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September 27, 2011

California Air Resources Board
James Goldstene, Executive Officer
1001 I Street, Sacramento, California

Submitted via weblink at:
http://www.arb.ca.gov/lispub/comm/bcsubform.php?listname=capandtrade10&comm_period=2

Re: Second Set of Proposed Modifications to the AB 32 Greenhouse Gas Cap-and-Trade Regulation (Second 15-Day Changes)

Dear Mr. Goldstene and members of the California Air Resources Board:

On behalf of our more than 300,000 members and activists, the Center for Biological Diversity submits these comments on the proposed modifications to the AB 32 Greenhouse Gas Cap-and-Trade regulation ("proposed modifications"). These comments focus on the sections of the Cap-and-Trade regulation related to offset credits, the forest offset protocol, forest biomass combustion, and the adaptive management program to mitigate environmental impacts to forests.

The proposed modifications include many improvements and clarifications, and we commend the staff of the California Air Resources Board ("ARB") for their thoughtful work on this rule and their commitment to implementing California's landmark effort to reduce statewide greenhouse gas ("GHG") pollution. However, the proposed modifications also include provisions that fail to address serious problems previously identified in the rule, and are silent on a number of points where modification of the rule is sorely needed.

The Center for Biological Diversity submitted extensive comments on the proposed Cap-and-Trade regulation on December 15, 2010 and the first set of proposed modifications on August 11, 2011. Those comments remain relevant to the revised regulation as proposed in the second 15-day notice, and are hereby incorporated by reference in their entirety. We ask that all of our previous comments on the Cap-and-Trade regulation, and all exhibits to those comments, be included in the administrative record of proceedings in this matter.

1. Determinations based on specific standardized criteria are needed to ensure that offset protocols fulfill the requirements identified in AB 32 and the Cap-and-Trade regulation.

As we have stated in our previous comment letters, the establishment of specific, standardized, quantitative criteria to be applied in the review of compliance offset protocols is critical to providing clarity, transparency, and consistency in offset protocols and the offset credits they generate. The Cap-and-Trade regulation should identify explicit determinations, based on standardized criteria, that ARB will apply in their evaluation of all offset protocols. For

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example, the regulation should require specific determination of the risk of non-additionality, reversal, and leakage associated with an offset protocol, based on a quantitative analysis with explicit standards. This determination should be provided in the context of the volume of offset credits an offset protocol is expected to generate, and also should include a comparison of these factors among project types within an offset protocol and among offset protocols.

To offer a specific example taken from Section 95792: "To be approved by the Board, a Compliance Offset Protocol must . . . (6) Ensure GHG emission reductions and GHG removal enhancements are permanent." This critical requirement is presented in the regulation here, and only here, as a general finding made by ARB upon adoption of an offset protocol. The permanence of GHG reductions, and the board's understanding of the risks associated with the protocol, would be much better assured if this provision required ARB to make a specific determination of the permanence of the credits provided by the protocol, based on a quantitative analysis of the persistence of the associated reductions, risk of reversals, and a comparison of those risks among different offset project types.

As stated in our previous comment letters, ARB's proposed regulation similarly lacks standards and safeguards necessary to ensure that offsets are "additional" as required by AB 32. AB 32 requires ARB to ensure that emissions reductions achieved through a market-based compliance program are "in addition to any greenhouse gas emission reduction otherwise required by law or regulation, *and* any other greenhouse gas emission reduction that otherwise would occur." Health & Saf. Code § 38562(d)(2) (emphasis added). As a threshold matter, the additionality requirements of proposed Section 95973 are not entirely consistent with the statutory langauge. Under the proposed regulation, "[t]he activities that result in GHG reductions and GHG removal enhancements, are not required by law, regulation, or any legally binding mandate applicable in the offset project's jurisdiction, and would not otherwise occur *in a conservative business-as-usual scenario*." Section 95973(a)(2)(A) (emphasis added); *see also* Section 95802(a)(3). The proposed regulation does not otherwise define "business-as-usual scenario," and the conservativeness principle—while certainly appropriate in this context—does not fully ensure that *all* reductions are in addition to those "that otherwise would occur," as AB 32 requires.

We appreciate that ARB may have intended to address this shortcoming of the regulation in part through Section 95972(a)(9), which as proposed in this 15-day notice requires Compliance Offset Protocols to: "Establish the eligibility and additionality of projects using standard criteria, and quantify GHG reductions and GHG removal enhancements using standardized baseline assumptions, emission factors, and monitoring methods." However, "standard criteria" in this provision is left undefined; again, the regulation provides no assurance that credits created under these protocols will be additional as required by AB 32.

Again, a more meaningful provision would require ARB to make a specific determination of the risk of non-additionality, reversal, and fraud associated with an offset protocol, based on a quantitative analysis with explicit standards, and provided in the context of the volume of offset credits an offset protocol is expected to generate and a comparison of these factors among project types within an offset protocol and among offset protocols. In addition, this provision should include the components of additionality set forth in subsection 95973(a)(2)(A) or be cross-referenced to that subsection.

2. Modifications to the requirements for offset protocols would permit leakage of GHG emissions from offset projects.

The proposed modifications would change Section 95972(a)(4) to read as follows: "[To be approved by the Board, a Compliance Offset Protocol must] . . . [a]ccount for activity-shifting leakage and market-shifting leakage for the offset project type, unless the Compliance Offset Protocol stipulates eligibility conditions for use of the Compliance Offset Protocol that eliminate the risk of activity-shifting and/or market-shifting leakage." The addition of this exception appears targeted toward the Compliance Offset Protocol U.S. Forest Projects ("Forest Offset Protocol"), which contains very high risks of leakage, especially when compared to other protocols. To be clear, the Forest Offset Protocol does not—and cannot—"eliminate" the risk of leakage.[1] At the very least, the regulation should require a specific quantitative determination of the risk of leakage associated with an offset protocol, provided in the context of the volume of offset credits an offset protocol is expected to generate, and a comparison of these factors among project types within an offset protocol and among offset protocols.

3. The Forest Offset Protocol does not comply with the additionality requirement as defined in the statute or the Cap-and-trade regulation.

As we have stated in previous comment letters, the Compliance Offset Protocol U.S. Forest Projects ("Forest Offset Protocol") contains provisions that fail to ensure compliance with the controlling additionality requirements of AB 32. Health and Saf. Code § 38562(d)(2). The Forest Offset Protocol also is unlikely to ensure compliance with ARB's proposed regulatory additionality requirements under Section 95973(a)(2)(A). In particular, as addressed in our previous comment letters, the Forest Offset Protocol allows projects to include in the project baseline forest growth projected to occur under the business-as-usual scenario described by long-term management plans required for timber operations under the California Forest Practice Rules.[2] Those flaws persist in the version of the Forest Offset Protocol currently before the Board; as a result, the protocol continues to fail the additionality test of AB 32.

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[1] We would be very surprised to hear that any of the proponents of the Forest Offset Protocol have asserted that the protocol contains conditions that *eliminate* the risk of leakage. In fact, under the Forest Offset Protocol, forest offset projects are not prohibited from shifting timber harvesting from project areas to elsewhere in their land ownership, and are not even required to report such leakage.

[2] *See* Center for Biological Diversity, Letter to Climate Action Reserve Re: Preliminary Guidance on Forest Project Protocol, Section 6.2.1.1 (Legal Requirements for Project Baseline; Supplemental Comments), April 30, 2010 (attached as Ex. 8 to our December 15, 2010 letter to ARB); Center for Biological Diversity, Letter to Climate Action Reserve Re: Comments on

Additionality problems are even more serious in earlier versions of the Forest Offset Protocol, in which the business-as-usual baseline is allowed to reflect the regulatory minimum (i.e. maximum potential harvest levels), regardless of whether the project developer ever could or would have operated at that baseline. As a result, version 2.1 of the Forest Offset Protocol used in early action measures includes a definition of project baseline that facilitates and invites non-additional credits to an even greater degree than the Forest Offset Protocol adopted by ARB as part of the cap-and-trade regulation. Yet ARB, in the current regulation, still proposes to allow credits generated under these prior versions of the protocol to be brought into the Cap-and-Trade compliance market as "early action" mechanisms. The result of this proposal will be the creation of a large number of demonstrably non-additional credits that will undermine the integrity of the compliance scheme as a whole and inhibit achievement of AB 32's emissions reduction goals.

The proposed modifications include some positive changes to require offset projects to transition to more recent versions of the Forest Offset Protocol in the future, and even to recalculate the project baseline at the time of transition. For example, "[a]t the time of transition the early action offset project must calculate its project baseline based according to all the provisions in Compliance Offset Protocol U.S. Forest Projects . . . ." Section 95990(k)(1)(D).

However, the regulation continues to allow the registration of early action credits generated under earlier versions of the protocol with no evaluation of the additionality of those credits. "ARB shall accept early action offset credits from early action offset projects registered with Early Action Offset Programs approved pursuant to section 95990(a), if the early action offset credits meet the criteria set forth in this section." Section 95990(b). In fact, the only substantive requirement for registration of early action forest offset credits is the contribution to the buffer account; that account, of course, is intended to mitigate the risk of *reversal*, not non-additionality. *See* Section 95990(c)(5)(D) ("Climate Action Reserve Forest Project Protocol versions 2.1 and 3.0 through 3.2, if the early action offset project contributes early action offset credits into a buffer account based on its reversal risk calculated according to the Compliance Offset Protocol U.S. Forest Projects, [DATE].").

It therefore appears that offset credits from forest projects registered as early actions using version 2.1 of the Forest Offset Protocol can continue to be registered through 2015 even if the forest project does not choose to transition to the compliance program. "Early action offset projects must transition to ARB Compliance Offset Protocols no later than February 28, 2015." Section 95990(k)(1). Therefore, non-additional credits can continue to be registered, and indeed can continue to be generated through 2015, using the non-additional baseline requirements of Forest Offset Protocol version 2.1.

Lastly, subsection 95990(a) allows the Executive Officer to "qualify" an early action program for offset credits by executive order. However, there is no provision, either in Section

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Proposed Amendments to Baseline Determination of the Forest Project Protocol Version 3.1, July 30, 2010 (attached as Ex. 9 to our December 15, 2010 letter to ARB).

95990 nor in subsection 95986(k) regarding ARB Approval of Offset Project Registries, to require an assessment of whether an early action program is consistent with AB 32 requirements. Thus, subsection 95990(a) would seem to allow the Executive Officer to unilaterally approve an early action program, without any assessment of its compliance with the requirements of AB 32 and without adoption by the ARB board. If this understanding is correct, this provision would violate the statutory requirement that the board adopt methodologies for offset credits. Health and Saf. Code § 38571 ("The [ARB] *board* shall adopt methodologies for the quantification of voluntary greenhouse gas emission reductions.") (emphasis added).

4. The Forest Buffer Account fails to adequately address the risk of forest project reversals.

Section 95983 (page A-269) is intended to address the risk of reversal of forest projects. "The amount of ARB offset credits that must be placed in the Forest Buffer Account shall be determined as set forth in Compliance Offset Protocol U.S. Forest Projects." That is, the contribution to the Forest Buffer Account is based on Appendix D, "Determination of a Forest Project's Reversal Risk Rating," at page 108 of the Forest Offset Protocol. However, the Forest Offset Protocol provides no calculations or rationale for the values attributed to the various reversal risks. For example, the risk of default due to overharvesting is set at 2%, with no explanation or citation.[3] At best, the risk estimates appear to be based on general averages with no refinement for particular forest or project types.

This also appears to be the case for the default risk due to forest fire. In this case, the general fire risk for a forest project is set at 4%, with risk reductions of 50% for projects with a "high level of fuel treatments," approximately 33% risk reductions for projects with a "moderate level of fuel treatments," and approximately 17% risk reductions for projects with a "low level of fuel treatments." No explanation for these values and no definition of high, medium, and low fuel treatments are provided. Ultimately, this provision does not identify the risk of reversal specific to any forest project, and thus fails to address the liability that reversal of forest projects brings to the offset program as a whole.

5. The proposed modifications fail to address the problems associated with the exemption of forest biomass combustion from compliance obligation.

The proposed modifications include no changes in response to our previous comments that GHG emissions from the combustion of woody biomass should be included under the cap and generate compliance obligations. "*Entities combusting these fuels should be excused from compliance obligations only to the extent that they can demonstrate that the production and use of the biomass fuel resulted in reduced or avoided greenhouse gas emissions over a timeframe*

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[3] The Forest Offset Protocol (page 112) sets the risk of reversal due to financial failure at 5%, illegal harvesting at 0%, land conversion (development) at 2%, changing regulations or economic conditions at 2%, insect and disease at 3%, and natural disturbance (other than fire) at 3%.

relevant to AB 32, that is, by 2020." Group comment letter, December 14, 2010. That is, any exemption from compliance obligations must be based on an explicit and source-specific determination of the GHG emissions associated with the production and combustion of the feedstock. In the case of forest biomass, such a determination would need to take into account fuel characteristics and sources, secondary emissions associated with harvesting and processing, land use impacts, and effects on future sequestration. The blanket exemption proposed in both the original draft regulation and the proposed modifications satisfies none of these criteria, and thus lacks any evidentiary basis.

From our numerous conversations with ARB staff on this topic we understand that ARB remains committed to this blanket exemption for the GHG emissions associated with the combustion of woody biomass. To date, however, ARB has not presented any analysis or evidence to support this approach. As our December 15, 2010 comments and the numerous scientific articles and studies attached thereto demonstrated, there is no basis in scientific fact for treating GHG emissions from biomass as if they have no effect on the climate.

Indeed, the scientific evidence against such an approach to biomass carbon accounting continues to mount.[4] For example, a recent paper released by the Scientific Committee of the European Environment Agency directly contradicts and warns against this type of blanket exemption for the GHG emissions from the combustion of plant biomass.

> "*It is widely assumed that biomass combustion would be inherently 'carbon neutral' because it only releases carbon taken from the atmosphere during plant growth. However, this assumption is not correct* and results in a form of double-counting, as it ignores the fact that using land to produce plants for energy typically means that this land is not producing plants for other purposes, including carbon otherwise sequestered. If bioenergy production replaces forests, reduces forest stocks or reduces forest growth, which would otherwise sequester more carbon, it can increase the atmospheric carbon concentration. If bioenergy crops displace food crops, this may lead to more hunger if crops are not replaced and lead to emissions from land-use change if they are. To reduce carbon in the air without sacrificing other human needs, bioenergy production must increase the total amount of plant growth, making more plants available for energy use while preserving other benefits, or it must be derived from biomass wastes that would

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[4] See, e.g., Opinion of the European Environment Agency ("EEA") Scientific Committee on the Greenhouse Gas Accounting in Relation to Bioenergy (September 15, 2011), *at* http://www.eea.europa.eu/about-us/governance/scientific-committee/sc-opinions/opinions-on-scientific-issues/sc-opinion-on-greenhouse-gas (attached as Ex. A); John S. Gunn, et al., *Biogenic vs. Geologic Carbon Emissions and Forest Biomass Energy Production*, GLOBAL CHANGE BIOLOGY BIOENERGY (2011), doi: 10.1111/j.1757-1707.2011.01127.x (attached as Ex. B); Jon McKechnie, et al., *Forest Bioenergy or Forest Carbon? Assessing Trade-Offs in Greenhouse Gas Mitigation with Wood-Based Fuels*, 45 ENVIRON. SCI. TECHNOL. 789 (2011) (attached as Ex. C).

> decompose and neither be used by people nor contribute to carbon sequestration." (EEA at 1, italics added.)
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> "Proper accounting needs to reflect not merely the loss of existing carbon stocks in the pursuit of biomass production for energy, but also any decline of carbon sequestration that would occur in the absence of bioenergy use. For example, forests worldwide, but particularly in the northern hemisphere, are accumulating biomass and carbon for a variety of reasons, and this growth absorbs carbon from the atmosphere. Some estimates of bioenergy potential suggest that biomass reduces greenhouse gas emissions so long as it only harvests this net forest growth and leaves the carbon stocks of the forests stable. But merely keeping carbon stocks stable ignores the additional carbon sequestration that would occur in the absence of wood harvest for bioenergy (the counterfactual) and therefore does not make bioenergy carbon neutral. *For this reason, sustainable forestry in the traditional sense does not necessarily mean that bioenergy produced from a forest is carbon neutral.*" (EEA at 5, italics added.)

ARB has never explained its proposal to adopt a complete exemption from compliance obligations for this category of greenhouse emissions. The facts, however, are clear: leaving all biomass emissions outside the cap, exempt from any compliance obligation whatsoever, ignores the physical realities of biomass production and combustion. This exemption will result in uncontrolled greenhouse gas emissions above and beyond the cap, and thus will interfere with the goals and purpose of AB 32. ARB has no authority to adopt regulations that conflict with fundamental statutory goals.

In short, the biomass exemption is arbitrary, capricious, and lacking in evidentiary support. ARB's failure throughout this year-long process to explain its decision to adopt this exemption also flies in the face of clear statutory procedural requirements. We urge ARB once again to refrain from adopting this unlawful, unscientific, and unwise exemption.

6. The proposed modifications remove the requirement that the transport of woody biomass materials not lead to the transport of insects or tree diseases.

The proposed modifications eliminate Subsection 95852.2(a)(4)(c), which had required that wood and wood waste materials to be combusted as biomass fuel "not transport or cause the transport of species known to harbor insect or disease nests outside zones of infestation…" (Page A-103.) The notice offers this explanation: "*Section 95852.2(a)(4)(C) was removed in response to comments received from stakeholders who claimed that tracking and enforcement of sources of wood and wood wastes is extremely difficult for energy generators.*" However, there is a high probability that commercial timber land owners—who may not be able to harvest trees killed by bark beetles and disease for lumber or other durable wood products—would welcome the opportunity to sell those trees to biomass energy generators. To the extent that it makes harvest and transportation of these trees economical, the biomass fuel market is likely to become a significant driver of the harvest of trees killed by insects and disease.

The elimination of this requirement openly invites the transport of infected and infested materials. This creates a substantial threat to California's forest resources and represents bad public policy. Purchasers of biomass fuels in large quantities—such as owners and operators of biomass power plants—can be expected for sound business reasons to enter into contracts with fuel suppliers such as large timber corporations and the United States Forest Service. Those contracts easily could specify that the operators will not accept fuels if doing so would require the transport of infested and diseased materials. Relieving a few "stakeholders" of this purported burden cannot outweigh ARB's responsibility, as an agency required to uphold the public trust, to ensure that its actions do not threaten California's forests as a whole by exposing them to transportation of insects and disease.

Thank you for your consideration of these comments.

The Center for Biological Diversity commends the staff of the California Air Resources Board for their thoughtful work on this rule and their commitment to implementing California's landmark effort to reduce statewide greenhouse gas pollution. We look forward to working with you to address these issues and to improve the integrity of the Cap-and-Trade program. Please contact us if you have any questions. Thank you for your consideration of these comments.

Sincerely,

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Attached References:

Ex. A: Opinion of the European Environment Agency ("EEA") Scientific Committee on the Greenhouse Gas Accounting in Relation to Bioenergy (September 15, 2011), *at* http://www.eea.europa.eu/about-us/governance/scientific-committee/sc-opinions/opinions-on-scientific-issues/sc-opinion-on-greenhouse-gas.

Ex. B: John S. Gunn, et al., *Biogenic vs. Geologic Carbon Emissions and Forest Biomass Energy Production*, GLOBAL CHANGE BIOLOGY BIOENERGY (2011), doi: 10.1111/j.1757-1707.2011.01127.x.

Ex. C: Jon McKechnie, et al., *Forest Bioenergy or Forest Carbon? Assessing Trade-Offs in Greenhouse Gas Mitigation with Wood-Based Fuels*, 45 ENVIRON. SCI. TECHNOL. 789 (2011).

European Environment Agency
Scientific Committee
15 September 2011

Opinion of the EEA Scientific Committee on Greenhouse Gas Accounting in Relation to Bioenergy

Important international and European efforts are under way to account for and reduce greenhouse gas (GHG) emissions and to increase the use of renewable energy. Several European Union energy directives encourage a switch from fossil fuels to renewable energy derived from plant biomass based on the premise that biomass combustion, regardless of the source of the biomass, would not result in carbon accumulation in the atmosphere. This mistaken assumption results in a serious accounting error.

Producing energy from biomass is meant to reduce GHG emissions. But burning biomass increases the amount of carbon in the air (just like burning coal, oil and gas) if harvesting the biomass decreases the amount of carbon stored in plants and soils, or reduces ongoing carbon sequestration. Two important factors that determine whether bioenergy reduces carbon in the atmosphere compared to fossil fuels are (i) where and (ii) how the biomass is produced and harvested. Hence, legislation that encourages substitution of fossil fuels by bioenergy, irrespective of the biomass source, may even result in increased carbon emissions – thereby accelerating global warming.

It is widely assumed that biomass combustion would be inherently ‘carbon neutral’ because it only releases carbon taken from the atmosphere during plant growth. However, this assumption is not correct and results in a form of double-counting, as it ignores the fact that using land to produce plants for energy typically means that this land *is not producing plants for other purposes*, including carbon otherwise sequestered. If bioenergy production replaces forests, reduces forest stocks or reduces forest growth, which would otherwise sequester more carbon, it can increase the atmospheric carbon concentration. If bioenergy crops displace food crops, this may lead to more hunger if crops are not replaced and lead to emissions from land-use change if they are. To reduce carbon in the air without sacrificing other human needs, bioenergy production must increase the total amount of plant growth, making more plants available for energy use while preserving other benefits, or it must be derived from biomass wastes that would decompose and neither be used by people nor contribute to carbon sequestration.

The potential consequences of this bioenergy accounting error are immense. Based on the assumption that all burning of biomass would not add carbon to the air, several reports have suggested that bioenergy could or should provide 20% to 50% of the world’s energy needs in coming decades. Doing so would require doubling or tripling the total amount of plant material currently harvested from the planet’s land. Such an increase in harvested material would compete with other needs, such as providing food for a growing population, and would place enormous pressures on the Earth’s land-based ecosystems. Indeed, current harvests, while immensely valuable for human well-being, have already caused enormous loss of habitat by affecting perhaps 75% of the world’s ice- and desert-free land, depleting water supplies, and releasing large quantities of carbon into the air.

Building on the bioenergy opinion of 2008, the Scientific Committee of the EEA recommends that:

- European Union regulations and policy targets should be revised to encourage bioenergy use only from *additional* biomass that reduces greenhouse gas emissions, without displacing other ecosystems services such as the provision of food and the production of fibre.
- Accounting standards for GHGs should fully reflect all changes in the amount of carbon stored by ecosystems and in the uptake and loss of carbon from them that result from the production and use of bioenergy.
- Bioenergy policies should encourage energy production from biomass by-products, wastes and residues (except if those are needed to sustain soil fertility). Bioenergy policies should also promote the integrated production of biomass that adds to, rather than displaces, food production.
- Decision makers and stakeholders worldwide should adjust global expectations of bioenergy use to levels based on the planet’s capacity to generate additional biomass, without jeopardizing natural ecosystems.

EEA Scientific Committee

Background Information

The European Commission and governments worldwide have implemented policies to promote bioenergy as a means both of reducing dependency on fossil energy and of reducing greenhouse gas (GHG) emissions. The Scientific Committee of the EEA is issuing this opinion because several policies inaccurately assess the greenhouse gas consequences of different forms of bioenergy, and because the scope of bioenergy suggested by many policy analyses could have serious adverse consequences on a range of environmental concerns.

In this document, bioenergy refers to any energy produced by combusting biomass. Biomass may be in solid form, such as wood chips or pellets burned for electricity, in liquid form, such as ethanol and biodiesel generated from crops or cellulose, or in gaseous form (biogas).

Proper Greenhouse Gas Accounting

In supporting bioenergy, many domestic regulations treat biomass combustion as carbon-neutral vis-à-vis the atmosphere, regardless of the specific source of the biomass. Although greenhouse gas accounting by these laws may count the emissions released by using fossil fuels to produce and refine the biomass[1] they do not count the carbon dioxide (CO_2) actually released by the burning of the biomass itself. They do so either because they explicitly leave this carbon out of the accounting of the emissions from bioenergy or because they endorse bioenergy without explicit greenhouse gas accounting at all on the assumption that bioenergy always reduces greenhouse gas emissions. In this sense, such regulations treat biomass as an inherently 'carbon neutral' energy source. For that reason, these laws may treat the shift from fossil fuels to any source of biomass as a 100% reduction in CO_2 emissions. This treatment is incorrect.

Replacement of fossil energy with biomass does not, in itself, reduce GHG emissions from exhaust pipes or chimneys. Burning one metric tonne of bone dry wood, for example, will release roughly 1.8 tonnes of CO_2 into the atmosphere. For this reason, while fossil-fuel related carbon emissions are reduced, the combustion of biomass results in its own CO_2 emissions.

Some justify treating biomass combustion as carbon neutral because they assume that the burning of biomass only returns the carbon to the atmosphere absorbed by growing plants. Plants do absorb carbon, but this thinking makes a 'baseline' error because it fails to recognize that if bioenergy were not produced, land would typically grow plants anyway, and those plants would continue to absorb carbon and help to reduce carbon in the air. It is double-counting to credit bioenergy for reducing carbon in the atmosphere through plant growth to the extent plants would grow and absorb that carbon anyway.

A simple example shows why. Imagine a hectare of cropland just abandoned and allowed to reforest. These growing plants would absorb carbon from the atmosphere into plant tissue, i.e. biomass. Some of that biomass would be consumed and the carbon released by animals, fungi or microorganisms and go back into the atmosphere. Other carbon would be stored in vegetation and soils as the forest grows, and that carbon absorption would have the effect of offsetting some of the emissions of carbon by burning fossil fuels and holding down global warming.[2] However, instead of allowing the forest to grow, if the land were used to grow energy crops and those crops were

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[1] Some accounting rules, for example those underlying the EU Renewable Energy Directive, also consider the GHG emissions from direct land use change. However, they fail to account for GHGs from indirect land-use change, which does not fix the accounting error addressed here for reasons discussed below.

[2] Baldocchi *et al.* (2008) *Aust J Botany* 56: 1-26 / Le Quéré *et al.* (2009) *Nature Geosci* 2: 831-836 / Richter and Houghton (2011) *Carbon Management* 2(1), in press.

then burned in an electric power plant, the use of that biomass (the crops) would displace fossil fuel emissions, but the actual CO_2 emitted by the power plant chimneys would not be reduced. Per unit of energy, the CO_2 emissions would typically even be higher than those of a fossil fuel-burning power plant because biomass contains less energy per unit of carbon than petroleum products or natural gas and because biomass is usually burned with a lower efficiency than fossil fuels. Although the growth of the bioenergy crops absorbs carbon, using the land to grow bioenergy crops sacrifices the use of the land to absorb and sequester carbon in the forest. The CO_2 released from the chimney could be legitimately ignored only in cases where, and to the extent that the carbon absorbed by the energy crops and burned in the power plant *exceeded* the carbon that would otherwise be absorbed and sequestered by the growing forest.

Simplifying the various steps in this story, the decision to use the land for bioenergy results in more carbon stored underground in fossil fuels, however this benefit comes at the expense of less carbon stored by plants and soils. Bioenergy reduces CO_2 emissions only to the extent the first effect is larger than the second.

The use of food crops for transportation biofuels provides another example. Food crops absorb carbon. If food crops that would grow anyway on existing cropland are diverted to bioenergy use, this alternative use of the crops alone does not necessarily result in additional plant growth and additional absorption of carbon to offset the emissions from energy use. For this reason, these crops do not justify failing to account for the carbon dioxide emitted from exhaust pipes, as is typical. However, this use of crops can set in motion a series of indirect responses by way of market forces:

- Food crops do not typically keep carbon away from the atmosphere for long periods of time because the crops are consumed by people and livestock. In the process of fuelling themselves with these crops, people and livestock return almost all carbon to the atmosphere as respiration and wastes. If food crops are used for bioenergy and not replaced, so fewer crops are consumed, there is a reduction in GHGs which occurs physically because people and livestock release less CO_2 to the atmosphere. However, reducing consumption of food by increasing prices is not a desirable way of reducing GHGs.

- If the crops are replaced elsewhere, then the greenhouse gas consequences of the bioenergy depend on how they are replaced. If more crops are grown on the same land, additional carbon is absorbed from the atmosphere. If more land is converted to crops, then the calculation must include the lost carbon storage or sequestration due to changing land-use.

Overall, the net indirect effects determine the CO_2 consequences of diverting crops to bioenergy. Only if and to the extent those indirect effects are *beneficial* can they justify ignoring some of the carbon dioxide emitted by vehicle tailpipes from the use of these biofuels.

The net effects of using land to produce biomass for energy use vary over time, and any comprehensive accounting system needs to consider many different aspects of land and energy use. Ultimately, however, it is useful to focus precisely on where and how physical changes occur in the absorption or emission of carbon through the use of bioenergy. Because bioenergy does not physically reduce emissions from exhaust pipes and chimneys, it must be true mathematically that bioenergy can reduce greenhouse gas emissions (except by reducing other human consumption of biomass, such as food) only if, and to the extent that:

(1) land and plants are managed to take up additional CO_2 beyond what they would absorb without conversion into bioenergy, or

(2) bioenergy production uses feedstocks, such as crop residues or wastes, that would otherwise decompose and release CO_2 to the atmosphere anyway.

Only biomass grown that is in excess of that which would be grown anyway or biomass that would otherwise decompose is “additional biomass," which contains "additional carbon,” and has the potential to reduce greenhouse gas emissions when used for energy.

The basic error in the assumption of general carbon neutrality of biomass is the failure to count the production and uses of biomass that land would generate *if not used for bioenergy (the counterfactual).* To assess the consequences on global warming alone, accounting must assess the rates of plant growth with and without bioenergy production, and the changes induced by bioenergy production in the total amount of carbon stored in terrestrial plants and soils. A few advantageous and detrimental examples help to illustrate the effects:

Advantageous examples:

- Some lands once covered with tropical forests are overrun by invasive grasses that frequently burn. These grasses generate few human benefits and only offer limited carbon storage. Planting bioenergy crops on these lands potentially increases the carbon absorbed by plant growth and reduces the carbon lost to fire, generating additional biomass for energy use without displacing carbon storage, food or fibre used by people.

- When bioenergy uses wastes that would otherwise be disposed of and allowed to decompose, it has the effect of reducing the carbon emitted by that waste. Although the burning of this biomass instead of fossil fuels still emits carbon, that carbon is offset by the reduced decomposition of this waste material.

- When bioenergy uses crop residues that would otherwise be burned, the same advantages occur. When bioenergy uses crop residues that would otherwise be ploughed back into the soil, there may also be a short-term net gain in carbon because much of those residues would otherwise decompose. However, care must be taken to ensure that this loss of residues does not lead to reduced productivity and therefore reduced plant growth or reduced carbon sequestration in soils.[3] Furthermore, the accounting must reflect any increases in GHG emission from fertiliser production required to replace the nutrients from the residues.

Likely disadvantageous or mixed examples:

- Clearing or cutting forests for bioenergy crops releases large stores of carbon into the atmosphere and may reduce ongoing carbon sequestration if the forest would otherwise continue to grow. Regrowing forests or planting bioenergy crops will absorb carbon that offsets the emissions from their combustion over time, but it may take decades for this carbon absorption to reach the level of the lost carbon storage and foregone carbon sequestration of the forest.[4]

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[3] Blanco-Canqui and Lal (2009) *Crit Rev Plant Sci*, 28, 139-163

[4] Searchinger et al. (2008) *Science* 319, 1238-1240 / Searchinger (2009) *Science*, *326,* 527-528 / Searchinger (2010) *Environm. Res. Lett.*, *5,* doi:10.1088/1748-9326/5/2/024007

- Using a food crop for bioenergy replaces fossil emissions with emissions from biomass combustion and does not absorb any additional carbon because the crop would be grown anyway. However, there may be indirect impacts, as discussed above. The loss of the crop could spur price increases and additional market reactions that may include reduced overall crop consumption, higher yields and therefore increased carbon absorption on existing farmland; or conversely cause the conversion of new lands to crops, which may release more carbon. The final greenhouse gas balance depends on the magnitude of each effect, but reduced food consumption may be an additional effect that must be guarded against.[5]

Proper accounting needs to reflect not merely the loss of existing carbon stocks in the pursuit of biomass production for energy, but also any decline of carbon sequestration that would occur in the absence of bioenergy use. For example, forests worldwide, but particularly in the northern hemisphere, are accumulating biomass and carbon for a variety of reasons,[6] and this growth absorbs carbon from the atmosphere. Some estimates of bioenergy potential suggest that biomass reduces greenhouse gas emissions so long as it only harvests this net forest growth and leaves the carbon stocks of the forests stable. But merely keeping carbon stocks stable ignores the additional carbon sequestration that would occur in the absence of wood harvest for bioenergy (the counterfactual) and therefore does not make bioenergy carbon neutral.[7] For this reason, sustainable forestry in the traditional sense does not necessarily mean that bioenergy produced from a forest is carbon neutral.

Eventually, if harvested forests are allowed to re-grow, they will achieve close to the same carbon storage levels as unharvested forests, as growth greatly slows as forests reach maturity. At that point, the use of the biomass would become carbon neutral. But achieving this parity may take decades or even centuries, which means there could be increases in greenhouse gases in the atmosphere for a long time, which goes against policy goals of carbon neutrality.[8]

Origins of the Accounting Error

The assumption that all biomass is carbon neutral results from a misapplication of the original guidance provided for national level counting under the United Nations Framework Convention on Climate Change (UNFCC). Under UNFCCC accounting, countries separately report their emissions from energy use and from land-use change. For example, if a hectare of forest is cleared and the wood used for bioenergy, the carbon lost from the forest is counted as a land-use emission. To avoid double-counting, the rules therefore allow countries to ignore the same carbon when it is released from a chimney. This accounting principle does not assume that biomass is carbon neutral, but rather that emissions can be reported in the land-use sector. This accounting system is complete and accurate because emissions are reported from both land and energy sectors worldwide.

These conditions do not apply to any treaties and regulations, such as the Kyoto Protocol, that seek to limit emissions from energy use but do not limit emissions from land-use, or do so only weakly and that do not apply worldwide. If the removal of trees from a forest does not count toward emissions limits on land-use under a legal rule that also exempts CO_2 emitted by bioenergy, then carbon needs to be counted when it goes up a chimney or out an exhaust pipe because it would otherwise be legally ignored completely.

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[5] Fargione et al. (2008). *Science* 319, 1235-1238

[6] Pan et al. (2011) *Science* 333: 988-993 / Richter and Houghton (2011) *Carbon Management* 2(1), in press / Erb et al. (2008) *J Industr. Ecol.*, 12, 686-703.

[7] Haberl et al. (2003) *Land Use Policy*, 20, 21-39.

[8] Cherubini et al. (2011) *GBC Bioenergy*, doi: 10.111/j.1757-1707.2011.01102.x, Cherubini et al. (2011) *Ecol. Modell.*, doi:10.1016/j.ecolmodel.2011.06.021 (in press).

A law that applies greenhouse limits only to the energy sector must therefore count CO_2 emissions from bioenergy combustion except emissions from burning 'additional biomass' in the manner discussed above, i.e. biomass whose production and harvest absorbs more carbon from the air than land and its plant growth would otherwise absorb or reduces non-energy emissions.[9] The Kyoto Protocol imposed only limited restrictions on emissions from land-use which do not apply worldwide, so new accounting rules are required to count CO_2 from bioenergy use. But the accounting regime adopted for the Kyoto Protocol improperly maintained the exemption of carbon from burning biomass. This error was followed by the following European directives or provisions:

- The European Union's Emissions Trading System[10] (which caps emissions from major factories and power plants) ignores CO_2 emissions from biomass combustion;
- The Renewable Energy Directive[11] (which requires that Member States increase their use of renewable energy to 20% by 2020) implicitly sets CO_2 emissions from biomass combustion to zero (see Annex to this opinion).

The European Union has also adopted two directives to spur transportation biofuels that at present also fail to include proper GHG accounting, specifically:

- The renewable fuels portion of the Renewable Energy Directive,[12] which requires that member countries use qualifying renewable energy for 10% of their transportation fuel, for which Member States have indicated that biofuels are to provide the great majority.
- The Fuel Quality Directive,[13] which requires reductions in the carbon intensity of transportation fuels.

Both these directives use the same lifecycle accounting systems to evaluate the greenhouse gas consequences of biofuels. Under these lifecycle systems, emissions involved in growing crops and refining biofuels are counted, as are those from direct land-use change. For example, if a bioenergy crop is planted in a previously forested area, the carbon released by the loss of the forest is counted as an emission of the bioenergy crop. But the accounting in these systems still ignores the *actual* emissions of CO_2 emitted from the exhaust pipes of vehicles that use biofuels, without any assurance that the biomass is additional. If the bioenergy is supplied by crops grown on existing cropland, the analysis in effect incorrectly assumes one of the following scenarios to be true: (i) this land would otherwise grow no plants, (ii) the crops it would generate are not otherwise replaced, or (iii) the crops are replaced

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[9] Searchinger (2009) *Science*, *326,* 527-528.

[10] Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a system for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC, as subsequently amended. For full documentary history, see http://ec.europa.eu/clima/documentation/ets/index_en.htm, for an overview see http://ec.europa.eu/clima/policies/ets/index_en.htm.

[11] DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/E.

[12] DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:en:PDF)

[13] Directive 2009/30/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions and amending Council Directive 1999/32/EC as regards the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EEC (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32009L0030:EN:NOT)

entirely by intensifying planting and harvesting of existing cropland. If the crops are grown on grassland, the analysis counts the emissions from the conversion to cropland (in carbon lost from soils and grass), but fails to assess the consequences of replacing the forage that this land would otherwise generate for livestock. Only a fully comprehensive accounting of indirect effects could fix this error.[14]

Even with proper accounting, care should be taken that biofuels are not credited with GHG reductions based on estimates that they will indirectly lead to reductions in food consumption.

Some people have suggested that as an alternative to accounting for indirect land use change, policymakers could use the same flawed accounting system but require that biofuels reduce greenhouse gas emissions by a higher percentage compared to fossil fuels, for example by 75% instead of the 50% that will be required in the EU Renewable Energy Directive. Doing so would not solve the problem. As long as the accounting ignores the CO_2 emissions from exhaust pipes without counting the indirect effects on land-use, the accounting assumes that plant growth cancels out exhaust pipe emissions regardless of whether there is additional plant growth.

Indeed, rather than a partial or compromise way of fixing this wrong accounting, higher greenhouse gas thresholds alone could exacerbate the problems. The incorrect accounting in effect only counts greenhouse gas emissions from the use of energy and other inputs in the making of biofuels while ignoring the effect of using land. Tighter thresholds will encourage making biofuels using more land, and more productive land, even to generate fewer litres of biofuels, if doing so reduces GHG emissions from inputs (such as energy or fertiliser), even when the true net GHG consequences would be worse.

For example, higher thresholds could encourage ethanol or biodiesel with extremely low yields on highly productive land over biofuels that attain far higher yields on less productive lands with the use of reasonable levels of fertilizer, and over biofuels from wastes and residues that need somewhat more energy in processing or transportation. Because of that effect, such a system would also incentivize biofuels with worse consequences for hunger, biodiversity and other ecosystem values.

Although estimating the indirect consequences of biofuels presents inherent uncertainties, the proper alternative cannot be to assume that biomass is carbon free and emits no CO_2, which is the assumption in existing biofuels directives. That approach is an error as the CO_2 is real and there may be no direct source of additional biomass. We strongly recommend that any accounting system quantify the greenhouse gas emissions attributable to the use of land, both direct and indirect, when evaluating the use of biofuels.

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[14] To be theoretically accurate, the accounting system should count the emissions emitted by exhaust pipes and then provide a credit for biomass to the extent it results in additional carbon reductions in the sense discussed in this opinion and its background document. The same result can be achieved backwards by assuming the biomass is carbon neutral, which means ignoring the emissions from exhaust pipes, and then adding the emissions from indirect land-use change. Incorporating indirect land-use change emissions into a typical lifecycle analysis therefore arrives at the correct GHG emission result. However, this approach will also credit biofuels for the GHG reductions due to reduced crop consumption, even if these result in hunger, and policy-makers need to exclude the reductions due to that effect unless they wish to pursue policies of reducing GHG emissions in that way.

Different Sources of Biomass

The following table of different forms of biomass highlights the degree of likely potential error in the existing directives:

Source of biomass	**Degree of likely accounting error**
Converting forests currently sequestering carbon to bioenergy crops	Very high
Harvesting live trees for bioenergy and allowing forest to regrow	High
Diverting crops or growing bioenergy crops on otherwise high-yielding agricultural land	High
Using crop residues	Variable
Planting high-yielding energy crops on unused invasive grasslands	Low
Using post-harvest timber slash	Little or none
Using organic wastes otherwise deposited in landfill	Little or none

Scope of the Consequences

The directives mentioned above are influenced by studies projecting bioenergy as a potentially large and carbon-free replacement for fossil fuels. For example, the International Energy Agency has projected bioenergy as potentially the source of more than 20% of world primary energy supply by 2050,[15] while a report by the Secretariat of the UNFCCC has claimed bioenergy can supply 800 exajoules per year (EJ/yr),[16] which is far in excess of total world energy use today. Policies that consider bioenergy as carbon neutral therefore may have significant ramifications.

Producing several hundred EJ/yr of bioenergy would require a multifold increase in the human harvest of the world’s plant production. Today, the total global biomass harvest for food, feed, fibre, wood products, and traditional wood use for cooking and heat amounts to approximately 12 billion tonnes of dry matter of plant material per year. This biomass has a chemical energy value of 230 EJ/yr, which is the maximum energy available if all harvested food, timber and residues were diverted to energy use. The agricultural and forestry practices implemented to generate these products have not, on balance, increased the total quantity of biomass production, but have in reality diverted production from natural ecosystems, which indicates the challenge of producing large volumes of additional biomass.[17]

Management of the world’s land and ecosystems for human needs can occur more or less sustainably, but virtually all human uses of land and consumption of plants have some environmental costs.[18] Generating food and fiber requires human use of perhaps 75% of the world’s highly productive, ice and desert-free land.[19] That includes direct use of roughly half of this land for agriculture, clearing of lands for crops and livestock grazing of grasslands and

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[15] International Energy Agency (2008), *Energy technology perspectives: Scenarios and strategies to 2050*. IEA, Paris.

[16] UNFCC Secretariat (2008), Challenges and opportunities for mitigation in the agricultural sector, Technical Paper (FCCC/TP/2008/8, Geneva) http://unfccc.int/resource/docs/2008/tp/08.pdf, p. 23.

[17] Haberl et al. (2007), *Proc. Natl. Acad. Sci.*, 104, 12942-12947. The figures in exajoules are computed from the quantities of biomass harvested for different human purposes set forth in this paper as well as in Krausmann et al. (2008). *Ecol Econ* 65: 471-487.

[18] Millennium Ecosystem Assessment (2005). *Ecosystems and Human Well-Being*. Washington, D.C.: Island Press

[19] Precise figures are limited by problems of definition, yet these general figures are reflected in Erb et al. (2010) *J Land Use Sci*, 2, 191-224 / UNEP (2007) *GEO-4 Environment for Development*. Nairobi: UNEP.

savannahs, and management of a substantial fraction of the world's forests for wood production. In addition, more than 70% of the water withdrawn from rivers and aquifers is used for current agriculture.[20] This agricultural intensification has doubled the amount of reactive nitrogen in the world, leading to the large-scale pollution of marine ecosystems, including extensive algal blooms and waters with low levels of oxygen.[21]

As human uses of land have already reached troubling levels, an important policy goal should be to minimise the environmental consequences of additional human demands on land-use.[22] It is very unlikely that a doubling of global human biomass harvest or more could come without serious environmental consequences.

Because of their inherently high demands for land and water, large bioenergy production targets will also compete with uses of land and water to meet other human needs or to reduce the consequences of our existing land-use. These needs and challenges include reducing malnutrition, increasing food production for a growing population, improving the well-being of animals used for livestock, and reducing the environmental pressures resulting from agriculture. Although there are potential biomass sources that can reduce greenhouse gas emissions and be generated sustainably, more realistic expectations for bioenergy potential are necessary to avoid causing harm. These estimates should focus on the potential to generate 'additional' biomass,' which means biomass that does not merely displace biomass now used to meet other human needs, or biomass used to maintain or build carbon stocks in plants and soils.

Appendix: GHG accounting in the Renewable Energy Directive

The Renewable Energy Directive (RED) uses the following methods to account for the GHG emissions from bioenergy (see Annex V to Directive 2009/28/EC):

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[20] Comprehensive Assessment of Water Management in Agriculture. 2007. Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. London: Earthscan, and Colombo: International Water Management Institute.

[21] Gruber and Galloway (2008) *Nature* 451, 293-296 / Erisman et al. (2008) *Nature Geosci* 1, 636-639.

[22] IAASTD (2009) *Agriculture at a Crossroads*. Washington, D.C.: Island Press.

Total GHG emissions from the use of a fuel = Emissions from extraction or cultivation of raw materials + annualised emissions from carbon stock changes resulting from direct land-use change + emissions from processing + emissions from transport and distributions + emissions from the fuel in use – emission savings from carbon accumulation via improved agricultural management – emission savings from carbon capture and geological storage – emission savings from carbon capture and replacement – emission savings from excess electricity from cogeneration.

However, emissions from the fuel in use are set to zero for biofuels and bioliquids, which implies that these fuels are assumed to be carbon neutral.[23]

The annualised emissions from carbon stock changes resulting from land-use change are calculated as follows:

Annualised emissions = $(CS_R - CS_A) \times 3.664 \times 1/20 \times 1/P - e_B$

In this formula, CS_R is the carbon stock of biota and soils under reference land-use, CS_A the carbon stock of biota and soils under land-use with bioenergy production. 3.664 is a factor to convert carbon to CO_2. 1/20 means that the change in C stocks ($CS_R - CS_A$) is evenly distributed over 20 years. P is the energy yield of the energy crop, and e_B is a bonus that is credited if the biofuel is obtained from restored degraded land.

This formula accounts for carbon emissions resulting from land-use change for energy crops as annualised stock change (20 years) resulting from the conversion of land to energy crops. It gives a credit to bioenergy produced on degraded land. However, while it provides a credit for all the carbon included in the crops diverted to biofuels, it neglects some essential components:

- Indirect land-use change: By ignoring the carbon emitted from the exhaust pipe when the fuel is used, when the crop would be grown anyway, the formula assumes carbon neutrality even when the plants used to produce the fuel did not absorb additional carbon. In effect, this formula does not account for the food, feed or fibre production of the 'reference land-use'. For example, if grassland is converted to bioenergy, the forage used as feed is not taken into account.[24] If food supply is to be held constant, the forage must be produced elsewhere, which potentially results in GHG emissions from land conversion elsewhere. If the forage is not replaced, there are greenhouse gas benefits but at potentially important costs to food production which vary with the productivity of the grassland.
- The land's ongoing carbon sequestration: If the land directly converted to energy crops is a growing forest, it would continue to sequester carbon. The loss of this sequestration is not accounted for.
- The opportunity cost: If the land would not be required for food, feed or fibre production, it could also be converted to another use to increase its carbon sequestration. For example, if grassland products are not required, the grassland could be converted to forests and would sequester large amounts of carbon over several decades if not centuries. This foregone carbon sequestration is another real cost that should also be considered when policymakers consider biofuels.

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[23] See http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:en:PDF (Annex V).
[24] Alberici et al. (2010) *Annotated example of a land carbon stock calculation using standard values*. Ecofys, London.

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OPINION

Biogenic vs. geologic carbon emissions and forest biomass energy production

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Abstract

In the current debate over the CO_2 emissions implications of switching from fossil fuel energy sources to include a substantial amount of woody biomass energy, many scientists and policy makers hold the view that emissions from the two sources should not be equated. Their rationale is that the combustion or decay of woody biomass is simply part of the global cycle of biogenic carbon and does not increase the amount of carbon in circulation. This view is frequently presented as justification to implement policies that encourage the substitution of fossil fuel energy sources with biomass. We present the opinion that this is an inappropriate conceptual basis to assess the atmospheric greenhouse gas (GHG) accounting of woody biomass energy generation. While there are many other environmental, social, and economic reasons to move to woody biomass energy, we argue that the inferred benefits of biogenic emissions over fossil fuel emissions should be reconsidered.

Keywords: bioenergy emissions, biogenic carbon, carbon debt, forest biomass, greenhouse gas accounting

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A recent letter to US House of Representatives Natural Resource and Energy and Commerce Committees signed by more than 100 academics from American universities articulated a concern over equating biogenic carbon (C) emissions with fossil fuel emissions in emerging state and federal legislation and rule making (Lippke *et al*., 2010). They stated that 'the combustion or decay of woody biomass is part of the global cycle of biogenic carbon and does not increase the amount of carbon in circulation. In contrast, carbon dioxide released from fossil fuels increases the amount of carbon in the cycle'. This view recently has been reiterated by many (e.g. Hale, 2010; Lucier, 2010; Strauch *et al*., 2010; Sedjo, 2011) as justification to promote policies that encourage the substitution of fossil fuel energy sources with biomass. This position ignores the inherent complexities associated with atmospheric greenhouse gas (GHG) accounting of woody biomass energy generation, including the consideration of the system boundaries used in net emissions calculations and the indirect effects associated with land-use change. According to some calculations, switching from fossil fuels to wood energy could actually result in increased levels of atmospheric GHGs, at least over a period of decades (e.g. Searchinger *et al*., 2009; Walker *et al*., 2010; McKechnie *et al*., 2011). This recent scientific approach to the issue has come about through the recognition by many in the scientific community that GHG accounting must consider explicitly the carbon dynamics of the woody biomass feedstock source and not dismiss it as immediately 'carbon neutral.' Though our comments below are driven by the US policy debate over how to treat biomass energy emissions, this desire to dismiss these important biogenic emissions is echoed internationally. In particular, the current Intergovernmental Panel on Climate Change (IPCC, 2006) GHG accounting approach accounts for feedstock carbon stock change, but does not attribute biogenic emissions to the energy sector. This approach risks creating incentives for bioenergy production that, in some circumstances, may emit more CO_2 than the fossil fuel alternatives over the whole life cycle of the bioenergy chain and considering indirect pay-back effects (Bird *et al*., 2011).

There are many credible environmental, social and economic reasons to move away from fossil fuels, including: reducing dependence on foreign petroleum, providing economic incentives to maintain forest management infrastructure, and encouraging conservation of working forests. But for the specific goal of mitigating

Correspondence: John S. Gunn, tel. + 207 721 9040, fax + 207 721 9144, e-mail: jgunn@manomet.org climate change, the critical question to answer is 'what will the atmosphere see and over what timescale?' as a result of switching from geologic to biogenic fuel sources. The physics of the greenhouse effect is indifferent as to the origin of the pollutant. Once a molecule of CO_2 is in the atmosphere its heating capacity is the same regardless of its source. It is the overall C budget and the net atmospheric concentration of greenhouses gases that are of concern. If greater use of wood energy has the unintended consequence of contributing to an increase in atmospheric CO_2 concentrations, then decisions to switch to biogenic fuels should be guided by careful accounting to determine net carbon fluxes to and from the atmosphere.

An earlier letter to the US House of Representatives and US Senate (Schlesinger *et al.*, 2010) from 90 American scientists stated that 'Although fossil fuel emissions are reduced or eliminated, the combustion of biomass replaces fossil emissions with its own emissions (which may even be higher per unit of energy because of the lower energy to carbon ratio of biomass)'. More research is needed to determine which biomass energy technology scenarios and forest ecosystems are most likely to result in greater biogenic emissions than the equivalent fossil fuel energy source. But recent work in the United States and Europe supports the Schlesinger *et al.* (2010) statement (e.g. Walker *et al.*, 2010; Bird *et al.*, 2011; McKechnie *et al.*, 2011). In addition, if biomass harvests involve living trees that would otherwise have remained alive and growing, the short-term net impact on the atmosphere will be greater than if logging residue or waste wood were used. All wood is not equal in terms of temporal impact to atmospheric GHG levels. Therefore, the use of wood for energy needs a strong quantitative basis ensuring policy based on evidence rather than opinion.

Wood energy harvests encompass a wide range of silvicultural treatments, but have the potential to increase the overall intensity and frequency of harvesting. This can reduce the net amount of carbon stored in forest biomass at any moment in time at landscape scales, particularly in natural forest systems with low risk of catastrophic disturbances and relatively slow growth rates. If overall harvesting intensity increases to meet new demand for wood energy, carbon stocks on the landscape can be depressed to a lower equilibrium storage condition therefore increasing overall atmospheric CO_2 even when considering the substitution benefits (Harmon *et al.*, 1990; Smithwick *et al.*, 2006; McKechnie *et al.*, 2011). In addition, when biomass energy is produced from land converted to nonforest uses; regrowth of forests and the associated uptake of C will not occur. As long as the world continues to experience net loss of forest cover (deforestation) and harvest intensity increases, the residence time period for biogenic C in the atmosphere is likely longer than what is assumed by many scientists. Moreover, most sequestration of this biogenic C in the atmosphere will likely occur beyond the critical timeframe for addressing climate change (e.g. the next 50 years). When we also consider the amount of biogenic C remaining in the atmosphere as a result of historical global conversion of forests, prairies, peatlands and wetlands (Birdsey *et al.*, 2006; Rhemtulla *et al.*, 2009; van der Werf *et al.*, 2009), it becomes clear that all sources of additional C emissions should be evaluated based upon their near term contribution to the atmosphere and their potential for re-sequestration by new biological growth. This historical debt also negates the argument that biogenic carbon can be banked in advance of consumption for energy (e.g. Sedjo, 2011). Again, what matters is the amount of CO_2 in the atmosphere, regardless of the source.

One rationale for increasing the use of forest biomass for energy is that the biogenic carbon cycle is in balance as long as trees are growing and sequestering carbon somewhere else within other forests (Lucier, 2010). While this argument makes sense when considering the sustained yield of wood products, it fails to consider the complete basis for calculating net GHG effect on the atmosphere of switching from fossil fuels to biomass. Moreover, when applied to carbon, this approach implies that the biogenic carbon cycle is separate from a global carbon cycle. It is indisputable that emissions from fossil fuels contribute to the atmospheric pool by releasing carbon from the geologic pool and are therefore new emissions to the atmosphere. However, the same is functionally true, in terms of climate implications, for any biological carbon emission with a low likelihood or a delayed return (>50 years) to the biogenic or oceanic pools. If alternatives to fossil fuels include use of forests where C is emitted and resides in the atmosphere for long periods of time (e.g. decades or longer), a reduction of atmospheric concentrations of CO_2 (e.g. to 350 ppm; Hansen *et al.*, 2008) will be difficult to achieve and may contribute to some degree of irreversible climate change (Solomon *et al.*, 2009). With this in mind, we must continue to ask ourselves whether we are truly using forests to their greatest atmospheric benefit.

What matters most in our climate change mitigation efforts is the movement of C from any pool into and out of the atmosphere (i.e. the net effect on atmospheric carbon concentrations). Consider the five major global pools of C in decreasing order of volume: oceanic; geologic; pedologic; atmospheric; and biogenic (Morgan *et al.*, 2010). The flow of C among these pools operates at varying temporal scales. It may take millions of years for C to move from the biogenic pool to the geologic pool, while fluxes between the atmospheric and biogenic pools are continuous. Humans influence movement among pools by burning fossil fuels and releasing C to the atmospheric pool. Likewise, we burn and clear forests from the biogenic pool to convert land to agriculture, development, and other nonforest uses, leading essentially in many cases to a permanent loss of biogenic C (van der Werf *et al.*, 2009; Hansen *et al.*, 2010). Movement of biogenic C from the atmosphere back into the biogenic pool cannot be automatically assumed. Biogenic C released from activities such as permanent deforestation, or the combustion of forest biomass for energy, must be replaced through photosynthesis and sequestration to maintain flow from the atmosphere back into the biogenic pool. In the context of climate change mitigation efforts, activities that generate emissions from biogenic or geologic C pools should be evaluated for the contribution it makes to the atmospheric pool and the timing of residence.

There is an immediate need to deal with the complexity of carbon accounting as it relates to wood-derived bioenergy. Scientists are studying the benefits and tradeoffs associated with different carbon management scenarios in a variety of forest types around the world (Harmon & Marks, 2002; Seidl *et al.*, 2007; Mitchell *et al.*, 2009; North *et al.*, 2009; Swanson, 2009; Hurteau *et al.*, 2010; Nunery & Keeton, 2010; Gunn *et al.*, 2011). As our understanding of this complexity improves, we need to carefully consider the role of forests as both a potential C sink and source (Ray *et al.*, 2009). If forests are going to be used to reduce our dependence on fossil fuels, we will need to determine where and when to provide the economic incentives to maintain the forest management infrastructure and our working forests. Independently verified sustainable forestry standards that conserve our forest resources in perpetuity provide one existing mechanism to prevent degradation and promote forest practices with C sequestration benefits. The opportunities to use our forests and maintain them as forests with their embedded ecosystem service values is worthy of balancing the carbon accounting issues mentioned here with the other management objectives (water, biodiversity, human livelihoods, recreation, energy, etc.). Ideally, balancing the flow of ecosystem service values from forests will benefit from global policies such as Reducing Emissions from Deforestation and Forest Degradation (REDD) that consider the whole suite of ecosystem goods and services including atmospheric benefits (Canadell & Raupach, 2008; Ebeling & Yasue, 2008; FAO UNDP, 2008). But first, we must be confident that our climate policies designed to reduce atmospheric GHGs in a time frame that matters actually *do* reduce GHG levels, and not unwittingly increase them.

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Forest Bioenergy or Forest Carbon? Assessing Trade-Offs in Greenhouse Gas Mitigation with Wood-Based Fuels

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The potential of forest-based bioenergy to reduce greenhouse gas (GHG) emissions when displacing fossil-based energy must be balanced with forest carbon implications related to biomass harvest. We integrate life cycle assessment (LCA) and forest carbon analysis to assess total GHG emissions of forest bioenergy over time. Application of the method to case studies of wood pellet and ethanol production from forest biomass reveals a substantial reduction in forest carbon due to bioenergy production. For all cases, harvest-related forest carbon reductions and associated GHG emissions initially exceed avoided fossil fuel-related emissions, temporarily increasing overall emissions. In the long term, electricity generation from pellets reduces overall emissions relative to coal, although forest carbon losses delay net GHG mitigation by 16–38 years, depending on biomass source (harvest residues/standing trees). Ethanol produced from standing trees increases overall emissions throughout 100 years of continuous production: ethanol from residues achieves reductions after a 74 year delay. Forest carbon more significantly affects bioenergy emissions when biomass is sourced from standing trees compared to residues and when less GHG-intensive fuels are displaced. In all cases, forest carbon dynamics are significant. Although study results are not generalizable to all forests, we suggest the integrated LCA/forest carbon approach be undertaken for bioenergy studies.

Introduction

Forests can contribute to greenhouse gas (GHG) mitigation strategies through capturing and storing atmospheric CO_2 in live biomass, dead organic matter, and soil pools, supplying a source for wood products that both stores carbon and can displace more GHG-intensive alternatives, and providing a feedstock for bioenergy to displace fossil fuel use. While the merit of each of these options has been individually investigated, trade-offs associated with forest resource utilization decisions must also be considered. Of particular interest is the relationship between harvest and forest carbon storage and how this impacts the GHG mitigation performance of forest products, including bioenergy. Existing tools employed to evaluate emissions associated with different forest resource use decisions are not individually well suited to considering such interactions.

Life cycle assessment (LCA) has been applied to bioenergy options, including electricity generation and transportation fuels. The GHG mitigation potential of bioenergy products depends on activities throughout the entire life cycle (LC), making such a perspective necessary for a comprehensive evaluation. Numerous LCAs have focused on agricultural biomass as feedstock for bioenergy, e.g., reviewed in ref (*1*). Comparatively few LCAs have evaluated bioenergy from forest biomass; those that have examined electricity generation (e.g., ref (*2*)), heating (e.g., ref (*3*)), and transportation (e.g., ref (*4*)). Bioenergy LCAs have generally found that the substitution of fossil fuel-derived energy with biomass-derived alternatives reduces GHG emissions, owing in part to the assumption that biomass-based CO_2 emissions do not increase atmospheric CO_2.

Conventional wisdom has generally accepted this assumption of biomass 'carbon neutrality', and thus, most of the LC GHG emissions associated with bioenergy production are attributed to fossil carbon inputs into the system (*5*). In practice, however, the assumption of carbon neutrality may not accurately represent carbon cycling related to biomass growth (e.g., ref (*6*)). The practice of annual or semiannual harvest in agriculture means that carbon uptake by biomass may reasonably match carbon release in bioenergy systems within a short time frame, although land use change impacts resulting from biomass production can upset this balance (*7*). In temperate forests, the harvest cycle can range from 60 to 100 or more years due to the relatively slow growth of forest species. It could therefore take a century for carbon stocks to be replaced, particularly under a clearcutting regime (harvest of all merchantable trees). Harvest patterns and associated implications for forest carbon stocks vary extensively, ranging from clearcuts to variable retention patterns, including shelterwood and selection cuts. Some variable retention approaches may actually increase forest regeneration, increasing the potential to recover carbon (*8*). Bioenergy production from harvest residues (tree tops and branches) also impacts forest carbon stocks; left uncollected, residues continue to store carbon until released by decomposition or treatment for forest regeneration. While sustainable forest management should ensure that harvest does not impair the long-term productivity of forests, harvest and other forest management activities clearly impact present and future forest carbon stocks. LCA, in its current form, is not well suited to consider the complexities of forest carbon dynamics.

Forest carbon studies have weighed the carbon balance of harvest with the GHG mitigation potential of forest products (e.g., refs *9*–*11*). Some studies have utilized sophisticated forest carbon models to track changes in carbon stored in living biomass (above ground and below ground), dead organic matter, and soil pools (e.g., refs *12, 13*). These studies, however, generally employ simplified assumptions regarding the GHG emissions of forest products (including bioenergy) and have not incorporated a full LC approach. Given the dependence of emissions on specific system

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characteristics (e.g., biomass source, bioenergy production process, fuel displaced), generalized assumptions regarding the GHG mitigation potential of bioenergy are inadequate for informing decision making and public policies.

State-of-the-art tools are available for independently evaluating both the LC emissions of bioenergy systems and forest carbon dynamics. Using these methods in isolation, as has been general practice, stops short of the comprehensive evaluation needed to properly assess the GHG emissions of forest products. In an assessment of GHG mitigation performance of structural wood products, ref (*14*) incorporated LCA with an analysis of forest carbon dynamics. While the study did not consider bioenergy as a product, the results illustrate the importance of considering forest carbon and LC emissions simultaneously when evaluating forest products. Applied to bioenergy, integrating LCA with forest carbon modeling would improve understanding of potential contributions to climate change mitigation.

Bioenergy has been treated inconsistently across energy and climate change policy initiatives in terms of how (or if) GHG emissions are quantified. Forest bioenergy policies that ignore carbon flows in the forest may prove ineffective at achieving actual emissions reductions (*15*). Exclusion of forest carbon from current initiatives is in part due to data issues, although emerging guidelines may ameliorate this situation (*16*). Tools that are able to synthesize forest carbon data and LCA and evaluate trade-offs between bioenergy and forest carbon remain to be developed.

Forest bioenergy has the potential to significantly reduce GHG emissions compared with fossil fuel alternatives. However, interactions between biomass harvest and forest carbon and the resulting effect on the GHG mitigation performance of bioenergy systems are inadequately understood. The objectives of this study are to demonstrate the integration of LCA and forest carbon modeling to assess the total GHG emissions (referred to as “emissions”) of forest-based bioenergy options and to determine how emissions reductions associated with bioenergy are impacted when forest carbon is taken into account. We demonstrate this approach through a case study investigating two bioenergy products (wood pellets, referred to as pellets, and ethanol) from two biomass sources (standing trees and harvest residues, referred to as residues) within the Great Lakes−St. Lawrence (GLSL) forest region of Ontario, Canada.

Methods

We develop a framework integrating two analysis tools: life cycle inventory (LCI) analysis and forest carbon modeling. See Supporting Information for additional detail on all methods. LCI analysis quantifies emissions related to the production and use of forest biomass-derived energy. The LCI is based on the assumption of immediate biomass carbon neutrality, as is common practice, and is therefore employed to quantify the impact of all emissions on atmospheric GHGs with the exception of biomass-based CO_2.

Forest carbon modeling quantifies the impact of biomass harvest on forest carbon dynamics, permitting an evaluation of the validity of the immediate carbon neutrality assumption. If biomass-based CO_2 is fully compensated for by forest regrowth, biomass harvest will have no impact on forest carbon stocks. Reduced forest carbon indicates that a portion of biomass-based CO_2 emissions contributes to increased atmospheric GHGs and should be attributed to the bioenergy pathway. The total emissions associated with a bioenergy system are the sum of the two sets of GHG flows (those resulting from the LCI and those from the forest carbon analysis)

$$\mathrm{GHG_{Tot}}(t) = \Delta\mathrm{FC}(t) + \mathrm{GHG_{Bio}}(t) \quad (1)$$

where $\mathrm{GHG_{Tot}}(t)$ is the total emissions associated with bioenergy, $\Delta\mathrm{FC}(t)$ is the change in forest carbon due to biomass harvest for bioenergy, and $\mathrm{GHG_{Bio}}(t)$ is the GHG emissions associated with bioenergy substitution for a fossil fuel alternative [all reported in metric tonne CO_2 equivlent (tCO_2equiv)] at time t.

The change in forest carbon, $\Delta\mathrm{FC}(t)$, is the difference in forest carbon stocks between harvest scenarios: those ‘with’ and ‘without’ bioenergy production. While we present this as a single parameter in eq 1, in reality forest carbon models consider the complexity of carbon fluxes between pools within the forest and between the forest and atmosphere. Carbon in biomass harvested for bioenergy is assumed to be immediately released to the atmosphere. However, forest regrowth will capture and store atmospheric CO_2 over time. There is therefore a time dependency to the carbon impact of forest harvest for bioenergy. Assessing the change in forest carbon requires consideration of the forest response following harvest and the fate of the biomass source if it is not harvested for bioenergy (standing trees could be harvested for other uses or never harvested; residues could decompose on site, be burned as part of site preparation, or be collected for other uses). Local conditions influence such factors and must inform specific applications of this method. Information relevant to the current case study is provided in the following methods subsection.

LCI quantifies emissions associated with all activities from initial resource extraction and fuel production through to the use of fuels, inclusive of transportation and distribution stages. Emissions related to the production of inputs are included based on their cradle-to-grave activities. Comparing emissions of a bioenergy product with the relevant reference fossil fuel alternative(s) determines the bioenergy GHG mitigation performance. The output of the bioenergy LCI models, emissions per functional unit, is not directly compatible with the output of forest carbon models, which quantify carbon stocks over relatively long time periods (e.g., 100 years) in order to fully capture the impact of management decisions. To integrate the assessment tools, we quantify the cumulative emissions associated with bioenergy production within the time period investigated with the forest carbon model (e.g., 100 years), considering GHG mitigation from fossil fuel displacement to be permanent. LCI results are converted to a quantity of emissions by

$$\mathrm{GHG_{Bio}}(t) = \int_0^t Q_i(t) \times \mathrm{GHG}_i \,\mathrm{d}t \quad (2)$$

where $\mathrm{GHG_{Bio}}(t)$ represents emissions associated with bioenergy substitution for fossil fuel alternative(s) at time t (tCO_2equiv), $Q_i(t)$ is the quantity of biomass used to produce bioenergy product i at time t (e.g., oven dry tonne (odt) biomass/year), and GHG_i is the emissions associated with bioenergy product i per unit biomass (tCO_2equiv/odt). Summing the bioenergy emissions (based on the LCI results) and the forest carbon emissions gives the total emissions of bioenergy utilization over time as shown in eq 1.

Considering emissions over a long time period is relevant to the carbon dynamics of a forest; however, this introduces uncertainty regarding future forest conditions, markets, and the performance of the energy systems investigated. The LCI and forest carbon analysis in this research consider that these conditions remain static throughout the time frame due to the difficulty of deriving reasonable estimates for these parameters. These issues are further examined in the Results and Discussion.

Application of LCI/Forest Carbon Model framework. We apply the above framework to investigate the impact of forest carbon dynamics on the total emissions associated with several forest-based bioenergy pathways. Forest biomass is assumed to be procured for the production of fuels for electricity generation and light-duty vehicle (LDV) transportation. Reference models are also developed for conventional fuel sources to which the bioenergy pathways are compared. We examine emissions of selected GHGs (CO_2, CH_4, N_2O), reported as CO_2equiv based on 100 year global warming potentials (*17*). See the Supporting Information for additional case study details and data.

The pathways considered are as follows. (1) Electricity generation: (a) Reference coal: production of electricity from coal at an existing generating station (GS) in Ontario; (b) Pellet cofiring, harvest residue: production of electricity at 20% cofiring rate (energy input basis) at retrofit coal GS, pellets produced from residues; (c) Pellet cofiring, standing tree: production of electricity at 20% cofiring rate (energy input basis) at a retrofit coal GS, pellets produced from standing trees. (2) Transportation: (a) Reference gasoline: gasoline use in LDV; (b) E85, harvest residue: ethanol/gasoline blended fuel use in LDV, ethanol produced from residues (biomass is not pelletized); (c) E85, standing tree: ethanol/gasoline blended fuel (85% ethanol by volume) use in LDV, ethanol produced from standing trees (biomass is not pelletized).

Biomass Sources. Biomass is supplied from standing trees and residues from 5.25 million hectares within the GLSL forest region in Ontario. This area represents 19% of provincially owned forest managed for timber production. Trees allocated for harvest that are not currently utilized for traditional products could serve as a source of biomass for bioenergy applications without impacting markets for conventional wood products. Residues do not have a useful purpose in the region's conventional forest products industry and are left to decompose in the forest. Competition for limited wood resources can result in diversion from current uses (e.g., pulp) to bioenergy (*18*) with potential indirect emissions consequences (*7*). By limiting the present study to biomass sources unutilized for conventional products, we avoid such market interactions.

Standing tree harvest and related forest operations (regeneration, road construction/maintenance, and transport to the pellet/ethanol facility) are assessed using a model developed in our previous work (*6*). Emissions related to residue collection are calculated by treating the residues as a byproduct of forest harvest. Only additional fuel use required for collection beyond that of current harvest operations is allocated to the residues; other forest operations are allocated to the primary forest product and are therefore not included in the present study. Residue collection consists of roadside chipping and loading.

Electricity Pathways. LCI models representing electricity generation from coal and cofiring of pellets from standing trees were developed in our prior work (*6*). The models consider emissions associated with the full fuel LCs from initial resource extraction through to combustion as well as upstream emissions related to process inputs. One kWh is selected as the functional unit for the analysis. We assume that pellet production from residues and their use for cofiring is similar to that of pellets from standing trees but modify the pelletization process to reflect that residues are chipped in the forest (standing trees are delivered as logs). For both sources, 15% of input biomass is assumed to be consumed during pellet production to dry the biomass. Avoiding fossil fuel use reduces emissions during the pelletization process but increases biomass input to pellet production and associated forest carbon impacts. Implications of this assumption are considered in Results and Discussion.

Transportation Pathways. Ethanol production, transportation, distribution, and use as E85 fuel in LDV are modeled based on the wood-to-ethanol biochemical conversion pathway in the Government of Canada's "well-to-wheel" model, GHGenius 3.17 (*4*). The gasoline portion of E85 fuel and the reference gasoline pathway are also taken from GHGenius. The functional unit for the transportation pathways is 1 km driven. Significant uncertainty exists in evaluating ethanol production from cellulosic feedstock as technological development and optimization is ongoing and production not yet at commercial scale (*19*).

Forest Carbon. The forest carbon dynamics related to biomass harvest are evaluated using FORCARB-ON, an Ontario-specific adaptation of the FORCARB2 model (*12*). FORCARB-ON quantifies carbon stocks (in living trees, soil, standing dead trees, down dead wood, forest floor, and understory vegetation pools) based on harvest schedules and inventories that producers are required to report to the Province. Harvest schedules take into account species and age composition of the forest, age classes eligible for harvest, natural disturbance frequency, growth rates, and forest succession. The model estimates forest carbon stocks over 100 years, a time frame relevant to the long-term perspective of forest management planning.

We evaluate forest carbon stocks for three potential harvest scenarios: (1) "current harvest" baseline, where biomass (standing trees, residues) is not collected for bioenergy production and therefore timber is removed solely to satisfy the current demand for traditional wood products; (2) "current + residue" harvest, with residue removal for bioenergy production; and (3) "maximum allowable" harvest, with additional standing tree harvest (compared to the baseline) for bioenergy production (residues are not collected). The difference in forest carbon stocks between the bioenergy production scenarios and "current harvest" baseline scenario is allocated to the bioenergy products. Additional standing tree harvest for bioenergy occurs as scheduled under forest management plans; following harvest, stands are regenerated by planting or natural regeneration, varying by site. If not harvested for bioenergy, standing trees eventually undergo natural succession and are subject to a small likelihood of natural disturbance. Residue collection is assumed to not impact soil carbon stocks; uncollected residues are assumed to decompose on site, either at the roadside or near where trees were felled. The consequence of collecting residues for bioenergy production is that this temporary carbon store is 'liquidated' immediately (combusted during bioenergy production and use) rather than decomposing slowly in the forest. Therefore, the associated change in forest carbon is the difference between immediate release (bioenergy) and decomposition over time if not collected. As noted previously, these factors could vary by location with a potentially significant impact on the assessed forest carbon emissions. We do not consider emissions related to the current harvest for traditional wood products or their use. Under the assumptions in this study, this is not affected by the decision to undertake additional harvest or collect residues for bioenergy production.

Results and Discussion

Life Cycle Inventory Results, Excluding Forest Carbon. LCI results for the pathways are shown in Table 1, using the assumption of immediate biomass carbon neutrality. LCI emissions for biomass are greater when sourced from standing trees than from residues. Upstream (fuel production) stages, however, are minor contributors to LC emissions of either pellets or ethanol. The majority of emissions arise from the combustion of fossil fuels, both as the fossil portion during bioenergy use and in the reference fossil pathways. Excluding changes in forest carbon, 20% pellet cofiring reduces LC emissions by 18% compared to coal-only operation (kWh basis) whether standing trees or residues are utilized, whereas an E85-fueled LDV reduces LC emissions by 57% compared to a gasoline LDV (km-driven basis). The greater emission reduction of E85 relative to pellet cofiring gives the appear-

TABLE 1. Life Cycle GHG Emissions Associated with Bioenergy Product (wood pellets, ethanol) Blended for Use and Substitution for Fossil Reference Pathway[a]

	electricity generation pathways			transportation pathways		
life cycle stage	coal[c,d] (g CO_2equiv/kWh)	20% pellet cofiring, residue (g CO_2equiv/kWh)	20% pellet cofiring, standing tree[c] (g CO_2equiv/kWh)	gasoline[f] (g CO_2equiv/km)	E85, residue (g CO_2equiv/km)	E85, standing tree (g CO_2equiv/km)
forest operations		1.9	4.3		5.1	11.7
bioenergy production, distribution [b]		9.5	9.6		46	46
upstream fossil energy component	62	50	50	77	16	16
fuel use (combustion)[e]	939	760	760	211	48	48
total life cycle emissions	1001	821	824	288	116	123

[a] Values assume immediate carbon neutrality and do not take into consideration forest carbon implications. [b] Includes transport of biomass to the production facility, bioenergy production, electricity coproduct credit from biochemical production of ethanol, and bioenergy transportation/distribution stages. [c] Reference (*6*). [d] Surface coal mining removes biomass and disturbs soil, which results in GHG emissions due to direct land use change. These emissions along with other mining process emissions are considered in our analysis. [e] Fuel use consists of GHG emissions from the fossil component of fuel (coal, gasoline) and non-CO_2 GHG emissions associated with bioenergy (pellet, ethanol) combustion. [f] Reference (*4*).

TABLE 2. Forest Carbon Impacts of Continuous Biomass Harvest

	forest carbon stock change ($MtCO_2$equiv)										
	year										
biomass source	0	10	20	30	40	50	60	70	80	90	100
residues	0[a,b]	−8.2	−11.8	−13.0	−13.5	−13.9	−14.3	−14.7	−15.0	−15.2	−15.2
standing trees	0	−43.6	−80.9	−106.3	−112.5	−113.4	−112.7	−132.8	−143.6	−150.8	−150.7

[a] Negative values indicate a GHG emission source (forest carbon stocks are reduced due to biomass harvest) that is attributable to bioenergy production. [b] Reported values are the total stock change due to continuous harvest. For example, 50 years of continuous standing tree harvest reduces total forest carbon stocks by 113.4 $MtCO_2$equiv.

ance that this pathway represents a preferred use of biomass for reducing emissions, but this results primarily from the cofiring scenario utilizing a lower proportion of biomass fuel (20%, energy basis) than E85 (79%, energy basis).

We convert the LC emissions from their initial functional units (kWh, km driven) to a basis of one odt of biomass removed from the forest for bioenergy production ($odt_{biomass}$). This makes the LCI and forest carbon model results compatible and facilitates a comparison of the two bioenergy pathways (electricity, ethanol) in terms of their effectiveness of biomass utilization in reducing emissions (see Supporting Information, equation S-3). Over their respective LCs, the production and use of pellets from standing trees displaces 1.49 tCO_2equiv/$odt_{biomass}$, while ethanol production and use displaces 0.51 tCO_2equiv/$odt_{biomass}$, exclusive of forest carbon impacts. Utilizing residues as a feedstock for pellets and ethanol displaces 1.50 and 0.53 tCO_2equiv/$odt_{biomass}$, respectively. Substitution of coal with pellets provides a greater mitigation benefit than substitution of gasoline with ethanol, primarily due to the higher GHG intensity of coal. To put these values into perspective, the constituent carbon in biomass is equivalent to 1.83 tCO_2equiv/odt. The significance of releasing this biomass-based CO_2 is considered subsequently.

Forest Carbon Analysis Results: Impact of Biomass Harvest. Sustainable biomass sources in the study area could provide, on average, 1.8 million odt/year from standing trees and 0.38 million odt/year from residues. Combined, these sources could provide 2.2% of annual electricity generation in the province or reduce gasoline consumption by 3.3% (see Supporting Information). Forest carbon loss due to undertaking biomass harvest in the study area over a 100 year period is shown in Table 2. For both sources (residues, standing trees), harvest reduces forest carbon asymptotically toward a "steady state". For standing trees, as more stands are harvested for bioenergy over time, the rate of carbon accumulation in regrowing stands increases toward a point where, under ideal conditions, carbon accumulation balances removals associated with continued harvest. For residues, a similar steady state is eventually achieved when the rate of carbon removals at harvest is matched by the expected rate of residue decomposition if harvest is not undertaken. Continuing biomass harvest once a steady state has been reached would not impact forest carbon stocks; however, initiating biomass harvest beyond current removals has significant emissions consequences in the near to medium term. Forest carbon loss due to harvest residue collection approaches a maximum of ~15$MtCO_2$equiv, whereas standing tree harvest for bioenergy results in a carbon loss exceeding 150 $MtCO_2$equiv after 100 years. Proportional to the quantity of biomass provided, standing tree harvest results in a greater impact on forest carbon than harvest residue collection because live trees would generally continue to sequester carbon if not harvested, whereas carbon in uncollected residues declines over time.

Total GHG Emissions: Combined LCI and Forest Carbon Analysis Results. Summing the cumulative emissions of the bioenergy options (LCI results Figure 1, dashed lines) and the forest carbon emissions (Figure 1, dotted lines) results in the total emissions of bioenergy production and use (Figure 1, solid lines). When reductions in forest carbon are included, emission mitigation is delayed and reduced compared to the case where immediate biomass carbon neutrality is assumed. For all scenarios investigated, total emissions from the bioenergy pathways initially exceed those of the reference fossil fuel pathways, indicating an initial increase in emissions resulting from bioenergy use. Emissions associated with forest carbon loss due to biomass harvest exceed the reduction of fossil fuel-based emissions provided by bioenergy substitution. The emissions increase associated with bioenergy, however, is temporary: the rate of forest carbon loss decreases with time, whereas the emissions reduction associated with utilizing bioenergy in place of fossil alternatives continues to increase throughout the 100 year period, proportional to the cumulative quantity of pellets or ethanol produced. A

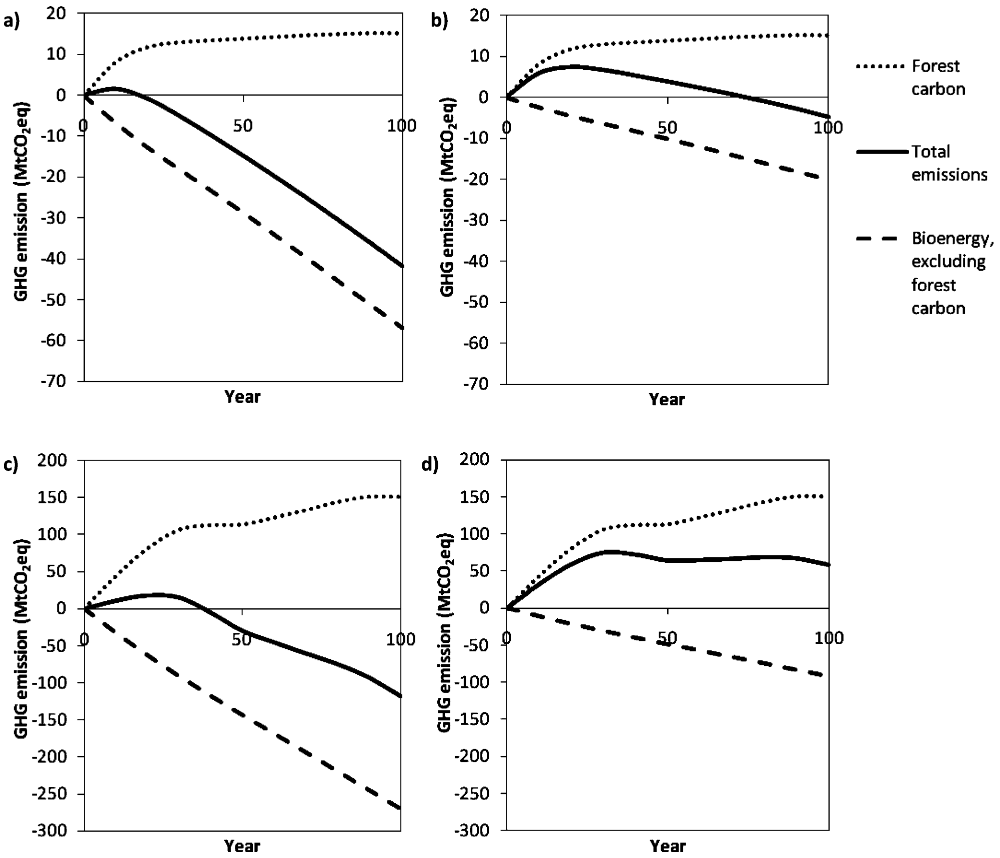

FIGURE 1. Cumulative GHG emissions from continuous biomass harvest for bioenergy production: (a) pellets produced from residues, displacing coal (20% cofiring), (b) ethanol produced from residues, displacing gasoline (E85 fuel), (c) pellets produced from standing trees, displacing coal (20% cofiring), and (d) ethanol produced from standing trees, displacing gasoline (E85 fuel). Positive values indicate an increase in GHG emissions to the atmosphere.

time delay therefore exists before bioenergy systems reach a "break-even" point where total emissions for the bioenergy and reference fossil pathways are equal. Only after the break-even point are net emissions reductions achieved.

Figure 1a and 1b shows the total emissions resulting from continuous use of residues for pellet and ethanol production, respectively, over a 100 year period. Excluding forest carbon, the emissions reduction associated with utilizing bioenergy in place of fossil alternatives increases steadily over time. The reduction of forest carbon stocks due to residue collection slows toward a steady state. Co-firing with pellets produced from residues reduces cumulative emissions relative to coal only after an initial period of increased emissions lasting 16 years. Forest carbon impacts of residue removal reduce the total emission mitigation at year 100 from 57 MtCO$_2$equiv (expected assuming immediate biomass carbon neutrality) to 42 MtCO$_2$equiv.

Compared to the electricity pathway results, utilization of residues for ethanol production is more greatly impacted by changes in forest carbon, due to the lower GHG intensity of the displaced fuel (gasoline compared to coal). An overall emission reduction occurs only after 74 years of continuous production of ethanol; total GHG reductions by year 100 are reduced by 76% from expected performance assuming immediate biomass carbon neutrality.

Due to the greater forest carbon impact of standing tree harvest compared to residue collection, bioenergy production from standing trees performs worse in terms of reducing emissions (Figure 1c and 1d). Pellet production from standing trees results in a greater initial emissions increase, reaching a break-even point only after 38 years of continuous production and use when displacing coal for electricity generation. The total emissions reductions from utilizing wood pellets from standing trees over a 100 year period, expected under the assumption of biomass carbon neutrality, is reduced by 56% when forest carbon impacts are considered.

As in the residue cases, for the standing tree cases forest carbon more significantly impacts total emissions of ethanol than those associated with pellets for electricity generation. Ethanol production from standing trees (Figure 1d) does not reduce emissions at any point within the 100 year period; instead, overall emissions to the atmosphere increase relative to the gasoline reference pathway. Disregarding biobased CO$_2$ emissions, as is common to most LCAs, would return an opposite, and erroneous, result. This contradiction, also identified elsewhere (*15*), illustrates the misleading consequence of assuming immediate biomass carbon neutrality when quantifying emissions of some bioenergy pathways.

Simply adding biobased CO$_2$ emissions associated with bioenergy production and use to the LCI totals presented in Table 1 would increase emissions associated with bioenergy. Pellet cofiring (at 20%) would result in (all in gCO$_2$equiv/kWh) 1039 (residue) and 1042 (standing tree) compared to 1001 for coal only. E85 would emit (all in gCO$_2$equiv/km) 711 (residue) and 718 (standing tree) compared to 288 for gasoline. This approach, however, would not accurately assess the impact of bioenergy production and use on the atmosphere. By only considering carbon in harvested biomass, near-term emissions would be underestimated (decomposition of uncollected biomass, for example, below ground biomass, is omitted). Mid- to long-term emissions would be overestimated as compensation for biobased CO$_2$ emissions within the forest (e.g., regrowth) is not considered.

Sensitivity Analysis. A sensitivity analysis is performed to assess the impact of key sources of uncertainty/variability in the LCI and forest carbon model parameters on the study results (see Supporting Information). The results are not sensitive to most parameters, and the general trends of the impacts of biomass harvest on carbon stocks and their contribution to overall emissions were not found to be impacted by uncertainty in the parameters. The pellet pathway results were found to be most sensitive to assumptions related to the quantity of biomass used for drying during pelletization (15% of input biomass in base case) (see Supporting Information Figure S-3). Reducing the consumption of biomass during the drying stage increases pellet output and fossil fuel displacement per unit of input biomass. Co-location of pelletization facilities with processes generating waste heat could reduce the drying energy requirement. If no input biomass is required for drying, there are larger emissions reductions associated with pellet use and the time before reaching break even with the fossil energy system is reduced from 16 to 11 years (residues) and from 38 to 29 years (standing trees). When forest carbon is excluded from the analysis, biomass utilization for drying energy has a minimal impact on LC emissions (*6*).

Study Implications. The simplified assumption of immediate biomass carbon neutrality has been commonly employed in bioenergy studies, owing in part to emissions from the energy and forest sectors being reported separately in national inventories (*17*). This study, however, shows that increasing biomass removals from the forest significantly reduces carbon stocks and delays and lessens the GHG mitigation potential of the bioenergy pathways studied. Ignoring the complex relationship between forest carbon stocks and biomass harvest by employing the carbon neutrality assumption overstates the GHG mitigation performance of forest bioenergy and fails to report delays in achieving overall emissions reductions.

Combining LCI analysis and forest carbon modeling as an analytical approach provides a more accurate representation of the role of forest bioenergy in GHG mitigation. When forest carbon dynamics are included in the case study, the use of forest-based bioenergy increases overall emissions for many years and, in the worst-performing scenario (standing tree harvest for ethanol production), does not yield any net climate mitigation benefit over the 100 year period. Carbon implications of bioenergy production are not limited to forests, and these results should not be taken to suggest that agricultural biomass is inherently preferable. Land use impacts associated with agriculture-sourced bioenergy can greatly increase LC emissions (*7*). Nonbioenergy systems can also impact carbon stocks (e.g., overburden removal in coal mining). While the contribution to total emissions may not be significant in all situations, a comprehensive evaluation of any fossil or renewable system should consider impacts of life cycle activities on terrestrial carbon stocks.

Do our results support continued reliance on fossil fuels for electricity generation and transportation? Fossil fuel use transfers carbon from the Earth's crust to the atmosphere; moving beyond reliance on these energy sources is imperative to address climate change and nonrenewable resource concerns. Bioenergy offers advantages over other renewable options that are limited by supply intermittency and/or high cost. However, effective deployment of bioenergy requires the thoughtful selection of appropriate pathways to achieve overall emissions reductions. Harvesting standing trees for structural wood products has been reported to reduce overall emissions: storing carbon in wood products and displacing GHG-intensive materials (steel, concrete) exceeds associated forest carbon impacts (*14*). In comparison, using standing trees for bioenergy immediately transfers carbon to the atmosphere and provides a relatively smaller GHG benefit from displacing coal or gasoline, increasing overall emissions for several decades. Identifying biomass supply scenarios that minimize forest carbon loss will improve the emission mitigation performance of forest bioenergy. Residues employed for bioenergy reduce emissions from coal after a much smaller delay than standing trees, while other forest biomass sources (e.g., processing residuals) could offer near-term emission reductions if used to replace GHG-intensive fossil fuels. Industrial ecology approaches (e.g., utilizing end-of-life wood products as a biomass source; integrating bioenergy production with other wood products to utilize waste heat for processing) could reduce forest carbon implications of bioenergy production and are deserving of further consideration.

Utilizing bioenergy to displace the most GHG-intensive fossil fuels minimizes initial emissions increases and reduces the time required before net GHG benefits are achieved. Ethanol production for gasoline displacement, under the modeled conditions, is not an effective use of forest biomass for GHG reductions. Displacing coal in electricity generation, in comparison, is superior in reducing emissions. However, this does not indicate that electricity applications are always preferable. The mitigation performance of biomass-derived electricity depends on the displaced generation source. Further, these results represent the expected near-term state of energy system technologies and do not consider changes in either the reference or the bioenergy pathways over the time frame studied. Performance improvements are inevitable with technological maturation and commercialization. Technological developments regarding thermal electricity generation (e.g., efficiency improvements; viable carbon capture and storage) would be applicable to both biomass and coal, while improvements in pellet production would not greatly influence total emissions. Emissions from producing ethanol, regarding both the ethanol production process and the appropriate reference pathway in the future given the limited petroleum supply and associated price volatility, is uncertain and in the future could prove a more effective means of emissions reductions than reported here. Ethanol can also play an important role in addressing economic and energy security concerns related to petroleum dependency.

Although the method demonstrated in this research is generalizable, site-specific characteristics of forests prevent the generalization of specific results from this study. Numerous factors would influence forest carbon dynamics and must be considered in specific analyses. Intensifying silvicultural practices (e.g., planting instead of natural regeneration, utilization of fast-growing species) could shorten, but not eliminate, the period of net emission increase found in our results. In some jurisdictions, residues are burned during site preparation for forest regrowth. Using such residues for bioenergy would not significantly impact forest carbon stocks.

While GHG mitigation is an important consideration of forest resource utilization, numerous other factors must be considered in the decision-making process. In particular, declines in Ontario's forest sector have negatively impacted communities that would welcome the investment and employment opportunities associated with bioenergy. Other environmental factors and technical constraints must be considered before implementing bioenergy production.

The potential of forest-based bioenergy to reduce emissions from fossil fuels must be balanced with forest carbon impacts of biomass procurement. This perspective is of particular importance as policies related to climate change mitigation, deployment of renewable energy, and the forest bioeconomy are developed and implemented. Considering bioenergy in isolation of its impact on forest carbon could inadvertently encourage the transfer of emissions from the energy sector to the forest sector rather than achieve real reductions. Accounting methods must be designed to measure the complete impact of mitigation options on the atmosphere. By considering the broader impacts of bioenergy production on the forest, particularly forest carbon pools, policy can lend support to effective uses of forest resources for climate change mitigation.

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Supporting Information Available

Additional detail on biomass sources, life cycle inventory of bioenergy systems, forest carbon analysis, and additional results and discussion. This material is available free of charge via the Internet at http://pubs.acs.org.

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