHANGE IN BIOFUELS LCAS[64]

	DIRECT LUC					INDIRECT LUC					
	Biofuel		Displaced			New		Displaced			
	Storage[65]	Flux	Storage	Flux	Nat Dist	Storage[66]	Flux	Storage	Flux	Nat Dist	Climate Change
Academic Articles											
Righelato[67]	-	ns[68]	C	C	-	-	-	-	-	-	-
Fargione[69]	(C)	ns[70]	C	-	-	-	-	-	-	-	-
Searchinger[71]	-	+	-	(M, N)[72]	n/a	-	(M, N)[73]	C	C	(C)[74]	-
Piñeiro[75]	-	(+)[76]	(C)[77]	(C)[78]	-	-	-	-	-	-	-
O'Hare[79]	C	ns	C	(C)[80]	-	C	ns	C	(C)[81]	(C)[82]	-
Melillo[83]	C	C, N	C	C, N	-	C	C, N	C	C, N	-	+[84]

64. Symbology is as follows: '+' indicates that all significant CO_2, CH_4, and N_2O exchanges are accounted for; 'C' indicates accounting for CO_2 exchanges; 'M' indicates accounting for methane (CH_4) exchanges; 'N' indicates accounting for N_2O exchanges; '-' indicates that no GHG exchanges are accounted for; parentheses indicate partial accounting; 'v' indicates that the framework allows the element to vary; 'ns' indicates that treatment of the term is not specified in the primary article or standard or its supporting documentation of methodology; and 'n/a' signifies that the element is not applicable. The table does not assess quality or accuracy of data used—only whether a given element is considered.

65. Refers to (temporary storage) in biomass. C accumulation in soil would be considered a flux.

66. Refers to (temporary storage) in biomass. C accumulation in soil would be considered a flux.

67. Renton Righelato & Dominick V. Spracklen, *Carbon Mitigation by Biofuels or by Saving and Restoring Forests?*, 317 SCIENCE 902, 902 (2007).

68. Data obtained from a variety of published LCAs.

69. Fargione et al., *supra* note 15, at 1235–37.

70. Data obtained from a variety of published LCAs.

71. Searchinger et al., *supra* note 2, 1238–40.

72. Assumes that emissions from producing replacement grain equal those of grain production displaced by biofuels.

73. Assumes that emissions from producing replacement grain equal those of grain production displaced by biofuels.

74. Implicitly accounted for in the case of regrowing forests.

75. Gervasio Piñeiro et al., *Set-Asides Can Be Better Climate Investment Than Corn Ethanol*, 19 ECOLOGICAL APPLICATIONS 277 (2009).

76. CO_2 flux includes changes in soil carbon only. CH_4 and N_2O data are obtained from a variety of sources and may not be complete.

77. Changes in soil carbon only.

78. Quantifies changes in soil carbon only.

79. O'Hare et al., *supra* note 35, at 1–7.

80. Includes displaced C flux from clearing of forests only.

81. Includes displaced C flux from clearing of forests only.

82. Implicitly accounted for in the case of regrowing forests.

83. Jerry M. Melillo et al., *Indirect Emissions from Biofuels: How Important?*, 326 SCIENCE 1397 (2009).

	DIRECT LUC					INDIRECT LUC					
	Biofuel		Displaced			New		Displaced			
	Storage[65]	Flux	Storage	Flux	Nat Dist	Storage[66]	Flux	Storage	Flux	Nat Dist	Climate Change
Hertel[85]	C	ns	C	(C)[86]	-	C	ns	C	(C)[87]	(C)[88]	-
Lapola[89]	ns	ns	C	-	-	(C)	-	C	-	-	-
Sustainability Standards											
UK RTFO[90]	C	N	C	-	-	-	-	-	-	-	-
EU RED[91]	C	C	C	-	-	-	-	-	-	-	-
CA LCFS[92]	-	(+)[93]	(C)	M, N	n/a	C	M, N	C	(+)[94]	(C)[95]	-
US RFS[96]	+[97]	+	+[98]	+	n/a	+[99]	+	+	(+)[100]	-	-
US RFS2[101]	+	+	+	+	n/a	+	+	+	(+)[102]	-	-
Frameworks											
GBEP[103]	-	+	C	-	-	-	-	C	-	-	-
GHGV[104]	+	+	+	+	+	+	+	+	+	+	-

84. Includes effects of CO_2 fertilization, climate change and variability, and ozone.

85. Thomas W. Hertel et al., *Effects of US Maize Ethanol on Global Land Use and Greenhouse Gas Emissions: Estimating Market-Mediated Responses*, 60 BIOSCIENCE 223 (2010).

86. Includes displaced CO_2 flux from clearing of forests only.

87. Includes displaced CO_2 flux from clearing of forests only.

88. Implicitly accounted for in the case of regrowing forests.

89. David M. Lapola et al., *Indirect Land-Use Changes Can Overcome Carbon Savings from Biofuels in Brazil*, 107 PROC. NAT'L ACAD. SCI. 3388 (2010).

90. U.K.'s 2007 Renewable Transport Fuel Obligation. GHG methodology is described in AUSILIO BAUEN ET AL., E4TECH, CARBON REPORTING WITHIN THE RENEWABLE TRANSPORT FUEL OBLIGATION—METHODOLOGY 4–28 (2008).

91. Council Directive 2009/28, 2009 O.J. (L 140) 16, 52–59 (EC).

92. CAL. ENVTL. PROT. AGENCY, STAFF REPORT: INITIAL STATEMENT OF REASONS, PROPOSED REGULATION TO IMPLEMENT THE LOW CARBON FUEL STANDARD, at IV-1 to IV-51 (2009).

93. For CO_2, emissions from lime only.

94. Includes displaced CO_2 sequestration from clearing of forests only and CH_4 and N_2O fluxes for agricultural lands only.

95. Implicitly accounted for in the case of regrowing forests.

96. Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program, 74 Fed. Reg. 24904 (proposed May 26, 2009) (to be codified at 40 C.F.R. pt. 80).

97. It is not specified whether carbon in aboveground biomass and roots in cropland is included.

98. It is not specified whether carbon in aboveground biomass and roots in cropland is included.

99. Misses CH_4 and N_2O fluxes in unmanaged ecosystems, which are generally minimal.

100. U.S. ENVTL. PROT. AGENCY, *supra* note 3, at 3–7.

101. Misses CH_4 and N_2O fluxes in unmanaged ecosystems, which are generally minimal.

102. GLOBAL BIOENERGY P'SHIP, THE GBEP COMMON METHODOLOGICAL FRAMEWORK FOR GHG LIFECYCLE ANALYSIS OF BIOENERGY 7–32 (2009).

103. Anderson-Teixeira & DeLucia *supra* note 6.

104. It is not specified whether carbon in aboveground biomass and roots in cropland is included.

Beyond the simple exclusion or inclusion of terms, it is important to consider which terms carry the most weight (i.e., have the greatest GHG effect). While this depends strongly on the type(s) of ecosystem(s) under consideration (Figure 2), a few generalizations may be made. First, the single most influential component in biofuels LCAs is typically the storage term of directly or indirectly displaced native ecosystems,[105] which consists primarily of CO_2 release. All of the more recent (post-2008) analyses reviewed here contain at least the CO_2 portion of this term; few include the CH_4 and N_2O that would be released through land-clearing fires.[106] Displaced CO_2 flux of natural ecosystems may also be important, particularly in the case of abandoned agricultural land;[107] this is accounted for in some LCAs. Another highly influential term is N_2O emissions from managed ecosystems;[108] this is accounted for in most recent analyses. Annual CH_4 flux can be meaningful when pastures or wetlands are involved, and have typically been counted in analyses that involve these land types.[109] For perennial grass biofuel crops, soil carbon sequestration (CO_2 flux) can be somewhat substantial;[110] many LCAs of perennial biofuel crops account for this. Terms that are relatively small—e.g., CH_4 and N_2O release from land clearing fires, carbon storage in crop ecosystems, CO_2 flux in agricultural ecosystems, and annual CH_4 and N_2O flux in native ecosystems—are commonly ignored (Table 1). While small in relation to terms such as CO_2 release from land clearing, they are not necessarily negligible; for example, CH_4 and N_2O release from land clearing fire in tropical forests are on the order of 30 Mg CO_2e ha^{-1} (Figure 2a).

Notably missing from most analyses is treatment of the effects of potential natural disturbances and impacts of climate change. Consideration of the potential for natural disturbances can reduce the *GHGV* of forests (Figure 3); for example, forests with a thirty percent chance of experiencing a catastrophic fire during a thirty-year time span would have their *GHGV*s reduced by about ten to twenty-five percent. Biofuels LCAs that employ the "Woods Hole" carbon data set[111] implicitly account for the effects of disturbance in regrowing forests, but not in mature forests. The total effect of probable natural disturbance on biofuels LCAs has not yet been evaluated. The issue is complicated by the fact that climate change is increasing the frequency of several types of natural

105. Fargione et al, *supra* note 15, at 1237; Searchinger et al., *supra* note 2, at 1238.
106. *See supra* Table l.
107. Piñeiro et al., *supra* note 75, at 281; Righelato & Spracklen, *supra* note 67, at 902.
108. Edward M.W. Smeets et al., *Contribution of N_2O to the Greenhouse Gas Balance of First-Generation Biofuels*, 15 GLOBAL CHANGE BIOLOGY 1, 19 (2009).
109. *See supra* Table l.
110. Anderson-Teixeira et al., *supra* note 23, at 80–83.
111. CAL. ENVTL. PROT. AGENCY, *supra* note 92, at IV-21; Hertel et al., *supra* note 85, at 225; O'Hare et al., *supra* note 35, at 4; Searchinger et al., *supra* note 2, at 1239 n.2.

disturbance[112] and is also likely to have profound effects on agricultural ecosystems.[113]

Only one analysis to date considers the effects of climate change.[114] This study uses predicted future climatic conditions to drive the terrestrial ecosystem model that simulates carbon and nitrogen dynamics in both natural and managed ecosystems, but it does not discuss how climate change affects the outcome of the analysis. There is a strong need, therefore, to clarify how climate change will impact LCAs through its effects on both natural and managed ecosystems. Moreover, no analysis to date considers how predicted increases in natural disturbance rates[115] will impact LCAs.

2. *Remaining Limitations and Recommendations*

As discussed above, biofuels LCAs have become fairly comprehensive in their inclusion of significant GHG contributions from ecosystems, although the probable effects of disturbance and climate change generally are not considered, thus potentially having a substantial effect on analysis outcomes. In addition, LCAs, as a body, are inconsistent in their inclusion of GHG terms (Table 1), highlighting the need for a consistent framework for quantifying the GHG contributions of ecosystems. *GHGV*,[116] as discussed above, is the most comprehensive framework available for valuing an ecosystem's biogeochemical climate services.

B. *Biophysical Forcings*

To date, no biofuels LCAs account for the biophysical climate forcings associated with LUC. There is, however, widespread recognition of this omission.[117] There is also evidence that widespread deployment of biofuel crops may be sufficient to alter regional climates; for example, large-scale replacement of corn-soy fields to perennial grasses like switchgrass or miscanthus may produce regional cooling in the Midwestern United States.[118] Because of the strong climatic influence of biophysical forcings, which outweigh the climate forcings from GHGs in

112. *See, e.g.*, Allen et al., *supra* note 56, at 668–71; Mann & Emanuel, *supra* note 56, at 241–44; Westerling et al., *supra* note 56, at 942–43.

113. INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2007: IMPACTS, ADAPTATION AND VULNERABILITY 38–40 (Martin Parry et al. eds., 2007).

114. Melillo et al., *supra* note 83, at 1397.

115. *See, e.g.*, Allen et al., *supra* note 56, at 661; Mann & Emanuel, *supra* note 56, at 233; Westerling et al., *supra* note 56, at 940–42.

116. Anderson-Teixeira & DeLucia, *supra* note 6, at 427.

117. *See, e.g.*, Christopher B. Field et al., *Biomass Energy: The Scale of the Potential Resource*, 23 TRENDS IN ECOLOGY & EVOLUTION 65, 67 (2008); O'Hare et al., *supra* note 35 at 1, 2.

118. M. Georgescu et al., *Potential Impact of U.S. Biofuels on Regional Climate*, 36 GEOPHYSICAL RES. LETTERS, Nov. 10, 2009, L21806, at 3.

some situations (Figure 8),[119] there is an urgent need for scientific research on how biophysical forcings would contribute to the climate effects of biofuels-related LUC. Inclusion of biophysical forcings in LCAs will be absolutely imperative to accurately quantify the climate effects of biofuels-related LUC.

C. Treatment of Time

1. Assessment of Treatment in LCAs

Treatment of time is an important cause of variation in the outcomes of biofuels LCAs.[120] This is particularly true when there are substantial GHG emissions from LUC,[121] as LUC generally creates a substantial GHG "debt"[122] that is repaid over time through the annual benefits of fossil fuel displacement, resulting in very different emissions profiles of biofuels and a fossil fuel baseline. Similarly to *GHGV*, several decisions on the treatment of time influence LCA results.

a. Emissions Time Frame

First, analyses are sensitive to the choice of an emissions time frame, or the assumed period of ethanol production. This has been referred to by terms such as "time period,"[123] "project horizon,"[124] or "production period."[125] When LUC is assumed to occur in the first year, as is the case with most biofuels LCAs, this is identical to T_E, the "ecosystem" or "emissions" time frame of *GHGV*. However, if an LCA were to assume—more realistically—that LUC would occur over multiple years, the analysis time frame would be distinct from T_E.

Emissions time frames in biofuels LCAs have varied widely (Table 2), thereby introducing variation in LCA outcomes.[126] Recently, major sustainability standards have selected time frames of twenty years (Europe: UK RTFO[127] and EU RED[128]) or thirty years (United States: CA

119. *See, e.g.*, Betts, *supra* note 60, at 189.

120. Sarah C. Davis et al., *Life-Cycle Analysis and the Ecology of Biofuels*, 14 TRENDS PLANT SCI. 140, 144 (2009).

121. *See, e.g.*, Fargione et al., *supra* note 15, at 1237; O'Hare et al., *supra* note 35, at 1–2.

122. The term "carbon debt" has been used to refer to CO_2 emissions from land clearing by Fargione et al., *supra* note 15, at 1235–36. As other GHGs may also be released through burning, this may be more properly referred to as "GHG debt."

123. Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program, 74 Fed. Reg. 24904 (proposed May 26, 2009) (to be codified at 40 C.F.R. pt. 80); U.S. ENVTL PROT. AGENCY, *supra* note 3, at 221.

124. CAL. ENVTL. PROT. AGENCY, *supra* note 92, at IV-23.

125. O'Hare et al., *supra* note 35, at 1.

126. *See, e.g.*, Davis et al., *supra* note 120, at 143.

127. AUSILIA BAUEN ET AL., E4TECH, THE RSB GHG ACCOUNTING SCHEME: FEASIBILITY OF A META-METHODOLOGY AND WAY FORWARD 36–37, 61 tbl.13 (2009).

LCFS[129] and US RFS2[130]). The longer time frames of the U.S. standards imply that, all else being equal, U.S. standards are more lenient in allowing more time for biofuels to repay any GHG debt associated with LUC.

b. Analytical Time Frame

GHG LCAs are sensitive to T_A—the "analytical" time frame over which climate effects are analyzed, or how many years into the future impacts are considered. Because different GHGs remain in the atmosphere for different lengths of time, their effects relative to CO_2 (i.e., CO_2e) vary as a function of T_A. Moreover, when the timing of emissions is properly accounted for (see below), the effects of future emissions—expressed relative to current emissions as CO_2e—vary as a function of T_A.

Most biofuels LCAs indirectly select a T_A of 100 years through use of the IPCC's GWP values for a 100-year time horizon. It must be noted, however, that improper accounting for the timing of emissions in most analyses implies that there is no single T_A for the entire analysis; rather, the effects of emissions from each year are evaluated 100 years into the future.

c. Treatment of Timing

The outcome of LCAs depends upon the treatment of the timing of emissions. There are several aspects to this. First, LUC may be assumed to occur either immediately or over multiple years following the initiation of biofuels production. Almost all LCAs assume that LUC will occur immediately; however, in reality, it is more likely that LUC—particularly indirect LUC—will occur over many years. Within a set analytical time frame, delayed LUC would have slightly smaller effects than immediate LUC.

Second, analyses may or may not be sensitive to the timing of GHG exchange between the ecosystem and the atmosphere; for example, CO_2 destined to be released by clearing a forest may be counted in the year of clearing, or it may be assumed that decomposition of wood products and CO_2 release from the soil occur over many years. Increasingly, many LCAs model—albeit simplistically—the timing of ecosystem-atmosphere exchange. If an analysis is sensitive to the timing of emissions, this has the overall effect of slightly reducing the costs of LUC; however, some

128. Council Directive 2009/28, 2009 O.J. (L 140) 28 (EC); BAUEN ET AL., *supra* note 127, at 36–37, 61 tbl.13.
129. CAL. ENVTL. PROT. AGENCY, *supra* note 92, at ES-3.
130. U.S. ENVTL. PROT. AGENCY, *supra* note 3, at 41.

LCAs that give explicit treatment to the timing of ecosystem-atmosphere exchanges lack an overall sensitivity to the timing of emissions (Table 2).

Third, emissions that occur over a multi-year time span may or may not be properly translated into radiative forcing impact.[131] Only one of the analyses reviewed here[132] accounts for the timing of CO_2 emissions[133] when calculating the climate impact of biofuels production over a multiple-year time span. This analysis shows that proper accounting for the timing of emissions makes biofuels less favorable relative to petroleum because, by any future date, upfront GHG emissions from LUC would impact the climate more strongly than GHG exchanges that occur over an extended time period.

Finally, discounting may or may not be applied to weight emissions—or, more properly, radiative forcing impacts—based on their timing. Most LCAs, including all the major sustainability standards, do not discount based on the timing of emissions.

131. *See* O'Hare et al., *supra* note 35, at 2; *supra* Part II.D.3–4.

132. O'Hare et al., *supra* note 35, at 5.

133. This analysis converts CH_4 and N_2O emissions to CO_2e before accounting for the effects of time, which is technically incorrect, but introduces relatively small amounts of error.

TABLE 2
TREATMENT OF TIME IN BIOFUELS LCAS[134]

			Sensitivity to Timing of Emissions				
	T_E[135]	T_A[136]	Timing of Indirect LUC	Ecosystem-Atmosphere Exchange	Radiative Forcing Impact[137]	Discounting[138]	Overall[139]
Academic Articles							
Righelato[140]	30	ns[141]	n/a	-	-	-	-
Fargione[142]	50[143]	ns[144]	n/a	-	-	-	-
Searchinger[145]	30	ns	-	-	-	-	-
Piñeiro[146]	93	ns	n/a	+	-	+	+
O'Hare[147]	25	0-100	-	(+)[148]	(+)[149]	-,+	+

134. Notation: '+' and '-' indicate sensitivity or lack thereof, respectively, to a particular aspect of timing; parentheses indicate partial treatment; 'v' indicates that the framework allows the element to vary; 'ns' indicates that treatment of the term is not specified in the primary article or standard or its supporting documentation of methodology; and 'n/a' signifies that the element is not applicable.

135. '≤' indicates that the entire LCA used the given number of years; however, LUC does not necessarily occur in the first year.

136. '100(+)' signifies application of 100-year GWP metric over a multiple-year time frame. Because the effects of all emissions are counted 100 years into the future from the time they occur, the actual T_A ranges from 100 to $100+T_E$.

137. Refers to translation of emissions into radiative forcing using proper accounting for the timing of emissions; also known as "fuel warming potential." O'Hare et al., *supra* note 35, at 3.

138. Also known as calculation of net present value (NPV).

139. Refers to overall sensitivity to the timing of emissions. An analysis may give explicit treatment to the timing of ecosystem-atmosphere exchanges, but the overall analysis will only be sensitive to time if this is combined with translation of GHG emissions to radiative forcing or discounting based on the timing of emissions.

140. Righelato & Spracklen, *supra* note 67, at 902.

141. Data obtained from a variety of published LCAs.

142. Fargione et al., *supra* note 15, at 1235.

143. This analysis focuses on "payback time," or the T_E required for annual GHG benefits from biofuels to outweigh the upfront GHG costs of LUC.

144. Data obtained from a variety of published LCAs.

145. Piñeiro et al., *supra* note 75, at 277.

146. Searchinger et al., *supra* note 2, at 1238.

147. O'Hare et al., *supra* note 35, at 1.

148. For LUC outside of the United States, assumes immediate loss of all biomass, which is generally not realistic.

149. Only CO_2 emissions were properly translated into radiative forcing. CH_4 and N_2O are converted to CO_2-equivalents (time horizon not specified) and then treated as CO_2.

			Sensitivity to Timing of Emissions				
	T_E[135]	T_A[136]	Timing of Indirect LUC	Ecosystem-Atmosphere Exchange	Radiative Forcing Impact[137]	Discounting[138]	Overall[139]
Melillo[150]	≤100[151]	ns	+	+	-	-	(+)
Hertel[152]	30	100(+)	-	+	-	-	-
Lapola[153]	n/a[154]	ns	-	-	-	-	-
<u>*Sustainability Standards*</u>							
UK RTFO[155]	20	100(+)	n/a	-	-	-	-
EU RED[156]	20	100(+)	n/a	-	-	-	-
CA LCFS[157]	30	100(+)	-	(+)[158]	-[159]	-	-
US RFS[160]	30,100	100(+)	-	(+)[161]	-	-,+	-
US RFS2[162]	30	100(+)	-	(+)[163]	-	-	-
<u>*Frameworks*</u>							
GBEP[164]	V	v	-	-	-	-	-
GHGV[165]	V	v	n/a	+	+	+/-	+

150. Melillo et al., *supra* note 83, at 1397.
151. The time frame of the entire LCA was 100 years; however, LUC does not necessarily occur in the first year.
152. Hertel et al., *supra* note 85, at 223.
153. Lapola et al., *supra* note 89, at 3388.
154. This analysis focuses on "payback time," or the T_E required for annual GHG benefits from biofuels to outweigh the upfront GHG costs of LUC.
155. U.K.'s 2007 Renewable Transport Fuel Obligation. GHG methodology is described in BAUEN ET AL., *supra* note 90, at 4–28.
156. Council Directive 2009/28, 2009 O.J. (L 140) 16, 52–59 (EC).
157. CAL. ENVTL. PROT. AGENCY, *supra* note 92, at IV-1 to IV-51.
158. Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard, 74 Fed. Reg. 24904 (proposed May 26, 2009) (to be codified at 40 C.F.R. pt. 80).
159. Assumes immediate loss of all aboveground biomass, which is generally not realistic.
160. The "fuel warming potential" approach of O'Hare et al., *supra* note 35, was considered, and may be used in the future.
161. For LUC outside of the United States, assumes immediate loss of all biomass, which is generally not realistic.
162. U.S. ENVTL. PROT. AGENCY, *supra* note 3, at 22.
163. For LUC outside of the United States, assumes immediate loss of all biomass, which is generally not realistic.
164. GLOBAL BIOENERGY P'SHIP, *supra* note 102, at iii.

2. *Remaining Limitations and Recommendations*

The treatment of time in biofuels LCAs remains inconsistent and gives insufficient attention to the timing of emissions (Table 2). There is a need for a more careful, deliberate treatment of time, and for more thorough consideration of how the treatment of time affects the outcome of LCAs.

a. Selection of T_E and T_A

Selection of T_E and T_A is primarily a policy—as opposed to a scientific—decision. There are, however, several scientific considerations that may help to guide these decisions. With regard to T_E, a reasonable choice would be the expected duration of biofuels production, as has been used as a criterion in the past.[166] Beyond the enormous uncertainty as to how long biofuels production would continue, a major limitation to this is that land use patterns would not revert to their previous state after the cessation of biofuels production. Other considerations include: (1) T_E should not be too short to capture the GHG release fated to occur by land clearing,[167] and (2) T_E could be excessively long if it exceeds the time frame over which conditions can be expected to remain reasonably predictable. In particular, the high likelihood that global change will impact annual GHG exchange and disturbance frequency in many ecosystems[168] and uncertainty as to future land use patterns imply increasing uncertainty at longer time scales.

As with T_E, choice of T_A is subjective. Because a T_A of 100 years has been used in most LCAs (Table 2), and because of the prominence of the IPCC's 100-year time horizon GWP metric,[169] there is strong precedent for the use of a 100-year time frame. While outcomes of analyses are sensitive to T_A (Figure 4b), 100 years is not an unreasonable choice.

There is an inherent tension between a limited time span of certainty regarding land use and ecosystem characteristics and the desire to evaluate the long-term climate consequences of land use decisions. On the one hand, high uncertainty regarding future conditions of ecosystems and land use patterns implies that highly reliable estimates of ecosystem climate services are possible only for relatively short T_Es. Moreover, to capture the full effects of the ecosystem-atmosphere exchanges that oc-

165. Anderson-Teixeira & DeLucia, *supra* note 6.
166. *See, e.g.*, O'Hare et al., *supra* note 35, at 3; Righelato & Spracklen, *supra* note 67, at 902; Searchinger et al., *supra* note 2, at 1239.
167. This time varies widely across ecosystem types. It generally increases with organic matter storage.
168. *See, e.g.*, Field et al., *supra* note 5, at 9, 20; O'Hare et al., *supra* note 35, at 6; Righelato & Spracklen, *supra* note 67, at 902; Searchinger et al., *supra* note 2, at 1240.
169. Forster et al., *supra* note 11, at 129, 206, 211.

cur over T_E, T_A should exceed T_E by at least fifty years. On the other hand, if T_E is less than T_A, there is a period when the effects of LUC are (unrealistically) assumed to disappear (i.e., the land is assumed to instantly revert to its original condition). Thus, for a full analysis of the climate change impacts of land use decisions relative to a certain target date, T_E and T_A should both equal the number of years until that target date.

Decisions regarding the treatment of time are particularly influential for ecosystems with high annual GHG flux or slow release of stored organic material (e.g., wetlands, aggrading ecosystems, and managed ecosystems). As biofuels LCAs invariably involve such ecosystems, careful justification of the choice of the T_E and the T_A is particularly important.

b. Treatment of Timing

Currently, most LCAs are insensitive to the timing of emissions, and none give thorough treatment to all aspects that must be considered to accurately determine the climate impact of biofuels-related LUC (Table 2). Future LCAs should give consideration to: (1) the timing of LUC, (2) the timing of ecosystem-atmosphere exchanges following LUC, (3) time-sensitive translation of GHG exchanges into radiative forcing impacts,[170] and (4) the appropriateness of discounting.

Regarding the latter, the application of a discount rate is appropriate when considering economic costs and benefits; however, it is not appropriate to apply discounting to the purely physical phenomena (i.e., GHG emissions or resulting radiative forcing).[171] Likewise, from a physical standpoint, discounting is not an appropriate method for offsetting future uncertainty, as it implies reduced impacts of future GHG exchanges, whereas uncertainty implies that their impacts could be smaller *or larger* than predicted. Rather, the purely physical effects of the timing of emissions should be accounted for using proper translation of a time course or GHG emissions into radiative forcing.[172]

V. POLICY IMPLICATIONS AND CONCLUSIONS

Biofuels LCAs and the policies based upon them rely upon the widely accepted premise[173] that carbon sequestration by terrestrial ecosystems is completely fungible with GHGs from other sources. This assumption is violated in all current LCAs, which are hampered by (1) lack

170. *See* O'Hare et al., *supra* note 35, at 3, 6; *supra* Part II.D.3–4.
171. *See, e.g.*, O'Hare et al., *supra* note 35, at 4.
172. *See id.*; *supra* Part II.D.3–4.
173. *See, e.g.*, Marland et al., *supra* note 4, at 150, 154–55.

of a thorough, consistent framework for calculating the *GHGV* of ecosystems (Table 1); (2) failure to treat biophysical effects of LUC; and (3) inconsistent and improper treatment of time (Table 3). Thus, the calculated GHG effects of LUC in current biofuel LCAs are *not equivalent* to GHG emissions from other sources. This violates the foundational assumption of LCAs that GHG savings or emissions from biofuel production are being realistically compared to those of LUC.

As demonstrated here and elsewhere in this issue,[174] uncertainty regarding the climate impacts of biofuels-related LUC remains high. There is urgent need to assess how the story might change when the climate impacts of LUC are properly quantified. The most influential factors that are not currently given adequate attention include probable effects of climate change and natural disturbance, accounting for biophysical effects, and the treatment of time. Moreover, LCA outcomes remain inconsistent because of variation in both the comprehensiveness of inventories (i.e., terms included) and system boundaries (e.g., time frames considered).[175]

Given the rapid pace of biofuels policy developments, there is an urgent need to assess the impacts of biofuels-related LUC. At present, because LCAs only partially quantify the climate services of ecosystems, biofuels policies run the risk of failing to advance the best climate solutions or even being counterproductive.[176] It is important to note that even thorough quantification of ecosystem climate services would fail to account for a host of other ecosystem services such as regulation of water flow and quality, preservation of habitats and biodiversity, food production, and utilization by native and marginalized peoples. As placing a value on such services remains a challenge,[177] GHG emissions from biofuels-related LUC will never be completely fungible with GHG emissions from other sources. For this reason, biofuels policy should proceed with extreme caution when introducing measures that may trigger LUC.

174. *See* Daniel A. Farber, *Indirect Land Use Change, Uncertainty, and Biofuels Policy*, 2011 U. ILL. L. REV. 381; David Zilberman et al., O*n the Inclusion of Indirect Land Use in Biofuels Regulation*, 2011 U. ILL. L. REV. 413.

175. Davis et al., *supra* note 120, at 143–44.

176. *See, e.g.*, Jackson et al., *supra* note 4, at 4; Marland et al., *supra* note 4, at 150, 155–56.

177. *See, e.g.*, Stephen R. Carpenter et al., *Science for Managing Ecosystem Services: Beyond the Millennium Ecosystem Assessment*, 106 PROC. NAT'L ACAD. SCI. 1305, 1308 (2009).