October 31, 2018

Joint Comments of Clean Air Task Force, Natural Resources Defense Council, Center for Biological Diversity, Clean Air Council, Clean Wisconsin, Conservation Law Foundation, Dogwood Alliance, Partnership for Policy Integrity, and Sierra Club on the Treatment of Biomass-Based Power Generation in EPA's Proposed Emission Guidelines for Greenhouse Gas Emissions from Existing Electric Utility Generating Units; Revisions to Emission Guideline Implementing Regulations; Revisions to New Source Review Program (83 Fed. Reg. 44746 (August 31, 2018)

Docket No. EPA-HQ-OAR-2017-0355

Submitted via regulations.gov

Environmental and public health organizations Clean Air Task Force, Natural Resources Defense Council, Center for Biological Diversity, Clean Air Council, Clean Wisconsin, Conservation Law Foundation, Dogwood Alliance, Partnership for Policy Integrity, and Sierra Club hereby submit the following comments on the "best system of emission reduction" and other issues EPA's proposed rule "Emission Guidelines for Greenhouse Gas Emissions from Existing Electric Utility Generating Units; Revisions to Emission Guideline Implementing Regulations; Revisions to New Source Review Program," 83 Fed. Reg. 44,746 (Aug. 31, 2018).

[I] Overview

Climate change continues to intensify and threaten public health and welfare. A recent report from the Intergovernmental Panel on Climate Change (IPCC) concludes that if greenhouse gas (GHG) emissions continue at the current rate, the atmosphere will warm by as much as 1.5°C (or 2.7°F) by 2040.[1] "Climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming of 1.5°C and increase further with 2°C."[2]

The power sector was responsible for 29 percent of the climate-warming GHGs emitted in the United States in 2017,[3] making it imperative that the U.S. Environmental Protection Agency

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[1] *See generally* Myles Allen, *et al.*, IPCC, *Global Warming of 1.5 °C: an IPCC special report on the impacts of global of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (Oct. 8, 2018), http://www.ipcc.ch/report/sr15/.

[2] *Id*. at SPM-11.

[3] EPA Regulatory Impact Analysis for the Proposed Emission Guidelines for Greenhouse Gas Emissions from Existing Electric Utility Generating Units; Revisions to Emission Guideline Implementing Regulations; Revisions to New Source Review Program (August 2018) at 2-26.

(EPA) make full and effective use of its statutory mandate to regulate power sector emissions of carbon dioxide (CO_2) and other GHGs.

Clean Air Task Force, Natural Resource Defense Council, and other organizations have submitted comments to this docket that describe EPA's obligation to limit power sector emissions under Section 111 of the Clean Air Act (CAA).[4] The comments provided here incorporate those other comments by reference, and expand upon those comments by focusing on the practice of co-firing wood and other types of biomass at coal-fired power stations. These comments explain why the practice of biomass co-firing (at least as it is described by EPA) does not reduce GHG emissions at coal-fired power stations and cannot be used to comply with CAA Section 111 without unlawfully contravening existing statutory text and other aspects of EPA's proposed regulatory text.

EPA's August 2018 regulatory proposal—titled "Emission Guidelines for Greenhouse Gas Emissions From Existing Electric Utility Generating Units; Revisions to Emission Guideline Implementing Regulations; Revisions to New Source Review Program"[5]—does not direct the owners/operators of coal-fired power stations to consider biomass co-firing as a way to reduce the stations' GHG emissions, nor does it consider biomass co-firing to be part of the best system of emission reduction (BSER). Nonetheless, relying on its "Statement of Agency Policy," EPA asserts that its "policy is to treat the combustion of biomass from managed forests at stationary sources for energy production as carbon neutral"[6] and encourages affected sources to comply with their state-established performances standards by co-firing biomass.

Neither EPA nor states can categorically treat the combustion of biomass from managed forests as a "carbon neutral" method of complying with CAA Section 111, for the following reasons:

- EPA has not demonstrated that biomass co-firing can achieve an "emission reduction" at a "stationary source," as required by CAA Section 111.
- It would be arbitrary, capricious, and otherwise unreasonable for EPA to allow states to base their CAA Section 111(d) compliance plans on nominal reductions from biomass co-firing.
- EPA's reliance on its "Statement of Agency Policy" and its proposal to treat all forms of forest biomass harvested from "managed forests" as carbon neutral is unfounded, contrary to established scientific findings, and does not "adequately demonstrate" that co-firing biomass harvested from managed forests constitutes an "emission reduction."
- A coal-fired power station that makes a modification so that it can co-fire biomass cannot, as a matter of course, be exempted from scrutiny under the CAA's New Source Review (NSR) provisions.

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[4] *See* Joint Environmental Comments on BSER Issues (filed in this docket October 31, 2018).

[5] 83 Fed. Reg. 44746 (August 31, 2018).

[6] 83 Fed. Reg. at 44766/1 (citing EPA Administrator Scott Pruitt, *EPA's Treatment of Biogenic Carbon Dioxide Emissions from Stationary Sources Use Forest Biomass for Energy Production* (April 23, 2018) (hereinafter "EPA Statement of Agency Policy") (https://www.epa.gov/sites/production/files/2018-04/documents/biomass_policy_statement_2018_04_23.pdf)).

Each of these points is discussed in greater detail below.

[II] Biomass co-firing does not achieve an "emission reduction" at a "stationary source" as required by CAA Section 111

[A] Biomass combustion emits more CO_2 per kilowatt-generated than coal combustion, so a shift to biomass co-firing does not produce an "emission reduction."

EPA listed power stations as a source category that "may reasonably be anticipated to endanger public health or welfare"[7] under CAA Section 111 nearly 40 years ago.[8] When it subsequently established standards of performance under CAA Section 111(b) for CO_2 from new power stations in 2015, EPA triggered an obligation to set standards of performance under Section 111(d) for existing power stations as well.[9]

Per CAA Section 111(a)(1), a standard of performance "reflects the degree of *emission limitation* achievable through the application of the best system of *emission reduction* … the Administrator determines has been adequately demonstrated."[10] Although the CAA authorizes states to set "standards of performance" for individual stationary sources, it makes EPA responsible for identifying the emission levels that can be achieved through the application of the best system of emission reduction. For the process to work, EPA *must* set an emission limit and state plans must be at least as stringent as the selected emission limit.

EPA's proposal—with its menu of voluntary heat rate improvements—lacks such a limit and thus fails to fulfill the Administrator's duty under CAA Section 111.[11] Moreover, by failing to establish a clearly discernible emission limit, the proposal lacks a benchmark for assessing the efficacy of state implementation plans, which the statute requires EPA to do.[12]

The proposal fails to set an emissions limit benchmark and defers to the states to perform case-by-case analysis to establish standards of performance for individual sources. Clearly an action that results in an emission *increase* cannot be the basis of a standard defined as an "emission limitation" based on the best system of "emission reduction."[13] Moreover, regardless of what

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[7] 42 U.S.C. § 7411(b)(1).

[8] *See* 44 Fed. Reg. 33,580 (July 11, 1979) (listing subpart Da); and 71 Fed. Reg. 38,482 (July 6, 2006) (listing subpart KKKK).

[9] 80 Fed. Reg. 64,510 (Oct. 23, 2015); 83 Fed. Reg. at 44,751 (EPA confirming its duty to issue CAA Section 111(d) regulations for power stations).

[10] 42 U.S.C. § 7411(a)(1) (emphasis added).

[11] *See* Joint Environmental Comments on BSER Issues and Joint Environmental Comments on Framework Regulations (both filed in this docket October 31, 2018).

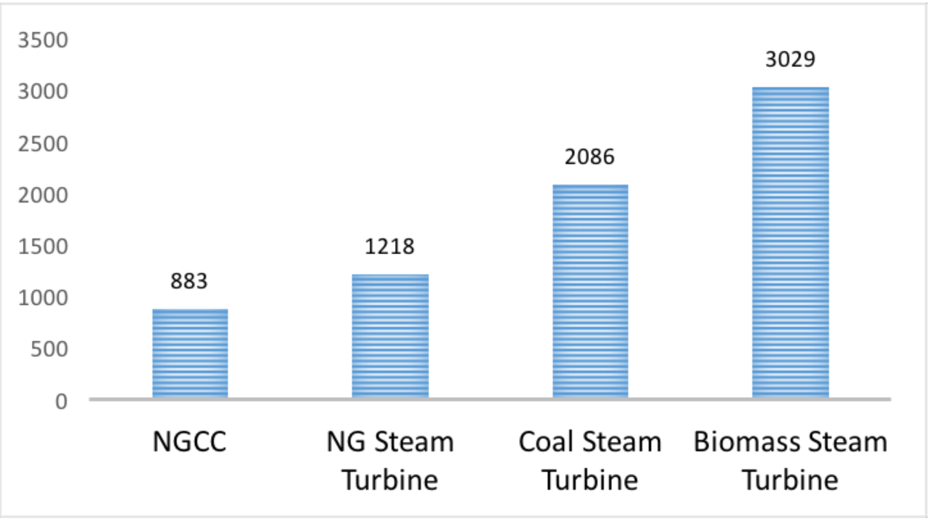
[12] 42 U.S.C. § 7411(d)(2)(A).

[13] Co-firing biomass at a coal-fired power station does not meet EPA's definition of "heat rate improvement" (HRI): "Heat rate is the amount of energy input, measured in British thermal units (Btus), required to generate one kilowatt-hour (kWh) of electricity. The lower an EGU's heat rate, the more efficiently it operates. As a result, an

measure the state bases the standard on, a source cannot comply with that standard by co-firing with biomass because that would increase CO_2 emissions.

Power stations that burn biomass (or a mix of biomass and coal) emit more CO_2 per kilowatt hour (kWh)-generated than otherwise identical power stations that burn just coal. As shown in the table below, the CO_2 emissions rate from the combustion of woody biomass at a utility-scale power station is 1.5 times higher than the CO_2 emissions rate from a coal-fired power station.

CO_2 Emissions Rate (in pounds of CO_2 per megawatt hour generated) for Select Fuels and Generating Technologies[14]



A shift to biomass co-firing at a coal boiler does not automatically reduce or limit the amount of CO_2 emitted from the source—rather, in nearly every scenario, it increases the source's CO_2 emissions.[15] Therefore, in accordance with the plain language of CAA Section 111, it cannot be the basis of a state-established standard of performance, or used to comply with it.

EGU with a lower heat rate will consume less fuel per KWh generated and emit lower amounts of CO_2 and other air pollutants per KWh generated as compared to a less efficient unit." 83 Fed. Reg. at 44755/3. Biomass combustion is less efficient than coal combustion; power stations that burn biomass consume *more* fuel per KWh generated and emit *higher* amounts of CO_2 per KWh generated as compared to coal-fired stations. Biomass combustion does not reduce heat rate relative to coal combustion and therefore cannot be considered an HRI measure. *See* 83 Fed. Reg. at 44748/1 ("First, EPA is proposing to determine the BSER for existing [electric utility generating units] based on HRI measures that can be applied at an affected source.")

[14] US EIA, Carbon Dioxide Emission Coefficients (for NGCC, NG steam turbine, coal steam turbine; value for coal is for "all types") (http://www.eia.gov/environment/emissions/co2_vol_mass.cfm); Oak Ridge National Laboratory, Biomass Energy Data Book v. 4 (2011) (assumes wood has higher heating value of 8,600 MMBtu/lb, is bone dry, and is composed of 50% carbon) (http://cta.ornl.gov/bedb); *see also* Thomas Walker, *et al*. Biomass and Carbon Policy Study (report by the Manomet Center for Conservation Sciences) 103-104 (2010) (https://www.manomet.org/publications-tools/sustainableeconomies/biomass-sustainability-and-carbon-policy-study-full-report).

[15] The extent to which CO_2 emissions change when a power station shifts from fossil fuel combustion to biomass combustion can vary depending on the type of fossil fuel used, the type of biomass used, and physical and

The ordinary meanings of the words *limit* ("to curtail or reduce in quantity or extent"[16]) and *reduce* ("to diminish in size, amount, extent or number"[17]) do not encompass processes that make the object in question—in this case, CO_2 emissions from a power station—larger in quantity, size, amount, extent, and number.[18] The proposal fails to explain how the increase in CO_2 emissions that typically results from a shift to biomass co-firing at a power station can constitute a "limitation" or "reduction" of CO_2 emissions for the regulated sources, as required by CAA Section 111.[19]

By failing to provide a lawful justification for its proposal "to treat biogenic CO_2 emissions resulting from the combustion of biomass from managed forests at stationary sources for energy production as carbon neutral,"[20] EPA repeats the mistake it made in 2011 when it tried to exempt biogenic CO_2 emissions from scrutiny under the Prevention of Significant Deterioration (PSD) program for three years. Then, as now, EPA "believe[d] that it has authority under the Clean Air Act to treat biogenic carbon dioxide sources differently because these sources have unique characteristics that were 'unquestionably unforeseen when Congress enacted [the] PSD' program."[21] The PSD exemption (known as the Deferral Rule) was vacated by the US Court of Appeals for the DC Circuit in *Center for Biological Diversity v. EPA* in 2013. After noting that "it is not possible to distinguish between the radiative forcing associated with a molecule of CO_2 originating from a biogenic source and one originating from the combustion of fossil fuel,"[22] the court pointed out that "nowhere in the Deferral Rule" did EPA provide a statutory analysis to support its contention that it could treat biogenic CO_2 emissions differently from fossil CO_2 emissions.[23]

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operational characteristics of the power station. EPA's proposal does not examine any scenarios that differ in these ways, though, nor does it make any attempt to determine if or when such scenarios might warrant different treatment under CAA Section 111(d). EPA simply differentiates "biomass from managed forests" from other kinds of biomass. *See* 83 Fed. Reg. at 44766/1 (citing EPA Statement of Agency Policy). As discussed in Part IV of these comments, the distinction that EPA draws between "biomass from managed forests" and other biomass is functionally meaningless.

[16] Meriam-Webster Online Dictionary (2018) (https://www.merriam-webster.com/dictionary/limit).

[17] Meriam-Webster Online Dictionary (2018) (https://www.merriam-webster.com/dictionary/reduce).

[18] *Chevron v. Natural Resources Defense Council*, 467 U.S. 837, 842-43 (1984) ("If the intent of Congress is clear, that is the end of the matter; for the court, as well as the agency, must give effect to the unambiguously expressed intent of Congress.").

[19] *See Motor Vehicles Manufacturers Ass'n v. State Farm* 463 U.S. 29, 43 (1983) (internal citations omitted) ("an agency rule would be arbitrary and capricious if the agency…offered an explanation for its decision that runs counter to the evidence before the agency"); *see also Owner-Operator Indep. Drivers Ass'n v. Fed. Motor Carrier Safety Admin*, 494 F.3d 188, 204 (D.C. Cir. 2007) ("complete lack of explanation for an important step in the agency's analysis was arbitrary and capricious").

[20] 83 Fed. Reg. 44766/1.

[21] *Center for Biological Diversity v. EPA*, 722 F.3d 401, 409 (D.C. Cir. 2013) (quoting EPA Respondent's brief to the court).

[22] *Id*. at 406.

[23] *Id*. at 409.

Little has changed. EPA continues to believe it can regulate stationary sources that combust biomass differently than it regulates sources that combust fossil fuel, much as it did when it defended the 2011 Deferral Rule. And, like the Deferral Rule, the Agency's current proposal provides no statutory analysis to support that belief. Consequently, because EPA has not demonstrated that co-firing biomass results in an "emission limitation" or "emission reduction" under CAA Section 111(a), the Agency cannot approve state implementation plans that rely on biomass co-firing to meet states' emission reduction obligations under Section 111(d).

The emission benefits sometimes attributed to biomass-burning power stations do not occur for years, decades, or even centuries after the station burns biomass to make energy. There is a significant delay between the time at which biomass is burned to generate kilowatts and CO_2 is emitted from the stations' smokestacks, and the time (if ever) at which emission reductions are achieved. For example, if standing trees are harvested and burned in a power station, it takes several decades or more for forest regrowth and the associated carbon absorption to fully make up for or pay back the additional CO_2 emissions and lost CO_2 sequestration associated with biomass combustion. If forestry residues, such as limbs and tree tops, are burned instead, the payback period is shorter because it is tied to the decomposition rate of that material, but still a matter of years or decades.[24]

EPA fails to demonstrate that the text of CAA Section 111 (specifically the CAA section 111(a)(1) term "emission reduction") authorizes EPA to credit a stationary source with countervailing emission reduction which—if it occurs at all—will happen years, decades, or even centuries after the source produced the associated energy. Likewise, had Congress meant for the terms "emission limitation" and "system of emission reduction" to include processes that do not reduce emissions for years (if at all), then Congress would have undoubtedly added language to that effect.[25]

Furthermore, interpreting "emission reduction" to include long-delayed reductions would frustrate the purpose of CAA Section 111(d). The additional CO_2 molecules emitted into the atmosphere by biomass-fueled power stations are hardly inert during the years or decades that it takes for harvested forests to fully grow back: they spend that time trapping heat radiated from the earth and contributing to global warming in precisely the same way that CO_2 molecules emitted from coal-fired power stations do. Similarly, the multi-year or multi-decade net increase in atmospheric CO_2 concentrations resulting from a shift to biomass co-firing negatively impacts the climate even if the near-term CO_2 emissions from biomass combustion are eventually netted out by plant growth and carbon absorption.

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[24] *See* footnotes 52-54, *infra*.

[25] *See e.g. Franklin Nat'l Bank v. New York*, 347 U.S. 373, 378 (1954) (finding "no indication that Congress intended to make this phase of national banking subject to local restrictions, as it has done by express language in several other instances"); *Meghrig v. KFC Western, Inc*., 516 U.S. 479, 485 (1996) ("Congress ... demonstrated in CERCLA that it knew how to provide for the recovery of cleanup costs, and ... the language used to define the remedies under RCRA does not provide that remedy."); *FCC v. NextWave Personal Communications, Inc*., 537 U.S. 293, 302 (2003) (when Congress has intended to create exceptions to bankruptcy law requirements, "it has done so clearly and expressly").

Higher concentrations of CO_2 in the near term would accelerate global warming at a pivotal moment in the effort to curb climate change. An approach that increases emissions for decades and does not provide a net benefit for, say, 50 years would frustrate efforts to reduce "air pollution which may be reasonably anticipated to endanger public health or welfare."[26] As such, biomass co-firing does not constitute a "system of emission reduction" per CAA Section 111 in the same way that the installation of carbon capture and storage equipment or other measures that prevent CO_2 emissions constitute a "system of emission reduction."

EPA has not demonstrated, and cannot demonstrate, how co-firing "biomass from managed forests" at a coal-fired power station could "limit[]" or "reduc[e]" CO_2 emissions, as those terms are used in CAA Section 111(a). As such, if the Agency were to finalize the proposal, it would violate the plain language of CAA Section 111.

[B] Biomass combustion is not a system of emission reduction for existing sources

The CO_2 emission reductions that are nominally attributed to biomass-based power stations happen in forests and on farmland when growth of additional plant matter absorbs more CO_2 from the atmosphere than would have occurred otherwise. In the proposal, EPA has not demonstrated how practices that do not lead to CO_2 emission reductions at the existing sources can be considered an "emission limitation" or an "emission reduction" under CAA Section 111.

The argument that biomass combustion reduces CO_2 emissions depends on an assessment of *net emissions*, in which CO_2 emissions from the existing sources are netted against subsequent CO_2 reductions attributed to plant matter regrowth and associated carbon absorption.

As detailed above, burning biomass rather than fossil fuel at a power station does not reduce the volume of CO_2 emitted by the station. To claim that a *net* CO_2 emissions reduction occurred, the owner/operator of the biomass-fueled power station must be able to take credit for carbon uptake that happens elsewhere—*i.e.*, in forests and other landscapes. This approach is consistent with the commonly-understood definition of a forest offset program used by the World Resources Institute and other authorities.[27] EPA's proposal fails to explain why a *de facto* offset program constitutes a "system of emission reduction" under CAA Section 111.

Even if an offset program was appropriate under Section 111—which it is not—a basic requirement of CO_2 offset accounting is that the reductions must be *additional*—that is, the volume of CO_2 uptake attributed to the offset program must be above and beyond what would

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[26] CAA § 111(b)(1)(A).

[27] WRI, *The Bottom Line on Offsets* 1 (2010) (defining an offset as "a unit of carbon dioxide-equivalent (CO_2e) that is reduced, avoided, or sequestered to compensate for emissions occurring elsewhere") (http://www.wri.org/sites/default/files/pdf/bottom_line_offsets.pdf).

have happened under a business-as-usual scenario.[28] Biomass combustors cannot simply take credit for carbon absorption rates that are no higher than those that would have occurred anyway in the relevant forest. For forest biomass-burning to generate CO_2 reduction credits in accordance with the requirements of offset programs, the relevant land managers must be able to demonstrate that the land under their control is sequestering more CO_2 under the harvest-combustion-regrowth scenario than under other scenarios that do not involve the harvest of wood for energy production (these other scenarios might involve managing the forest to supply wood for lumber and other long-lived products).

Indeed, biomass combustion was characterized as an offset program in *Center for Biological Diversity v. EPA*. In his concurrence, then-Judge Kavanaugh wrote that EPA decided not to apply PSD and Title V to biomass-burning facilities "because it thinks that regrowth of plant life—and the resulting recapture of carbon dioxide—might 'offset' emissions of biogenic carbon dioxide." According to Judge Kavanaugh, though, it is irrelevant whether the emissions are in fact offset or not. "[T]he statute forecloses that kind of 'offsetting' approach," he wrote, "because the statute measures emissions from stationary sources that 'emit' (or have the potential to emit) air pollutants."[29]

Judge Kavanaugh's point is at least equally applicable to CAA Section 111(d), which also measures emissions from stationary sources that "emit or may emit" CO_2 and requires those sources to achieve "standard of performance ... which reflects a degree of emission limitation achievable through the application of the best system of emission reduction."[30]

Because EPA has failed to demonstrate how practices that do not lead to emission reductions at existing sources can be considered an "emission limitation" or an "emission reduction," the proposal would violate the plain language of CAA Section 111.

[III] EPA's proposal to allow biomass co-firing as method of compliance with CAA Section 111(d) is arbitrary, capricious, and otherwise unreasonable

[A] EPA's proposed treatment of biomass co-firing cannot be squared with key elements of the Agency's interpretation of CAA Section 111

EPA's proposed treatment of power stations that co-fire biomass is arbitrary, capricious, and otherwise unreasonable because several aspects of its approach would contradict key elements of the Agency's overall interpretation of CAA Section 111. (We reiterate that EPA's overarching interpretation of its authority under Section 111(d) is unlawful and otherwise problematic for

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[28] Alternatively, if the power station burns biomass that was not alive when it was harvested (*e.g.,* forestry residue), the basis for claiming an offsetting CO_2 emission reduction is that emissions are avoided by preventing the biomass from decomposing *in situ*.

[29] *Center for Biological Diversity v. EPA*, 722 F.3d 401, 413-414 (D.C. Cir. 2013) (Kavanaugh, J., concurring).

[30] CAA § 111(a)(3), (a)(5), (b)(1)(B), (d)(1).

the reasons set forth in comments submitted by Clean Air Task Force, Natural Resources Defense Council, and other organizations.[31]

First, the proposal insists that EPA's Clean Power Plan[32] improperly "departed from a traditional, source-specific approach to regulation" and that EPA's determination of the BSER under CAA Section 111(d) is "limited to emission reduction measures that can be applied to or at an individual stationary source."[33] According to the proposal, emission reduction measures that an owner/operator "can implement at another location" are beyond the scope of CAA Section 111(d).[34]

By EPA's logic, the emission reductions that are typically attributed to biomass-based power generation are also beyond the scope of CAA Section 111(d) and cannot be used to comply with the Agency's proposed rule, or state-established standards. Any net reduction in CO_2 emissions attributed to biomass co-firing would *not* occur "at [or] on the premises of the facility for an affected source." Biomass co-firing processes are not "technologies or systems of emission reduction" that "are applicable *to, at, and on the premises of the facility* for an affected source."[35] CO_2 emission reductions nominally attributed to biomass combustion occur because of processes that cannot be applied to, at, or on the premises of the facility for an affected source. As explained above in Part II of these comments, the nominal reductions are the result of processes (*e.g.*, regrowth) that happen in forests and on farmland. Any assertion that biomass combustion reduces CO_2 emissions depends on an assessment of *net emissions*, in which emissions from a stationary source are presumed to be offset by plant matter regrowth elsewhere.

As such, it would be arbitrary and capricious and otherwise unreasonable for EPA to determine that a coal power station that co-fires biomass—and, consequently, depends on offsite emission reductions—would meet its obligations under this proposed rule.

Second, by allowing affected sources to rely on biomass co-firing to meet their CO_2 reduction obligations under CAA Section 111(d), EPA would contravene its commitment to "ensur[ing] that coal fired power plants … address their contribution to climate change by reducing their CO_2 intensity."[36] Biomass co-firing does not reduce the CO_2 intensity of a coal-fired power station; as detailed above in Part II of these comments, the CO2 emissions intensity of woody biomass combustion is 50 percent higher than the CO_2 emissions intensity of coal combustion. It would be arbitrary and capricious and otherwise unreasonable for EPA to determine that a coal power station that co-fires biomass—and, consequently, increases its CO_2 intensity—would meet its obligations under this proposed rule.

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[31] *See* Joint Environmental Comments on BSER Issues (filed in this docket October 31, 2018).

[32] 80 Fed. Reg. 64662 (October 23, 2015).

[33] 83 Fed. Reg. at 44752/1.

[34] *Id*. at 44752/1.

[35] *Id*. at 44748/1.

[36] *Id*.

Third, a source that co-fires biomass cannot demonstrate that it "actually reduce[s] its emissions rate" in accordance with EPA's proposed criteria for assessing the effectiveness of control measures. EPA writes:

> To demonstrate that measures taken to meet compliance obligations for a source actually reduce its emission rate, EPA proposes that the measures should meet two criteria: (1) They are implemented at the source itself, and (2) they are measurable at the source of emissions using data, emissions monitoring equipment or other methods to demonstrate compliance, such that they can be easily monitored, reported and verified at a unit.[37]

The practice of biomass co-firing, as it is broadly described in the proposal and EPA's April 2018 "Statement of Agency Policy", fails to meet both of these criteria and "should be disallowed for compliance."[38] As discussed above, measures intended to achieve a net reduction in CO_2 emissions by harvesting, combusting, and re-growing biomass cannot be "implemented at the source itself." No CO_2 reductions whatsoever can be attributed to biomass-based power generation if the harvested biomass is not regrown—and that regrowth inevitably occurs somewhere other than at the power station.

Furthermore, measures intended to achieve a net reduction in CO_2 emissions by harvesting, combusting, and re-growing biomass are *not* "measurable at the source of emissions," nor can they "be easily monitored, reported and verified at a unit." As explained in Part II of these comments, if a power station shifts to biomass co-firing, the only CO_2 impact that can be "measur[ed] at the source of emissions" will be an *increase* in the amount of CO_2 emitted per KWh generated.

The net reductions in CO_2 that are attributed to biomass-based power generation cannot be directly observed. The claimed reductions are based on either (at best) modeled projections of forest growth and other complex natural systems or (at worst) unsupported assumptions about carbon neutrality. The only relevant data a power station that co-fires biomass can reliably measure are the emissions of CO_2 from its stack, which will be higher than the CO_2 emissions from an otherwise identical power station that burns fossil fuel only (on a tons CO_2 emitted per KWh generated basis). As a result, the net reductions attributed to biomass-based power generation cannot be "easily monitored, reported and verified at a unit," because the process of showing a net reduction in CO_2 emissions from biomass combustion typically necessitates the use of lifecycle models that depend on subjective, non-verifiable assumptions about numerous factors.

EPA's proposed treatment of biomass-based power generation also contravenes its assertion that:

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[37] *Id*. at 44765.

[38] *Id*.

> EPA has historically and consistently required that obligations placed on sources be quantifiable, nonduplicative, permanent, verifiable, and enforceable. EPA is similarly proposing that standards of performance places on affected EGUs as part of a state plan be quantifiable, non-duplicative, permanent, verifiable, and enforceable.[39]

As explained above, even if the net reductions in CO_2 emissions that are sometimes attributed to biomass co-firing were cognizable under CAA Section 111(d), such reductions are not readily "quantifiable" or "verifiable." The process of quantifying or verifying a bioenergy-based net reduction in CO_2 emissions is complicated and rife with uncertainty. At a minimum, the process necessitates the use of lifecycle emissions models, but EPA has failed to require the use of such tools in its proposal.

Similarly, EPA has not established a protocol for ensuring that net reductions tied to the regrowth of trees and other biomass harvested for bioenergy are not "duplicative" of CO_2 reductions attributed to the forest sector. Nor has EPA explained how the re-sequestration of CO_2 in plant matter represents a "permanent" reduction in CO_2 emissions (given that the plants in question will eventually release the CO_2 when they die or are harvested), or how it would "enforce" the volume, the non-duplicative nature, or the permanence of the claimed reductions.

It would be arbitrary and capricious and otherwise unreasonable for EPA to determine that biomass co-firing is an emission control measure that can be "implemented at the source itself," that net emission impacts associated with biomass co-firing "are measurable at the source of emissions" and "can be easily monitored, reported and verified at [the] unit," or that those emission impacts are "quantifiable, non-duplicative, permanent, verifiable, and enforceable."

> [B] Net CO_2 reductions attributed to biomass-based power generation are too uncertain, too speculative, and too dependent on actions beyond the control of an affected source to allow it to comply with its standard of performance by co-firing biomass

Assuming arguendo that the language of CAA Section 111 authorized a power station to meet its state-established standard of performance by demonstrating a *net* reduction in emissions (but see Part II of these comments), there is no basis for claiming a net reduction *unless* the owner/operator of the power station can guarantee that a greater volume of CO_2 will be absorbed by subsequent plant matter regrowth.

The owners/operators of power stations are rarely in a position to make a guarantee of that kind, because they usually have little or no role in managing the land (forests, farmland, etc.) on which the relied-upon regrowth would occur. They are rarely if ever involved in decisions that ultimately affect the net lifecycle emissions of the bioenergy they generate—decisions such as

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[39] *Id*. at 44765/3.

whether to replant and cultivate the harvested land,[40] what species to replant on the land,[41] and when to conduct the next harvest of that land.[42] Thus, any net reduction in CO_2 emissions that might be achieved in connection to biomass co-firing depends on a range of actions and events that, in most cases, happen outside the control of the owners/operators of the power station, and cannot be attributed to that power station when determining whether it has reduced CO_2 emissions in compliance with CAA Section 111.

> [C] The cost of a given technology or system is irrelevant under CAA Section 111 if it does not actually reduce emissions.

EPA indicates that some power stations with access to relatively inexpensive biomass may want to comply with their CAA Section 111(d)-based obligation to reduce CO_2 emissions through biomass co-firing. However, whether biomass is "economically attractive for certain individual sources" or not is irrelevant because co-firing biomass does not reduce the rate of CO_2 emitted by the regulated source.

EPA's proposed determination that biomass co-firing does not constitute BSER because it is too expensive wrongly assumes that power stations that co-fire biomass will reduce the amount of CO_2 they emit "at [or] on [their] premises." EPA writes:

> While there are some existing coal-fired EGUs that currently co-fire with biomass fuel, those are in relative close proximity to cost-effective biomass supplies; and, there are regional supply and demand dynamics at play. As with the other emission reduction measures discussed in this section, EPA that the use of some types of biomass may be economically attractive for certain individual sources. However, on a broader scale, biomass is more expensive and/or less achievable that the measures determined to be part of the BSER. As such, EPA is not proposing that the use of biomass fuels is part of the BSER because too few individual sources will be able to employ that measure in a cost-reasonable manner.[43]

Biomass should not be part of the BSER, but not necessarily for the cost-based reasons invoked by EPA. The Agency's cursory analysis puts the cart before the horse: it objects to the cost of biomass co-firing even though it has not yet "adequately demonstrated" that a stationary source that co-fires biomass will emit less CO_2.[44] As detailed above, power stations that burn biomass (or a mix of biomass and coal) emit more CO_2 per kWh generated than power stations that burn just coal. The rate at which biomass combustion produces CO_2 is a matter of physics

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[40] If land that is harvested to supply biomass fuel for power generation is subsequently used for something other than growing plant matter—*e.g.*, if the land is converted into a residential development—there will be virtually no CO_2 reductions to net against the CO_2 emissions that occurred when the biomass was burned for energy.

[41] Some plant species regrow faster—and absorb CO_2 more quickly—than other species.

[42] Harvesting trees less frequently (such that the trees are older and larger when they are cut) can increase the amount of carbon stored in a forest.

[43] 83 Fed. Reg. at 44762/3.

[44] *See* CAA §111(a)(1).

and chemistry; it does not depend in any way on the price that a power station might pay for biomass feedstock. The cost of a given technology or system is irrelevant under CAA Section 111 if the technology or system does not actually reduce emissions.

EPA says it "recognizes that some entities may be interested in using biomass as a compliance option for meeting the state determined emission standard," especially in states where "biomass may be economically attractive."[45] However, EPA cannot approve a State Implementation Plan (SIP) unless the plan shows how the state's affected sources will achieve emission reductions from such sources. So far, EPA has pointed to the April 2018 "Statement of Agency Policy", which is wholly inadequate for the reasons detailed in Part IV of these comments.

[IV] EPA's reliance on its "Statement of Agency Policy" and its proposal to treat all forms of forest biomass harvested from "managed forests" as carbon neutral is unfounded, contrary to established scientific findings, and does not "adequately demonstrate" that co-firing biomass harvested from managed forests constitutes a "system of emission reduction."

EPA has proposed to "treat biogenic CO_2 emissions resulting from the combustion of biomass from managed forests at stationary sources for energy production as carbon neutral"[46] and provides its definition of "managed forest" in an April 2018 "Statement of Agency Policy" titled "EPA's Treatment of Biogenic Carbon Dioxide (CO_2) Emissions from Stationary Sources that Use Forest Biomass for Energy Production."[47] Even if EPA's proposal to treat biomass co-firing as categorically "carbon neutral" fit within the language and purpose of CAA Section 111 (which it does not), the "Statement of Agency Policy" is scientifically flawed and unreasonable. This policy is not supported by the established peer-reviewed science, which rejects the idea that biomass from managed forests is categorically carbon neutral, and which affirms the variability of carbon impacts of forest-derived biomass feedstocks. These findings are also articulated by the EPA's Science Advisory Board (SAB), which underscored that an *a priori* assumption of carbon neutrality for biomass from managed forests, specifically, is unsupportable.

Requiring that stationary sources burn biomass fuel sourced from a "managed forest" as defined by the Agency, does nothing to guarantee carbon benefits, let alone determine carbon neutrality. Moreover, equating notions of "sustained yield" or regional carbon stock changes with carbon neutrality violates established principles of carbon accounting and is scientifically indefensible.

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[45] 83 Fed. Reg. at 44765/3.

[46] 83 Fed. Reg. at 44766.

[47] "'Managed forest' is a forest subject to the process of planning and implementing practices for stewardship and use of the forest aimed at fulfilling relevant ecological, economic and social functions of the forest (IPCC). Also, in this document, it specifically comprises lands that are currently managed or those that are afforested, to ensure the use of biomass for energy does not result in the conversion of forested lands to non-forest use." EPA "Statement of Agency Policy" at 1, n.1.

Finally, EPA's "Statement of Agency Policy" misconstrues and misrepresents Congressional intent. The Congressional record underlying the biomass provisions in the Consolidated Appropriations Act of 2018 demonstrates that Congress aimed to direct federal agencies to assess particular instances in which biomass from managed forests is carbon neutral. The Agency's proposal "to treat biogenic CO_2 emissions resulting from the combustion of biomass from managed forests at stationary sources for energy production as carbon neutral"[48] fails to draw any meaningful, actionable distinctions, and thus promotes a policy that cannot be squared with statute.

> [A] Categorical carbon neutrality of biomass from managed forests is not supported in the established peer-reviewed science and has been rejected by the EPA's SAB.

Proponents of the idea that forest-derived biomass is categorically "carbon neutral" argue that power stations burning forest-derived biomass are zero emissions sources because CO_2 emissions are automatically offset—or canceled out. They argue that this automatic mitigation occurs because forests sequester CO_2 from the atmosphere through photosynthesis.[49]

This assumption has been widely rejected in the scientific peer-reviewed literature, which has shown that most forms of forest-derived biomass increase CO_2 emissions to the atmosphere and that the net emissions from biomass energy systems are highly variable, depending upon biomass feedstocks, regions, forest management regimes and alternative fates of the biomass, among other factors. In particular, a *priori* assumptions about the categorical carbon neutrality of biomass from managed forests have been rejected by the EPA's SAB, which unequivocally established that carbon impacts to the atmosphere vary widely among different types of forest-derived biomass feedstocks from varying forest management regimes.

> > [1] *A priori* carbon neutrality of biomass from managed forests is not supported by the established peer-reviewed science, which shows that most forms of forest-derived biomass increase emissions to the atmosphere.

When biomass from managed forests is burned for electricity, it immediately emits CO_2 to the atmosphere. It is well established that the net emissions from this combustion persist in the atmosphere for time periods ranging from years to centuries.[50] This temporal variation depends

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[48] 83 Fed. Reg. at 44766.

[49] In its Statement of Agency Policy, EPA states "through photosynthesis, plants absorb CO_2 from the atmosphere and add it to their biomass as carbon, a process referred to as sequestration." EPA Statement of Agency Policy at 2.

[50] Pierre Bernier, *et al.*, *Using ecosystem CO_2 measurements to estimate the timing and magnitude of greenhouse gas mitigation potential of forest bioenergy*. GCB Bioenergy, (Jan, 2013) (appended to these comments), https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1757-1707.2012.01197.x; Bjart Holtsmark, *Harvesting in boreal forests and the biofuel carbon debt*, Clim. Change, (May, 2012), https://link.springer.com/article/10.1007/s10584-011-0222-6; Jerome Laganière, *et al.*, *Range and uncertainties in estimating delays in greenhouse gas mitigation potential of forest bioenergy sourced from Canadian forests*, GCB Bioenergy, (Feb, 2017) (appended to these comments), https://onlinelibrary.wiley.com/doi/abs/10.1111/gcbb.12327; Jon McKechnie, *et al.*, *Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels*, Environ. Sci. Technol., (Jan, 2011) (appended to these comments), http://www.pfpi.net/wp-content/uploads/2011/05/McKechnie-et-al-

upon many factors, including the type of feedstock and the conditions specific to the production and use of that feedstock as fuel: for example, how the material is harvested; how quickly forest regrowth occurs; the alternative fate of the material; and what would have happened to forest carbon stocks in the absence of biomass demand.[51]

In the case of whole trees and other large diameter materials, it can take anywhere from 35 years to several centuries for forest regrowth and the associated carbon sequestration just to reach net emissions parity[52] with fossil fuels (the actual timing depends in large part on whether biomass combustion is compared to the coal combustion or natural gas combustion).[53] In a scenario where forestry residues that would otherwise decay and release their carbon are burned, the payback period is typically shorter because it is tied to the decomposition rate of that material and its size, but still can be on the order of decades.[54]

EST-2010.pdf; K. Pingoud, *et al.*, *Global warming potential factors and warming payback time as climate indicators of forest biomass use,* Mitigation and Adaptation Strategies for Global Change, (Apr, 2012); Anna Stephenson, *et al.*, *Life Cycle Impacts of Biomass Electricity in 2020: Scenarios for Assessing the Greenhouse Gas Impacts and Energy Input Requirements of Using North American Woody Biomass for Electricity Generation in the UK*, UK Department of Energy and Climate Change, (Jul, 2014), www.gov.uk/government/uploads/system/uploads/attachment_data/file/349024/BEAC_Report_290814.pdf; Michael Ter-Mikaelian, *et al.*, *Debt repayment or carbon sequestration parity? Lessons from a forest bioenergy case study in Ontario, Canada,* GCB Bioenergy, (Jul, 2015) (appended to these comments), https://onlinelibrary.wiley.com/doi/abs/10.1111/gcbb.12198; Giuliana Zanchi, *et al.*, *Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel*, GCB Bioenergy, (Nov, 2012) (appended to these comments), https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1757-1707.2011.01149.x.

[51] Richard Birdsey, *et al.*, *Climate, Economic, and Environmental Impacts of Producing Wood for Bioenergy*, Env. Res. Letters, (Mar, 2018) (appended to these comments), http://iopscience.iop.org/article/10.1088/1748-9326/aab9d5/pdf; Stephen Mitchell, *et al.*, *Carbon Debt and Carbon Sequestration Parity in Forest Bioenergy Production*, GCB Bioenergy, (May, 2012), https://onlinelibrary.wiley.com/doi/full/10.1111/j.1757-1707.2012.01173.x; Ana Repo, *et al.*, *Sustainability of Forest Bioenergy in Europe: Land-use-related Carbon Dioxide Emissions of Forest Harvest Residues*, GCB Bioenergy, (Mar, 2014) (appended to these comments), https://onlinelibrary.wiley.com/doi/full/10.1111/gcbb.12179; Thomas Walker, *et al.*, *Sustainability and Carbon Policy Study*, The Manomet Center for Conservation Sciences, (Jun, 2010) (Executive Summary appended to these comments), http://www.forestguild.org/publications/research/2010/Manomet_Biomass_Report_Chapter5.pdf.

[52] Carbon sequestration parity is achieved when the sum of carbon in the regenerating stand and the GHG benefits of replacing fossil fuel reaches the amount of carbon in the stand if it had remained unharvested. *See* Ter-Mikaelian, *et al*. (2014).

[53] Andrea Colnes, *et al.*, *Biomass Supply and Carbon Accounting for Southeastern Forests*, The Biomass Energy Resource Center, Forest Guild, and Spatial Informatics Group, (Feb, 2012) (Executive Summary appended to these comments), www.biomasscenter.org/images/stories/SE_Carbon_Study_FINAL_2-6-12.pdf; John Hagan, *Biomass Energy Recalibrated*, The Manomet Center for Conservation Sciences, (Jan, 2012), http://magazine.manomet.org/winter2012/biomass.html; Mitchell, *et al*. (2012).

[54] Repo, *et al*. (2014); Stephenson, *et al*. (2014); Mary Booth, *Not carbon neutral: Assessing the net emissions impact of residues burned for bioenergy*, Environmental Research Letters, (Feb, 2018) (appended to these comments), http://iopscience.iop.org/article/10.1088/1748-9326/aaac88.

These findings are supported by two recent independent meta-analyses[55] of published studies over the past 25 years of the carbon emissions from forest-derived biomass. They show that over 80 percent of peer-reviewed assessments found positive net emissions associated with the use of woody biomass feedstocks. Carbon payback periods in these studies range from years to many centuries. Similarly, a study done jointly by the Spatial Informatics Group and the Woods Hole Research Center has found that "the vast majority of all published quantitative assessments of the GHG emissions of forest-derived biomass for electricity production have concluded that there are net emissions associated with the use of woody biomass feedstocks to generate energy when compared to generating an equivalent amount of energy from fossil sources, even when accounting for subsequent regrowth and avoided emissions."[56]

Taken together, these studies show that EPA's treatment of biomass from managed forests as carbon neutral is not supported in the peer-reviewed scientific literature. In the "vast majority"[57] of cases, forest-derived biomass for energy has been demonstrated to increase emissions to the atmosphere, in many cases for decades to centuries. Moreover, because net emissions impacts of biomass from managed forests have been demonstrated to vary widely and depend on factors specific to a particular biomass feedstock, the Agency's proposed categorical treatment of all biomass from managed forests as carbon neutral is in direct contradiction with the established science. A broad carbon neutrality premise defies the technical reality and offers no defensible scientific foundation for a carbon emissions policy.[58]

In addition to the peer-reviewed literature, numerous academies, committees, and agencies have reached the conclusion that the use of forest-derived biomass is not carbon neutral and will risk increasing carbon emissions to the atmosphere over the long term, similar to many of the findings noted above. Three are summarized below:

The European Environment Agency Scientific Committee on Greenhouse Gas Accounting in Relation to Bioenergy[59] described the carbon neutrality assumption as a "serious accounting

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[55] Two comprehensive meta-analyses on the topic of greenhouse gas emissions of woody biomass energy, Buchholz et al. (2016) and Bentsen (2017), summarize the full breadth of quantitative studies conducted over the past 25 years that assess the extent of carbon impacts/benefits incurred by burning biomass to produce energy. Thomas Buchholz, *et al.*, *A global meta-analysis of forest bioenergy greenhouse gas emission accounting studies*, GCB Bioenergy, (Mar 2016), https://onlinelibrary.wiley.com/doi/abs/10.1111/gcbb.12245; Niclas Bentsen, *et al.*, *Carbon debt and payback time – Lost in the forest?,* Renew. Sustain. Energy Rev, (Jun 2017), https://www.sciencedirect.com/science/article/pii/S1364032117302034.

[56] John Gunn, *et al.*, *Scientific Evidence Does Not Support the Carbon Neutrality of Woody Biomass Energy: A Review of Existing Literature*, Spatial Informatics Group Report 2018-01, (Oct, 2018), https://www.sig-nal.org/reports-and-tools.

[57] *Id*.

[58] *See Motor Vehicles Manufacturers Ass'n v. State Farm* 463 U.S. 29, 43 (1983) (internal citations omitted) ("an agency rule would be arbitrary and capricious if the agency…offered an explanation for its decision that runs counter to the evidence before the agency"); *see also Owner-Operator Indep. Drivers Ass'n v. Fed. Motor Carrier Safety Admin*, 494 F.3d 188, 204 (D.C. Cir. 2007) ("complete lack of explanation for an important step in the agency's analysis was arbitrary and capricious").

[59] European Environment Agency Scientific Committee, *Opinion of the EEA Scientific Committee on Greenhouse Gas Accounting in Related to Bioenergy,* September 15, 2011:

error" while the UK Bioenergy Strategy 2012 specifically warned against using "entire trees" because of high carbon impacts.[60] The Joint Research Centre of the European Commission concluded that "the use of stemwood from dedicated harvest for bioenergy would cause an actual increase in GHG emissions compared to those from fossil fuels in the short term and medium term (decades)."[61]

A study by the European Academies Science Advisory Council, representing the consensus conclusions of the national science academies of all EU Member States, states that "increasing the carbon storage in existing forests is a cost-effective measure to decrease net carbon emissions, but EU policies are currently biased towards the use of forest biomass for energy with potential negative effects on the climate over the short to medium term."[62]

Finally, the IPCC in its 5th Assessment Report has warned that "IPCC Guidelines do not automatically consider biomass used for energy as 'carbon neutral,' even if the biomass is thought to be produced sustainably."[63]

The IPCC addresses whether "the CO_2 (carbon dioxide) emitted from biomass combustion is climate neutral because the carbon that was previously sequestered from the atmosphere (before combustion) will be re-sequestered if the growing stock is managed sustainably" and finds that "[t]he shortcomings of this assumption have been extensively discussed in environmental impact studies and emission accounting mechanisms."[64] The authors further reject carbon neutrality as a fundamental misunderstanding of its guidelines, arguing "the neutrality perception is linked to a misunderstanding of the guidelines for GHG inventories."[65]

> [2] An *a priori* assumption of carbon neutrality of biomass from managed forests, specifically, has been rejected by the EPA's SAB, which has unequivocally established that carbon impacts vary widely among forest-derived feedstocks.

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file:///C:/Users/slyutse/Downloads/SC%20Opinion%20on%20GHG%20in%20rel%20bioenergy%20-%20final%2015%20September%202011%20(1).pdf.

[60] Department for Transport, Department of Energy and Climate Change, Department for Environment, Food, and Rural Afairs, *UK Bioenergy Strategy*, (Apr, 2012). https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48337/5142-bioenergy-strategy-.pdf.

[61] European Commission, *Carbon accounting of forest bioenergy,* 2014: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC70663/eur25354en_online.pdf.

[62] European Academies' Science Advisory Council, *Commentary by the European Academies' Science Advisory Council on Forest Bioenergy and Carbon Neutrality*, (June 2018) https://easac.eu/fileadmin/PDF_s/reports_statements/Carbon_Neutrality/EASAC_commentary_on_Carbon_Neutrality_15_June_2018.pdf.

[63] IPCC Task Force on National Greenhouse Gas Inventories, Frequently Asked Questions, Q2-10 https://www.ipcc-nggip.iges.or.jp/faq/faq.html.

[64] Intergovernmental Panel on Climate Change, *Fifth Assessment Report, Working Group III Agriculture, Forestry and Other Land Use (AFOLU)*, Section 11.13.4, at 879, (2014) http://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_chapter11.pdf.

[65] *Id.*

In September 2011, EPA released a *Draft Accounting Framework for Biogenic CO_2 Emissions from Stationary Sources,* which reviewed numerous analytical methods for assessing biogenic CO_2 emissions from stationary sources. This Framework was peer reviewed by the Biogenic Carbon Emissions Panel (Panel) appointed by EPA's SAB. The final peer review report was approved by the SAB, submitted jointly by the full SAB and Panel,[66] and was published on September 28, 2012.[67]

The Agency subsequently revised its 2011 Framework to address issues raised in the peer review and released a revised *Framework for Assessing Biogenic CO_2 Emissions from Stationary Sources* in 2014 ("the revised Framework").[68] The SAB was asked by the EPA Office of Air and Radiation to review and comment on the revised Framework pursuant to specific charge questions.

Both draft Frameworks rely fundamentally on a methodology for assessing net carbon impacts using the "Biogenic Assessment Factor" (BAF), which is a factor that "weights" (or discounts) stack emissions to account for the growth, harvest, processing, and end-use of biomass feedstocks on CO_2 emissions to the atmosphere. The BAF "is an accounting term developed in the Framework to denote the offset to total emissions (mathematical adjustment) that reflects a biogenic feedstock's net carbon emissions after taking into account its sequestration of carbon, in biomass or soil, or emissions that might have occurred with an alternate fate had it not been used for fuel."[69]

The SAB's process of reviewing EPA's 2011 accounting Framework and 2014 revised Framework generated a range of disagreements around complex issues. At the same time, there has been widespread support among members of the SAB and the Panel for rejecting an *a priori* assumption of categorical biomass carbon neutrality and for emphasizing the heterogeneity in carbon impacts of forest-derived biomass. This support is reflected in the SAB's final report to EPA in 2012, as well as the SAB's draft report to EPA in 2018 in response to the Agency's follow-up charge questions.

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[66] SAB Review of EPA's Accounting Framework for Biogenic CO2 Emissions from Stationary Sources (September 2011)—Cover Letter to EPA from Drs. Deborah L. Swackhamer, Chair of Science Advisory Board and Madhu Khanna, Chair of SAB Biogenic Carbon Emissions Panel to EPA, (September 28, 2012) ("Cover Letter to SAB Review 2012") (https://yosemite.epa.gov/sab/sabproduct.nsf/0/57B7A4F1987D7F7385257A87007977F6/$File/EPA-SAB-12-011-unsigned.pdf).

[67] SAB Review of EPA's Accounting Framework for Biogenic CO_2 Emissions from Stationary Sources (September 2011), (September 28, 2012) ("SAB Review 2012") (https://yosemite.epa.gov/sab/sabproduct.nsf/0/57B7A4F1987D7F7385257A87007977F6/$File/EPA-SAB-12-011-unsigned.pdf).

[68] U.S. EPA, Office of Air and Radiation, *Framework for Assessing Biogenic CO_2 Emissions from Stationary Sources* (November, 2014) https://yosemite.epa.gov/sab/sabproduct.nsf/0/3235DAC747C16FE985257DA90053F252/$File/Framework-for-Assessing-Biogenic-CO2-Emissions+(Nov+2014).pdf

[69] U.S. Environmental Protection Agency, Science Advisory Board, Draft Review of EPA's 2014 Framework for Assessing Biogenic CO_2 Emissions from Stationary Sources, at i (August 2018).

In EPA's charge to review the 2011 Framework, the Agency asked the SAB to review the validity of a categorical exclusion (carbon neutrality), which would treat emissions as zero. The SAB's response was to reject *a priori* assumptions of carbon neutrality. The SAB instead affirmed the need for the specific assessment of carbon impacts of individual feedstocks. In its finding, the SAB noted that net biogenic carbon emissions will vary considerably, and therefore carbon neutrality cannot be assumed:

> Carbon neutrality cannot be assumed for all biomass energy *a priori*. There are circumstances in which biomass is grown, harvested and combusted in a carbon neutral fashion but carbon neutrality is not an appropriate *a priori* assumption; it is a conclusion that should be reached only after considering a particular feedstock's production and consumption cycle. There is considerable heterogeneity in feedstock types, sources and production methods and thus net biogenic carbon emissions will vary considerably. Of course, biogenic feedstocks that displace fossil fuels do not have to be carbon neutral to be better than fossil fuels in terms of their climate impact.[70]

These findings are affirmed in the SAB's draft 2018 report on the revised Framework:

> "[T]here can be wide variation in the net effect of using bioenergy on emissions of carbon dioxide to the atmosphere and thus it is scientifically indefensible to assume all bioenergy has no net carbon dioxide emissions to the atmosphere, or the reverse, that all emissions represent a net addition to the atmosphere." [71]
>
> "There is no single answer to what these BAFs should be, as not all biogenic emissions are carbon neutral nor net additional to the atmosphere, and assuming so is inconsistent with the underlying science."[72]

The SAB's final recommendations to EPA in 2012 expressly rejected carbon neutrality as it applies to "forest-derived woody biomass" in particular.[73] The SAB established without ambiguity that forest-derived biomass feedstocks have individual and varying degrees of carbon

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[70] SAB Review 2012 at 3.

[71] U.S. Environmental Protection Agency, Science Advisory Board, Draft Review of EPA's 2014 Framework for Assessing Biogenic CO_2 Emissions from Stationary Sources, at 5 (August 2018) https://yosemite.epa.gov/sab/sabproduct.nsf/0/521CDCBF9B028BCE852582F80065B320/$File/Biogenic_Carbon_+Qual_Rev-8-29-18.pdf

[72] *Id.* at 2

[73] SAB Review 2012 at 5.

impacts. The SAB called for counterfactual modeling[74] on a case-by-case basis to assess carbon impacts of different forest-derived feedstocks and determine their associated BAF.[75]

Specifically, the SAB explicitly identified numerous individual categories of forest-derived feedstocks across several management regimes and recommended calculating individual BAFs for each category.[76] These include forest residues, forests with short accumulation times, forests with long accumulation times, and industrial wood wastes. Their recommendation reads as follows (emphasis added):

> Develop a ***separate*** BAF equation for each feedstock category as broadly categorized by type, region, prior land use and current management practices. Feedstocks could be categorized into short rotation dedicated energy crops, crop residues, forest residues, municipal solid waste, trees/forests with short accumulation times, trees/forests with long accumulation times and agricultural residue, wood mill residue and pulping liquor.
>
> - For long-accumulation feedstocks like roundwood, use an anticipated baseline approach to compare emissions from increased biomass harvesting against a baseline without increased biomass demand.
>
> - For residues, consider alternate fates (e.g., some forest residues may be burned if not used for bioenergy) and information about decay. An appropriate analysis using decay functions would yield information on the storage of ecosystem carbon in forest residues.[77]

Importantly, each of the biomass feedstock categories suggested by the SAB are significantly narrower than EPA's sweeping "biomass from managed forest" category. Moreover, the SAB finds that the carbon impact of biomass from each category must be analyzed—i.e., carbon neutrality is not a valid *a priori* assumption for any of the categories.

The counterfactual modeling recommended by the SAB to develop these feedstock-specific BAFs involves assumptions about baseline scenarios and biomass harvest scenarios. No set of assumptions, scenarios, or counterfactuals can be considered universal. This is especially true for the forestry sector where land use decisions depend on land managers, market conditions, and other factors that vary widely. Absent universally-applied assumptions, scenarios, and/or counterfactuals, it is impossible for the Agency to establish carbon neutrality across all biomass feedstocks derived from managed forests.

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[74] In a cover letter to the SAB's 2012 Final Report reviewing EPA's 2011 Framework, SAB Dr. Chair Deborah L. Swackhamer and Panel Chair Dr. Madhu Khanna wrote jointly: "…the Framework should provide a means to estimate the effect of stationary source biogenic feedstock demand, on the atmosphere, over time, comparing a scenario with the use of biogenic feedstocks to a counterfactual scenario without the use of biogenic feedstocks." Cover Letter to SAB Review 2012 at ii.

[75] SAB Review 2012 at 5.

[76] *Id*. at 15, Table 1.

[77] *Id*. at 7-8.

Finally, the SAB also recommended that EPA consider an approach that would use "default" BAFs to analyze individual carbon impacts and distinguish among each feedstock category – and here again, its recommendations squarely recognize the variability of carbon impacts for different types of woody biomass from managed forests.[78]

Notably, the SAB suggested that BAFs could be combined and "weighted" according to a facility's feedstock use, further underscoring the differences among different types of biomass from managed forests.[79] This recommendation shows that even in its methodology, the SAB is discarding categorical assumptions: no weighting would be necessary if the SAB had contemplated that EPA might assume that all forest biomass carbon impacts were equivalent, let alone carbon neutral.

In sum, an *a priori* assumption of carbon neutrality of biomass from managed forests, specifically, has been rejected by the EPA's SAB. Instead, the SAB has unequivocally established that carbon impacts vary widely among forest-derived feedstocks. If an agency relies "solely on data…roundly criticized by its own experts, [it] fail[s] to fulfill [its] duty" to exercise its discretion in a reasoned manner.[80]

> [B] Requiring that stationary sources burn biomass fuel that has been sourced from a so-called "managed forest" does nothing to guarantee that any regrowth or avoided decomposition that occurs offsite will offset the CO_2 emitted by biomass-burning power stations.
>
> > [1] EPA's definition of a "managed forest" offers no defensible rationale or criteria for ensuring any carbon benefits, let alone demonstrating carbon neutrality.

The proposed rule states that "EPA's policy is to treat biogenic CO_2 emissions resulting from the combustion of biomass from managed forests at stationary sources for energy production as carbon neutral"[81] and provides its definition of "managed forest" in its "Statement of Agency Policy":

> 'Managed forest' is a forest subject to the process of planning and implementing practices for stewardship and use of the forest aimed at fulfilling relevant ecological, economic and social functions of the forest (IPCC). Also, in this document, it specifically comprises lands that are currently managed or those that are afforested, to ensure the

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[78] *Id*. at 8.
[79] *Id*.
[80] *Public Employees v. Hopper*, 827 F.3d 1077, 1083 (D.C. Cir. 2016).
[81] 83 Fed. Reg. at 44766.

> use of biomass for energy does not result in the conversion of forested lands to non-forest use.[82, 83]

This definition appears to specify two criteria for how forest management, as defined by EPA, might be construed to justify carbon neutrality. Neither of these criteria provides a supportable rationale for demonstrating carbon benefits, let alone carbon neutrality.

The first criterion, a "process of planning and implementing practices for stewardship and use of the forest," is so general that it is meaningless and offers no guidance with respect to documenting and ensuring any carbon benefits or carbon neutrality from biomass use for energy production.

The second criterion, that "the use of biomass for energy does not result in the conversion of forested lands to non-forest use," has implications for net carbon balance in the atmosphere, but alone is insufficient to demonstrate or justify the carbon neutrality of forest-derived biomass used for energy, for the reasons articulated below.

The conversion of a forest to non-forest use leads to a loss of terrestrial carbon stocks, and an associated carbon debt in the atmosphere that is likely permanent.[84] However, avoiding forest conversion does not automatically translate into stable or increasing forest carbon stocks. On lands that are "managed," as defined by EPA, many forestry practices that generate biomass fuel will also produce a lasting loss of terrestrial carbon and associated long-term carbon increases in the atmosphere. These biomass harvest practices include but are not limited to: increasing the intensity of existing silvicultural practices, reducing the existing rotation age, changing regeneration techniques, reducing the average stand age, and increasing frequency of commercial and pre-commercial removals.[85]

Therefore, a prohibition on conversion alone cannot determine carbon benefits or carbon impacts. While it is a necessary condition for ensuring carbon benefits, it cannot be used as the sole, determinative condition for carbon neutrality of forest-derived biomass as EPA appears to be proposing. Ignoring the many other forest management actions that can contribute to forest carbon loss on the landscape is arbitrary and unfounded.

[2] Using overall changes in regional forest carbon stocks as a surrogate for carbon impacts of a stationary source is scientifically indefensible.

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[82] EPA Statement of Agency Policy at 1, n.1.

[83] EPA also observes that "[c]ertain kinds of biomass, including that from managed forests, have the potential to offer a wide range of economic and environmental benefits, including carbon benefits. However, these benefits can typically only be realized if biomass feedstocks are sourced responsibly, which can include ensuring that forest biomass is not sourced from lands converted to nonforest uses." 83 Fed. Reg. at 44766.

[84] Zanchi, *et al*. (2012).

[85] Colnes, *et al*. (2012); Stephenson, *et al*. (2014); Ter-Mikaelian, *et al*. (2015); Walker, *et al*. (2010);

As noted above, EPA cannot rationally assert that avoiding forest conversion will necessarily translate into stable or increasing forest carbons stocks, either within a stand or in a given region.[86]

Independent of questions of forest conversion, using an increase in regional carbon stocks as a proxy for carbon neutrality has been roundly rejected by the EPA's SAB in its final report on the Agency's 2011 Framework. In that report, the SAB considered the scientific validity of an approach proposed in a dissenting opinion by a single SAB Panel member,[87]which would "exempt biogenic CO2 emissions from greenhouse gas regulation so long as aggregate measures of land-based carbon stocks are steady or increasing."[88]

The SAB recommends against such an approach:

> This dissenting opinion is based on an accounting guideline from the Intergovernmental Panel on Climate Change (IPCC) which recommends that emissions from bioenergy be accounted for in the forestry sector. This is not the general consensus view of the SAB. The IPCC approach to carbon accounting would not allow for a causal connection to be made between a stationary facility using a biogenic feedstock and the source of that feedstock.[89]

The SAB report explains that while this approach

> "can be used to determine if stock of carbon is increasing or decreasing over time, it cannot be used to determine the net impact of using a biogenic feedstock on carbon emissions as compared to what the emissions would have been if the feedstock had not been used. In order to adjust the emissions of a stationary facility using biogenic material it is important to know the net impact of that facility on carbon emissions – which requires knowing what the emissions would have been without the use of bioenergy and comparing it with emissions with the use of bioenergy. If EPA were to apply the IPCC approach, as long as carbon stocks are increasing, bioenergy would be considered carbon neutral. Under this approach, forest carbon stocks may be increasing less with the use of bioenergy than without—and atmospheric concentrations of CO2 could be increasing as a result—but forest biomass would still be considered carbon neutral. Application of the IPCC accounting approach is not conducive to considering the incremental effect of bioenergy on carbon emissions" and "would not be appropriate because it does not allow a link between the stationary source that is using biomass feedstocks and the emissions that are being measured."[90]

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[86] Numerous other changes in silvicultural practices to meet additional biomass demand, such as those articulated above, as well as other exogenous factors such as wildfires, can produce carbon stock reductions and net atmospheric emissions even under circumstances where forest conversions are not occurring.

[87] SAB Review 2012 at 17.

[88] Cover Letter to SAB Review 2012 at iii.

[89] *Id*. at iii.

[90] SAB Review 2012 at 3.

The IPCC itself later corrected its accounting error and clarified its revised approach in its Fifth Assessment Report in a way that directly echoes the SAB's recommendation to use counterfactual carbon accounting: "If bioenergy production is to generate a net reduction in emissions, it must do so by offsetting those emissions through increased net carbon uptake of biota and soils. *The appropriate comparison is then between the net biosphere flux in the absence of bioenergy compared to the net biosphere flux in the presence of bioenergy production. Direct and indirect effects need to be considered in calculating these fluxes*."[91]

> [3] Sustained yield from a "regulated" forest is not a sufficient condition for carbon neutrality. Equating sustained yield with carbon neutrality violates established principles of carbon accounting.

EPA should reject the erroneous premise that sustained yield forestry equals carbon neutrality. Under a sustained yield approach, landowners manage a "regulated" forest in which annual cutting occurs (on average) in an area equal to the total managed forest area divided by the age of the stand.[92] These increments of forest are cut to generate a product while the remaining forest regrowth replaces the removed forest stock annually.

Full carbon accounting of this regime requires using a counterfactual approach, which, as discussed above, has been widely demonstrated as the only defensible means to determine actual carbon benefits or impacts.[93] The central requirement of this approach is that any emission reductions credited by EPA must be *additional*—that is, the emissions reductions must be above and beyond what would have happened under a business-as-usual (BAU) scenario.[94] For forest biomass to generate CO_2 emission reduction credits, regulated entities must demonstrate that stored forest carbon is increasing under the biomass harvest scenario compared to the BAU scenario (which might involve, e.g., managing the forest to supply wood for lumber, pulp, and other relatively long-lived products).

By definition, sustained yield programs are existing, ongoing, long-term commitments by a landowner to a forest management program. Therefore, the sustained yield program, *not* the bioenergy scenario, represents a BAU baseline. As such, an existing sustained yield forestry program cannot be treated *a priori* as a carbon-beneficial land management approach. Any

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[91] Intergovernmental Panel on Climate Change, (2014) at 877 (emphasis added) http://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_chapter11.pdf.

[92] The total area of the managed forest divided by the age of the stand represents the amount that can be cut each year without reducing the total growing stock – assuming the cut forests are replanted and regrow at the same rate as the overall stand.

[93] Cover Letter to SAB Review 2012 at ii; Helmut Haberl, *et al.*, *Correcting a fundamental error in greenhouse gas accounting related to bioenergy*, Energy Policy, (Jun, 2012) (appended to these comments) https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3617913/; McKechnie, *et al*. (2011); Mitchell, *et al*. (2012); Pingoud, *et. al*. (2012).

[94] Timothy Searchinger, *et al.*, *Europe's renewable energy directive poised to harm global forests*, Nature Communications, (Aug, 2018) https://www.nature.com/articles/s41467-018-06175-4.pdf; https://ucanr.edu/sites/forestry/files/212529.pdf. Ter-Mikaelian, *et al.* (2015); Walker, *et al*. (2012).

carbon impacts or benefits must be assessed using a scenario where biomass feedstocks are harvested over-and-above what would have happened anyway under the sustained yield program. According to Ter-Mikaelian et. al., in a review of carbon accounting methods used to assess carbon emissions from forest-derived materials:

> An assumption that bioenergy harvesting in forests managed on a sustained yield (also called sustainable yield) basis does not create a carbon deficit is one of the most common errors in forest bioenergy accounting…*Stating that sustained yield management is carbon neutral is incorrect* because it fails to account for the case involving no harvest for bioenergy in the reference fossil fuel scenario.
>
> Although sustained yield harvesting is a valid approach in traditional forestry for providing a steady flow of wood, the claim that it is carbon neutral can only be made by ignoring the principles of carbon mass balance accounting.[95]

Moreover, arguments supporting carbon neutrality, more generally, typically assume that trees harvested from managed forests will be replaced by regrowth of new forests elsewhere in the landscape, either concurrently or in the future, which automatically offset the CO_2 emissions from biomass combustion. Numerous commentaries propose that because biomass from managed forests is part of the natural carbon cycle it is necessarily carbon neutral. These arguments also fail the test of additionality. Instead of demonstrating that the CO_2 emissions reductions are above and beyond what would have happened under a BAU scenario, they rely on a simplistic and erroneous framing of baseline issues without demonstrating additionality, an approach that has been widely rejected.[96] Taking credit for forest growth and carbon sequestration that would be happening anyway represents a major carbon accounting error and fails to accurately identify emissions from stationary sources burning forest-derived biomass.

> [C] EPA's "Statement of Agency Policy" on forest biomass carbon neutrality misconstrues and misrepresents Congressional intent, which aimed to direct agencies to assess particular instances in which biomass from managed forests is carbon neutral.

According to the proposed rule, EPA's treatment of biomass from managed forest as carbon neutral, as articulated in its underlying policy statement "aligns with provisions in the Consolidated Appropriations Act, 2018, which calls for EPA, the Department of Energy and the Department of Agriculture to establish policies that, consistent with their missions, jointly 'reflect the carbon-neutrality of forest bioenergy and recognize biomass as a renewable energy

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[95] Michael Ter-Mikaelian, *et al.*, *The Burning Question: Does Forest bioenergy Reduce Carbon Emissions? A Review of Common Misconceptions About Forest Accounting,* Journal of Forestry, (Nov, 2014), (emphasis added) (appended to these comments).

[96] Haberl, H., *et al*. (2012); Ernst-Detlef Schulze, *et al*. *Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral*, Global Change Bioenergy, (2012) (appended to these comments); Searchinger *et al*. (2018); Ter-Mikaelian, M., *et al*. (2014); Ter-Mikaelian, M., *et al*. (2015); Walker, *et al.* (2010); Zanchi, *et al*. (2012).

source, provided the use of forest biomass for energy production does not cause conversion of forests to non-forest use.' "[97]

The Agency's proposed policy to treat *all* biomass from managed forests as carbon neutral misconstrues and misrepresents congressional intent. As demonstrated below, the intent of the language passed in the FY18 Continuing Resolution (H.R. 1625) was to *reflect the opportunities where forest biomass is carbon neutral*, as distinct from a categorical treatment. Never did Congress expect EPA to pursue a scientifically indefensible policy of categorically granting carbon-neutral status to all sources of forest biomass from managed forests.

When the legislative language initially passed the Senate, a colloquy among the cosponsors reviewed the intent of the language. When this legislative language was subsequently enacted into law as part of H.R. 1625, the same considerations applied.

A total of seven senators made colloquy statements, including three of the eight original co-sponsors of the language. Most noted that not all biomass is created equal, and that scientific consensus on carbon neutrality exists for only some sources. To varying degrees, all seven statements offer specifics clarifying that the legislative language intends to direct agencies to distinguish among forest-derived feedstocks from managed forests. Taken in total, the colloquy statements underscore that EPA should distinguish among differing biomass feedstocks and reflect those distinct opportunities where biomass is carbon neutral when it develops policy.[98]

Senator Edward Markey underscored the differences among biomass feedstocks, noting that the intent of the language is to support those forms that are deemed to be carbon neutral, suggesting an Agency determination on the distinction, and expressly calling out an example of a category of forest-derived feedstocks that is not carbon neutral:

> But ***not all biomass energy is created equal***. I understand the amendment's intent to support ***biomass energy that is determined to be*** carbon neutral.
>
> Some practices like clear-cutting forests and ***burning whole trees for energy should never be considered carbon neutral***.[99]

Senator Jeff Merkley stated that the intent of the language is to identify those cases where forest biomass is carbon neutral and to reflect those particular opportunities for carbon reductions in agency actions:

> When EPA takes regulatory action, it should ***reflect the opportunities where biomass is carbon neutral***.[100]

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[97] 83 Fed. Reg. at 44766, n.35.

[98] Congressional Record, February 3, 2016, S551-S554.

[99] *Id.* at 553-554 (emphases added).

[100] *Id.* at 553 (emphases added).

Senator Susan Collins repeatedly referred to “carbon benefits” of forest bioenergy – which can vary – as distinct from zero carbon:

> In November of 2014,100 nationally recognized forest scientists, representing 80 universities, wrote to the EPA stating the long-term ***carbon benefits of forest bioenergy***. This group weighed a comprehensive synthesis of the best peer-reviewed science and ***affirmed the carbon benefits*** of biomass.[101]

Senator Collins also indicated that the intent of the bill is to push federal policy to “reflect” the principle that forest-derived biomass has the *potential* to mitigate GHG emissions:

> A literature review of forest carbon science that appeared in the November 2014 "Journal of Forestry" confirms that "wood products and energy resources derived from forests ***have the potential to*** play an important and ongoing role in mitigating greenhouse gas (GHG) emissions." So Federal policies for the use of clean, renewable energy solutions, including biomass, should be clear and simple and ***reflect these principles***.[102]

Senator Amy Klobuchar echoed the need to clarify that the language is intended to reflect the carbon benefits, but not absolute neutrality.

> Without clear policies that recognize the carbon benefits - ***and I will say that again: the carbon benefits - of forest biomass***, private investment throughout the biomass supply chain will dry up.[103]

Senator Maria Cantwell made the clear distinction between carbon neutral biomass and biomass that is not carbon neutral, noting the example of forest-derived mill residuals as one type of feedstock that avoids emissions.

> ***We agree that some biomass is clearly "carbon neutral" and some biomass is not "carbon neutral."*** A study by the National Council for Air and Stream Improvement showed that mills using biomass residuals avoid 181 million tons of CO_2 emissions.[104]

In sum, when Congress chose the words “reflect the carbon neutrality,” its intent was to identify those *particular cases* where forest-derived biomass is carbon neutral. EPA’s proposal “to treat biogenic CO_2 emissions resulting from the combustion of biomass from managed

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[101] *Id.* at 551 (emphasis added).
[102] *Id.* (emphasis added).
[103] *Id.* (emphasis added).
[104] *Id*. at 553 (Emphases added).

forests at stationary sources for energy production as carbon neutral"[105] is lacking in these distinctions and thus misconstrues and misrepresents congressional intent.

EPA has not demonstrated that biomass co-firing achieves an "emission reduction" at a "stationary source," as required by CAA Section 111. The Agency cannot overcome that problem by offering an interpretation of H.R. 1625 that is unreasonably broad and inconsistent with the stated intent of the provision's cosponsors.

[D] EPA's "Statement of Agency Policy" provides no basis for rational, informed decision-making

EPA acknowledges that its "Statement of Agency Policy" "is not a scientific determination" and "does not represent a final agency action."[106] Nevertheless, the statement announced the Agency's substantive conclusion as well as its regulatory intent.

EPA cannot use the "Statement of Agency Policy" to justify state compliance under this rulemaking. "When [an] agency applies the policy in a particular situation, it must be prepared to support the policy just as if the policy statement had never been issued. An agency cannot escape its responsibility to present evidence and reasoning supporting its substantive rules by announcing binding precedent in the form of a general statement of policy."[107] While the intent behind EPA's proposal is to apply the policy approach announced in its "Statement of Agency Policy"—*i.e.*, "to treat biogenic CO_2 emissions resulting from the combustion of biomass from managed forests at stationary sources for energy production as carbon neutral"[108]—the Agency's proposal does not even attempt to "support the policy just as if the policy had never been issued." The proposal offers no "evidence" nor any "reasoning support" for treating biomass co-firing as carbon neutral. It merely indicates that "states that intend to propose the use of forest derived biomass by affected units may refer to EPA's April 2018 statement," reiterates the conclusion of its "Statement of Agency Policy," provides a web address where the Statement can be found, and asserts without explanation that the Statement "aligns" with the carbon neutrality provision in the Consolidated Appropriations Act of 2018.[109] No support for the policy—no legal analysis, no scientific analysis—is provided in the proposal.

The proposal states that EPA policy is to treat the combustion of biomass from managed forests as carbon neutral and refers individual states to the Statement itself, while the Statement only articulates the Agency's intent to promulgate the policy in forthcoming rulemakings, and—by the Agency's own admission—lacks any scientific basis or determination. Even if the economic, market certainty, and broader forest benefits alleged in the "Statement of Agency Policy" were proven true, the mere assertion of those benefits cannot substitute for the scientific rationale

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[105] 83 Fed. Reg. at 44766.

[106] EPA Statement of Agency Policy at 2.

[107] *Pac. Gas & Electric Co. v. Fed. Power Comm'n*, 506 F.2d 33, 38-39 (D.C. Cir. 1974).

[108] EPA Statement of Agency Policy at 1.

[109] *See* 83 Fed. Reg. at 44766/1.

and justification required of the Agency. The meager support EPA provides for its decision to apply its carbon neutrality policy to this rulemaking is circular and therefore arbitrary.

[V] EPA cannot, as a matter of course, exempt facilities that co-fire biomass from scrutiny under NSR

As explained in other comments submitted to this docket by Clean Air Task Force, Natural Resources Defense Council, and other organizations, changes that EPA proposes to make to the NSR regulations would violate clearly-stated requirements in the CAA.[110] The proposed changes to the NSR program would also be arbitrary and capricious because they are overbroad in their reach, they cannot be justified by the rationales or analysis put forth by EPA, and they would impermissibly enable significant emissions increases beyond what the statute permits. If finalized (even on a limited basis), this seriously overbroad proposal would be arbitrary and capricious. It violates the Agency's statutory duty to protect public health and the environment, by creating a scheme that increases air pollution, creates the potential for increment violation, and otherwise causes significant public health and environmental harms. As was true of the NSR changes that EPA proposed in 2005 and 2007, EPA does not and cannot claim that this aspect of EPA's proposed rule would promote the protection of public health, air quality, the environment, national parks and wilderness areas, or any of the other clean air objectives of the Prevention of Significant Deterioration (PSD), NSR programs, or the CAA generally.

EPA's proposal is not limited to power stations that undertake heat rate improvement projects; by its terms, the proposed new applicability requirements would apply to *any* modification undertaken at a power station, including the installation of equipment for handling and combusting biomass feedstocks.[111]

In these comments, we provide specific additional reasons why EPA cannot categorically exempt power stations that shift to biomass co-firing from NSR. In many instances, the process of shifting to biomass co-firing constitutes a physical change or change in the method of operation at a major stationary source and will lead to a significant increase in CO_2 emissions from that source.

The installation of equipment for handling and combusting biomass feedstocks can trigger an applicability assessment under the NSR program. A coal-fired steam electric plant of more than 250 million BTUs per hour heat input that co-fires biomass meets the statutory definition of a "major emitting facility"[112] and the regulatory definition of a "major stationary source."[113] The installation of biomass co-firing equipment at a coal-fired power station constitutes a "physical

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[110] *See* Joint Environmental Comments on NSR Issues (filed in this docket October 31, 2018).

[111] 83 Fed. Reg. at 44781/2 ("EPA is proposing that this NSR hourly emissions test would apply to all EGUs"). Indeed, EPA fails to explain why if its legal theory is correct (which it is not) its proposal should not apply to all source types and categories.

[112] *See* CAA §169(1).

[113] *See* 40 C.F.R. 51.166(b)(1)(i), (5).

change" and/or a "change in the method of operation,"[114] and the physical change(s) or change(s) in the method of operation that a coal-fired power station would undertake when shifting to biomass co-firing can easily lead to a "significant emissions increase."[115] Consequently, if a coal-fired power station with a heat input of more than 250 million BTUs per hour makes physical or operational change so that it can co-fire biomass, and those changes result in an significant emissions increase, EPA cannot lawfully exempt that source from scrutiny under the NSR program.

In addition, the emission reductions that are sometimes attributed to biomass-based power generation cannot be netted against the power station's emission increase in a NSR applicability analysis, regardless of whether that analysis is conducted according to current regulations or EPA's newly proposed four-step process. Under existing EPA regulations,

> Net emissions increase means, with respect to any regulated NSR pollutant emitted by a major stationary source, the amount by which the sum of the following exceeds zero:
>
> > (a) The increase in emissions from a particular physical change or change in the method of operation *at a stationary source* as calculated pursuant to paragraph (a)(7)(iv) of this section; and
> >
> > (b) Any other increases and decreases in actual emissions *at the major stationary source that are contemporaneous with the particular change* and are otherwise creditable[.][116]

As discussed in Parts II and III of these comments, the emission reductions from bioenergy production (*i.e.*, the absorption of emitted CO_2 through subsequent plant regrowth) do not occur "at the major stationary source." They occur offsite in forests, farms, and other landscapes, and thus cannot be included in a calculation of net emissions for the purpose of assessing NSR applicability. Nor are bioenergy-related emission reductions "contemporaneous with the particular change." As discussed above in Part II, if biomass-based power generation delivers any net reduction in CO_2 emissions, those reductions would occur years or decades after a coal-fired power station makes the physical and operational changes that are involved in a shift to biomass co-firing. Consequently, the offsite emissions reductions that are sometimes attributed to biomass co-firing cannot be netted against emissions from the source itself.

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[114] *See* CAA §111(a)(4) and 40 C.F.R. 51.166(b)(2)(i); *see also* Doosan *Babcock, Biomass Cofiring and Conversion* (offering the engineering, procurement, and construction services to existing power stations that want to install biomass combustion technologies; listed services include: fuel handling and milling, dedicated burners and combustion, systems, direct and indirect flexible fuel systems, heating surface conversions, and integrated steam turbine retrofitting) (http://www.doosanbabcock.com/en/thermal/biomass/).

[115] *See* 40 C.F.R. 51.166(b)(39). As discussed in Part II of these comments, a shift from coal combustion to biomass co-firing will almost always cause the affected source to increase in the amount of CO_2 it emits.

[116] 40 C.F.R. 51.166(b)(3) (emphasis added). "In simplest terms, a net emissions change is the sum of the emissions increases from the project and any other increases and decreases *at the entire source* that are contemporaneous and creditable." Minnesota Pollution Control Agency, *Facts About Determining Applicability of New Source Review* at 5 (July 2010) (emphasis added) (https://www.pca.state.mn.us/sites/default/files/aq4-25.pdf).

Accordingly, EPA lacks the authority to implement regulations that exempt power stations that shift to biomass co-firing from NSR scrutiny, nor can it net the emission reductions that are sometimes attributed to biomass-based power generation against the power station's emission increase in an NSR applicability analysis.

[VI] Conclusion

EPA must withdraw its proposal to treat the combustion of biomass from managed forests as carbon neutral. First, the Agency has not demonstrated that biomass co-firing can achieve an "emission reduction" at a "stationary source," as required by CAA Section 111.

Second, it would be arbitrary, capricious, and otherwise unreasonable for EPA to allow a state to base its CAA Section 111(d) compliance plans on nominal reductions from biomass co-firing when those reductions cannot be squared with key elements of Agency's interpretation of CAA Section 111 and are highly uncertain, highly speculative, and highly dependent on actions beyond the control of an affected source.

Third, EPA's reliance on its "Statement of Agency Policy" and its proposal to treat all forms of forest biomass harvested from "managed forests" as carbon neutral is unfounded, contrary to established scientific findings, and does not "adequately demonstrate" that co-firing biomass harvested from managed forests constitutes an "emission reduction."

Finally, a coal-fired power station that makes a modification so that it can co-fire biomass cannot, as a matter of course, be exempted from scrutiny under the CAA's NSR provisions.

Thank you for the opportunity to provide comments on EPA's proposed treatment of biomass-based power generation under CAA Section 111.

Respectfully submitted,

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APPENDIX

1. Pierre Bernier, *et al.*, *Using ecosystem CO_2 measurements to estimate the timing and magnitude of greenhouse gas mitigation potential of forest bioenergy*. GCB Bioenergy, (Jan, 2013).

2. Richard Birdsey, *et al.*, *Climate, Economic, and Environmental Impacts of Producing Wood for Bioenergy*, Env. Res. Letters, (Mar, 2018).

3. Mary Booth, *Not carbon neutral: Assessing the net emissions impact of residues burned for bioenergy*, Environmental Research Letters, (Feb, 2018).

4. Andrea Colnes, *et al.*, *Biomass Supply and Carbon Accounting for Southeastern Forests-Executive Summary*, The Biomass Energy Resource Center, Forest Guild, and Spatial Informatics Group, (Feb, 2012).

5. Helmut Haberl, *et al.*, *Correcting a fundamental error in greenhouse gas accounting related to bioenergy*, Energy Policy, (Jun, 2012).

6. Jerome Laganière, *et al.*, *Range and uncertainties in estimating delays in greenhouse gas mitigation potential of forest bioenergy sourced from Canadian forests*, GCB Bioenergy, (Feb, 2017).

7. Jon McKechnie, *et al.*, *Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels*, Environ. Sci. Technol., (Jan, 2011).

8. Stephen Mitchell, *et al.*, *Carbon Debt and Carbon Sequestration Parity in Forest Bioenergy Production*, GCB Bioenergy, (May, 2012).

9. Ana Repo, *et al.*, *Sustainability of Forest Bioenergy in Europe: Land-use-related Carbon Dioxide Emissions of Forest Harvest Residues*, GCB Bioenergy, (Mar, 2014).

10. Ernst-Detlef Schulze, *et al*. *Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral*, Global Change Bioenergy, (2012).

11. Michael Ter-Mikaelian, *et al.*, *Debt repayment or carbon sequestration parity? Lessons from a forest bioenergy case study in Ontario, Canada,* GCB Bioenergy, (Jul, 2015).

12. Michael Ter-Mikaelian, *et al.*, *The Burning Question: Does Forest bioenergy Reduce Carbon Emissions? A Review of Common Misconceptions About Forest Accounting,* Journal of Forestry, (Nov, 2014).

13. Thomas Walker, *et al.*, *Sustainability and Carbon Policy Study-Executive Summary*, The Manomet Center for Conservation Sciences, (Jun, 2010).

14. Giuliana Zanchi, *et al.*, *Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel*, GCB Bioenergy, (Nov, 2012).

1. Pierre Bernier, *et al.*, *Using ecosystem CO_2 measurements to estimate the timing and magnitude of greenhouse gas mitigation potential of forest bioenergy*. GCB Bioenergy, (Jan, 2013).

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Using ecosystem CO_2 measurements to estimate the timing and magnitude of greenhouse gas mitigation potential of forest bioenergy

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Abstract

Forest bioenergy opportunities may be hindered by a long greenhouse gas (GHG) payback time. Estimating this payback time requires the quantification of forest-atmosphere carbon exchanges, usually through process-based simulation models. Such models are prone to large uncertainties, especially over long-term carbon fluxes from dead organic matter pools. We propose the use of whole ecosystem field-measured CO_2 exchanges obtained from eddy covariance flux towers to assess the GHG mitigation potential of forest biomass projects as a way to implicitly integrate all field-level CO_2 fluxes and the inter-annual variability in these fluxes. As an example, we perform the evaluation of a theoretical bioenergy project that uses tree stems as bioenergy feedstock and include multi-year measurements of net ecosystem exchange (NEE) from forest harvest chronosequences in the boreal forest of Canada to estimate the time dynamics of ecosystem CO_2 exchanges following harvesting. Results from this approach are consistent with previous results using process-based models and suggest a multi-decadal payback time for our project. The time for atmospheric carbon debt repayment of bioenergy projects is highly dependent on ecosystem-level CO_2 exchanges. The use of empirical NEE measurements may provide a direct evaluation of, or at least constraints on, the GHG mitigation potential of forest bioenergy projects.

Keywords: Fluxnet, fossil fuel, *Picea mariana*, *Pinus banksiana*, respiration

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Introduction

Increasing the use of bioenergy is one of the most immediate opportunities for reducing fossil fuel emissions as biomass is in fact a form of captured solar energy. In spite of its attractiveness, the use of forest biomass energy (forest bioenergy) for reducing GHG emissions is challenged by the counter-intuitive argument that it may not generate an immediate effect of mitigating anthropogenic GHG emissions (Richard, 2010; Zhang *et al.*, 2010). The numerous processes and assumptions used to evaluate the GHG balance of bioenergy systems may lead to different outcomes (Cherubini, 2010), but ultimately an accurate evaluation of the GHG mitigation potential of a bioenergy system must be based on the accounting of all net project-related GHG exchanges with the atmosphere.

In bioenergy systems based on the ‘Forest Land Remaining Forest Land’ land-use type (IPCC, 2006a), the GHG preconsumption emissions involved in forest harvesting, forest management, transportation and fuel processing generally represent a very small fraction of total GHG emissions (Zhang *et al.*, 2010; McKechnie *et al.*, 2011; Repo *et al.*, 2011). By contrast, the C dynamics of a forest ecosystem in which biomass is sourced contribute substantially to a bioenergy project's C balance sheet over time and are, *in fine*, responsible for the recapture of CO_2 emitted in the bioenergy chain. Proper quantification of these exchanges is therefore critical. In a recent review on bioenergy certification initiatives, van Dam *et al.* (2010) concluded that given the complexity of biomass energy systems, there is a need for reaching an international agreement on the methodology used for calculating GHG balances.

To date, forest C dynamics of bioenergy systems have been estimated using simulation models (e.g. Zhang *et al.*, 2010; McKechnie *et al.*, 2011; Repo *et al.*, 2011). Long-term prediction of soil and vegetation C dynamics may be greatly influenced by the choice of model and its parameterization. For example, different models may yield differences in long-term soil C accumulation (Falloon & Smith, 2002), as results from long-term soil experiments indicate that changes in soil C over time are not easily predictable (Richter *et al.*, 2007). Also, many simulation models of carbon accounting use forest growth curves based on individual tree growth that may not capture stand-level tree dynamics or the decomposition of organic material. For example, Garet

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et al. (2009) showed that using wood volume change over time since disturbance instead of a yield curve generated major differences in the estimated biomass content of old forests. In addition, tests show that agreement is often poor among process models for the simulation of forest CO_2 exchanges (Schwalm *et al.*, 2010).

In the last decade, forest C dynamics have been studied in great detail around the world using the eddy covariance technique in which continuous measurements of CO_2 exchanges between a forest ecosystem and the atmosphere are taken from a tower located above the forest. This technique provides empirical measurements of net fluxes between the forest and the atmosphere and therefore provides an integration of all CO_2 fluxes from decomposition, respiration and photosynthesis. In Canada, the Fluxnet Canada Research Network and its now terminated successor, the Canadian Carbon Program, took such measurements at sites located across the country (Coursolle *et al.*, 2006; Margolis *et al.*, 2006) with a particular emphasis on the impact of disturbances on forest C dynamics (Amiro *et al.*, 2010). This study proposes, as a new approach, incorporating empirical data from these measurement programs into the analysis of forest bioenergy systems. We use this approach to evaluate the GHG reduction dynamics over time of a hypothetical bioenergy project that uses tree stems from live trees from the Canadian boreal forest as feedstock. As the net exchange of CO_2 between the forest and the atmosphere varies with forest development stage, chronosequences of sites representing the full range of time since harvest are necessary to run this exercise.

Materials and methods

In this hypothetical bioenergy project, the bioenergy scenario involves the use of tree stems as feedstock, but with branches left on site to maintain site fertility. In the reference scenario against which it is compared, the forest stands are left unharvested and fossil fuel is used as feedstock. We use the framework detailed by Cherubini (2010) to evaluate the GHG balance of these two scenarios in which the bioenergy feedstock comes from the 'Forest Land Remaining Forest Land' land-use type (IPCC, 2006a). Briefly, the full chain of both systems (bioenergy and fossil fuel reference) is compared for the delivery of the same service. In our hypothetical project, the fossil fuel used as a reference is heating oil, the final product is heat as it would be produced by a domestic pellet heating system, and the energy recovery efficiency is assumed to be 95% for both feedstocks. Our analysis treats the project as a yearly stream of feedstock use and related emissions and therefore integrates over time the cumulative impacts of yearly forest-level extraction of biomass. All computations are presented for the yearly production of 1 GJ of thermal energy.

In our analysis, we consider CO_2 emissions from three sources linked to the use of either biomass or fossil fuel. The first source is the CO_2 emission 'at the chimney' from the combustion of feedstock. The second is an aggregation of 'preconsumer' emissions linked to the extraction, transport and processing of energy feedstock, often referred to as 'well-to-tank' for oil. Preconsumer emissions are expressed as a fraction of the emissions in final end-use for energy production, and are taken to be equivalent to preconsumer energy use as a fraction of feedstock energy content. Preconsumer and chimney-level emissions are grouped within the 'feedstock' emission category in Table 1. The third source are the ecosystem CO_2 emissions from biophysical processes from forest sites where the bioenergy feedstock is harvested or not depending on the scenario.

For emissions 'at the chimney', we use the IPCC (2006b) default CO_2 emission factors for oil and wood of 74.1 $tCO_2\ TJ^{-1}$ and 112 $tCO_2\ TJ^{-1}$, respectively (see Moomaw *et al.*, 2011). For preconsumer emissions from forest biomass, reported values of energy input to energy produced are 1 : 22 or 4.5% (Pimentel & Pimentel, 2008), 1 : 35 or 2.8% (Gautam *et al.*, 2010) for case studies in Ontario, and 6.75% for pellet production in a boreal case in Ontario (McKechnie *et al.*, 2011). We therefore

Table 1 Cumulative CO_2 emissions (+) or capture (−) (kg CO_2) for a bioenergy project using tree stems as feedstock and the reference fossil fuel scenario using oil as feedstock for the production of 1 GJ of energy per year. Preconsumer emissions are the CO_2 emissions from extraction, transport and processing activities, and are set at 5% and 25% of the energy content of the biomass and oil feedstock, respectively. Chimney emissions are the amount of CO_2 released per unit of intrinsic energy content (IPCC default emission factors of 112 Kg $CO_2\ GJ^{-1}$ and 74.1 Kg $CO_2\ GJ^{-1}$ for wood and oil, respectively), corrected for an assumed 95% efficiency of the technology used for heat production. Values of ecosystem emissions are from net ecosystem exchange (NEE) measurements over stands (Fig. 1) and are negative when the stand captures CO_2 from the atmosphere.

	Tree Stems			Reference (Oil)		
Source Description	Feedstock Preconsumer and chimney	Ecosystem NEE following harvest	Total	Feedstock Preconsumer and chimney	Ecosystem NEE from unharvested mature forests	Total
At year 10	1176	126	1302	926	−11	915
At year 50	5880	−268	5612	4631	−245	4386
At year 100	11760	−4714	7046	9263	−974	8289

use a preconsumer emission value of 5% for bioenergy. For oil, estimates of well-to-tank emissions for automotive fuels range from 19% (Institute for Environment & Sustainability, 2008) to 27% (Air Resources Board, 2009). We use a well-to-tank value of 25% in our analysis.

Ecosystem-level CO_2 dynamics are derived from field-based empirical observations of CO_2 exchanges from boreal forest sites in Canada obtained by the Fluxnet Canada Research Network and the subsequent Canadian Carbon Program (Margolis *et al.*, 2006). The sites from which we used measurements represent two chronosequences of harvesting disturbance. The first chronosequence is within stands dominated by *Pinus banksiana* (jack pine) and is located in the province of Saskatchewan, Canada. The second chronosequence is within stands dominated by *Picea mariana* (black spruce) and is located in the province of Quebec, Canada. The jack pine chronosequence has four stands originating from harvests done in 1975, 1994 and 2002. The oldest stand in the chronosequence originates from a burn in 1919. The black spruce chronosequence is composed of three upland stands, with the oldest from a *circa* 1890 fire, and the two others from harvests done in 1975 and 2000. Both chronosequences were initially selected by Fluxnet Canada investigators because they provided representative examples of commercial harvesting operations in much of the Canadian boreal forest. Details on site properties are available in Amiro (2001) and Amiro *et al.* (2010).

For each site within the chronosequences, tower-mounted instruments were used to provide measurements of ecosystem CO_2 dynamics, also called net ecosystem exchange (NEE). The NEE is the sum of the photosynthesis-driven downward CO_2 flux from atmosphere to vegetation, and the upward flux of CO_2 to the atmosphere emitted by the decomposition of dead organic material and the respiration of living plant tissues and organisms. By definition, NEE is negative when there is a net CO_2 capture by the forest ecosystem, and is positive when there is a net flux of CO_2 from forest to atmosphere. Vertical CO_2 fluxes are measured many times per second by instruments mounted on a tower above the stand, and cumulated to ultimately provide series of yearly NEE for that site. Multi-year measurements were carried out by investigators from Fluxnet Canada and the Canadian Carbon Program from about 2002 to 2011, with exact record length varying according to site. NEE measurements for the four sites within the jack pine chronosequence are from Amiro *et al.* (2010). NEE measurements at the three sites within the black spruce chronosequence are from Coursolle *et al.* (personal communication). Details of measurements techniques and of postprocessing and gap-filling methodologies can be found in Coursolle *et al.* (2006).

A time series of NEE values was created by fitting a model of linear segments between the clusters of points formed by the multi-year measurements at each site using the TRANSREG procedure of the SAS statistical package (SAS Institute Inc., Cary, NC, USA). Initial analysis had revealed considerable overlap between the two chronosequences in their resulting time dynamics of CO_2 debt in comparison with the reference fossil fuel scenario. The yearly values of NEE from both chronosequences were therefore merged to produce an upland boreal conifer chronosequence for our analysis. The resulting function (Fig. 1) is:

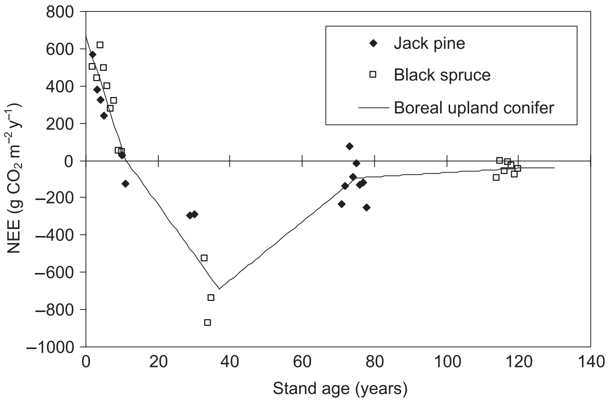

Fig. 1 Net ecosystem exchange (NEE) for pure jack pine and pure black spruce forest stands at different ages following harvest or fire replacement for the two older stands. Each point represents a single year of integrated NEE measurements over a stand. NEE is positive for a net CO_2 flux to the atmosphere. The solid line is our boreal upland conifer NEE and is a least-square fit of straight segments used to interpolate NEE values for the analysis. NEE measurements were produced by the Fluxnet Canada/Canadian Carbon Program Research Network.

$$y = \begin{cases} 181.82 - 16.42x, & 0 \le x \le 11 \\ 81.14 - 7.27x, & 11 \le x \le 35 \\ -346.06 + 4.28x, & 35 \le x \le 75 \\ -48.59 + 0.31x, & 75 \le x \le 120 \\ -11.20, & x \ge 120 \end{cases} \tag{1}$$

where y is the NEE (gC m^{-2} y^{-1}) and x is the number of years since harvest or stand initiation. Fit statistics for this function are RMSE of 31.4 and adjusted r^2 of 0.89. The intercept of 181.82 for the first segment represents the initial rate of net CO_2 loss from the forest ecosystem following tree harvest as photosynthesis is reduced to nearly zero. The constant 11.2 gC m^{-2} y^{-1} for the fifth segment represents the NEE of mature stands that would be left unharvested in the fossil fuel scenario, and in which photosynthesis is on average only slightly greater than decomposition.

All emissions were computed for a project that would produce 1 GJ of energy per year, with the appropriate feedstock emissions cumulated over time. The NEE of a given harvested area was assumed to follow the time course starting at year '0' in Fig. 1. The NEE of an area not harvested, as per the fossil fuel scenario, was assumed to follow the time course starting at year '120' in Fig. 1, with a constant negative NEE (net CO_2 uptake by the forest as per Eqn. 1). These yearly NEE values were cumulated over time for a given area that was either harvested or not harvested, depending on the scenario, for a single year of energy generation, and cumulated over space as new areas were harvested (or not harvested) for successive years of energy generation. Ecosystem emissions represented by Eqn. 1 were scaled down by 15% so that the cumulative NEE at year 100 would be equal to the above-ground biomass of the mature jack pine site (Zha *et al.*, 2009). This adjustment ensured consistency between the mass-based CO_2 emissions from wood combustion based on the energy content of 20.59 MJ kg^{-1} (Singh & Kostecky, 1986) and the area-based CO_2 emissions from the ecosystem.

Results

As seen in Fig. 2(a and b), emissions related to the production and combustion of both the biomass and the fossil fuel scenarios are constant over time. However, their respective ecosystem CO_2 emissions are quite different as a result of harvesting impacts on the biological processes of CO_2 exchanges (photosynthesis, autotrophic and heterotrophic respiration). In the fossil fuel scenario, the older mature stands left unharvested accumulate a small but constant amount of CO_2 per unit land area, which is set by the fifth line segment of Eqn. 1 scaled to 1 GJ y^{-1} of energy production. Accruing areas of unharvested stands therefore generate a small but accruing annual offset to feedstock emissions from oil (Fig. 2b). For the bioenergy scenario, the dynamics of CO_2 exchanges from the individual harvested sites follow the complete postharvest NEE time course shown in Fig. 1, with an initial net emission of CO_2 (positive NEE) followed by an increasingly large net capture of CO_2 as photosynthesis increases through the expansion of tree canopies and leaf area. As new areas are harvested each year, the yearly CO_2 exchange from decomposition and photosynthesis over the harvested landscape follows the pattern shown in Fig. 2a, with initial net emissions replaced gradually by important net CO_2 uptake as forest regrowth eventually becomes the dominant process over an increasing proportion of the harvested landscape. However, the combination of all these processes generates a major CO_2 debt for the bioenergy scenario that takes upwards of 90 years to be paid back, a point reached when the cumulative difference in emissions between the two scenarios becomes zero (Fig. 2c).

Further analysis shows that the time for debt repayment is very sensitive to age of harvest. In our example (Fig. 2), we assumed that harvested stands were mature (120 years old) and therefore used the low and constant net CO_2 uptake associated with that stand age in Fig. 1. Harvesting stands for energy feedstock at younger ages pushes the time for debt repayment far beyond 90 years (Fig. 2c) as the greater productivity (more negative values of NEE) of the younger stands (Fig. 1) provides a larger offset against fossil fuel emissions in the fossil fuel scenario. Of course, these results apply only to our boreal forest type. In areas where forests grow much faster, the time course of NEE in Fig. 1 would probably be compressed into fewer years, and the debt payback time would be shorter.

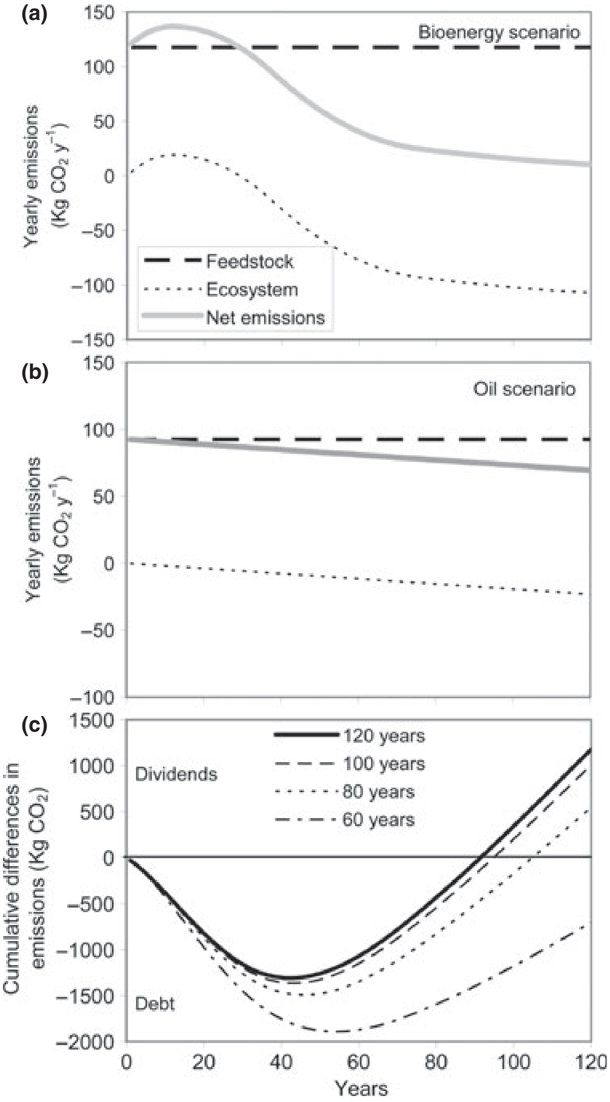

Fig. 2 CO_2 emissions for a bioenergy project using tree stems as energy feedstock. (a) Yearly emissions include fixed feedstock emissions and variable ecosystem emissions for both the bioenergy (a) and the fossil fuel (b) scenarios (see Table 1 for definitions). In (b), negative emissions denote a continued net CO_2 capture by unharvested forests and provide an offset against feedstock emissions. In (c), the cumulative difference in total CO_2 emissions between the two scenarios is negative when cumulative CO_2 emissions of the bioenergy project are greater than those of the reference fossil fuel scenario. The time for debt repayment is reached when the cumulative difference in emissions between the two scenarios crosses the '0' line, at year 90 in (c). Also shown in (c) is the impact of stand age (60–120 years) at the time of harvesting. A stand age of 120 years at harvesting was used for calculations in (a). The vertical scale hides the small ecosystem NEE values at year 1 of the project.

Discussion

The debt payback time of 90 years for our hypothetical project is within the range of payback times found for a range of bioenergy projects (McKechnie *et al.*, 2011; Repo *et al.*, 2011). By comparison, Holtsmark (2012), using a modelling approach in assessing ecosystem fluxes, found a carbon payback time ranging from 190 to 340 years when tree stems from boreal forests are used for bioenergy. His study incorporates the decrease in landscape-level carbon on account of increased harvesting intensity, a result that highlights the importance of ecosystem process representation in the evaluation of GHG mitigation potential of forest bioenergy.

Estimating ecosystem-level CO_2 exchanges within a model is both complex and uncertain as it involves numerous fluxes and processes that change dynamically with forest development stage (e.g. Schwalm *et al.*, 2010). However, as seen above, proper representation of these processes is of paramount importance because only ecosystem-level CO_2 dynamics enable forest bioenergy projects to generate GHG mitigation benefits. Empirical ecosystem CO_2 exchange data integrate all biological processes as well as some of the effects of inter-annual climate variability on these processes, thereby providing a constrained estimate of ecosystem-level CO_2 dynamics. We believe that using such empirical data provides a robust methodology for evaluating forest bioenergy projects, with modelling used as a complement when existing NEE data come from environments or depict conditions that do not fully correspond to project parameters.

Studies have also shown the importance of feedstock type on the timing and importance of GHG mitigation benefits of forest bioenergy projects, with a significant contrast between biomass from fine residues or stumps left after harvest (Repo *et al.*, 2011) and from green trees (McKechnie *et al.*, 2011; Holtsmark, 2012) such as the example that we present here. Estimating payback time for forest harvest residues is straightforward as it is usually assumed that the only difference between the biomass and reference scenario is the progressive return to the atmosphere of unused decaying residues. Therefore, for this type of feedstock, one needs only to model one ecosystem component over a relatively short period of time. Estimates of decay rates of harvest residues have been suggested to be about 6% per year (Hyvönen *et al.*, 2000), which suggests a time for debt payback of a few years. Apart from industrial mill residues, forest harvest residues currently are the most likely feedstock to be sourced from forests for new bioenergy projects in Canada (Paré *et al.*, 2011).

Salvaging dead trees following insect attack or fire is another potentially large bioenergy feedstock pool in Canada (Dymond *et al.*, 2010). Flux measurements from a fire chronosequence (Amiro *et al.*, 2006, 2010) and from sites within a large mountain pine beetle epidemic in British Columbia (Schwalm *et al.*, 2010) show a delayed decay response of dead trees as they remain standing and dry, and a fast recovery in terms of a positive site-level CO_2 uptake. The large decay pulse when snags finally fall to the ground may take several years to materialize. Empirical evidence suggests a wait period of up to 20 years for jack pine forests (Amiro *et al.*, 2010; their Fig. 1) before this happens. Angers *et al.* (2010) estimated the half-life of standing dead snags to be 20–25 years for boreal conifers, and 12 years for aspen. Mitchell & Preisler (1998) report a 3- to 5-year wait before beetle-killed lodgepole pines (*Pinus contorta*) fall to the ground. These observations suggest that the release of CO_2 through the decomposition of fire- or insect-killed trees may be spread over a few decades, with a resulting delay in time for CO_2 debt repayment in forest bioenergy projects based on such feedstock. A more complete set of empirical CO_2 exchange data would provide a solid foundation for such an analysis, but the few existing empirical NEE data could already contribute to project evaluations.

In our analysis, we used two sets of forest chronosequence data. Amiro *et al.* (2010) also summarized other chronosequence data from harvested and burned forest sites for North America, as well as partial chronosequences for insect- and wind-damaged stands. These NEE data from chronosequences are particularly useful because they integrate all ecosystem processes and also capture time dynamics following a disturbance. On the negative side, the complete integration of processes within the NEE term makes it difficult to apply it to circumstances not covered by the experimental design, such as a different intensity of biomass removal or different biomass origin (fine residues, stumps, etc.). In addition, such datasets are not common, and their creation requires significant financial investments over multi-year periods as well as relevant expertise to run these instruments and perform the appropriate data processing tasks. In a less direct manner, NEE datasets could be used as benchmarks against which to test the CO_2 exchange models used to assess ecosystem contributions to bioenergy project emissions. Such use of empirical data would then ensure some level of realism in model results.

Finally, computations as described above are made for stands that are treated as independent spatial units and for which the deterministic reference scenario assumes their indefinite maintenance in the landscape. In reality, however, the emerging properties of forested landscapes include a probability of total or partial disturbance, by fire or insects, or even by harvesting as harvesting plans change over time. The analysis of forest bioenergy projects should therefore allow for probabilities of disturbance and the resulting changes in ecosystem emissions, with the use of appropriate empirical measurements when available.

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EDITORIAL

Climate, economic, and environmental impacts of producing wood for bioenergy

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Abstract

Increasing combustion of woody biomass for electricity has raised concerns and produced conflicting statements about impacts on atmospheric greenhouse gas (GHG) concentrations, climate, and other forest values such as timber supply and biodiversity. The purposes of this concise review of current literature are to (1) examine impacts on net GHG emissions and climate from increasing bioenergy production from forests and exporting wood pellets to Europe from North America, (2) develop a set of science-based recommendations about the circumstances that would result in GHG reductions or increases in the atmosphere, and (3) identify economic and environmental impacts of increasing bioenergy use of forests. We find that increasing bioenergy production and pellet exports often increase net emissions of GHGs for decades or longer, depending on source of feedstock and its alternate fate, time horizon of analysis, energy emissions associated with the supply chain and fuel substitution, and impacts on carbon cycling of forest ecosystems. Alternative uses of roundwood often offer larger reductions in GHGs, in particular long-lived wood products that store carbon for longer periods of time and can achieve greater substitution benefits than bioenergy. Other effects of using wood for bioenergy may be considerable including induced land-use change, changes in supplies of wood and other materials for construction, albedo and non-radiative effects of land-cover change on climate, and long-term impacts on soil productivity. Changes in biodiversity and other ecosystem attributes may be strongly affected by increasing biofuel production, depending on source of material and the projected scale of biofuel production increases.

Introduction

Scenarios used by the Intergovernmental Panel on Climate Change (IPCC) that limit climate warming to less than 2 °C by 2100 involve major reductions in greenhouse gas (GHG) emissions, together with large-scale removal of CO_2 via carbon capture mechanisms starting before 2050, leading globally to net-negative emissions starting around 2070 (IPCC 2014). Enhancing terrestrial C sinks, substituting renewable energy sources for fossil fuels, and capturing and storing CO_2 are key mitigation elements that are expected to help achieve targeted reductions. Land management activities and replacing fossil fuels with bioenergy feedstock are already taking place worldwide and could expand significantly. In nearly all IPCC scenarios, CO_2 removal is assumed to occur via bioenergy combined with technology to capture and store CO_2 bioenergy (known as 'bioenergy with CO_2 capture and storage'—BECCS). Feasibility of large-scale deployment of BECCS has not been demonstrated, nor have its potential and risks including consequences of devoting so much land area to energy crops been fully examined (e.g. Creutzig *et al* 2015, Fuss *et al* 2014, Smith *et al* 2016).

Much has been written about the complexities of assessing impacts on climate from using renewable wood for bioenergy, yet there has been a strong push by policy makers to declare bioenergy 'carbon neutral' (Haberl *et al* 2012, Searchinger *et al* 2009, Ter-Mikaelian *et al* 2015). The accounting construct of carbon neutrality is often justified by the fact that emissions from the burning of biomass are reported by the land sector, and therefore do not need to be reported in the energy sector. Carbon neutrality may also be justified by assuming that emissions from wood combustion will be offset through forest regrowth in the future, even though there is no guarantee that this will actually occur. Using this highly simplified accounting method to assess climate change mitigation options may lead to counter-productive outcomes, because it does not fully reflect the impacts of bioenergy use on the atmosphere (Kurz *et al* 2016). This is the case regarding export of wood pellets from North America to Europe where wood-based biofuel is used to replace fossil fuels in electricity generation (Brack 2017). A recent study (Booth 2018) demonstrated that in contrast to being carbon neutral, common uses of wood for bioenergy resulted in net increases of CO_2 in the atmosphere, depending on fuel source and alternative fate of burned material.

Increasing demand for woody biomass for fuel has raised concerns and produced conflicting statements about how to assess impacts on GHG concentrations and other forest values (Colnes *et al* 2012, Dale *et al* 2015, Manomet Center for Conservation Sciences 2010). Assessments are often based only on estimates of supply-chain fossil-fuel emissions and combustion efficiencies, and fail to account for impacts on the terrestrial carbon cycle that supplies the biomass, or other induced effects on the environment. Recent studies show that with full accounting, the GHG effects are conditional upon many factors such as source of biomass (i.e. wood residues or whole trees and their fate if not used for bioenergy), time horizon of analysis, and assumptions about what would happen if biofuel production were not increased (Miner *et al* 2014, Smyth *et al* 2017, Ter-Mikaelian *et al* 2015, Booth 2018).

Wood-pellet production and exports from the southeastern US (SE) have grown substantially since the early 2000s, and in 2015, 98% of these pellets were shipped to the European Union (EU) for bioenergy (US International Trade Commission 2016, Dale *et al* 2017). The key policy driver of increasing demand for pellets is the Renewable Energy Directive (RED) of the EU, and the key policy drivers supporting increased SE pellet supply are based on forest inventories and sustainability policies (Abt *et al* 2014), plus the potential for increased revenue from timber sales by increased utilization of low-grade wood. Based on the EU RED, the demand for pellets will increase significantly over the next decade, and it is highly likely that biomass imported from the SE and Canada will dominate the non-EU sources in the future (Lamers *et al* 2014). Increasing biomass exports from the US and Canada will increase the land-sector GHG emissions reported by these countries because, under international GHG reporting rules, the emissions from wood products are reported for the land sector of the country in which the wood was harvested and in which the forest regrowth will occur (Kurz *et al* 2016). Setting energy policies based only on the emissions of the country that uses bioenergy does not adequately capture the policy impacts on the atmosphere.

The most recent EU RED policies declare biofuel to be carbon neutral regardless of the source of biofuel (Schiermeier 2018); therefore, energy generating facilities may claim zero emissions even though the fuel producing country incurs an emissions debit in the land sector. However, numerous studies of increasing bioenergy use have revealed that depending on feedstock, changes in the forest supplying the feedstock can have significant impacts on the overall net emissions of GHGs and therefore need to be considered as a significant part of the complete carbon footprint (Agostini *et al* 2013, Giuntoli *et al* 2016, Guest *et al* 2013).

Here we concisely examine effects on GHGs and other impacts on climate and the environment of using wood for biofuel based on our selection of the most relevant and objective literature. We also reference several recent case studies of increasing exports of wood pellets from the SE and Canadian forests to EU electricity producers and of increasing domestic use of wood biofuel. We identify the specific circumstances under which GHG effects are positive or negative over different time horizons, and highlight accounting methods that factually assess climate benefits and the attribution of carbon credits and debits to wood suppliers and consumers. As appropriate, we make recommendations for additional research necessary to resolve inconclusive findings.

Review of accounting to determine net climate benefits of using wood for bioenergy

Assessing the climate impacts of burning wood requires a systems approach because of the connections between forests, wood products, land use, and energy production (Kurz *et al* 2016, Lemprière *et al* 2013, Nabuurs *et al* 2007). As described by Nabuurs *et al* (2007), the forest sector is embedded in a much broader array of societal activities (figure 1). Activities that occur within the forest sector are linked with other sectors of the economy and have impacts on GHG emissions from those sectors.

Assessing effects of bioenergy on GHG emissions requires comparing bioenergy scenarios with a projected reference scenario to accurately estimate the incremental net change in emissions. Applying this 'additionality' concept ensures that estimated impacts of bioenergy production are relative to what would have happened in the absence of proposed activities. A common mistake in bioenergy accounting by the energy sector is failure to consider the effects of using wood for bioenergy on forest carbon stocks over time

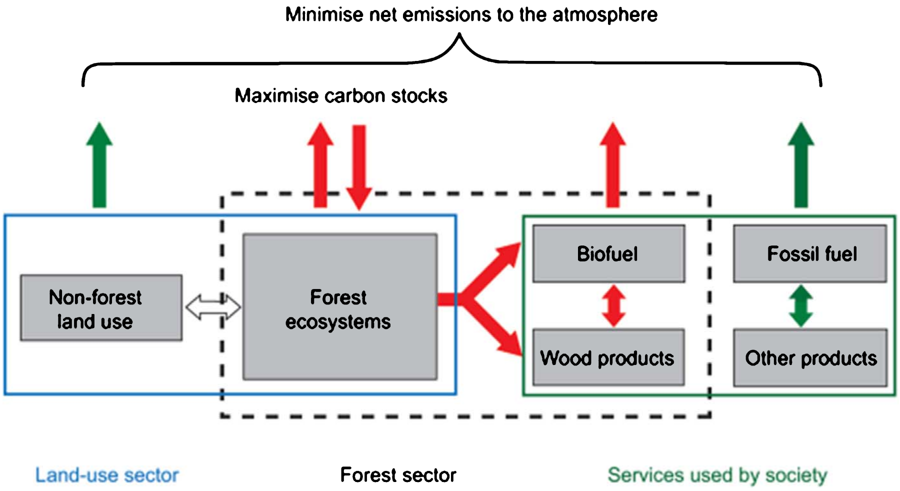
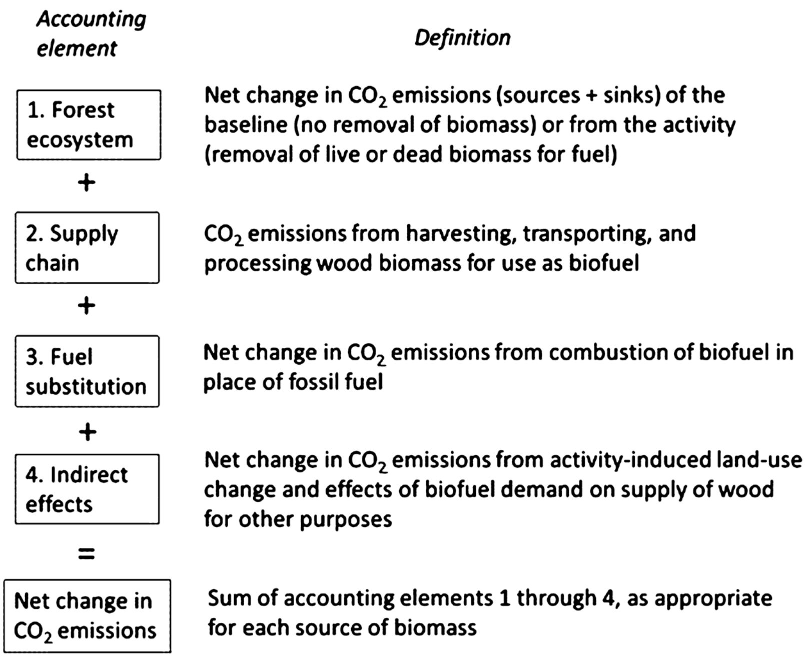


Figure 1. The forest sector in relation to land use, wood products, and energy. Full and accurate accounting for the impacts of forestry activities on greenhouse gases requires estimates of changes in all of these linked systems. Graphic reproduced from Nabuurs *et al* (2007), IPCC Assessment Report 4, Working Group 3.



Accounting element	*Definition*
1. Forest ecosystem	Net change in CO_2 emissions (sources + sinks) of the baseline (no removal of biomass) or from the activity (removal of live or dead biomass for fuel)
+	
2. Supply chain	CO_2 emissions from harvesting, transporting, and processing wood biomass for use as biofuel
+	
3. Fuel substitution	Net change in CO_2 emissions from combustion of biofuel in place of fossil fuel
+	
4. Indirect effects	Net change in CO_2 emissions from activity-induced land-use change and effects of biofuel demand on supply of wood for other purposes
=	
Net change in CO_2 emissions	Sum of accounting elements 1 through 4, as appropriate for each source of biomass

Figure 2. Elements of accounting for direct effects on CO_2 emissions from substituting wood biofuel for fossil fuel, showing which elements are associated with sources of biomass.

and comparing this with a reference case that does not include increasing bioenergy (Ter-Mikaelian *et al* 2015). The same additionality principle applies to using wood or mill residues that are produced during harvest and processing operations for non-bioenergy wood products (e.g. Domke *et al* 2012, Repo *et al* 2012).

There are several *essential elements of accounting* for estimating effects of bioenergy on net emissions of CO_2 (figure 2): (1) changes in net emissions associated with the land that provides the biomass, including long-term effects on nutrients and productivity; (2) emissions associated with the harvest, processing, and transport of the biomass (often referred to as 'supply-chain emissions'); (3) emissions associated with combustion efficiencies of different fuels (referred to as 'fuel substitution'); and (4) indirect effects such as changes in land use induced by increasing the supply of biomass or changes in supply of other timber products. Taken together, estimating the *net change in emissions* from these four categories will describe the direct and indirect impacts of substituting wood bioenergy for fossil energy on the concentration of GHGs in the atmosphere. Besides accounting for changes in GHGs, it is widely recognized that there are direct effects on climate from changes in albedo and other biophysical processes that can either enhance or diminish the climate impact of GHGs (Cherubini *et al* 2012, Holtsmark 2015).

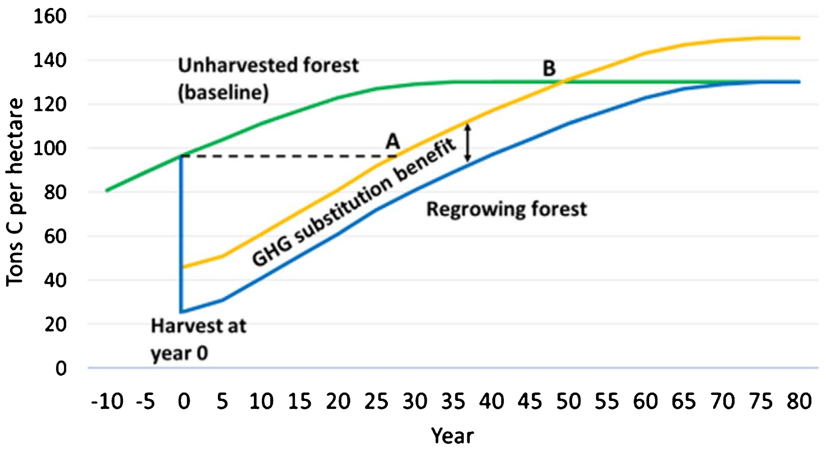


Figure 3. Hypothetical effect of harvesting a southeast US forest for bioenergy, replacing coal used to generate electricity. 'GHG substitution benefit' represents the reduction in life cycle GHG emissions from using wood instead of coal, not counting the effect on forest CO_2 net emissions. The 'carbon debt' from harvesting at year 0 is 'repaid' when the regrowing forest plus the GHG benefit equals the carbon stock in the forest at time of harvest (point A). The net benefit of harvesting, regrowth, and GHG substitution equals the baseline at point B, after which decreases in atmospheric GHGs occur. Adapted from Ter-Mikaelian *et al* (2015). Copyright © 2015 Society of American Foresters.

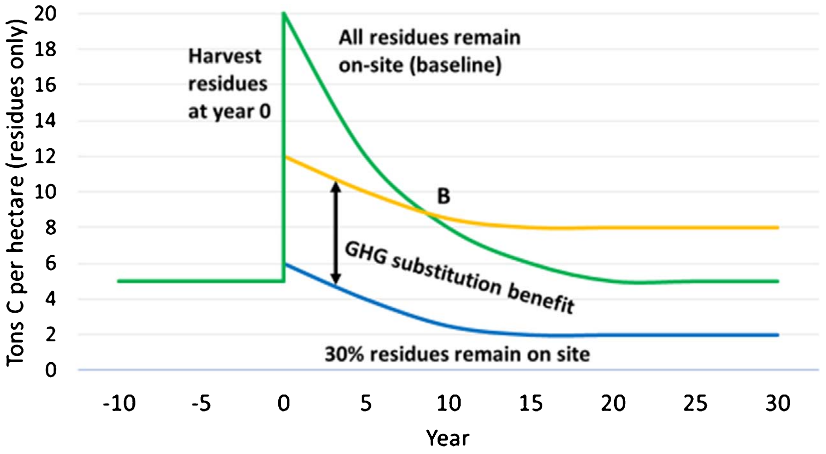


Figure 4. Hypothetical effect of using 70% of harvest residues from a southeast US forest for bioenergy, replacing coal used to generate electricity. 'GHG substitution benefit' represents the reduction in life cycle GHG emissions from using wood instead of coal, not counting the effect on net emissions of GHGs from residues. The net benefit of using residues for bioenergy and accounting for decomposition of residues that remain on site equals the baseline at point B, after which decreases in atmospheric GHGs occur. Only harvest residues in the forest ecosystem are shown. Note scale differences compared with figure 3.

If harvesting live trees for bioenergy, the loss of stored biomass has been considered a 'carbon debt' that needs to be re-payed, and the 'carbon payback period' is the time required to recover the CO_2 that is lost from the forest plus the net benefits of substituting wood for another fuel source (point A on figure 3) (Buchholz *et al* 2016). More importantly, net reductions in atmospheric CO_2 will only occur after reaching the time to carbon sequestration parity, which may take decades or centuries depending on initial biomass density, how much biomass is removed, and how fast the forest regrows. The time to carbon sequestration parity (point B on figure 3) refers to the point at which the accumulated net (or 'additional') GHG effect from using the wood for bioenergy equals the net GHG effect of the baseline, which is often a 'no-harvest' scenario that accounts for the continued growth if the forest had not been harvested (Ter-Mickaelian *et al* 2015).

Using wood residues (e.g. tops, stumps, branches) for bioenergy that would otherwise have been left to decompose (typical in the SE) or burned to reduce wildfire risk (typical in Canada) results in net emissions reductions over a shorter term, often less than 20 years (figure 4, Lamers *et al* 2014). On the other hand, if the wood residues would otherwise have been used in a long-lived product such as particle board, it could take decades for the use of this material for bioenergy to have a positive effect of reducing atmospheric CO_2. In such cases using the available biomass for products other than bioenergy, such as composite panels, may achieve greater climate mitigation benefits (Smyth *et al* 2014). In general, maximizing the proportion of harvested wood that goes into long lived products, and using only the remainder for bioenergy will increase mitigation benefits.

The land-use history of forests used for bioenergy also impacts the GHG benefit. There are significant differences among (1) establishing a plantation on nonforest land specifically for bioenergy (Amichev *et al* 2012); (2) increasing use of wood from existing plantations; and (3) converting unmanaged forests to intensify wood production. Converting nonforest land to forest increases the stock of carbon in biomass and likely soils, could have significant induced impacts on land used for other purposes such as crop production, and in some regions, has a strong and direct biophysical effect on climate. The growing biofuel market may also serve as an incentive for maintaining forest areas and/or increasing forest productivity, thus maintaining or enhancing the carbon sequestration and storage capacity of forests (Miner *et al* 2014). Changing the wood product mix to allocate more harvested wood to bioenergy without changing the rates of harvest will not affect carbon stocks on the land but will cause shifts in the emissions associated with displaced timber or other materials because of induced changes in supplies of products with different life cycle emissions.

Supply-chain emissions (figure 2) are highly variable, depending on the source of biofuel, transportation methods and distances, and how the biomass is converted to fuel. Combustion efficiencies of different fuels are also highly variable. It is important to consider which fossil energy sources will be reduced if bioenergy is increased, and account for the differences in emissions. Wood has a lower energy content than fossil fuels, and wood burning is generally associated with higher CO_2 emissions per unit of energy produced (Environmental Protection Agency 2014). For example, emissions of CO_2 per unit of energy produced by combusting wood is significantly more than coal and nearly twice the emissions from combusting natural gas (IPCC 2006).

Lastly, broader economic impacts of increasing bioenergy can significantly affect GHG emissions. For example, increasing harvest for bioenergy has impacts on traditional wood-using industries, timber prices, and land use, each having impacts on carbon storage and emissions. Generally, the demand and supply responses are difficult to predict because many factors outside the bioenergy domain must also be factored into the analysis (Abt *et al* 2012).

Properly constructed life cycle analysis (LCA) is critical to account for the energy inputs and carbon emissions or sinks for each product category and for comparing alternatives. Two LCAs are needed for bioenergy analyses to assess additionality. First, an assessment of the emissions associated with producing and using bioenergy, which will include silviculture operations, emissions associated with logging equipment, transportation of wood, and processing biomass into biofuel, as well as GHG emissions from biofuel combustion. Nakano *et al* (2016) provided estimates of the energy-related emissions associated with forestry activities for producing wood, from tree planting to transport of the harvested roundwood to the roadside. The second LCA is for the baseline scenario (i.e. fuel that is being displaced,) which includes accounting for similar energy inputs plus GHG emissions from combustion. The net effect of increasing bioenergy is the difference between the results of these two LCAs.

Case studies: GHG and climate effects of using wood for biofuel exports and local use

Recent studies employing a life-cycle approach have estimated effects on GHGs of exporting pellets to Europe or increasing domestic biofuel use, and the conditions under which increasing biofuels will have either favorable or unfavorable effects on net CO_2 emissions and other environmental impacts, over different time horizons. Several different models have been used in these studies, and though their accounting schemes and assumptions are different, there is sufficient information to highlight how results are affected by accounting practices, the circumstances under which there would be net increases or decreases in GHG emissions, and other effects on climate and ecosystems. The case studies we reviewed are summarized in the supplementary material available at stacks.iop.org/ERL/13/050201/mmedia, and a synthesis of findings presented in table 1.

Increasing use of sawmill residues will have short-term benefits and few if any long-term impacts, unless there were an alternate use of these residues for long-lived wood products that would have a larger GHG reduction benefit. The additional available supply of sawmill residues is very limited because most are already used as fuel or material for composite panels. Because this activity would only affect biomass that has already been removed from the forest under existing harvesting operations, there is no effect on land-use or other forest values such as biodiversity.

Increasing use of logging residues for biofuel that would have otherwise been burned in the forest has a short time to carbon parity, likely to be less than a decade. If the harvest residues would otherwise be left to decay in the forest then the time to carbon parity would be typically longer than a decade. But like sawmill residues, the supply of harvest residues is limited by the extent of current harvesting activities (up to about 20 million dry tons per year in the US according to US Department of Energy 2016). Unlike sawmill residues, there are likely to be long-term impacts on soil productivity if too little logging debris is left in the forest, and the magnitude and timing of benefits are strongly dependent on how the logging residues would have been treated

Table 1. Greenhouse gas and climate effects of using different wood biomass feedstocks from the southeast US for electricity generation[a].

Feedstock	Available supply	Impacts on net greenhouse gas emissions	Temporal effects on emissions	Additional and indirect effects
Sawmill residues	Limited—most already used for fuel by mills. Could increase if harvesting for other wood products increases.	Will reduce net emissions compared with alternative fuel if emissions from combustion and supply-chain emissions are low.	Emissions reductions occur in a few years; no long-term effects since harvesting occurs for other wood products.	Few other effects since using biomass that would otherwise be wasted. Mill residues used for other wood products could be reduced.
Logging residues	Limited—generally involves areas harvested for other products. Subject to sustainability guidelines on leaving residues on-site for other purposes.	Will reduce net emissions compared with alternative fuel if emissions from combustion and supply-chain emissions are low, and effects on soil C and post-harvest tree growth are low.	Net emissions reductions may occur in 20 years or less, depending on decay rates that would have occurred if residues were left in forest (figure 4), or if residues would have been burned on-site.	May affect site productivity if insufficient biomass left on site. May affect wildlife habitat. May help forest landowners retain forest as forest because of increased income. 20 years may be a long time if climate policies require reductions sooner.
Roundwood	Large because growth exceeds removals in many regions especially for hardwoods. Subject to sustainability guidelines and willingness of landowners to harvest.	Will increase net emissions in most cases because emissions from combustion plus supply-chain emissions plus loss of future forest growth and soil C is larger than displaced emissions from alternative fuel.	Over several decades to a century or more, or over multiple rotations, net emissions may be reduced instead of increased because of the cumulative effects from displaced emissions plus re-growth (figure 3).	Depends on source of roundwood. Other effects may be small if roundwood is low-grade wood associated with harvest for higher-value products. If forest is harvested specifically for bioenergy, then other effects may be large including albedo changes, impacts on forest retention, effects on wildlife, etc.

[a] Based on analyses by Brack (2017) and this review paper. Additional references and case studies described in supplemental material.

in the absence of increased use for biofuel. Logging residues are also highly valued for wildlife habitat and biodiversity, so increasing their use is likely to have ecological consequences that go well beyond soil productivity (Janowiak and Webster 2010, Venier *et al* 2014).

Unless derived from additional bioenergy plantations, increasing harvest of roundwood for bioenergy or pellet exports almost always increases net emissions of CO_2 compared to obtaining the same amount of energy from burning fossil fuels. Only after some time (decades or longer) will bioenergy use from wood reach 'carbon parity' after which point the bioenergy alternative reduces GHG emissions relative to the fossil fuel alternative. Results are sensitive to variables including source of feedstock, the alternative fate of the feedstock, time horizon of analysis, energy emissions associated with the supply chain and fuel substitution, and impacts on forest ecosystems. Energy emissions associated with the displaced fossil fuel must also be accounted for, and could be very large in remote areas or off-grid communities, potentially favoring a more localized source of non-fossil energy. Besides these factors, indirect effects may be considerable including induced land-use change, albedo and non-radiative effects of land-cover change on climate, and long-term impacts on soil productivity. Likewise, additional forest harvesting will have significant effects on many other values of forests depending on forest stand and landscape-scale characteristics (Turner 2010).

Discussion

The supply of roundwood in forests that is potentially available for increasing pellet exports is quite large (close to 100 million dry tons per year in the US; US Department of Energy 2016), but net emissions of GHGs from increasing harvest of roundwood are likely to increase for several decades if not longer because of emissions from harvest operations, loss of existing carbon stocks, and foregone growth of the harvested forests. Moreover, converting roundwood into long-lived wood products and using only harvest, milling and other residues for bioenergy is likely to have a much greater mitigation benefit than using roundwood as bioenergy feedstock (Smyth *et al* 2014). Over the longer term, reductions in emissions are possible from harvesting roundwood for bioenergy because of the cumulative effects of displacement of fossil fuels and forest regrowth, especially if multiple short rotations are possible as in the case of fast-growing SE forests. But harvesting roundwood has many other impacts on ecosystems that will also need to be considered and these will likely reduce supplies compared with what is technically feasible.

Additional supplies of roundwood are also restricted because not all landowners are willing to harvest their trees. A study commissioned by the UK Department of Energy and Climate Change assessed the likelihood that the most intensive biofuel supply scenarios might happen now or in the future, based on a literature review and a stakeholder survey

(Ricardo Energy and Environment 2016). Only a few of the high supply scenarios were considered moderately likely but of limited scale based on stakeholder experience: increased removal of coarse or fine forest residues; additional wood harvest from intensively-managed pine plantations; and additional wood from conversion of unmanaged forest to managed forest near pellet plants.

Increasing use of all types of wood biofuel feedstocks will affect supply and price of other wood products, and may induce land-use changes as well as change harvest rates for long-lived wood products, both of which will affect the net carbon balance. Increased use of logging residues and increased harvest of roundwood will change forest albedo, generally causing a cooling effect that would partially offset the warming effect of increases in net CO_2 emissions. However, the effect of albedo on climate may be significantly modified by locally important non-radiative effects (Bright *et al* 2017).

In all cases, we strongly recommend performing an assessment of proposed activities that includes a full accounting of effects on the forest ecosystem, the supply chain, fuel substitution, and indirect effects, with consideration of the different sources of biomass, the time horizon of analysis, and type of fossil fuel that is displaced. The assessment should compare the emissions associated with the proposed activity against the emissions associated with the baseline. Life-cycle analysis using appropriate emissions or displacement factors, and a landscape-specific assessment of transportation, is a recommended approach (Smyth *et al* 2017).

Our analysis did not consider the 'carbon capture and storage' element of BECCS. By capturing and storing emitted CO_2 from electricity generation before it reaches the atmosphere, the benefits of fuel substitution would be significantly greater and would likely greatly reduce the time to reach carbon sequestration parity.

International accounting for bioenergy impacts on GHGs is based on IPCC GHG inventory reporting guidelines, which separate reporting for substitution effects and land effects to the energy and land-use sectors, respectively. This has led to the erroneous concept of 'carbon neutrality' of bioenergy use because the emissions associated with biomass burning are reported in the land sector. As a result, policy makers erroneously perceive the mitigation benefit of bioenergy use as only the reduction in fossil fuel emissions while ignoring the increased emissions in the land sector. Mitigation benefits of bioenergy use cannot be quantified from emissions reported in the energy sector alone. Only when the combined changes in emissions in both the energy and land sector are taken into consideration, will the real impact on the atmosphere be understood. The continuing policy discussion regarding the Renewable Energy Directive of the European Union is an example where the adoption of over-simplified assumptions about effects of bioenergy on climate could lead to undesired outcomes in a global context.

Conclusions and research needs

Our main conclusions are:

1. Because biomass is less energy intensive than fossil fuels, the use of biomass to substitute for fossil fuels will nearly always initially increase emissions to the atmosphere.
2. Increasing use of logging and mill residues that would otherwise decompose or burn without energy capture will typically have a net benefit in less than 20 years; however, there is a limited supply of residues that is unlikely to meet projected increases in demand.
3. Harvesting live trees for pellets or other biofuel, regardless of quality, will initially increase net GHG emissions because of emissions associated with harvesting and lost forest productivity. It will take decades to centuries to reach the point at which there will be net reductions in GHG emissions compared to burning fossil fuels.
4. There are many economic co-effects of increasing use of wood for bioenergy that may be significant for policy formulation: increased prices for other wood products; increased income for landowners and greater likelihood of 'forests remaining forests'; and reductions in cropland areas and food production.
5. Biomass supplies are finite and proposed large increases in biomass uses for energy may reduce the availability of wood for use in long-lived wood products which keep carbon out of the atmosphere for longer and can achieve greater substitution benefits than bioenergy uses.
6. Changes in biodiversity and other ecosystem attributes may be strongly affected by increasing biofuel production, depending on source of material. Harvesting additional roundwood and increasing removal of logging debris could have significant landscape-scale impacts.
7. The notion of 'carbon neutrality' is an easy-to-grasp concept that simplifies accounting and monitoring, but does not accurately represent the impact of substituting biofuel for fossil fuel except in very specific circumstances and timeframes. When all of the main impacts are counted, the net reduction in emissions to the atmosphere is almost always considerably less than implied by a 'carbon neutrality' accounting assumption. Not only does carbon neutrality accounting overestimate atmospheric benefits currently, the concept would likely underestimate benefits with BECCS.

It is important to maintain a long-term perspective and develop projections of 100 years or more. Not only does this allow many regions to experience multiple harvesting rotations and accumulated emissions reductions from forest growth and effective use of wood products, it fosters the notion of retaining forests as forests rather than being diverted to other land uses that store significantly less carbon. There may be a tangible benefit to keeping fossil carbon out of the biosphere and leaving it securely stored underground where it does not have to be managed in some way to mitigate climate change.

It would benefit the science and policy communities to have user-friendly analysis tools with full capability to perform detailed life-cycle and landscape-specific analyses for both the baseline and the mitigation options. Users should be able to define wide boundaries of analysis since different sectors are influential on the assessment of net benefits on climate, environment, and economics, all of which are important to consider in policy formulation.

The scientific and policy communities should move beyond comparing lifecycle GHG emissions from woody bioenergy with emissions from fossil fuels by considering a wide range of scenarios that allow society to meet the top-line climate policy goals of limiting warming to 1.5 or 2.0 °C. In this broader context, being 'better than fossil fuels' is not necessarily good enough, especially on the decadal to century time horizons considered here.

Existing analyses of this broader issue have major limitations. Scenarios presented in the Working Group 3 contribution to the Intergovernmental Panel on Climate Change Fifth Assessment Report (AR5) use models that focus primarily on the energy sector and in many cases treat the land sector cursorily. They achieve atmospheric CO_2 removal largely through massive deployment of BECCS, a technology that has not been demonstrated at the scale needed. The various models used to generate these scenarios in AR5 produce highly divergent projections of future land use, in both baseline and mitigation scenarios (reference: AR5, working group 3, chapter 6, section 6.3.5). This reflects differing assumptions and/or model formulations, and demonstrates a lack of consensus on the role of bioenergy and land generally in climate mitigation.

Finally, it is not clear how CO_2 removal and net negative emissions would be achieved and what role forest bioenergy would play if the above-mentioned limitations, and others, were addressed. A re-visitation of the role of land and the constraints on biomass availability in meeting top-line climate policy goals is urgently needed.

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Not carbon neutral: Assessing the net emissions impact of residues burned for bioenergy

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Abstract

Climate mitigation requires emissions to peak then decline within two decades, but many mitigation models include 100 EJ or more of bioenergy, ignoring emissions from biomass oxidation. Treatment of bioenergy as 'low carbon' or carbon neutral often assumes fuels are agricultural or forestry residues that will decompose and emit CO_2 if not burned for energy. However, for 'low carbon' assumptions about residues to be reasonable, two conditions must be met: biomass must genuinely be material left over from some other process; and cumulative net emissions, the additional CO_2 emitted by burning biomass compared to its alternative fate, must be low or negligible in a timeframe meaningful for climate mitigation. This study assesses biomass use and net emissions from the US bioenergy and wood pellet manufacturing sectors. It defines the ratio of cumulative net emissions to combustion, manufacturing and transport emissions as the net emissions impact (NEI), and evaluates the NEI at year 10 and beyond for a variety of scenarios. The analysis indicates the US industrial bioenergy sector mostly burns black liquor and has an NEI of 20% at year 10, while the NEI for plants burning forest residues ranges from 41%–95%. Wood pellets have a NEI of 55%–79% at year 10, with net CO_2 emissions of 14–20 tonnes for every tonne of pellets; by year 40, the NEI is 26%–54%. Net emissions may be ten times higher at year 40 if whole trees are harvested for feedstock. Projected global pellet use would generate around 1% of world bioenergy with cumulative net emissions of 2 Gt of CO_2 by 2050. Using the NEI to weight biogenic CO_2 for inclusion in carbon trading programs and to qualify bioenergy for renewable energy subsidies would reduce emissions more effectively than the current assumption of carbon neutrality.

Introduction

Meeting the Paris Agreement goal of limiting global temperature increase will require fast deployment of zero-emissions energy and greatly increased carbon sequestration. In developing pathways to limit atmospheric CO_2, many climate mitigation models include a doubling or more of bioenergy to at least 100 EJ in the coming decades [1–3], with much of the fuel assumed to come from forestry and agricultural residues [3]. Though oxidizing 100 EJ of biomass would emit about 9 Gt of CO_2 each year, most mitigation models assign bioenergy zero net emissions.

The assumption of bioenergy carbon neutrality underpins many renewable energy investments, including in the EU, UK and Asia where dried wood pellets are imported as a replacement for coal. Such policies, and the lucrative subsidies they provide, have driven rapid growth in the wood pellet sector in North America, with US exports growing from less than 0.1 Mt in 2008 [4] to 4.9 Mt in 2016 [5]. Canadian pellet exports increased 46% from 2015–2016 [6], and US pellet exports are projected to double or triple from 2016 levels by 2025 [5, 7].

Biomass power plants tend to emit more CO_2 than fossil fueled plants per MWh, and as shown by a number of studies, net emissions from bioenergy can exceed emissions from fossil fuels for decades [8–12]. Nevertheless, some studies conclude rapid carbon benefits from burning wood pellets by employing various assumptions: that forest planting will increase in response to demand for wood [13]; that replanting occurs immediately after harvest [14]; or that forest growth elsewhere compensates for emissions from harvesting and combusting trees [15, 16] (for a review, see Ter-Mikaelian *et al* 2015 [17]). Some discussions of bioenergy in mitigation modeling include similar assumptions that burning 'sustainable,' 'optimal' [1, 3] or 'surplus' [18] forest wood can reduce net CO_2 emissions as long as forest carbon stocks are increasing. Such assumptions often disregard the role of the forest carbon sink, thus the controversy around bioenergy carbon accounting continues.

However, on one aspect of bioenergy carbon accounting there is wide agreement: that when biomass is sourced from residues from forestry, wood products manufacturing, or agriculture, net carbon emissions are properly assessed as the difference between emissions from their use as fuel (which can include emissions from fuel manufacturing and transport), and emissions from an alternative fate, such as leaving material onsite to decompose or burning it without energy recovery [8–10, 12 19–23].

Studies using this approach generally conclude net bioenergy emissions are not zero over varying periods of time. Nonetheless, many policies still treat bioenergy as having zero or negligible emissions. European Commission guidance for the EU carbon trading program explains bioenergy emissions should be 'taken to be zero,' and that wood pellets consist of 'processing residues from forest based industries' [24]. The IPCC acknowledges harvesting trees for fuel can increase cumulative emissions for years to centuries, but concludes that 'agricultural and forestry residues can provide low-carbon and low-cost feedstock for bioenergy' [3]. The IPCC renewable energy report identifies potential for 100 EJ of bioenergy specifically from residues [18] and does not discuss potential emissions.

For the assumption that residues have negligible net emissions to be reasonable, at least two conditions must be met. First, biomass classified as residues must actually be residues—that is, materials generated by some other process, where the alternative fate is decomposition or burning without energy recovery. Second, net emissions from bioenergy, that is, the cumulative additional CO_2 emitted from processing and burning biomass versus from an alternative fate, must be low, if not negligible, within a timeframe meaningful for climate mitigation.

What should 'low net emissions in a meaningful timeframe' mean? Most scenarios for climate change mitigation that constrain temperature rise consistent with Paris Agreement goals require emissions to peak between 2020 and 2030 and decline to less than half 2010 levels by 2050 [25], with negative emissions shortly thereafter. Actions that reduce or end emissions in the next ten years are thus essential, given that elevated CO_2 is already driving essentially irreversible polar ice loss, permafrost melting, and ocean acidification, along with thermal sea-level rise, which has been shown to respond to temperature changes from short-lived climate pollutants in a ten-year timeframe [26].

Here, 'low net emissions' from bioenergy implies a comparison to gross or 'direct' emissions from manufacturing and burning biomass. This study uses a simple model to calculate a new metric, the 'net emissions impact' (NEI), which is the ratio of cumulative net emissions to direct emissions from burning residues for energy. The NEI expresses the proportion of direct CO_2 emissions that contributes an additional warming effect over a fifty-year period. Fuel and feedstock use, net emissions and the NEI are calculated for three main case studies: the existing US bioenergy sector, new wood-burning plants using chipped wood, and wood pellets that are exported to the EU to be burned as a replacement for coal.

Approach

Built in Excel, the model calculates cumulative net emissions as cumulative direct emissions (CO_2 from combustion for energy plus CO_2 from harvesting, producing, and transporting biomass, or 'HPT emissions'), minus cumulative counterfactual emissions (what emissions would be if the biomass were left in the field to decompose or were burned without energy recovery). The net emissions impact (NEI) is the ratio of cumulative net emissions to cumulative direct emissions.

HPT emissions are calculated as explained below. Direct combustion emissions are calculated as joules of heat input for each fuel multiplied by fuel-specific CO_2 emission factors [27] (non-CO_2 greenhouse gas emissions are not included in this version of the model). The spreadsheet sums cumulative counterfactual emissions from biomass collected in each year in columns, then sums across columns to calculate cumulative emissions by each year from all biomass collections up to and including that year.

Counterfactual carbon emissions (with conversion to CO_2 at the last step) are calculated as:

$$\mathrm{PE}'(t) = 1 - (e^{-k' t}) \tag{1}$$

$$\mathrm{cE}'(t) = \mathrm{BC}' * \mathrm{PE}'(t) \tag{2}$$

$$\mathrm{CE}(t) = \sum_{1}^{t} \mathrm{cE}'(t) \tag{3}$$

where

$\mathrm{PE}'(t)$ = proportion of carbon from biomass collected in a given year that has been emitted by year t

k' = rate-constant for decomposition of biomass collected in a given year

$\mathrm{cE}'(t)$ = carbon from biomass collected in a given year that has been emitted by year t

BC' = carbon content of biomass collected in a given year

$\mathrm{CE}(t)$ = carbon emitted by year t from biomass collected in all years

Table 1. Model inputs for biomass burned for energy in the US. Heat input is average summed value per year for the industrial and non-industrial sectors, 2001–2016. See text for details.

Fuel	GJ yr^{-1}	CO_2 EF	HPT factor	Alternative fate	k
Agricultural biomass	31.7	0.101	7.5%	Decomposition	0.65
This constitutes a small percentage of biomass burned in the US, but can represent a large variety of materials, including crop stover, nut hulls, and sugarcane bagasse. The *k*-constant produces a half-life for residues of one year.					
Black liquor	800.5	0.087	—	Burn w/o ER	—
This is a high moisture content material left residue of pulp- and paper-making. The model assumes no net emissions from burning it for energy.					
Other biomass solids	18.3	0.101	4%	Burn w/o ER	—
EIA does not specify what these materials are. While there are likely processing costs, the model assumes a minimal 4% HPT emissions to be conservative.					
Sludge waste	6.3	0.072	—	Burn w/o ER	—
Sludge waste is another residue of pulp- and paper-making.					
Wood liquor	11.3	0.072	—	Burn w/o ER	—
This material is related to black liquor.					
Wood solids	548.8	0.081	4%	Decomposition	0.083
This includes forestry wood, mill residues, urban tree trimmings, and construction and demolition wood. For consistency with wood pellet scenarios below, the *k*-constant is 0.083.					

To evaluate emissions from the US bioenergy industry, the model uses bioenergy data from the Energy Information Administration (EIA) for 2001–2016 [28] and CO_2 combustion emission factors used by the US Environmental Protection Agency (EPA) for power sector modeling (original units short tons mmbtu^{-1}; converted here to metric tonnes GJ^{-1}) [27]. Alternative fate emissions are calculated using *k*-constants particular to each fuel (table 1).

The model includes HPT emissions for forestry residues and other wood as equivalent to 4% of the carbon content of green chips, based on Domke *et al* (2012) and reviews of other studies [9, 29]. The model assumes the alternative fate for agricultural residues is decomposition, as crop burning occurs on less than 1% of agricultural acres in the US [30]. Selecting an HPT factor for agricultural residues is not straightforward, as emissions from harvest, transport, shredding, baling, and sometimes pelletizing can be significant. Depending on how system boundaries are drawn, emissions from crop cultivation, including N_2O from fertilizers, can be ascribed to residues [31]. Storage also imposes lifecycle emissions because agricultural materials can only be collected at fixed intervals. Most importantly, removing agricultural residues can deplete soil carbon [32]; some estimates of total HPT emissions including soil C loss sum to more than 100% of fuel carbon content [31]. This model used an HPT factor of 7.5% for agricultural residues based solely on harvest and transport estimates for corn stover in Whitman *et al* (2011) and did not include soil carbon impacts because this factor was not included for forestry residues. As agricultural residues provided a small percentage of total fuels, the choice of HPT factor had only a trace effect, but any study of large-scale use of agricultural residues should include soil carbon effects.

Data on wood use by the US pellet manufacturing sector was obtained from the forest-industry tracking company Forisk [33]. Five pellet scenarios were modeled to examine how the *k*-constant and changing use through time affect net emissions (details in table 2). Scenarios 1–4 estimated HPT emissions (which include harvesting, transport to plant, debarking, chipping, pulverization, pellet extrusion, drying, and oversea transport) as 322 kg CO_2 per tonne of pellets, following Jonker *et al* [15], similar to an estimate by Dwivedi *et al* [14]. Also following Jonker *et al* the model assumed that pellet drying consumes 0.51 green tonnes of residues per tonne of pellets, an estimate confirmed by checking the dryer fuel to pellet production ratio in permits for two industrial-scale plants in the US [34, 35]. The model assumed residues burned to dry pellets would decompose with a *k*-constant of 0.15 if not burned for energy. Facilities that use fossil fuels to dry pellets have much higher HPT emissions [36], but this effect was not included.

Results and discussion

Sources of biomass burned for heat and power in the US

The US bioenergy sector can be divided into industrial plants, which mostly burn black liquor and wood to generate onsite heat and power for paper and wood products manufacturing, and non-industrial plants, which mostly burn wood to generate power for the electrical grid (figure 1). The industrial sector mostly utilizes biomass for heat; on average, just 21% of fuel energy was used for electricity generation from 2001–2016, while the smaller non-industrial sector allocated 87% of fuel energy to electricity generation [28].

Combined, industrial and non-industrial facilities burning biomass generated less than 1% of total electricity in the US in 2016 [37]. However, average annual generation over a three-year period in the non-industrial sector increased 62% from 2001–2003 to 2014–2016, while electricity generation stayed relatively constant in the industrial sector.

Table 2. Five scenarios for wood pellet manufacturing and use.

Scenario	10 years (2020)			25 years (2035)			40 years (2050)		
	Direct CO_2 (t)	Net CO_2 (t)	NEI	Direct CO_2 (t)	Net CO_2 (t)	NEI	Direct CO_2 (t)	Net CO_2 (t)	NEI
1: 1 tonne pellets yr^{-1}, $k = 0.15$	25	14	55%	62	21	34%	99	26	26%
2: 1 tonne pellets yr^{-1}, $k = 0.03$	25	20	79%	62	40	64%	99	54	54%
	Direct CO_2 (Gt)	Net CO_2 (Gt)	NEI	Direct CO_2 (Gt)	Net CO_2 (Gt)	NEI	Direct CO_2 (Gt)	Net CO_2 (Gt)	NEI
3: Actual US exports to year 7 (2017); modeled 15% yr^{-1} increase to 12.8 Mt yr^{-1} at year 15 (2025); continue at that level; $k = 0.083$	0.09	0.07	73%	0.53	0.28	53%	1.01	0.40	39%
4: Like Scenario 4, but cease use at year 20 (2030); $k = 0.083$	0.09	0.07	73%	0.37	0.16	43%	0.37	0.08	21%
5: Actual global demand of 13 Mt tonne pellets yr^{-1}, increasing to 28.2 Mt at yr 6 (2016); modeled increase to 66.4 Mt yr^{-1} at year 15 (2025); continue at that level; $k = 0.083$	0.63	0.44	71%	2.92	1.48	51%	5.35	1.99	32%

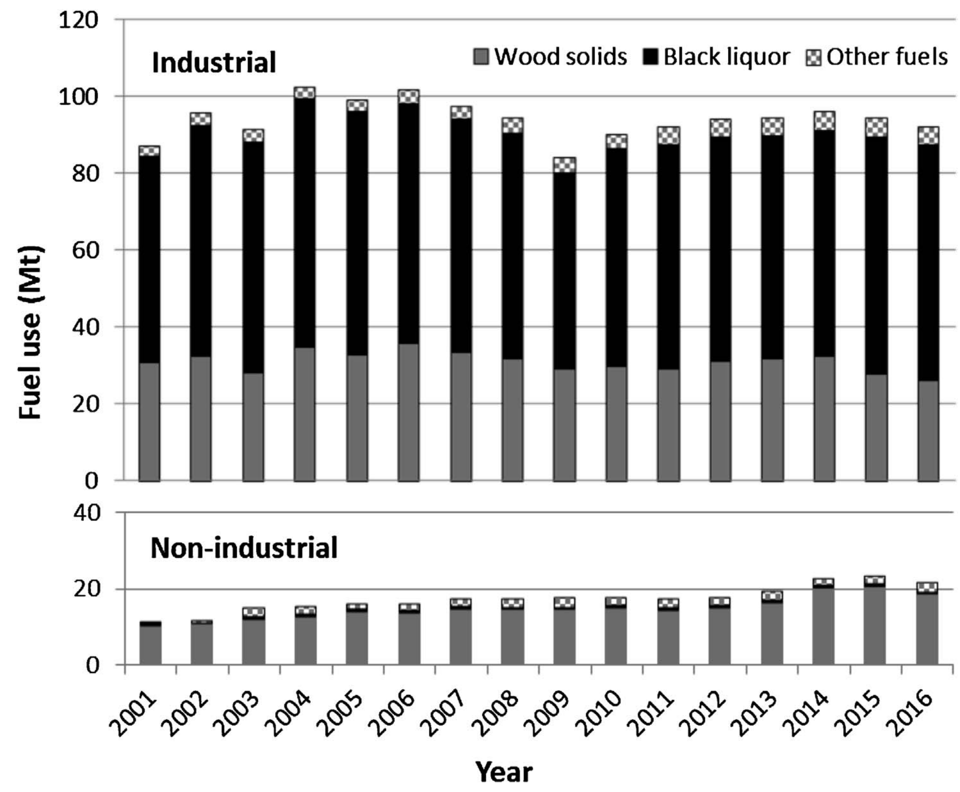

Figure 1. Fuels burned by the US industrial and non-industrial bioenergy sectors, 2001–2016 [28]. Wood burning for electricity generation in the non-industrial sector increased by about 60% from the beginning of the period.

The dominance of black liquor as fuel for industrial bioenergy means that many facilities at least partially meet the first of the low carbon conditions—that fuels genuinely be residues of some other process. However, the provenance is less clear for wood burned by the industrial and non-industrial sectors, which totaled 45 Mt (green) in 2016 [28]. Forisk estimates wood use by US biomass facilities at 35 Mt (green), a figure that omits certain large industrial users reported by the EIA, and reported as of late 2016 that operating and under-construction plants were burning pulpwood (7.4%); 'dirty chips/forest residues' (49.6%); urban wood (19.4%); and mill residues (23%) [33].

Residues appear to provide the most fuel for US bioenergy sector, but since there is no set definition for 'residues,' it is not possible to know if this wood is truly the product of some other process. Conservative definitions for forest residues are found in Domke *et al*: the 'tip, portion of the stem above the merchantable bole, and all branches, and excluding foliage'

Figure 2. Trucks lined up waiting to deliver pellet feedstock to North Carolina plant owned by Enviva, the largest US pellet manufacturer. Much of the wood is tree trunks, not tops and limbs (Photo: Dogwood Alliance).

[20], and Laganière *et al*: 'all woody debris generated in harvest operations for traditional wood products (e.g. branches, tree tops, bark), excluding stumps and downed nonmerchantable trees' [12]. However, practices on the ground vary. For example, Dominion Energy Resources in Virginia, which re-fired three coal plants with wood and has a total bioenergy capacity of over 250 MW, wrote to the EPA that waste wood 'to us' means 'forest materials including residues (tree tops, non-merchantable sections of stem, branches, and bark), small trees and other low value materials' [38]. Some facilities clearly burn whole trees for fuel, like a new 70 MW plant in Berlin, New Hampshire that burns 113 tonnes of 'clean wood chips' per hour, including 'whole tree chips' [39] (Forisk lists this plant as burning 408 000 green tonnes of hardwood pulpwood and 408 000 green tonnes of residues per year [33]). The evidence for use of whole trees as fuel suggests that many facilities do not burn materials that meet conservative definitions of residues (i.e. branches, tree-tops, and bark left over from other harvesting).

Sources of wood utilized by the US pellet manufacturing industry

As of late 2016, annual production capacity at operating and under-construction wood pellet manufacturing facilities in the US was 13.2 Mt, requiring about 28.6 Mt of green wood as feedstock [33], though not all plants produced at capacity. Pellet companies emphasize use of residues, downplaying the use of roundwood as feedstock [40]. However, exported wood pellets must meet specifications including restrictions on bark content [41], thus there is a limit on the amount of low-diameter branches and tops that can be used. Accordingly, industry data indicate about 56% of pellet feedstock is supplied from pulpwood (41% from softwood, 14% from hardwood); 42% from mill residues, 1% from urban wood; and just 1% from logging residues [33]. Investigations of pellet feedstock at some large US mills have confirmed that a significant portion of feedstock is bolewood (figure 2). The feedstock supply from small pellet producers in the Northeastern US also appears to avoid residues; a study of nine pellet mills in Maine found only 2% came from tops and limbs, with the remainder classified as pulpwood or small diameter trees [42].

Similarly, company-supplied data on sources of wood pellets burned in the UK indicate that the majority of US pellets burned by the coal- and wood-fired Drax power station in 2015 was sourced from logs that 'formed part of the trunk of a tree which grew for at least ten years' from harvesting that was a 'mix of clearfell and thinning' [43]. While mill residues currently constitute a proportion of pellet feedstock in the US, they will not supply a meaningful amount for future capacity, because supplies are limited [44]. The dominance of pulpwood and the documented use of bolewood thus indicate that pellets often fail to meet the first condition for low carbon residues, that feedstocks genuinely be residues that if not collected would otherwise decompose or be burned without energy recovery.

Emissions from the US biomass industry

Emissions modeling examined the industrial and non-industrial bioenergy sectors separately. The model estimated cumulative direct CO_2 emissions from industrial facilities at 1135 Mt at year 10. However, because black liquor and other wastes provide a large proportion of industrial sector biomass, and the assumed alternate fate for these materials is combustion without energy recovery, cumulative net emissions are 224 Mt, for an NEI of 20% (figure 3(*a*)). Cumulative direct emissions for the smaller non-industrial sector are 208 Mt at year 10, but because the majority of fuel for this sector is wood and the weighted *k*-constant is lower, cumulative net emissions are 120 Mt and the NEI is 58% at year 10 (figure 3(*b*)). Both sectors show cumulative net emissions still increasing in the 40–50 year period, though less steeply than in the initial decades.

This analysis calculates emissions at the sector level as if all units initiated operation at the same time, while ideally, sector-level accounting would consider how long each facility has been operating. While inadequate data render this impractical, in general, the industrial sector has shrunk since the 1980s [45] and the present day NEI should be shifted toward the right (lower), as facilities are on average older. In contrast,

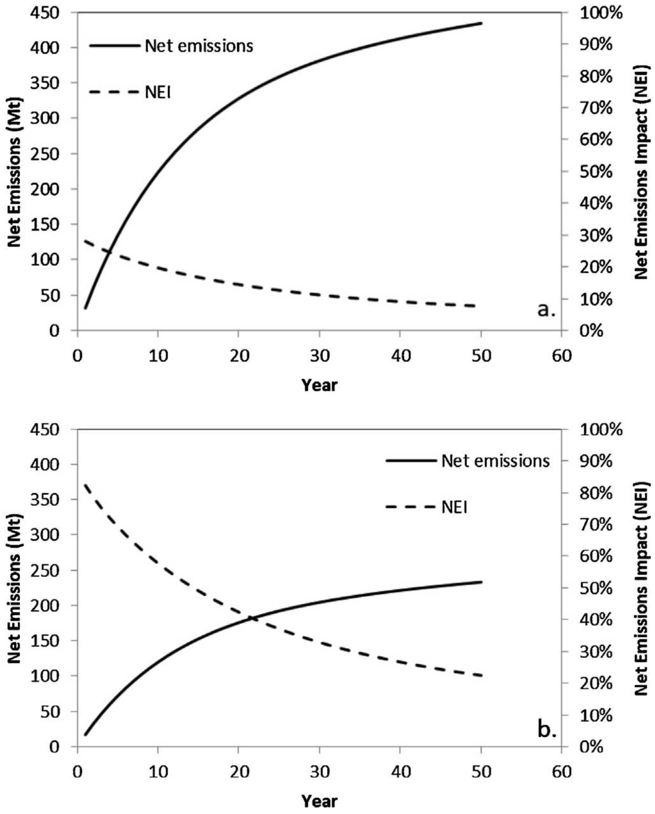

Figure 3. Cumulative net emissions and the NEI for the industrial (*a*) and non-industrial (*b*) bioenergy sectors over a 50 year timeframe, estimated using the average fuel mix for 2001–2016. High use of black liquor as fuel reduces the NEI for the industrial sector, while greater reliance on wood increases it for the non-industrial sector.

new construction of wood burning power plants and coal-to-wood conversions in the non-industrial sector since the early 2000s (figure 1) [28] means the average age of the sector is younger, shifting the NEI to the left (higher).

Refined emissions estimates for new wood-burning power plants

The industry-level analysis assumed an average *k*-constant for wood of 0.083, but plotting the NEI against the full range of *k*-constants (figure 4) demonstrates that the NEI for facilities burning forest residues exceeds 70% at year 10 for all decomposition constants lower than 0.07, and exceeds 40% at year 10 for the full range of decomposition constants for North American forests [46]. This conclusion is likely valid even if the alternative fate for wood is not being left in the forest to decompose, but disposal in a landfill. Conversion of carbon in landfilled wood to landfill gas (carbon dioxide and methane) is generally less than 3% after landfilling [47], thus even taking methane's global warming potential into account, the NEI from burning wood that would otherwise be landfilled is greater than 40% at year 10.

On a practical level, estimating stack emissions from a biomass power plant is easy, but estimating net emissions can be difficult, because the *k*-constant for wood can vary [48, 49]. One solution is to 'bracket' likely net emissions using a range of decomposition constants to estimate the NEI. Since burning a tonne of green wood emits about one tonne of CO_2, yearly direct emissions assuming a 4% HPT adjustment are about 1.04 tonnes per tonne of fuel, and cumulative direct emissions at year 10 are 10.4 tonnes. Taking a biomass facility located in the US southeast as an example, average decomposition constants for southeastern hardwoods (0.082) and softwoods (0.057) [46] translate to values of 67% and 75% on the ten year NEI curve; multiplying these NEI values by direct emissions gives cumulative net emissions of 6.97–7.80 tonnes of CO_2 at year 10 for each tonne of wood burned at such a facility. This approach to bracketing emissions could have policy applications. For instance, using the NEI to estimate net biogenic emissions could help integrate biomass power plants into carbon trading and carbon tax programs, as well as qualify bioenergy for renewable energy subsidies.

Emissions from wood pellets manufactured from residues

Emissions estimates for pellets calculated by the model certainly underestimate actual CO_2 impacts because tree boles constitute a large proportion of pellet feedstock, and it is unlikely that the true alternative fate for these materials is to be left onsite to decompose. However, calculating emissions as if claims about use of residues [40] were fully accurate can establish one type of 'best case' scenario for pellet emissions. Modeled

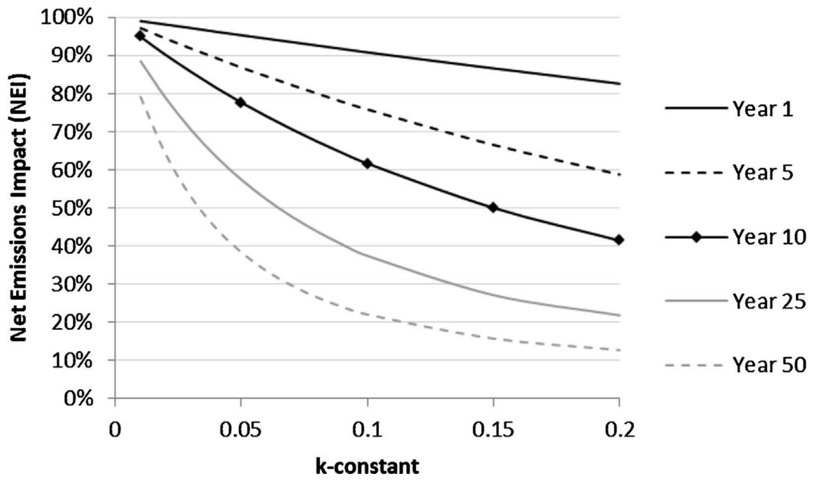

Figure 4. The NEI as a function of the *k*-constant at different points in time, assuming a 4% HPT adjustment. The NEI at year 10 is always greater than 40%, even when decomposition is assumed to be rapid.

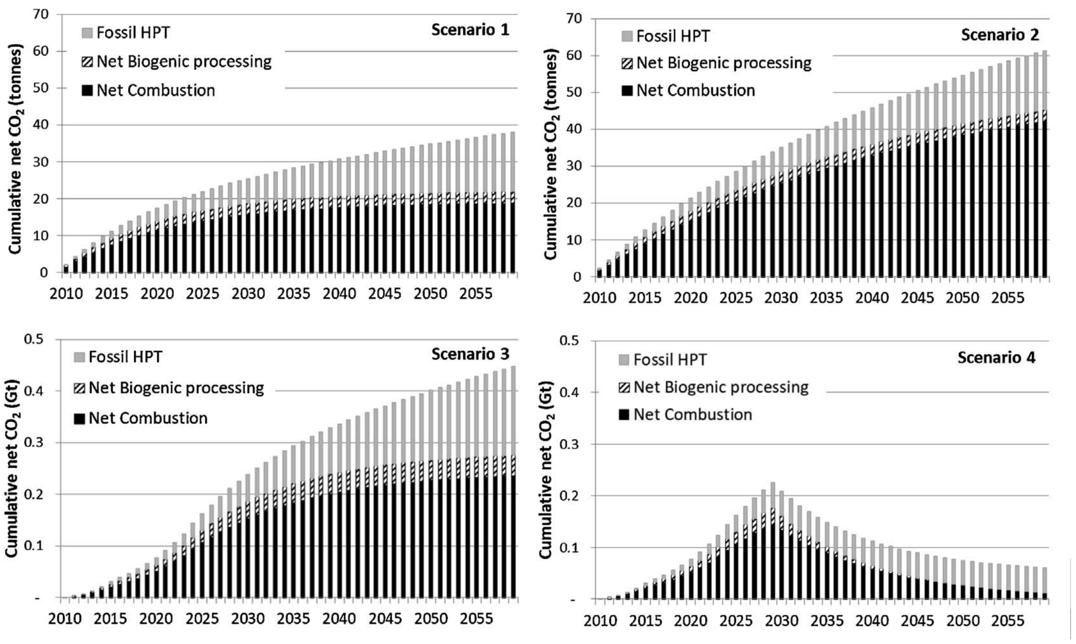

Figure 5. Cumulative net emissions for wood pellet scenarios 1–4 (details provided in table 2).

scenarios 1 and 2 estimate emissions from producing and burning one tonne of pellets per year from roundwood that is assumed to otherwise decompose onsite (figure 5 and table 2), illustrating the importance of the *k*-constant for net emissions. Even assuming very rapid decomposition ($k = 0.15$) as the counterfactual, the NEI for Scenario 1 is 55% at year 10. Scenario 2 employs a low *k*-constant (0.03) representing slower decomposition in a cool climate [11] such as Canada, and has an NEI of 79% at year 10; by year 25, cumulative net emissions are 40 tonnes CO_2 per tonne of pellet capacity, nearly double those of Scenario 1. Thus for both scenarios, simply counting cumulative direct emissions at year 10 would provide a closer representation of the emissions impact than characterizing pellets as 'carbon neutral,' as is current practice.

Scenarios 3 and 4 estimate net emissions from actual US pellet exports 2010–2016 [4, 5, 50, 51] followed by an increase to 12.8 Mt in 2024, commensurate with US exports meeting half of predicted short-term global demand for utility and industrial-use wood pellets by 2025 [5, 7]. These scenarios use a *k*-constant of 0.083, following a UK government-commissioned study on lifecycle impacts of wood pellets [11] that used values from a study of forest wood decay in North Carolina [52]. Accelerating use in the first part of scenario 3 elevates the NEI because decomposition emissions do not come into equilibrium with combustion emissions while pellet use keeps increasing. The NEI is 73% at year 10, 39% at year 40 and 34% at year 50. Scenario 4, where pellet use is terminated at year 20 (2030), has an NEI of 43% at year

25, because cumulative decomposition emissions of the counterfactual still have not caught up to combustion emissions from the early years of the scenario. This scenario shows a carbon benefit in terms of reduced emissions over time, but it requires actually stopping use of the fuel for this to occur.

Scenario 5 (shown in table 2 but not figure 5) uses actual data on global pellet use for 2010–2016, then projects growth to 66.4 Mt in 2025 [53], after which the model assumes demand is flat. It assumes not all pellets are manufactured in North America, thus HPT emissions are reduced by 15% to reflect shorter transport distances. With a pellet energy content of 17.5 MJ kg^{-1} [54], peak use of 66.4 Mt yr^{-1} represents 1.16 EJ annually, or just over 1% of the 100 EJ of new bioenergy projected to play a role in some mitigation models [1–3]. By year 40 (2050), cumulative net emissions are 1.99 Gt and are growing at 30 Mt per year.

The pellet scenarios demonstrate that fossil HPT emissions increase continuously with pellet use and represent a substantial 'non-vanishing' [25] fraction of net emissions. In reality, the model probably undercounts HPT emissions because it does not include releases of nitrous oxide emissions from fertilizer used on tree plantations [55] or methane emissions from wood chip piles [56] and finished pellets [36, 57]. Buildup of methane and other hazardous gases during transport and storage [58] is of concern to the wood pellet industry [59], and has the potential to add significantly to lifecycle greenhouse gas emissions [36]. The model also omits combustion emissions of black carbon, a significant climate forcer [60].

Most importantly, calculating net emissions from wood pellets as if feedstocks are derived from forest residues underestimates emissions because a large proportion of pellets are made from trees, not residues [41 61]. For instance, Stephenson and McCay (2014) [11] found net emissions were 10–12 times higher at year 40 when native hardwood trees are harvested for fuel, a practice that has been well documented in the US south [33, 41, 62, 63].

Conclusions

For bioenergy to offer genuine climate mitigation, it is essential to move beyond the assumption of instantaneous carbon neutrality. The NEI approach provides a simple means to estimate net bioenergy emissions over time, albeit one that tends to underestimate actual impacts. The model finds that for plants burning locally sourced wood residues, from 41% (extremely rapid decomposition) to 95% (very slow decomposition) of cumulative direct emissions should be counted as contributing to atmospheric carbon loading by year 10. Even by year 50 and beyond, the model shows that net emissions are a significant proportion of direct emissions for many fuels. Similarly, the model concludes that for wood pellets manufactured from residues in in the US and shipped overseas, even a rapid decomposition counterfactual produces an NEI of 55% at year 10, while a slow decomposition counterfactual produces an NEI of 79%. By year 40, net emissions still represent 25% to more than 50% of direct emissions. Scenarios that increase the amount of biomass burned each year, as is currently occurring in the EU, have even larger net emissions impacts.

Models like this have their critics. The IPCC warns that using a 'simple sum of the net CO_2 fluxes over time' to highlight the 'skewed time distribution between sources and sinks,' is probably insufficient to understand the climate implications of bioenergy, which instead requires models that include temperature effects and climate consequences [3]. Bioenergy advocates have seized on models that emphasize the importance of cumulative emissions for warming, pointing out that bioenergy can reduce carbon impacts over time compared to fossil fuels [23], though they say little about carbon impacts when bioenergy displaces zero-emissions technologies.

However, since the IPCC's call for more complex bioenergy modeling was published in 2014, the intensity of the climate crisis has deepened; in the US, legislation has been enacted that compels the EPA to treat bioenergy as carbon neutral [64]; and combustion of forest wood by the EU, UK and Asia is increasing each year, unmitigated by the carbon capture and storage that some climate models say is required [65]. Also while the climate modeling community ponders, governments are making practical decisions about renewable energy funding, as in the UK, where the government provided £809 m (about $1.2 b) [66 67] in subsidies to biomass electricity in 2015, the same year it announced it was terminating subsidies for offshore wind earlier than planned [68]. Since residues would eventually release carbon to the atmosphere whether through burning or decomposition, any putative reduction in CO_2 emissions actually depends on residues-fueled bioenergy displacing fossil fuels, but in the UK, it appears bioenergy may instead be displacing zero emissions technologies, while prolonging the life of coal plants that partially switch to subsidized wood burning.

There is no time like the present to reduce emissions. Given the anticipated role for bioenergy in climate mitigation, climate-related policies should be reformed immediately to account for bioenergy impacts. Using the NEI to weight biogenic CO_2 for inclusion in US and EU carbon trading programs and to qualify bioenergy for renewable energy subsidies would reduce emissions more effectively than continuing with the current assumption of zero emissions, though for wood pellets sourced from bolewood, counting direct emissions is a more protective and accurate approach.

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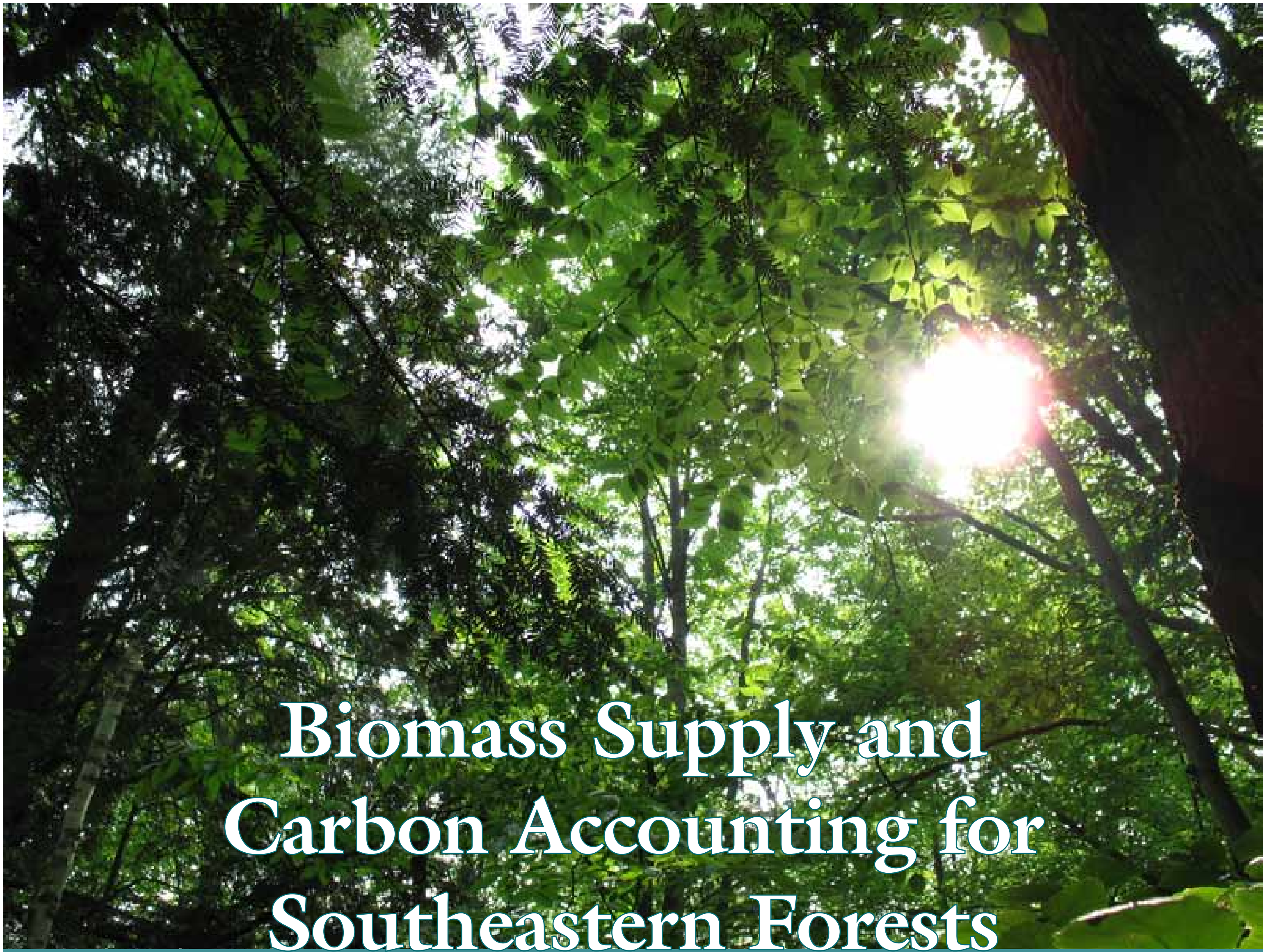

Biomass Supply and Carbon Accounting for Southeastern Forests

February 2012

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EXECUTIVE SUMMARY

It is important to note that due to the emphasis in the Southeast on biomass electric power production, this study examines only the use of biomass for large-scale electric power generation (and electric-led combined heat and power, or CHP).

As climate change policy develops, forest biomass is consistently recognized as an alternative fuel with the potential to replace fossil fuels and mitigate the build-up of atmospheric carbon. In response to these issues, the southeastern United States has seen recent interest in significantly expanding the biomass energy sector, including building new power plants, co-firing with coal power in existing plants, pellet manufacture for export to Europe, and producing cellulosic ethanol. While some look to these developments and see promise, others look with great concern at pressures on the region's forests, implications for forest health and sustainable wood supply, and impacts on cumulative greenhouse gas emissions.

Until recently, governmental policies have almost unanimously reflected the opinion that energy from biomass is beneficial from a greenhouse gas (GHG) perspective. Biomass typically is included in energy portfolios as a renewable energy source in the same classification as wind and solar and is eligible for the same public incentives and subsidies. Starting in the early to mid 1990s, however, a number of studies looked more closely at the net GHG benefits of burning biomass and resulted in refined calculations of benefits depending on site factors, forest growth modeling, and timing of emissions and sequestration (Manomet, 2010). In the past few years, direct challenges to the accuracy of accounting approaches spurred a rethinking of carbon accounting for biomass (Searchinger, 2009).

As part of this emerging research, the US Environmental Protection Agency (EPA) is revisiting the premise that burning biomass for energy is carbon neutral in the context of the natural carbon cycle of the earth (EPA, 2011) and is considering regulating carbon emissions from biomass combustion. This study provides an example of how the "comparative" approach can be used for a specific region. It can be further evaluated by EPA to inform its criteria for an "accounting framework for biogenic CO_2 emissions from stationary sources."

KEY QUESTIONS

To address these complex issues as relevant to southeastern forests, this study seeks to address two key questions relevant to the biomass electric power sector in this region of the country:

- How much biomass (primarily wood) is available on a sustainable basis to source the expanding southeastern biomass electric power sector? And, what is the potential of public policy to create demands that exceed sustainable supply levels?
- How will the increased use of forest biomass for electric power generation in the Southeast affect atmospheric carbon over time, and how does biomass energy compare to several fossil fuel energy alternatives in terms of cumulative GHG emissions over time?

It is important to note that due to the emphasis in the Southeast on biomass electric power production, this study examines only the use of biomass for large-scale electric power generation (and electric-led combined heat and power, or CHP). Thermal energy pathways were not examined and due to their much higher efficiencies, these thermal technologies would have significantly shorter carbon payback periods and different overall impact on atmospheric carbon levels when compared to fossil fuel technologies (Manomet, 2010).

WOOD SUPPLY REVIEW

To assess the potential for sustainably harvested biomass (primarily wood) to fuel an expanded biomass energy sector in the Southeast, the study presents a literature review of several key biomass resource assessments conducted to date, examines the current and possible future energy policies that could drive the expansion of biomass energy development, and compares the supply with this potential demand. This portion of the study has three main parts:

1. assessment of the biomass resource literature for the seven-state region
2. examination of the energy policies in the seven-state region
3. comparison of the resource supply to the potential demand

The study does not present new primary fuel-supply analysis, but is based on a review of existing information. Main findings include the following points:

- Most studies conducted in the past six years quantify the gross or total amount of woody biomass material generated on an annual basis and do not quantify how much is already being used. Most of these studies focus on residues produced from other primary activities while evidence suggests nearly all the mill and urban wood residues are already used by existing markets.
- The evidence clearly suggests that any expanded biomass energy in the Southeast will come from harvested wood (either tops and limbs left behind from timber harvesting, whole trees, or pulpwood sourced from the main stem of a harvested tree).
- Whether logging slash, whole trees, or pulpwood will be used in the expansion of biomass energy in the Southeast will depend on the following:
  1. Which market the wood is going to (pellet mills need high-quality fiber from pulpwood while biomass plants are less particular about quality)
  2. How much demand increases within the pellet and power market sectors over time
  3. What happens with the pulp and paper industry in the southeast region in the future
- Prior to 2009, most fuel availability studies presented estimates of supply without any acknowledgment of the influence price has on the availability of these woody biomass resources. Since then, different studies have examined the economics using different indicators—making it difficult to compare results among the studies. For a clear assessment of the economics of woody biomass resources, the total delivered price paid by the receiving facilities is the best indicator to use.
- Various studies reviewed in this chapter used widely divergent assumptions regarding what percentage of the total amount of logging residue can be recovered from a harvested area. While the range observed in the literature was from roughly 50-100 percent, it should be noted that there is a difference between how much residue *can* be recovered and how much *should* be recovered when ecological factors are taken into account. While examining how much wood fuel could be generated if 100 percent of this material was recovered is useful for academic purposes, it is unrealistic to assume that such a high level can and should be realized. Ideally, studies would look at two critical issues when factoring the overall recovery rate—percentage of recovered residues on individual harvest operations and percentage of harvest operations where residues can be recovered.

It should be noted that there is a difference between how much [logging] residue *can* be recovered and how much *should* be recovered when ecological factors are taken into account.

EXECUTIVE SUMMARY *(cont'd)*

- The availability of logging residues will largely depend on extraction methods. Where whole-tree harvesting systems can be used, these residues can be cost effectively accessed, however, the potential ecological effects of whole-tree logging need to be considered. Where mechanized cut-to-length and manual stem-only harvesting are used, these residues will not be easily accessible. Further analysis that determines how much whole-tree harvesting systems versus stem-only harvesting systems are used across this region would be very useful.
- Of all the states in the seven-state study region, North Carolina has had the most in-depth and sophisticated level of study of its biomass energy potential. In contrast, Alabama and Tennessee both had very little publicly available reports estimating biomass resources.
- Evidence suggests that there is likely enough wood to meet a 15 percent federal Renewable Energy Standard (RES) applied to each of the seven states (with the exception of Florida) when woody biomass sourced from local forests accounts for no more than 20 percent of the overall renewable electric generation target (or 3 percent of electricity supplied). It also appears, however, that adequate wood fuel resources are quite sensitive to the RES allocation. For example, if 30 percent of a 15 percent RES was allocated to forest biomass, it is likely there would not be enough wood fuel available within the region. A more aggressive RES standard for biomass leads to a higher likelihood of shortages and a greater probability of pulpwood displacement.
- Capacity to access and utilize residues is also a function of how much roundwood harvest occurs. More demand for roundwood generates more residues. The extent to which biomass power plants transition their wood procurement away from residues and toward roundwood is governed by the strength of the rest of the forest products industry. If the forest products industry strengthens as a result of greater lumber demand, it will increase its wood fiber consumption and as a result, biomass power plants would procure more residues at a lower cost and less pulpwood at a higher cost. If the forest products industry as a whole continues to contract, however, biomass power plants will likely transition toward procurement of chipped fuel from whole trees assuming they can absorb the higher cost associated with that transition.

While some believe that biomass power demand will likely transition to procuring roundwood and displacing wood from the pulp and paper industry, it is actually more likely that growth in pellet markets—which demand higher fiber quality found in roundwood (not slash)—will be the market that most immediately displaces pulpwood. Therefore, pellet mills and biomass power plants have somewhat complementary (almost symbiotic) procurement needs. Pellet production, especially the export market to Europe, will continue to play the wild card role in future wood fuel markets.

While some believe that biomass power demand will likely transition to procuring roundwood and displacing wood from the pulp and paper industry, it is actually more likely that growth in pellet markets—which demand higher fiber quality found in roundwood (not slash)—will be the market that most immediately displaces pulpwood.

- The supply review performed as part of this study does not directly address potential ecological impacts of biomass energy sourcing. Additional analysis will be necessary to assess these impacts on other forest resources and values.
- The potential recovery rate for harvest residue is a key variable in determining the quantity of available wood fuel. Further research is needed to assess both the current achievable residue recovery rates and reasonable future recovery rates. Projected recovery rates need to consider woody biomass retention rates to meet wildlife and biodiversity, water quality, and soil productivity needs.

While this report has identified and probed some of the issues regarding the forest resource's capacity to produce more energy in the Southeast, there are numerous areas where key information is missing. More specific research is needed in the areas of: existing forest residue utilization, use of different harvesting systems, a comprehensive wood fiber assessment for the entire seven-state region, the price elasticity of demand between fuel chips and pulpwood, and the likely impacts of federal renewable energy standards on the economic incentives that drive project development.

ATMOSPHERIC CARBON ANALYSIS

To examine the atmospheric effects of biomass electric power generation in the Southeast, this study developed a new carbon accounting framework that integrates lifecycle carbon accounting with forest carbon accounting and utilizes forest growth, forest management practices, and supply data related to the specific situation in the Southeast. The framework is based on what we will call a "landscape-woodshed approach" where actual supply zones for specific facilities across the landscape are defined and aggregated as the basis for the study. Essentially, the study framework is designed to answer policy questions related to how atmospheric carbon would be affected if certain activities were promoted. It develops a "business-as-usual" baseline and then projects the atmospheric carbon effect of different future scenarios of creating electricity from woody biomass versus creating it from fossil fuels.

The framework [for this study] is based on what we will call a "landscape-woodshed approach" where actual supply zones for specific facilities across the landscape are defined and aggregated as the basis for the study.

Given the dynamics of the southeastern forestry sector, this study assumes that most of the trees modeled would eventually be harvested for pulp or other management objectives (such as to initiate the new stand under even-aged management) versus being left untouched if not harvested for biomass energy. The study excludes all public lands and 21 percent of private lands as not available for harvesting.

This is a more dynamic approach than was recommended in EPA's accounting framework for biogenic sources released in September 2011. Although, EPA acknowledged the "comparative" approach used in this study as a more comprehensive accounting method, it chose a "reference point" approach because of the perceived difficulties and challenges in applying a more dynamic approach to actual situations in the field.

EXECUTIVE SUMMARY *(cont'd)*

This study provides an example of how more dynamic accounting can be accomplished and should be considered by EPA in its carbon accounting deliberations. The results are consistent with other studies from other states or regions using similar analytical methods (Manomet, 2010 and McKechnie, 2011). Others have recently voiced opinions over which accounting methods are most appropriate. The SAF Task Force Report, Managing Forests because Carbon Matters: Integrating Energy, Products, and Land Management Policy (Malmsheimer et al., 2011), recommends a reference-point approach to establish forest biomass as carbon neutral. The European Environment Agency's Scientific Committee on Greenhouse Gas Accounting (European Environmental Agency, 2011) recently offered an opinion championing a comparative approach to fix a serious flaw in current GHG accounting.

Carbon Modeling Results

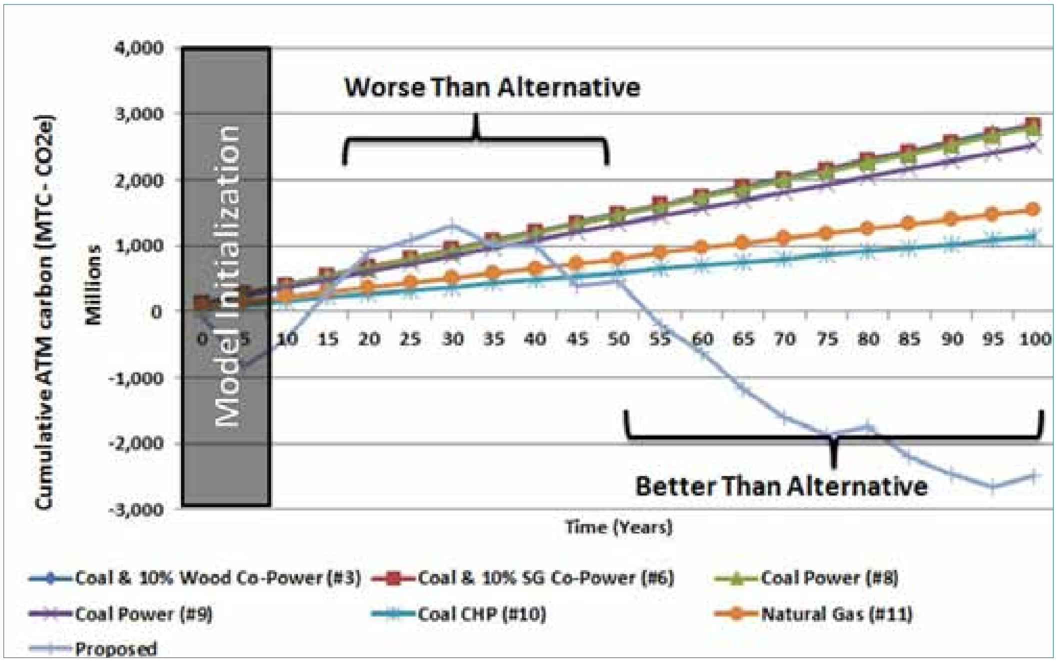
- The study modeled 22 new power plants as proposed to be developed over the next several years (1014 MW and 3.05 million tons of pellet production) added to an existing base of 17 power plants. The list of proposed plants is a snapshot compiled in May 2011 by the Southern Environmental Law Center. Additional large plants have since been proposed and are under development. As biomass demand increases with more facilities beyond the

Figure 22.

The study found that using southeastern forests for an expansion of electric power generation produced a significant long-term atmospheric benefit, but at short-term atmospheric cost.

The expanded biomass scenario creates a carbon debt that takes 35-50 years to recover before yielding ongoing carbon benefits relative to fossil fuels after this time period. (The initial apparent sequestration in the graph is a modeling artifact. It is a function of the simulation resolution and is due to the 5-year cycle with harvests mid-decade. This creates a 5-year growth period before harvest simulation.)

Figure 22. Cumulative atmospheric carbon balance over 100 years using coal and natural gas technologies to meet energy demand of proposed biomass facilities.



22 modeled, the ability of the forested landscape to provide biomass supply and store carbon may become more limited, particularly in localized areas with strong demand.

- The results indicated that the 17 existing biomass facilities were now generating and would continue to generate an improved atmospheric carbon benefit relative to fossil fuel technologies.
- The study found that using southeastern forests for the modeled expansion of power generation produced a significant long-term atmospheric benefit, but at short-term atmospheric cost. The expanded biomass scenario creates a carbon debt that takes 35-50 years to recover before yielding ongoing carbon benefits relative to fossil fuels after this time period (see Figure 22 on page 95). This outcome depends on the fossil fuel pathway used for comparison and assumes forests re-occupy the site through planting or natural regeneration, with no forest land conversion. This finding is consistent with other recent studies and naturally creates tension between climate scientists who assert that the next 20-30 years are a critical time for reducing carbon additions to the atmosphere and those who are more focused on long-term cumulative atmospheric carbon levels. This tension can only be resolved by well-informed energy and climate policy decisions.
- The efficiency of combustion technology was shown to be a critical factor influencing carbon emissions over time. The study used a mid-range value of 6,800 Bone Dry Tons (BDT) per megawatt hour per year. Using less-efficient combustion technology that requires more biomass per unit of power (e.g., using 8,000 BDT per megawatt hour per year) extends the payback period to 53 years. Using more efficient technologies would shorten this payback period. This study does not address biomass for thermal applications. While less common in the study area, strictly thermal applications or CHP applications are significantly more efficient and have much shorter carbon payback periods (in the range of 5-10 years in similar studies) than conventional combustion for base-load electrical generation that produces significant amounts of unused “waste” heat. The study also found that there is wide variability in carbon outcomes for different fuel types across different combustion systems.
- The use of logging residuals, when available from current harvests, leads to an improved carbon balance versus using standing roundwood because of the higher relative carbon storage of pulpwood versus residuals. The availability of harvest residue, however, is highly dependent on other parts of the wood products economy to generate sufficient demand for harvesting that creates residue material.
- The study did not model the use of dedicated energy crops for feedstock or crops that could be grown on fallow land and not jeopardize current sequestration and carbon stocks in existing forests. It attempted to analyze switchgrass based on information from a literature review, but this did not provide adequate or comparable information to what was available from our forest biomass modeling. Hence, a switchgrass analysis was dropped from the carbon modeling.

EXECUTIVE SUMMARY *(cont'd)*

DISCUSSION

One central issue to recognize is that [carbon] policy discussions include two competing perspectives—one long term and one short term—that will need to be assessed and weighed in the development of effective climate and energy policy.

The complex flux of forest-based carbon and the 35-50 year payback periods for the electric generation technologies modeled present both an intellectual and policy challenge. One central issue to recognize is that policy discussions include two competing perspectives—one long term and one short term—that will need to be assessed and weighed in the development of effective climate and energy policy. The long-term perspective focuses on the much lower amounts of atmopheric carbon that will eventually be realized if biomass is substituted for fossil fuels and the related beneficial effects for climate change and future generations. From this perspective, the 35-50 year payback period of biomass is less consequential. The short-term perspective, by contrast, believes near-term emission reductions are critical. This perspective is concerned with near-term "tipping points"—climate events that might be triggered by near-term increases in atmospheric carbon. From that perspective, the 35-50 year payback periods for biomass electric power are considered unacceptable climate and energy policy.

To further inform this discussion, it is useful to note that the carbon debt period shown in this study is consistent with other studies (Manomet, 2010, McKechnie, 2011) that have used life-cycle analysis, forest carbon accounting, and a business-as-usual baseline to compare biomass to other forms of energy production. As shown schematically in Figure 1 on the following page based on the Manomet study, there is an initial carbon "debt" relative to fossil fuels in the combustion of biomass for energy. Following a variable "payback" period, this debt is recovered and beyond that point biomass energy results in lower atmospheric carbon than fossil fuel alternatives.

The Manomet modeling produced a 42-year payback period for biomass- versus coal-generated electricity and the McKechnie modeling indicated 17-38 year payback periods for generating electricity with biomass instead of coal. Although these patterns are basically consistent, there are differences in debt periods, which are attributable to different forest types and harvest scenarios. In addition, our framework includes a more precise modeling of actual harvesting methods in real stands across the study region and linked to specific facilities.

Also there are significant differences between this study and the Manomet study in the time it takes to re-sequester all the emitted carbon and reach the point commonly called "carbon neutral." Our modeling indicates 53 years are required for this southeastern study region while the Manomet results for Massachusetts indicate more than 100 years are required.

Beyond the tension between this long- and short-term perspective, analyzing the climate implications of the biomass technologies modeled in this report is informed by several additional issues. First, recent climate studies indicate that whatever the ultimate peak in atmospheric carbon, it will take much longer than previously thought—hundreds or thousands of years—for the earth's systems to bring it back down to what are considered safe levels. This further complicates the understanding of how to address the short- versus long-term atmospheric carbon implications of biomass energy.

Second, it is possible to imagine future scenarios where technology leaps allow the retirement of such major sources of combustion as coal and biomass within 50 years. If realized, this would significantly shorten the payback period for biomass since facilities would be retired, biomass harvesting would stop, and re-sequestration would accelerate to shorten the payback periods. Conversely, it is possible to imagine land-use changes that would adversely affect the availability of biomass and negatively affect the payback periods. Concern over land-use change is well documented in the Southeast.

Third, it is necessary to fully consider any negative climate implications or events that could be triggered by the carbon debts created by the biomass scenarios. One should also consider whether these climate effects would eventually be triggered by continuation of the fossil fuel scenarios in the absence of biomass or other alternative fuels. Evaluating the cumulative costs and benefits to ecosystems and society of these factors over time is the task in front of policy makers in the southeastern region and at the national level.

Fourth, much of the carbon accounting debate for biomass centers on assumptions of baseline conditions. It is not uncommon to see studies that rely on generic "growth-to-removal" ratios as the key indicator of carbon accounting. The rationale is that as long as overall carbon stocks are being maintained in some specified area, then any biomass removal in that area is considered carbon neutral. This approach oversimplifies the accounting and can overlook very significant changes in forest carbon stock at the local level. They also do not accurately portray the foregone tons of new sequestration that would continue to accrue if those forests were not harvested for biomass.

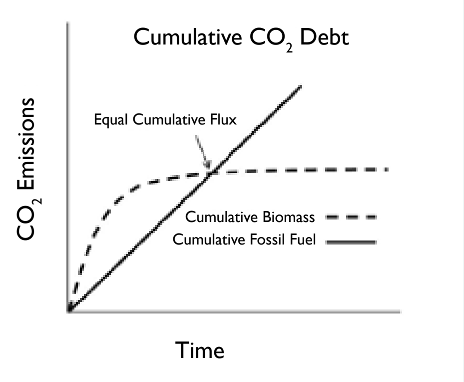


Figure 1.

Landscape-Scale Cumulative Carbon Debts and Dividends (Walker, 2012).

This study relies on a comparative approach that realistically estimates both the level of forest harvesting and the level of forest sequestration going forward in the absence of new biomass harvesting as a more accurate baseline approach. The approach used in this study can be applied to a region or an individual facility and should be useful for EPA as it develops regulations for GHG emissions.

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Viewpoint

Correcting a fundamental error in greenhouse gas accounting related to bioenergy

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ABSTRACT

Many international policies encourage a switch from fossil fuels to bioenergy based on the premise that its use would not result in carbon accumulation in the atmosphere. Frequently cited bioenergy goals would at least double the present global human use of plant material, the production of which already requires the dedication of roughly 75% of vegetated lands and more than 70% of water withdrawals. However, burning biomass for energy provision increases the amount of carbon in the air just like burning coal, oil or gas if harvesting the biomass decreases the amount of carbon stored in plants and soils, or reduces carbon sequestration. Neglecting this fact results in an accounting error that could be corrected by considering that only the use of 'additional biomass' – biomass from additional plant growth or biomass that would decompose rapidly if not used for bioenergy – can reduce carbon emissions. Failure to correct this accounting flaw will likely have substantial adverse consequences. The article presents recommendations for correcting greenhouse gas accounts related to bioenergy.

1. Introduction

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. In our opinion, several of these policies – some European examples are discussed below – inaccurately assess the GHG emission consequences of different forms of bioenergy and are likely to have serious adverse environmental consequences if not remedied (van Renssen, 2011).

This viewpoint article discusses the scientific background of an Opinion on bioenergy published in September 2011 by the Scientific Committee of the European Environment Agency (EEA).[1] In this article, 'bioenergy' refers to any energy produced by combusting

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[1] http://www.eea.europa.eu/about-us/governance/scientific-committee/sc-opinions/opinions-on-scientific-issues/sc-opinion-on-greenhouse-gas (accessed: 2.1.2012).

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biomass whether 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).

2. Bioenergy supply: Expectations and challenges

Correctly addressing the carbon implications of bioenergy is critical because a variety of studies and policies contemplate use of very large quantities of biomass in the belief that bioenergy is almost a GHG-neutral replacement for fossil fuels. Many projections imply at least doubling the total human harvest of world plant material. For example, the International Energy Agency has projected that bioenergy could supply over 20% of the world's primary energy by 2050 (IEA, 2008). A report by the Secretariat of the UNFCCC has claimed bioenergy can supply 800 EJ/yr (UNFCC Secretariat, 2008), which is far more than total world energy use today. The IPCC Special Report on Renewable Energy (SRREN) suggests that the global bioenergy potential could be as high as 500 EJ/yr (Chum et al., 2012), comparable to current fossil energy use. By contrast, 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 (Krausmann et al., 2008) with a chemical energy value of 230 EJ.

An increase in the use of bioenergy of this magnitude could create substantial adverse impacts on natural ecosystems, compete with food production, and undermine other goals to reduce present impacts of agricultural production on the environment, and improve the well-being of farm animals (Erb et al., 2012; Haberl et al., 2011; Lambin and Meyfroidt, 2011; Smith et al., 2010). Ecosystems can be managed for satisfying human needs more or less sustainably, but all human uses of land and consumption of plants have environmental costs. Generating food, fiber and other biomass-based products that people currently consume utilizes roughly 75% of the world's vegetated land (Erb et al., 2007; UNEP, 2010). Agriculture, including livestock grazing, accounts for more than half of this area; in addition, a substantial fraction of the world's forests are managed for wood production. Moreover, over 70% of the water withdrawn from rivers and aquifers is used by agriculture (Comprehensive Assessment of Water Management in Agriculture, 2007). In addition, fertiliser use has doubled the amount of reactive nitrogen in the world, leading to large-scale pollution of aquatic ecosystems, extensive algal blooms and bodies of waters with low levels of oxygen (Erisman et al., 2008; Gruber and Galloway, 2008).

Even so, agricultural and forestry practices have not, on balance, increased the total quantity of biomass production: they have merely transformed natural ecosystems to produce goods and services for human consumption (Haberl et al., 2007). As human uses of land have already reached troubling levels (Foley et al., 2005, 2011; IAASTD, 2009; Millennium Ecosystem Assessment, 2005), and as large additional demands exist for food and timber (Smith et al., 2010), the challenges that would result from a doubling of global human biomass harvest for bioenergy (or even higher increases) should not be underestimated, and the full greenhouse gas emissions that would result from such an increase in bioenergy production are uncertain.

3. Correct greenhouse gas accounting

Many policies consider biomass combustion as 'carbon-neutral,' regardless of the source of the biomass. Although these policies may acknowledge the carbon emissions from using fossil fuels to produce and refine biomass, as well as trace-gases, they omit the carbon dioxide (CO_2) released by the burning of the biomass itself (Bird et al., 2011). They do so either by omitting these emissions when accounting for emissions from bioenergy or by simply endorsing all bioenergy on the assumption that it emits no net carbon dioxide (Searchinger et al., 2009). Such policies and regulations thus treat biomass as an inherently 'carbon neutral' energy source. This is not correct.

Replacement of fossil sources of energy with biomass does not reduce GHG emissions from combustion. For example, burning one metric tonne of bone-dry wood will release about 1.8 t of CO_2 into the atmosphere. While bioenergy reduces or eliminates carbon emissions from fossil fuels, the combustion of biomass results in its own carbon emissions (Bird et al., 2011; Searchinger, 2010).

The assumption of carbon neutrality is often justified on the grounds that burning biomass only returns the carbon absorbed by growing plants to the atmosphere. Plants do absorb carbon, but this line of thought makes a 'baseline' error because it fails to recognize that if bioenergy were not produced, plants not harvested would continue to absorb carbon and help to reduce carbon in the air. Because that carbon reduction would occur anyway and is counted in global projections of atmospheric carbon, counting bioenergy that uses this carbon as carbon-neutral results in double-counting.

An example shows why. Imagine a hectare of cropland just abandoned and allowed to reforest. These growing plants would absorb carbon from the atmosphere to form plant tissue, i.e., biomass. Some of that biomass would be consumed and the carbon released by animals, fungi or microorganisms and would 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 (Baldocchi, 2008; Le Quere et al., 2009; Richter et al., 2011). If the land were used instead to grow energy crops to be burned in a power plant, fossil fuel emissions would decline but not the carbon emitted by the power plant chimneys. Per unit of energy, the CO_2 emissions would typically even be higher than those of a fossil fuel-burning power plant because (i) biomass contains less energy per unit of carbon than petroleum products or natural gas do and (ii) biomass is usually burned with a lower efficiency than fossil fuels (Bird et al., 2011). Although the growth of bioenergy crops absorbs carbon, using the land to grow bioenergy crops sacrifices the sequestration of carbon in the forest. This foregone carbon sequestration, which is not considered in current GHG accounting related to bioenergy, may be substantial. For example, in the western Ukraine forest growth following abandonment of farmland resulted in a net carbon sink of almost one ton of carbon per hectare forest and year (Kuemmerle et al., 2011).

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

The use of food crops for the production of transportation biofuels provides a comparable story as they also absorb carbon whether used for bioenergy or not. Their use for bioenergy does not by itself result in additional plant growth, offset the emissions from energy use, or justify failing to account for the carbon emitted from exhaust pipes. This use of crops can only reduce carbon emissions through a series of 'indirect' market responses:

- Food crops do not usually keep carbon away from the atmosphere for long periods of time because they are consumed by people and livestock, who nourish themselves and thereby return almost all carbon to the atmosphere as respiration and waste. If food crops used for bioenergy are not replaced, there is a reduction in carbon emissions because people and livestock will release less CO_2 to the atmosphere, but that is not a desirable way of reducing GHGs.

Table 1
Degree of likely accounting error when CO_2 emissions from biomass combustion are not properly considered.

Source of biomass	**Degree of likely accounting error**	Form of error
Converting forests currently sequestering carbon to bioenergy crops	Very high	Ignoring both immediate release of carbon and often continuing carbon sequestration of the forest if unharvested
Harvesting live trees for bioenergy and allowing forest to regrow	High	Same
Diverting crops or growing bioenergy crops on otherwise high-yielding agricultural land	High	Ignoring ongoing uptake of carbon on cropland and likely release of carbon in replacing the crops or reduced crop consumption
Using crop residues	Variable	Potentially ignores existing uses, need to replace nutrients, or potential effects on soil productivity (Blanco-Canqui and Lal, 2009)
Planting high-yielding energy crops on unused invasive grasslands	Low	Little or no error
Using post-harvest timber slash	Little or none	Could ignore temporal dimension of decomposition or existing uses
Using organic wastes otherwise deposited in landfill	Little or none	Little or no error

- If crops used for bioenergy are replaced by food production elsewhere, then the carbon emission consequences of bioenergy depend on how this is done. If more crops are grown on a unit of land, additional carbon is absorbed from the atmosphere.[2] If more land is converted to crops, then the calculation must include the lost carbon storage or sequestration due to changing land-use.

Only if, and to the extent to, these indirect effects are beneficial on balance could they justify ignoring some of the carbon emitted by the combustion of biomass such as biofuels.

It is important to be precise where and how physical changes occur in the absorption or emission of carbon in the use of bioenergy. Because bioenergy does not physically reduce emissions from exhausts, 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 grow additional biomass and 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.

To reiterate: only biomass grown in excess of that which would have grown anyway, or biomass that would otherwise have decomposed anyway, is ‘additional biomass’ containing ‘additional carbon,’ and has the potential to reduce carbon emissions when used for energy (Searchinger, 2010). The basic error in the carbon neutrality of biomass assumption is the failure to count the production and use of biomass that land would generate if not used for bioenergy (the counterfactual).

Correct GHG accounting needs to reflect not merely the loss of existing carbon stocks when biomass is produced and used for energy, but also any decline in carbon sequestration that would occur in the absence of bioenergy use. For example, forests particularly in the northern hemisphere are accumulating biomass for a variety of reasons (Erb et al., 2008; Pan et al., 2011; Richter et al., 2011) and this growth absorbs carbon from the atmosphere. Some estimates of bioenergy potential suggest that biomass reduces greenhouse gas emissions so long as harvest is ‘sustainable’: if harvesting is kept below the level of forest growth, carbon stocks are argued to remain constant. But this line of reasoning ignores the additional carbon sequestration that would occur without wood harvesting for bioenergy (the counterfactual), which does not make bioenergy carbon neutral (Haberl et al., 2003; Holtsmark, in press).

If a forest is allowed to re-grow after harvest, it achieves approximately the same carbon storage level as an unharvested forest when the build-up of carbon stocks slows down and eventually stops as the forest reaches maturity.[3] At that point, the use of the biomass becomes carbon-neutral. But achieving this parity may take decades or even centuries, which means that the CO_2 remains in the atmosphere for a long time before it is removed by plant growth, resulting in a ‘pulse’ of climate forcing that takes decades or centuries before being compensated by forest regrowth – thereby counteracting the goal of achieving GHG reductions in the next few decades (Cherubini et al., 2011a, 2011b). Increasing the harvest level in forests over longer time periods to achieve a sustained fuel wood flow permanently reduces the forest’s carbon stock and thereby creates a ‘carbon debt’ that may require centuries to be repaid, even if forest area is conserved (Holtsmark, in press). Thus, 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.

The studies projecting large quantities of bioenergy potential discussed above do not rule out double-counting of biomass already used or sequestering carbon and mostly neglect the true counterfactual. For example, large bioenergy potential estimates assume the availability of abandoned or unused agricultural land in present and future, but such land is not a free resource as its reversion to forest and grassland is a major component of the global terrestrial carbon sink (Pan et al., 2011). Bioenergy potential studies also call for harvesting forest carbon growth in excess of timber harvest, but that would also reduce the carbon sink and therefore add carbon to the air (Holtsmark, 2011). Nevertheless, there are indeed potential biomass sources that can reduce greenhouse gas emissions and that could be generated sustainably. Realistic expectations of such truly ‘additional biomass’ should be the focus of climate change strategies.

Table 1 highlights the likely advantageous and disadvantageous forms of biomass and the likely potential error in the

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[2] Increasing yields through agricultural intensification often requires more inputs such as fertilizer which often result in higher GHG emissions. This must of course also be considered.

[3] While this process is reasonably well understood for the aboveground component, uncertainties related to belowground carbon storage are larger.

existing directives of different forms of biomass highlights, showing that some bioenergy sources figuring prominently in current bioenergy policies are prone to be erroneously evaluated under current accounting rules.

4. Origins of the accounting error

The assumption that all biomass is carbon-neutral results from a misapplication of the original guidance provided for the national-level carbon accounting under the United Nations Framework Convention on Climate Change (UNFCC). Under the UNFCCC accounting rules, countries report their emissions from energy use and from land-use change separately. 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 after combustion. 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.

The accounting rule under the Kyoto Protocol is different: it caps emissions from energy use but does not apply worldwide and it applies only incompletely to land use even in the Annex I countries. By excluding biogenic emissions from the energy system, the Protocol erred because this practice means that those emissions are in many cases never accounted for at all. Similarly, many national and European policies and, as well as many lifecycle and other analyses, mistakenly ignore biogenic emissions from energy use without including changes in land-based carbon as a result of that bioenergy use.

5. European policies affected by the accounting error

In order to show how important these considerations are in a policy context, we focus on the example of Europe.[4] European policies making this accounting error include at least:

- The European Union's Emissions Trading System[5] (which caps emissions from major factories and power plants) ignores CO_2 emissions from biomass combustion but does not apply to land use;
- The Renewable Energy Directive[6] (which requires that Member States increase their use of renewable energy to 20% by 2020) explicitly sets CO_2 emissions from biomass combustion to zero regardless of the source of the biomass.

The European Union has also adopted two Directives to promote transportation biofuels that at present fail to include proper GHG accounting:

- The renewable fuels portion of the Renewable Energy Directive,[7] which requires that the Member States use qualifying renewable energy, which is expected to be almost exclusively biofuels, for 10% of their transportation fuel.
- The Fuel Quality Directive,[8] which requires reductions in the carbon intensity of transportation fuels.

To measure GHG emissions related to bioenergy, these Directives use life-cycle analyses (LCA) that count emissions involved in growing crops and refining biofuels, as well as those from direct land use change, if a bioenergy crop is planted in a previously forested area or other high carbon ecosystems. But this accounting strategy still ignores the actual emissions of CO_2 by 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 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 replaced, or (iii) the crops are replaced 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 (i.e., 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 can fix this error. 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 and could even exacerbate 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 or reduced decomposition. Tighter thresholds will encourage making biofuels using more land, and more productive land (and perhaps even generate fewer litres of biofuels due to reduced yields), if doing so reduces GHG emissions from inputs (such as energy or fertiliser), even when the true consequences for greenhouse gases, hunger and biodiversity would be worse.

Although estimating the indirect consequences of biofuels is inherently uncertain, 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 erroneous as the CO_2 emissions from the use of bioenergy are real and there may be no additional plant growth or reduced decomposition to compensate those emissions. We strongly recommend that any accounting system should fully quantify

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[4] Europe was chosen as an example because most authors are Europeans. This choice should not interpreted as a judgement of accounting standards in European bioenergy policies compared to those of other regions.

[5] 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.

[6] 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.

[7] 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).

[8] 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).

the greenhouse gas emissions attributable to the use of land, both direct and indirect, when evaluating the use of biofuels.

Recent developments in Europe indicate that political awareness of issues related to greenhouse gas accounting for bioenergy is rising. For instance, EU legislation such as the Renewable Energy Directive and the Fuel Quality Directive set out sustainability criteria for biofuels. More detailed provisions under the existing legislation are under discussion.[9] We hope that the issues raised in this viewpoint will be taken up in the on-going political process in order to strengthen the environmental integrity of EU policies.

6. Recommendations

Based on the above-discussed considerations the authors recommend that:

- Policies and their goals 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 count all the carbon and other GHGs releases by the combustion of carbon (as emissions), and should count as an offset additional plant growth or reduced decomposition of biomass, which together make up additional sequestration. The balance reflects the net effect of 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 and potential to levels based on the planet's capacity to generate additional biomass, without jeopardizing natural ecosystems.

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Range and uncertainties in estimating delays in greenhouse gas mitigation potential of forest bioenergy sourced from Canadian forests

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Abstract

Accurately assessing the delay before the substitution of fossil fuel by forest bioenergy starts having a net beneficial impact on atmospheric CO_2 is becoming important as the cost of delaying GHG emission reductions is increasingly being recognized. We documented the time to carbon (C) parity of forest bioenergy sourced from different feedstocks (harvest residues, salvaged trees, and green trees), typical of forest biomass production in Canada, used to replace three fossil fuel types (coal, oil, and natural gas) in heating or power generation. The time to C parity is defined as the time needed for the newly established bioenergy system to reach the cumulative C emissions of a fossil fuel, counterfactual system. Furthermore, we estimated an uncertainty period derived from the difference in C parity time between predefined best- and worst-case scenarios, in which parameter values related to the supply chain and forest dynamics varied. The results indicate short-to-long ranking of C parity times for residues < salvaged trees < green trees and for substituting the less energy-dense fossil fuels (coal < oil < natural gas). A sensitivity analysis indicated that silviculture and enhanced conversion efficiency, when occurring only in the bioenergy system, help reduce time to C parity. The uncertainty around the estimate of C parity time is generally small and inconsequential in the case of harvest residues but is generally large for the other feedstocks, indicating that meeting specific C parity time using feedstock other than residues is possible, but would require very specific conditions. Overall, the use of single parity time values to evaluate the performance of a particular feedstock in mitigating GHG emissions should be questioned given the importance of uncertainty as an inherent component of any bioenergy project.

Keywords: carbon debt, carbon dioxide emissions, carbon parity time, climate change, forest ecosystems, life cycle assessment, logging residues, renewable energy, salvage logging, wood pellets

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Introduction

The use of forest-based bioenergy to replace fossil fuels in heat and electricity generation has the potential to reduce greenhouse gas (GHG) emissions. Under sustainable forest management practices, forests can provide renewable feedstock for bioenergy as the CO_2 released during wood combustion is later recaptured by photosynthesis as the forest regrows. However, the presumed 'C neutrality' of forest bioenergy has been the subject of much debate recently (Searchinger *et al.*, 2009; Manomet, 2010) because of the three following points: (i) Wood emits more CO_2 than fossil fuel per unit of energy released (Gómez *et al.*, 2006); (ii) the release of CO_2 is much faster when wood is combusted than when wood undergoes natural decomposition; and (iii) CO_2 recapture by vegetation is not immediate and is usually achieved on decade- to century-long timescales. Therefore, there is a period of variable length during which cumulative CO_2 emissions to the atmosphere from an energy plant are greater for bioenergy than for fossil fuel. The delay before atmospheric GHG benefits are achieved has been referred to as C payback time (or C debt repayment time) when preharvest C levels are reached (absolute C balance), or as time to C parity when C levels of a reference case are reached (relative C balance) (see Lamers & Junginger, 2013, for a thorough discussion on terminology).

Canada is among the largest producers and exporters of solid bioenergy (Lamers *et al.*, 2012; Goh *et al.*, 2013). To date, case studies assessing the C debt and potential CO_2 emission savings of different forest bioenergy projects in Canada have yielded varying results, from instant atmospheric benefits to C payback/parity times of over 100 years. For example, cofiring pellets with coal

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in Ontario for electricity generation resulted in C debt repayment times of 16 and 38 years when pellets were made from harvest residues and green trees, respectively (McKechnie *et al.*, 2011). Using eddy covariance flux towers in Saskatchewan and Quebec to estimate net ecosystem exchanges, Bernier & Paré (2013) obtained a multidecadal time to C parity (>90 years) for a scenario that used wood chips from green trees to replace diesel oil in heat generation. A study in British Columbia forests impacted by the mountain pine beetle (MPB) (*Dendroctus ponderosae* Hopkins) showed that some scenarios had immediate atmospheric benefits (no C debt) and that using harvest residues and nonmerchantable trees for pellet production was more C beneficial than a stand protection alternative with no harvest (Lamers *et al.*, 2014).

Factors regulating the GHG mitigation potential of bioenergy projects and the underlying large variation in C parity times include biomass feedstock source and processing, the type of fossil fuel replaced, energy conversion efficiency, tree growth rate, and the definition of the counterfactual 'reference' scenario, that is, what would have happened to the forest land if biomass had not been sourced and used for bioenergy? (Lamers *et al.*, 2013; Buchholz *et al.*, 2014, 2015). Because many of those factors usually differ among studies, it is often difficult to compare C parity times among a variety of forest bioenergy uses. This situation stresses the need for a common accounting system to support decision-making (Buchholz *et al.*, 2015).

Furthermore, Buchholz *et al.* (2015) recommend that future studies assessing the C balance of bioenergy pathways consider quantifying and reporting uncertainties, which have rarely been addressed in past life cycle assessment (LCA) studies (e.g., Johnson *et al.*, 2011; Caputo *et al.*, 2014; Cherubini *et al.*, 2014; Röder *et al.*, 2015). Indeed, sources of uncertainty are encountered all along the supply chain as well as within the forest ecosystem, where various ecological factors may impact tree regeneration and decay rates. Understanding how variability in key parameters affects the mitigation potential of a bioenergy system is necessary to appreciate the full range of possible outcomes and make informed decisions and establish the right policies.

The aim of this study was therefore to compare, using a common framework, the mitigation potential and timing of atmospheric benefits for different bioenergy deployment scenarios sourcing their biomass from Canadian forests. Specific objectives were to quantify the uncertainties associated with such scenarios and identify how such uncertainties could be reduced to increase confidence in the timing and scale of GHG benefits for major forest bioenergy pathways. To this end, we developed a landscape-scale GHG emission calculator based on a LCA approach in which sources of variation and uncertainty are explicitly identified. Carbon parity times and their associated uncertainty were calculated for scenarios sourcing biomass from different feedstock types (harvest residues, salvaged trees (i.e., trees killed by natural disturbances), or green trees) typical of biomass production in Canada used to replace three fossil fuel types (coal, oil or natural gas) in heating or power generation. Results from this study may provide guidance for defining policies aimed at promoting the best forest bioenergy pathways for GHG mitigation. A free Web-based version of the calculator will be made available at https://apps-scf-cfs.rncan.gc.ca/calc/en (section GHG Bioenergy).

Materials and methods

Study area description

Our study focuses on the Canadian managed forest, which is estimated at 153 million ha (NRCan, 2014b). The area encompasses five terrestrial ecozones (i.e., Atlantic maritime, Boreal shield, Mixedwood plain, Montane cordillera, and Pacific maritime), where mean annual temperature (MAT) and mean annual precipitation range from −1 to 5 °C and from 400 to 3000 mm, respectively (Environment Canada, 2015). On average (1990–2013), forest harvesting occurs on 1.0 million ha annually, whereas fire and insects disturb 3.1 and 19.1 million ha, respectively (NRCan, 2014a). Frequency and severity of natural disturbances are expected to increase in the future (Soja *et al.*, 2007; Boulanger *et al.*, 2014), potentially making salvage wood an increasing feedstock source for harvested wood products, which include bioenergy.

Model framework for GHG accounting

The components of our LCA for GHG accounting include emissions from feedstock production and use, forest C dynamics, and energy conversion efficiency (Fig. S1). The GHG mitigation potential over time for a given bioenergy scenario needs to be assessed relative to a baseline, or counterfactual, scenario, which implies the use of fossil fuel. The GHG mitigation potential is calculated as follows:

$$\Delta\mathrm{GHG}_t = \frac{\mathrm{GHG}_{t\,\mathrm{BIO}} + \mathrm{FC}_{t\,\mathrm{BIO}}}{\mathrm{CE}_{\mathrm{BIO}}} - \frac{\mathrm{GHG}_{t\,\mathrm{FOSSIL}} + \mathrm{FC}_{t\,\mathrm{FOSSIL}}}{\mathrm{CE}_{\mathrm{FOSSIL}}}, \quad (1)$$

where $\Delta\mathrm{GHG}_t$ is the cumulative difference in $\mathrm{CO_2}$eq emissions between the bioenergy and fossil fuel scenarios at time *t* (in kg $\mathrm{CO_2}$ emitted per GJ of bioenergy produced), $\mathrm{GHG}_{t\ \mathrm{BIO}}$ and $\mathrm{GHG}_{t\ \mathrm{FOSSIL}}$ are cumulative emissions from the bioenergy and fossil fuel systems (production and use) at time *t*, respectively, $\mathrm{FC}_{t\ \mathrm{BIO}}$ and $\mathrm{FC}_{t\ \mathrm{FOSSIL}}$ are the forest C status (reported in $\mathrm{CO_2}$) of the bioenergy and fossil fuel systems at time *t*, respectively, and $\mathrm{CE_{BIO}}$ and $\mathrm{CE_{FOSSIL}}$ are the energy conversion efficiency of bioenergy and fossil fuel, respectively. When $\Delta\mathrm{GHG}_t$ reaches zero, the C parity time has been reached and GHG mitigation benefits begin to occur (Fig. 1). All emissions were derived

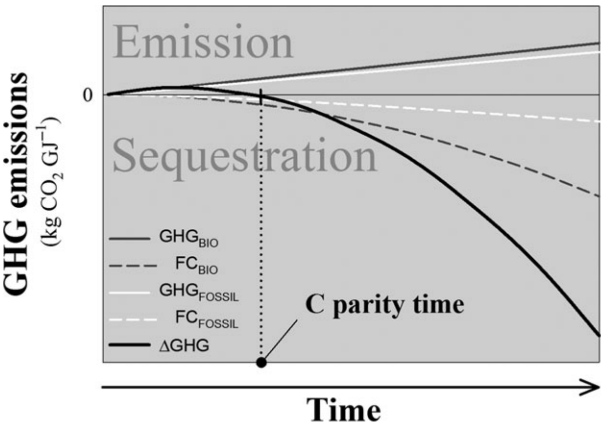

Fig. 1 The C parity time concept illustrated using the current model framework for C accounting. GHG_{BIO} and GHG_{FOSSIL} are emissions from the bioenergy and fossil fuel systems (production and use), respectively; FC_{BIO} and FC_{FOSSIL} are the forest C status of the bioenergy and fossil fuel systems, respectively; ΔGHG is the difference in CO_2 emissions between the bioenergy and fossil fuel scenarios. When ΔGHG reaches zero, C parity time has been reached and GHG mitigation benefits begin to occur.

from the production of 1 GJ of energy per year for a 100-year period (landscape-scale analysis). All modeling was performed using SAS 9.3 (SAS Institute Inc., Cary, NC, USA).

Our forest C analysis assumes constant soil C stocks although in theory a certain fraction of the deadwood decaying on the ground should eventually contribute to the soil C stock. Hence, some modeling results suggest that continual residue removal may permanently reduce forest floor C storage and delay time to C parity (Repo *et al.*, 2011, 2012). However, there is little empirical support for systematic and significant long-term mineral soil C changes following harvesting across the boreal and temperate forest biomes (Johnson & Curtis, 2001; Nave *et al.*, 2010; Thiffault *et al.*, 2011). In addition, forest floor C is usually quickly replenished as the forest regenerates (Nave *et al.*, 2010). In our opinion, additional research assessing long-term impact of residue removal on soil C is still warranted to consider with confidence soil C dynamics in forest bioenergy C accounting studies.

Forest carbon dynamics in bioenergy and counterfactual scenarios

Harvest residues. Harvest residues are defined as all woody debris generated in harvest operations for traditional wood products (e.g., branches, tree tops, bark), excluding stumps and downed nonmerchantable trees. Harvest residues can be left on site to decompose or, as it is still the practice in parts of Canada, they can be piled by the roadside and burned under controlled conditions to reduce the fire hazard. In the case in which unused residues are burned by the roadside, the CO_2 release from these residues happens nearly at the same time whether the energy is generated from biomass or from fossil fuel, with no consequences for time to C parity. Combustion of the residues burned by the roadside is assumed to be complete although some fraction may contribute to the soil C pool in the form of charcoal. In the case in which harvest residues are not harvested for bioenergy and left on site to decompose, the multiyear delay in the release of CO_2 must be accounted for in the GHG comparison between bioenergy and fossil fuel scenarios. In our calculator, we used the following exponential decay function to express CO_2 release over time:

$$C_{t\,\mathrm{WD}} = C_{0\,\mathrm{WD}} \times e^{-k \times t}, \tag{2}$$

where $C_{t\ \mathrm{WD}}$ is the quantity of C (kg CO_2) stored in woody debris at time t (years), $C_{0\ \mathrm{WD}}$ is the initial quantity of C stored in woody debris (kg CO_2), and k is the decomposition rate of woody debris (year^{-1}). Because temperature is the main driver of decomposition rates in these forests (Litton & Giardina, 2008; Laganière *et al.*, 2012), we used the temperature-dependent decay function of the Canadian forest C budget model CBM-CFS3 (Kurz *et al.*, 2009) to compute the decay rate (year^{-1}) across the range of temperatures found in the Canadian managed forest:

$$k = \mathrm{BDR}_k \times \mathrm{TempMod}, \tag{3}$$

where BDR_k is the base decomposition rate of woody debris (aboveground fast pool = 0.1435 year^{-1}) at a reference MAT of 10 °C, and TempMod is the temperature modifier that reduces the decay rate for MAT below the reference MAT and is calculated as:

$$\mathrm{TempMod} = e^{((\mathrm{MAT}_f - \mathrm{RefMAT}) \times \ln(Q_{10}) \times 0.1)}, \tag{4}$$

where MAT_f is the MAT of the forest area (−1 to 5 °C in Canada's managed forest), RefMAT is the reference MAT of 10 °C, and Q_{10} is the temperature sensitivity of decomposition set at 2. Because BDR_k varies markedly among tree species (Tarasov & Birdsey, 2001; Brais *et al.*, 2006; Shorohova & Kapitsa, 2014), we performed a sensitivity analysis on this parameter.

Salvaged trees. In scenarios sourcing their biomass from salvaged trees (i.e., standing trees killed by natural disturbances), the stemwood is harvested for bioenergy while the residues are left on site (i.e., the fate of the residues is not considered in the accounting). In the counterfactual scenario, the standing dead trees (i.e., snags) are assumed to start decaying immediately after tree death at a BDR_k of 0.0187 year^{-1} (Kurz *et al.*, 2009) following Eqn. 2, until they fall to the ground following Eqn 5, where they start to decay at a BDR_k of 0.0374 year^{-1} (Kurz *et al.*, 2009) following Eqn 2. The equation for snag C transfer to the ground is as follows:

$$C_{t\,\mathrm{snag}} = C_{0\,\mathrm{snag}} \times e^{-\mathrm{CTR} \times t}, \tag{5}$$

where $C_{t\ \mathrm{snag}}$ is the quantity of C (kg CO_2) stored in snags (standing woody debris) at time t (years), $C_{0\ \mathrm{snag}}$ is the initial quantity of C stored in snags (kg CO_2), and CTR is the C transfer rate of snags (year^{-1}) that varies between 0.04 and 0.10 (Hilger *et al.*, 2012).

Green trees. In scenarios sourcing their biomass from green trees (living biomass), we assume that only the stemwood is harvested for bioenergy (tree tops and branches are left on site) and that no harvesting is carried out and there is only a negligible risk of disturbance in the reference forest in the counterfactual scenario. Because we consider harvesting of green trees for bioenergy to complement, not to compete with, that for traditional forest products, harvesting of green trees for bioenergy is viewed as 'additional harvesting' meaning that this feedstock would not be used in the counterfactual scenario due to various reasons (e.g., species unused by the traditional forest industry, fiber quality unsuitable for traditional products but suitable for bioenergy). Scenarios where the feedstock competes for its use (bioenergy vs. traditional products) were not explored in the current study.

The time required for the forest C of the bioenergy system to balance itself with that of the fossil fuel system depends on the regeneration rate of the harvested forest and also on the rate at which the forest continues to grow in the counterfactual scenario. We define three generic forest growth curves: fast, medium, and slow, reaching an age of maximum mean annual increment (MAI) at 45, 75, and 120 years, respectively (Fig. S2). We assume that a forest is harvested at age of maximum MAI. The time required to reach maximum MAI following harvesting is the time required for the harvested forest to recapture all of the biogenic CO_2 emitted in a year from the combustion of 1 GJ of biomass (112 kg CO_2). Using this approach, we can convert absolute stand volume (m^3 ha^{-1}) into relative measures of time required to reach the original stand volume in units of % of initial harvestable volume. To account for the growth of the reference forest that is not harvested and thus continues to sequester C, we use the portion of the curves that follows maximum MAI, that is, after reaching 100% harvested stand biomass regeneration (Fig. S2).

Upstream emissions

Biomass production in bioenergy scenarios. The GHG emissions associated with biomass production include those related to biomass collection (harvesting, forest stand renewal, and road construction/maintenance), processing (chipping and pelletization), and transportation (transport to processing plant and to local or international market). We used an emission factor of 2.63 kg CO_2eq GJ^{-1} for roundwood collection (salvaged and green trees), averaged from values found in studies on Canadian forests (i.e., Magelli *et al.*, 2009; Meil *et al.*, 2009; McKechnie *et al.*, 2011; Pa *et al.*, 2012; Lamers *et al.*, 2014). For harvest residue collection, we used 0.84 kg CO_2eq GJ^{-1}, as in McKechnie *et al.* (2011). For roundwood and harvest residue chipping, we used 0.76 kg CO_2eq GJ^{-1} and 0.05 kg CO_2eq GJ^{-1}, respectively, as in Lamers *et al.* (2014). For the pelletization process, which includes drying, milling, and pelletizing, we used 2.14 kg CO_2eq GJ^{-1} for pellets made from harvest residues, and 10.45 kg CO_2eq GJ^{-1} for pellets made from roundwood (i.e., salvaged and green trees), as in Lamers *et al.* (2014).

Fossil fuel production in counterfactual scenarios. Upstream emissions for fossil fuels include extraction, distribution and storage, production, transmission, land-use changes, gas leaks, and flares. Emission factors used for coal, oil, and natural gas were 6.4, 14.9, and 9.0 kg CO_2eq GJ^{-1}, respectively ($(S\&T)^2$, 2015).

Energy use

For coal, oil, and natural gas combustion, we used the following emission factors: 90.6, 71.1, and 50.3 kg CO_2eq GJ^{-1}, respectively ($(S\&T)^2$, 2015). For wood biomass, we used the default IPCC emission factor of 112.0 kg CO_2eq GJ^{-1} IPCC (2006). The conversion efficiency factors used for heat and electricity were 75% and 26% for biomass, 80% and 33% for coal, 82% and 35% for oil, and 85% and 45% for natural gas, respectively ($(S\&T)^2$, 2015).

Scenario development (parameters and definition of uncertainty)

We calculated C parity time (in years) and potential emission reductions (in kg CO_2 GJ^{-1}) of forest bioenergy sourced from different feedstocks (harvest residues, salvaged trees, or green trees) to replace three fossil fuel types (coal, oil, or natural gas) for two uses (heating or power generation). An uncertainty period was defined as the range in C parity times between predefined best-case (shortest C parity time) and worst-case (longest C parity time) scenarios for each scenario, with several potential cases lying in between (Fig. 2). To define the two end cases, we varied model parameters, including transportation distance to final users (local use or exportation), biomass processing (chips or pellets), and environmental characteristics (i.e., MAT, C transfer rate from snags to the ground). For example, for scenarios using harvest residues as feedstock, the best case implied: (i) collection of residues in the warmer part of our study area (MAT = 5 °C; the decomposition rate of residues left on site in the counterfactual scenario is high); (ii) processing into wood chips; and (iii) local use of wood chips (100 km of truck transport to final user). The worst case implied: (i) collection of residues in the colder part of the study area (MAT = –1 °C, which translates into a slow decomposition rate for biomass left on site in the counterfactual scenario); (ii) processing into pellets, which produces additional emissions

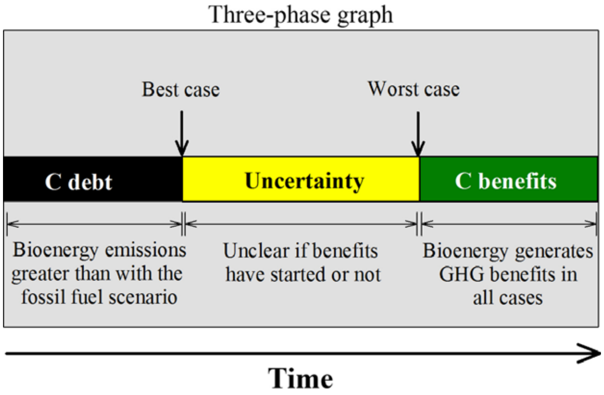

Fig. 2 Three-phase graph used in the current study to represent estimates of C parity time and the associated uncertainty phase.

relative to wood chips; and (iii) transoceanic shipping from British Columbia to the United Kingdom (100 km by truck, 1000 km by train, and 16 000 km by vessel). Therefore, there are two types of parameters contributing to uncertainty: those based on choices related to the supply chain (i.e., transportation distance and biomass processing), and those based on variable ecological processes or environmental characteristics. Feedstock-specific details on the parameters defining the different cases are found above.

Sensitivity analysis

A sensitivity analysis was performed on a set of bioenergy scenarios substituting coal in power production. We investigated how silviculture, energy conversion efficiency, and deadwood decay rate affected the performance of these scenarios (timing and uncertainty).

Silviculture. Because silvicultural operations (e.g., site preparation, tree planting, weed control) that increase tree growth following harvesting are widespread in Canada, we added scenarios where tree growth rate in the bioenergy system was 1.5 (Growth ×1.5), 2 (Growth ×2), and 2.5 (Growth ×2.5) times higher than that in the counterfactual fossil fuel system. In other words, age of maximum MAI of the forest is reduced by 1.5, 2, or 2.5 times in the bioenergy system relative to that in the counterfactual one. These estimates of potential growth increases via silviculture are conservative considering that the average timber yield in Canada forest is around 1 m^3 ha^{-1} yr^{-1} while that of extensive plantations in Canada usually reaches 2–6 m^3 ha^{-1} yr^{-1} (Messier *et al.*, 2003; Paquette & Messier, 2010). Although regeneration failure (i.e., when predisturbance biomass levels are never recovered without proper forest management) may happen following clear-cut or natural disturbance (Lecomte *et al.*, 2006; Thiffault *et al.*, 2013), this possibility was not explored in the present study.

Conversion efficiency. We investigated how electricity conversion efficiency may affect timing and the uncertainty period by increasing the parameter from 26% to 35%, by 3% increments.

Decay rate of woody debris. Because the default base decomposition rate of CBM-CFS3 represents an average value that does not necessarily capture all the variability in decay rates among tree species across Canada, we performed a sensitivity analysis on selected scenarios (i.e., harvest residues and salvaged trees replacing coal in electricity generation) with elevated BDR_k (i.e., decomposition rate doubled or tripled) to reflect the faster decay rates of intolerant hardwood species such as aspen and birch (Tarasov & Birdsey, 2001; Brais *et al.*, 2006; Shorohova & Kapitsa, 2014). These tree species usually have a low economic value and are often viewed as nonmerchantable by the industrial forest sector of timber and pulp.

Results

The uncertainty phase

The estimate of C parity time follows three temporal phases (Fig. 2): (i) a phase of C debt representing the period of time during which all cases for a given scenario, even the best case, do not provide any C benefits; (ii) a phase of C parity uncertainty, representing the range of C parity values between the best and the worst cases; and (iii) a phase of C benefits for all cases, during which even the worst cases provide C benefits. The length of the second phase, C parity uncertainty, during which it is unclear whether the benefits have started or not, varies from a few years to several decades and depends on the bioenergy feedstock, the type of fossil fuel replaced, silvicultural practices, energy conversion efficiency, and environmental characteristics. As shown in Fig. 3, the

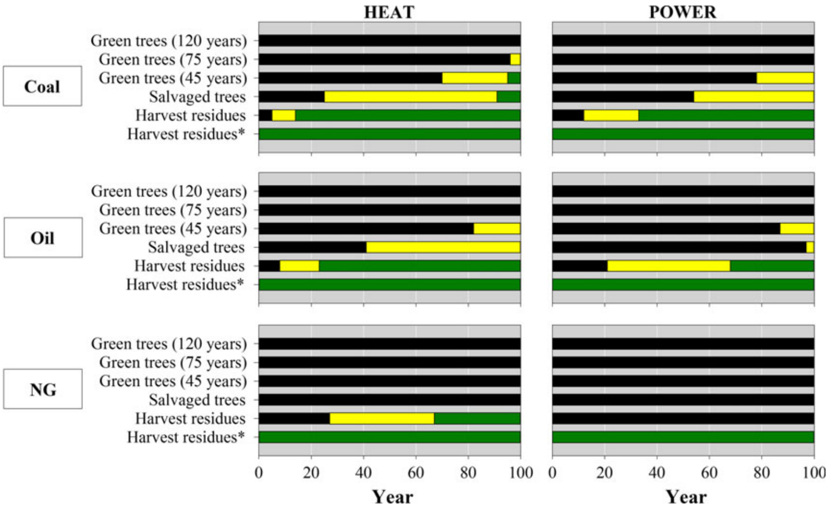

Fig. 3 Length of the C debt (black), uncertainty (yellow), and C benefit (green) phases for scenarios using different bioenergy feedstock to replace different fossil fuels for heat and power production. The asterisk indicates that harvest residues are burned by the roadside instead of left to decompose on the harvest site in the counterfactual scenario. NG: natural gas.

uncertainty is usually small for harvest residues, intermediate for green trees, and large for salvaged trees, and it increases with the efficiency of the fossil fuel in the following order: coal < oil < natural gas.

The effect of biomass feedstock, type of fossil fuel replaced, and energy use

Substitution of coal by forest bioenergy generates GHG emission savings over the shortest time frame, followed by oil and natural gas (Table 1; Fig. 3). Except for some residue-based cases (i.e., heat generation), substitution of natural gas by forest bioenergy does not provide any atmospheric benefits within a 100-year period.

Immediate C benefits occur when bioenergy is sourced from residues normally burned by the roadside, irrespective of the choices in model parameters (Table 1; Fig. 3). Cumulative CO_2 emissions saved after 100 years vary from 4.6 to 11.8 Mg GJ^{-1} for heat generation and from 6.5 to 28.6 Mg GJ^{-1} for power production, depending on

Table 1 Range of C parity time, uncertainty phase, and C balance for each best- and worst-case bioenergy scenario

Scenario			Carbon parity time (year)	Uncertainty phase (year)	Carbon balance (Kg GJ^{-1})		
Feedstock	Fossil fuel	Use			25 years	50 years	100 years
Harvest residues*	Coal	Heat	0	0	−**2449** to −**2 962**	−**4897** to −**5 923**	−**9795** to −**11 846**
Harvest residues	Coal	Heat	5–14	9	−**571** to −**1520**	−**2478** to −**4 152**	−**6839** to −**9 600**
Salvaged trees	Coal	Heat	25–91	66	1130 to −**11**	1249 to −**1327**	−**426** to −**5592**
Green trees (45 years)	Coal	Heat	70–95	25	1914–1124	2487–907	−**778** to −**3938**
Green trees (75 years)	Coal	Heat	96–>100	>4	1980–1190	3379–1799	2894 to −**265**
Green trees (120 years)	Coal	Heat	>100	>0	1886–1096	3768–2189	4917–1757
Harvest residues*	Coal	Power	0–0	0	−**5668** to −**7148**	−**11 336** to −**14 295**	−**22 672** to −**28 590**
Harvest residues	Coal	Power	12–33	21	604 to −**1932**	−**2030** to −**6561**	−**8626** to −**16 264**
Salvaged trees	Coal	Power	54–>100	>46	4893–1764	7337–364	7585 to −**6394**
Green trees (45 years)	Coal	Power	78–>100	>22	6540–4261	8764–4207	−**67** to −**9181**
Green trees (75 years)	Coal	Power	>100	>0	6871–4593	11 767–7209	11 651–2536
Green trees (120 years)	Coal	Power	>100	>0	6713–4434	13 243–8686	18 484–9370
Harvest residues*	Oil	Heat	0	0	−**2039** to −**2552**	−**4078** to −**5104**	−**8156** to −**10 208**
Harvest residues	Oil	Heat	8–23	15	−**116** to −**1054**	−**1535** to −**3194**	−**4908** to −**7652**
Salvaged trees	Oil	Heat	41–>100	>59	1552–420	2118 to −**434**	1384 to −**3734**
Green trees (45 years)	Oil	Heat	82–>100	>18	2304–1514	3243–1663	680 to −**2480**
Green trees (75 years)	Oil	Heat	>100	>0	2377–1587	4157–2578	4412–1252
Green trees (120 yrs)	Oil	Heat	>100	>0	2289–1499	4565–2986	6487–3328
Harvest residues*	Oil	Power	0	0	−**4462** to −**5941**	−**8923** to −**11 882**	−**17 847** to −**23 765**
Harvest residues	Oil	Power	21–68	47	2068 to −**408**	1083 to −**3359**	−**2140** to −**9679**
Salvaged trees	Oil	Power	97–>100	>3	6171–3091	10 034–3198	13 382 to −**318**
Green trees (45 years)	Oil	Power	87–>100	>13	7633–5354	10 815–6258	3734 to −**5380**
Green trees (75 years)	Oil	Power	>100	>0	8007–5728	13 947–9390	15 790–6676
Green trees (120 years)	Oil	Power	>100	>0	7882–5604	15 529–10 972	22 923–13 809
Harvest residues*	Gas	Heat	0	0	−**1162** to −**1675**	−**2324** to −**3350**	−**4649** to −**6700**
Harvest residues	Gas	Heat	27–67	40	825 to −**98**	393 to −**1244**	−**988** to −**3707**
Salvaged trees	Gas	Heat	>100	>0	2447–1327	3943–1425	5133–85
Green trees (45 years)	Gas	Heat	>100	>0	3152–2363	4907–3327	3933–773
Green trees (75 years)	Gas	Heat	>100	>0	3236–2446	5854–4274	7749–4589
Green trees (120 years)	Gas	Heat	>100	>0	3157–2367	6288–4708	9899–6740
Harvest residues*	Gas	Power	0	0	−**1615** to −**3095**	−**3230** to −**6189**	−**6460** to −**12 378**
Harvest residues	Gas	Power	>100	>0	5859–3604	9343–5231	15 337–8158
Salvaged trees	Gas	Power	>100	>0	9281–6379	16 767–10 438	28 334–15 653
Green trees (45 years)	Gas	Power	>100	>0	10 063–7785	15 183–10 626	11 365–2 251
Green trees (75 years)	Gas	Power	>100	>0	10 594–8 315	18 788–14 231	24 661–15 547
Green trees (120 years)	Gas	Power	>100	>0	10 593–8315	20 760–16 203	32 896–23 782

The '>' sign is used when C parity time or uncertainty phase has reached the 100-year time boundary of this study and therefore cannot be estimated precisely. C balance with a negative sign (in bold) indicates that the bioenergy scenario generates net atmospheric benefit (sequestration) relative to the counterfactual scenario.

*Harvest residues are normally burned by the roadside in the counterfactual scenario.

the type of fossil fuel replaced (Table 1). When bioenergy is sourced from harvest residues normally left to decompose *in situ*, C parity times range from 5 to 67 years for heat generation and from 12 to over 100 years for power production, depending on the type of fossil fuel replaced (Table 1; Fig. 3). Cumulative CO_2 emissions saved after 100 years are slightly lower than in the burned residues scenarios, that is, from 0.9 to 9.6 Mg GJ^{-1} for heat generation and from no savings to 16.3 Mg GJ^{-1} for power generation (Table 1).

When bioenergy is sourced from salvaged trees, C parity times range from 25 to over 100 years for heat production and from 54 to over 100 years for power production (Table 1; Fig. 3). Cumulative CO_2 emissions saved after 100 years for salvaged trees range from no savings to 5.6 Mg GJ^{-1} for heat production and from no savings to 6.4 Mg GJ^{-1} for power production (Table 1).

When bioenergy is sourced from fast-growing trees (age of maximum MAI = 45 years), C parity times range from 70 to 95 years for heat production and from 78 to 100 years for power production (Table 1; Fig. 3). Cumulative CO_2 emissions saved after 100 years vary from 0.8 to 3.9 Mg GJ^{-1} for heat production and from 0.1 to 9.2 Mg GJ^{-1} for power production (Table 1). When medium- or slow-growing trees are used (maximum MAI of 75 and 120 years, respectively), no emission savings generally occur on a 100-year time frame, except for medium-growing trees in the coal-heating scenario.

Sensitivity analysis

When silvicultural operations resulting in 1.5-, 2-, and 2.5-fold increases in tree growth rate are carried out, time to C parity and the length of the uncertainty phase are reduced (Fig. 4). Parity times of bioenergy sourced from salvaged trees to replace coal in power generation are under 62 years for 'Growth ×1.5', under 43 years for 'Growth ×2', and under 34 years for 'Growth ×2.5' (Fig. 4), with cumulative CO_2 emissions saved reaching 26.1, 40.2, and 54.6 Mg GJ^{-1}, respectively (data not shown). When silvicultural operations are carried out, fast- and medium-growing trees may also become suitable feedstock options to achieve short- to medium-term mitigation benefits. Parity times for bioenergy sourced from fast-growing green trees are under 61 years for 'Growth ×1.5', under 44 years for 'Growth ×2', and under 33 years for 'Growth ×2.5', while parity times for bioenergy sourced from medium-growing green trees are under 92 years for 'Growth ×1.5', under 66 years for 'Growth ×2', and under 51 years for 'Growth ×2.5' (Fig. 4). Cumulative CO_2 emissions saved for 'Growth ×1.5', 'Growth ×2', and 'Growth ×2.5' reach 32.7, 54.0, and 77.6 Mg GJ^{-1}, respectively, for fast-growing trees, while they reach 12.7, 26.9, and 41.2 Mg GJ^{-1}, respectively, for medium-growing trees (data not shown).

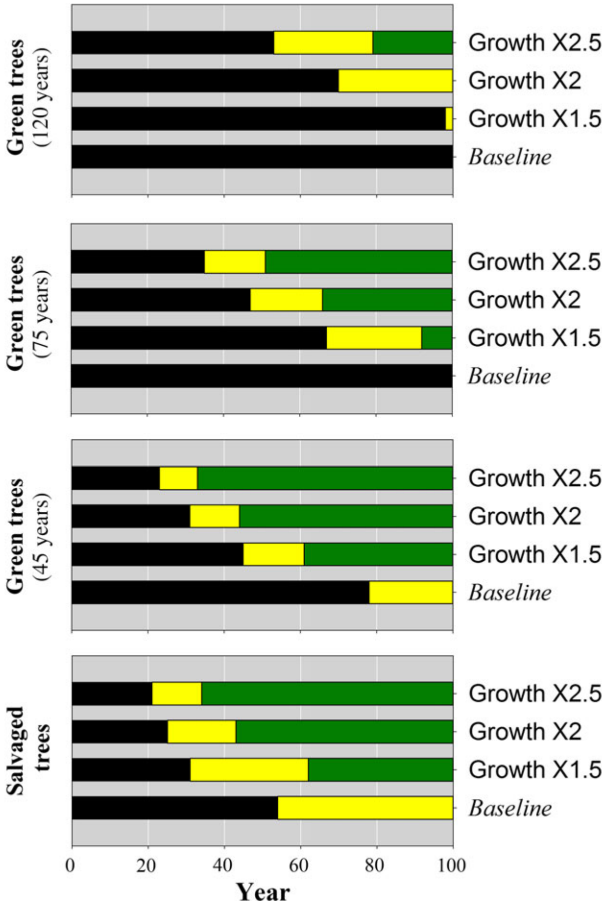

Fig. 4 Timing of GHG benefits and length of the uncertainty phase of scenarios using different bioenergy feedstock to replace coal for power production. For each feedstock, scenarios show the effect of silvicultural operations that increase the growth rate in regenerating forest stands by 1.5- (Growth ×1.5), 2- (Growth ×2), and 2.5-fold (Growth ×2.5) relative to the reference growth rate of forests in the counterfactual scenario. The 'no silviculture' scenario (baseline), in which growth rates are equal to the reference growth rate, is also shown.

Increasing energy conversion efficiency decreases time to parity of all bioenergy scenarios, but more so for salvaged trees (Fig. 5). Parity times of best-case scenarios using salvaged trees decrease from 54 years (without efficiency improvement) to 34 years with 3% improvement, to 21 years with 6% improvement, and to 12 years with 9% improvement. Moreover, improving efficiency by 9% allows the best case of the harvest residue scenario to achieve immediate benefits compared with 12 years without efficiency improvement (baseline scenario).

Increasing the basal decay rate (BDR) of the model by two and three times reduces parity time and the length

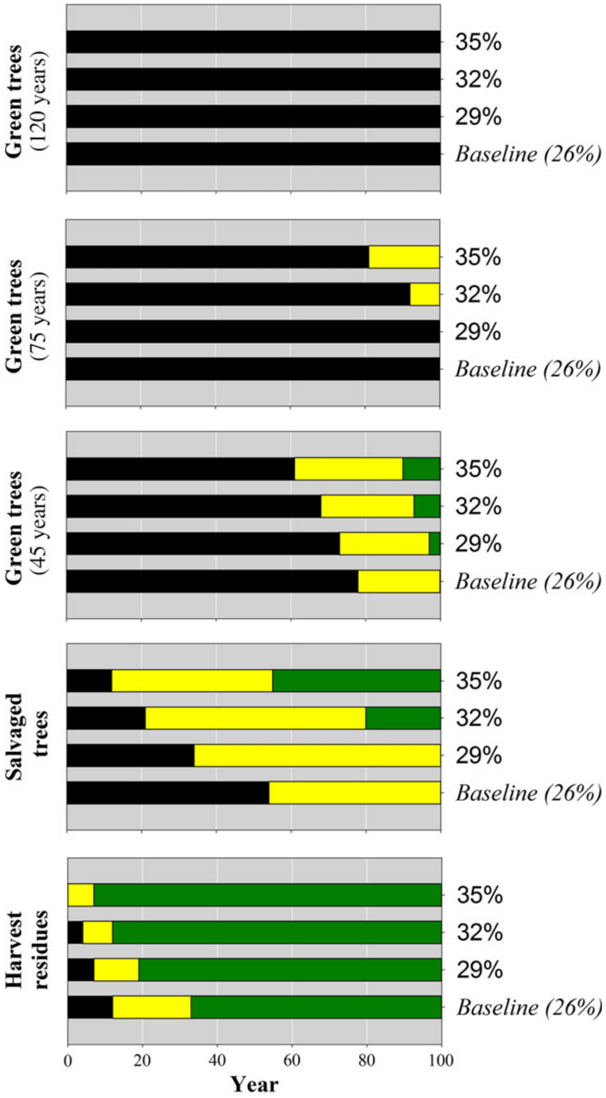

Fig. 5 Timing of GHG benefits and length of the uncertainty phase of scenarios using different bioenergy feedstock to replace coal for power production. For each feedstock, scenarios show the effect of enhanced energy conversion efficiency of biomass relative to a baseline value.

of the uncertainty phase (Fig. 6), but not as much as does the improvement of conversion efficiency (Fig. 5). Increasing conversion efficiency by 9% has a more beneficial effect on the reduction of C parity time of harvest residues than tripling the BDR.

Decomposing the uncertainty

In a scenario using salvaged trees to replace coal in power generation, the key parameters to reducing the length of the uncertainty phase and C parity time in the worst case are, in decreasing order of importance, transportation distance (local use vs. export), feedstock processing (chips vs. pellets), and mean annual temperature (MAT = 5 vs. −1 °C), whereas the rate of C transfer from snag to the ground (CTR = 0.10 vs. 0.04 year^{-1}) only has a minor effect (Fig. 7). This ranking is also true for scenarios involving different feedstock sources, fossil fuel types, and uses (results not shown).

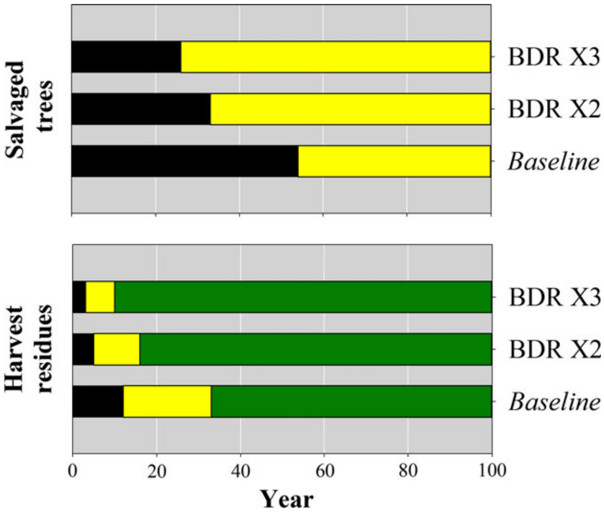

Fig. 6 Timing of GHG benefits and length of the uncertainty phase of scenarios using salvaged trees and harvest residues as bioenergy feedstock to replace coal for power production. For each feedstock, scenarios show the effect of doubling and tripling the basal decay rate (BDR) of the model relative to the baseline rate to account for tree species decaying faster than average. BDR of the baseline scenario at a reference temperature of 10 °C is 0.144 and 0.037 year^{-1} for residues and salvaged trees, respectively.

Discussion

Mitigation potential and timing of bioenergy sourced from Canadian forests

Biomass feedstock and the type of fossil fuel replaced greatly affect the GHG mitigation potential and timing of forest bioenergy scenarios. The results indicate short-to-long ranking of parity times for residues < salvaged < green trees and for replacing the less efficient fossil fuels (coal < oil < natural gas). Not surprisingly, bioenergy sourced from harvest residues yielded the fastest atmospheric benefits. The uncertainty around the estimate of C parity time was also the smallest. Most studies documented parity times <20 years for bioenergy sourced from harvest residues excluding stumps (Repo *et al.*, 2011, 2012; Lamers & Junginger, 2013; Lamers *et al.*, 2014). Branches and tree tops are small woody debris that quickly decompose on the forest floor (Tarasov & Birdsey, 2001; Palviainen *et al.*, 2004; Preston *et al.*, 2012), and the parity time between the

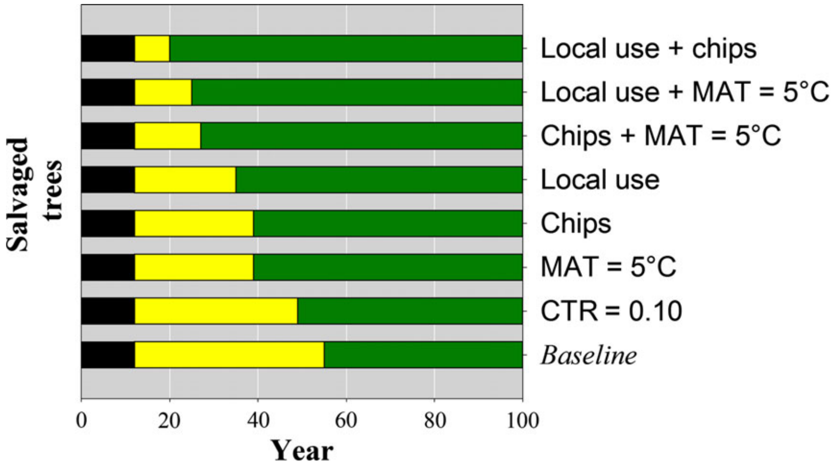

Fig. 7 Length of the uncertainty phase of scenarios using salvaged trees as bioenergy feedstock (with elevated conversion efficiency of 35%) to replace coal for power production. Uncertainty is generated through choices in parameter values for snag C transfer rates (CTR = 0.10 or 0.04 year^{-1}), mean annual temperatures (MAT = 5 °C or −1 °C), biomass processing (chips or pellets), and transportation distances (local use or export). Scenarios are identified by which parameters are set as fixed while all others are varied to generate the uncertainty. For the baseline, all parameters are varied.

bioenergy system, in which biomass emits C to the atmosphere to produce energy, and the reference fossil fuel system, in which biomass is left to decompose in the forest, is therefore quickly reached. Furthermore, in the case of harvest residues that are normally burned by the roadside to reduce the fire hazard, the use of bioenergy to replace fossil fuel generates immediate atmospheric benefits (C parity time = 0 year). Likewise, increasing biomass conversion efficiency to 35% can generate immediate benefits in some cases of harvest residues normally left to decompose *in situ*. Given that the environmental cost of delaying GHG emission reductions is increasingly being recognized (IPCC, 2014), residue-based bioenergy therefore is a suitable feedstock for mitigating GHG emissions in a short time frame.

By contrast, using medium- and slow-growing green trees showed little to no atmospheric benefits over the 100-year period. In northern forests, trees grow slowly and harvested lands usually take many decades to regenerate and regain C levels that are similar to pre-harvest levels (Seely *et al*., 2002; Kurz *et al*., 2013). Furthermore, when the reference forest is assumed to be unharvested in the counterfactual scenario, CO_2 may still be taken up from the atmosphere while the land harvested for bioenergy slowly starts to regenerate. Accordingly, C parity time for procuring biomass from living trees takes many decades to be reached. Bernier & Paré (2013) obtained a time to C parity of over 90 years for a scenario that used wood chips from boreal tree species to replace oil in heat generation. Other studies also documented multidecadal parity times (or payback times) for bioenergy made from green trees in northern forests (McKechnie *et al*., 2011; Holtsmark, 2012; Mitchell *et al*., 2012; Ter-Mikaelian *et al*., 2015). However, using silviculture to increase tree growth rate in the regenerating stand can improve the performance of this feedstock source and generate atmospheric benefits within a shorter time frame. Silvicultural practices as seen in Canada may increase timber yield from two to six times relative to natural forests (Paquette & Messier, 2010). Higher tree productivity and faster C capture through silviculture allow to reach parity time faster. Similar conclusions were obtained by the Ter-Mikaelian *et al.* (2015) study, in which coal was replaced by wood pellets sourced from Ontario forests. Moreover, Lamers *et al.* (2014) assumed faster tree growth (2×) for replanted sites relative to natural forests and obtained a parity time of 84 years for slow-growing spruce-fir stands, which falls well within our range of parity times for a comparable scenario (the one in which bioenergy is obtained from slow-growing green trees, i.e., 120 years). In summary, while using trees is most often associated with long-term parity time, some specific cases may show parity time <50 years. These cases would involve growth enhancement by silviculture, which would happen only with bioenergy scenarios and also good growing conditions (productive stand types with relatively short rotation periods).

Salvaged trees had intermediate parity times between that of harvest residues and that of green trees. This feedstock also had a very wide phase of uncertainty, indicating that some cases present reasonable parity times that meet short- and medium-term GHG emission reduction targets, while others do not. For example, using bioenergy sourced entirely from slow-decomposing dead stemwood (e.g., pine species in cold regions) without regeneration improvement through silviculture is perhaps not an option to prioritize, given that the parity time would likely always be over 75 years. However, if silviculture is performed in the regenerating stand following harvesting and biomass procurement, this feedstock source may become more interesting in terms of C savings, with several cases falling below 40 years before achieving atmospheric benefits. Results from Lamers *et al.* (2014) also highlighted the potential of using salvage wood from MPB-impacted stands to mitigate GHG emissions. Relative to a reference 'no harvest' scenario, they obtained immediate benefits and a parity time of 22 years when pine-only (85% dead trees) and pine-dominated (62% dead trees) stands were first harvested for pellets, replanted (assuming a twofold growth yield in plantations relative to natural forest), and then harvested for sawlog timber with the residues used for pellets. Jonker *et al.* (2014) varied the forest management intensity levels and obtained >50% reduction in time to C parity in high-intensity management scenarios relative to low-intensity ones. In summary, as is the case for green trees, specific conditions need to be present to reduce the time to parity in salvaged wood scenarios. These conditions often involve silviculture. An interesting example is given in Barrette *et al.* (2013), where black spruce (*Picea mariana*) stands showed little regeneration 8 years after fire while jack pine (*Pinus banksiana*) stands showed a good regeneration. Harvesting biomass for bioenergy in the black spruce site would facilitate the silvicultural treatment carried out to restore forest productivity, while it would probably not enhance forest productivity in the jack pine site.

Increasing the base decomposition rate (BDR) of the model to account for tree species decaying faster than average indicates that sourcing bioenergy from fast-decomposing species such as intolerant hardwoods (e.g., aspen, birch) would be another potentially suitable GHG mitigation option, especially if the feedstock is collected in warmer regions. Although our knowledge of logs' decomposition rate is limited (Weedon *et al.*, 2009), empirical observations in northern forests showed that the logs of such species may achieve almost complete decomposition (85–95%) within 57 years, while pine and spruce species may take over 80 years (Tarasov & Birdsey, 2001; Brais *et al.*, 2006; Shorohova & Kapitsa, 2014).

Salvaged trees have the potential to generate relatively fast atmospheric benefits, but would require a good tracking system to reduce uncertainty and meet precise time frames. As shown in our analysis, favoring wood chips over pellets and local use over transoceanic export are good options to prioritize in order to reduce the uncertainty period. Moreover, the speed at which parity time is reached is also impacted by the regional climate and tree species, which regulate the decomposition rate of deadwood (in the counterfactual scenario). Performing silviculture and improving energy conversion efficiency can also greatly reduce the time to GHG mitigation of bioenergy sourced from dead trees.

Overall, our results are coherent with the perspective of Haberl *et al.* (2012) on C emission reduction by bioenergy. Short- to medium-term atmospheric benefits (<50 years C parity time) must involve the use of 'additional biomass', defined as biomass from additional vegetation growth or biomass that would decay rapidly if not used for bioenergy. Such parity times are possible in some cases under salvaged tree scenarios, but more likely under specific conditions involving important gains in forest productivity (silviculture) under either green tree or salvage tree scenarios.

Taking uncertainty into account

To our knowledge, few studies have addressed the uncertainty around the estimation of C debt in a forest bioenergy context (Johnson *et al.*, 2011; Caputo *et al.*, 2014; Röder *et al.*, 2015). To date, studies have mostly focused on estimating a unique and precise C debt repayment time or C parity time for particular case studies without addressing any sources of variation. For correct accounting, however, estimates need to take uncertainty into account, from variations in the biomass supply chain to the realism of the counterfactual scenario (Johnson *et al.*, 2011; Bowyer *et al.*, 2012; Buchholz *et al.*, 2014, 2015). We found that the length of the uncertainty period can be short and inconsequential for some scenarios (e.g., harvest residues). However, for other scenarios, it can be large enough to cast doubts as to whether a particular feedstock should be considered in GHG mitigation efforts in the short term. In the current study, the length of the uncertainty phase depends on how we define the best and worst cases, that is, which parameters will vary and to what extent. In our scenarios involving green trees as feedstock, only upstream emissions (processing, transport) could affect uncertainty. By contrast, for salvaged trees, upstream emissions, MAT (which impacts the decomposition rate), and snag C transfer rate all are elements whose range of possible values contributed to uncertainty. These additional sources of variation explained the longer phase of C debt uncertainty in the salvaged tree scenarios relative to the green tree scenarios, while the slower decay rate of stemwood (salvaged trees) than of branches (residues) explained the longer uncertainty phase relative to harvest residues. Varying the tree growth rate in a scenario involving green trees (instead of making separate scenarios) or adding natural disturbances (Buchholz *et al.*, 2015) would push the length of the uncertainty period for green tree-based scenarios beyond that of scenarios involving salvaged trees.

Not all sources of uncertainty were tested in our analysis. Some parameters including the emission factor for combustion of biomass and fossil fuel, fossil energy conversion efficiency, and temperature sensitivity of decomposition (Q_{10}) were set as constants, based on averaged values found in the literature. The IPCC default emission factor for biomass combustion is 112 kg CO_2 GJ^{-1}, but its 95% confidence limits range from 95 to 132 kg CO_2 GJ^{-1} (IPCC, 2006). The heating value of wood also varies among tree species (Singh & Kostecky, 1986; Telmo & Lousada, 2011; Barrette *et al.*, 2013). Similarly, energy conversion efficiency for a given fossil fuel may vary substantially depending on factors such as generator capacity, age, and technology (Koop *et al.*, 2010). Jonker *et al.* (2014) varied the conversion efficiency of a coal power plant from 35% to 46% and observed decadal differences in payback and parity times of bioenergy under low- and high-efficiency scenarios. Röder *et al.* (2015) also pointed out the impact of wood chip storage duration on methane emissions, which greatly affect the C balance of forests and sawmill residues. As we gain confidence in understanding belowground processes and long-term impact of forest harvesting intensification, soil C (which was set as constant here) may become an important parameter to consider in the C balance of forest bioenergy, given the large share of ecosystem C that resides in soils (Laganière *et al.*, 2015). These additional sources of uncertainty could make the uncertainty phase even longer than what is presented here. Evidently, proper knowledge of both the bioenergy and the reference fossil fuel systems is required in order to accurately evaluate the potential of a bioenergy project to mitigate GHG emissions.

Key to reducing uncertainty around estimates of C parity time is a better assessment of ecological processes (e.g., forest regeneration and growth rate, decomposition dynamics), as also pointed out by Caputo *et al.* (2014). Favoring local use of wood chips over the export of wood pellets can also reduce the length of the uncertainty period. Potential economic feedback between biomass procurement practices and other forest management activities should also be considered: Adding bioenergy to the basket of products that can be sourced from a given stand or landscape may increase the profitability of overall forest operations and foresters' belief in future markets, creating new incentives for forest management (Bellassen & Luyssaert, 2014). Overall, the current study brings into question the use of single parity time values to evaluate the performance of a particular feedstock to mitigate GHG emissions given the importance of uncertainty as an inherent component of every bioenergy project. More specifically, it suggests that some feedstock, such as green or salvaged trees that are usually associated with long and uncertain time to parity, can, under some very specific circumstances, show shorter and less uncertain parity times.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Simplified supply chain and system boundary of LCA when living biomass (i.e. green trees) and deadwood (i.e. harvest residues or salvaged trees) are used as a feedstock.

Figure S2. Stand regeneration curves used in scenarios sourcing biomass from green trees. Age of maximum mean annual increment (MAI) is reach at 100%.

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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)

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

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

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

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

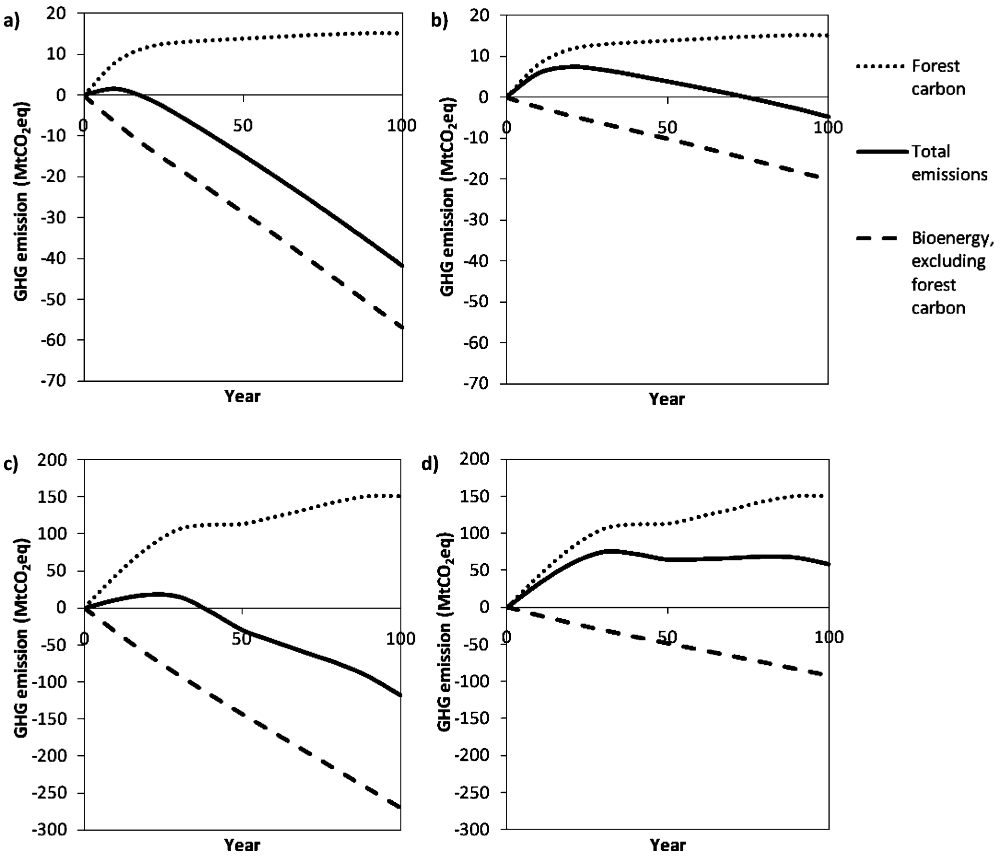

FIGURE 1. Cumulative GHG emissions from continuous biomass harvest for bioenergy production: (a) pellets produced from residues, displacing coal (20% cofiring), (b) ethanol produced from residues, displacing gasoline (E85 fuel), (c) pellets produced from standing trees, displacing coal (20% cofiring), 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_2equiv/kWh) 1039 (residue) and 1042 (standing tree) compared to 1001 for coal only. E85 would emit (all in gCO_2equiv/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.

Acknowledgments

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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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Carbon debt and carbon sequestration parity in forest bioenergy production

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Abstract

The capacity for forests to aid in climate change mitigation efforts is substantial but will ultimately depend on their management. If forests remain unharvested, they can further mitigate the increases in atmospheric CO_2 that result from fossil fuel combustion and deforestation. Alternatively, they can be harvested for bioenergy production and serve as a substitute for fossil fuels, though such a practice could reduce terrestrial C storage and thereby increase atmospheric CO_2 concentrations in the near-term. Here, we used an ecosystem simulation model to ascertain the effectiveness of using forest bioenergy as a substitute for fossil fuels, drawing from a broad range of land-use histories, harvesting regimes, ecosystem characteristics, and bioenergy conversion efficiencies. Results demonstrate that the times required for bioenergy substitutions to repay the C Debt incurred from biomass harvest are usually much shorter (< 100 years) than the time required for bioenergy production to substitute the amount of C that would be stored if the forest were left unharvested entirely, a point we refer to as C Sequestration Parity. The effectiveness of substituting woody bioenergy for fossil fuels is highly dependent on the factors that determine bioenergy conversion efficiency, such as the C emissions released during the harvest, transport, and firing of woody biomass. Consideration of the frequency and intensity of biomass harvests should also be given; performing total harvests (clear-cutting) at high-frequency may produce more bioenergy than less intensive harvesting regimes but may decrease C storage and thereby prolong the time required to achieve C Sequestration Parity.

Keywords: bioenergy, biofuel, C cycle, C sequestration, forest management

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Introduction

The search for alternatives to fossil fuel energy has yielded several possibilities, many of which are derived from biomass. Bioenergy has been viewed as a promising alternative to fossil fuels because of its capacity to increase the energy security in regions that lack petroleum reserves and because their production and combustion does not require a net transfer of C from Earth's lithosphere to its atmosphere. While bioenergy is understandably among the most heavily promoted and generously subsidized sources of renewable energy, recent research has brought greater attention to the environmental costs of broad-scale bioenergy production (Fargione *et al.*, 2008; Searchinger *et al.*, 2008, 2009) as well as the limits of how much energy it can actually produce (Field *et al.*, 2008).

One alternative to crop-based biofuels is woody biomass harvested directly from forests, an avenue thought to be more promising than harvesting non-woody species for a variety of reasons. First, woody biomass stores more potential energy per unit mass than non-woody biomass (Boundy *et al.*, 2011). Second, many forms of non-woody biomass are often utilized following a lengthy conversion process to ethanol or biodiesel, a process which results in a significant loss of potential energy of the harvested biomass (Field *et al.*, 2008) as well as additional energy that may be expended in the conversion process itself (Walker *et al.*, 2010). By contrast, woody biomass is more readily utilized for energy production without any further modifications (Richter *et al.*, 2009). Third, landscapes managed for bioenergy production using woody biomass are able to store more C per unit of land area than crop-based biofuels.

Woody biomass is already a primary source of energy for 2 billion people; the FAO estimates that over half of the world's total round wood removals from forests and trees outside forests are intended for bioenergy production (FAO; Parikka, 2004). Many of these harvests are specifically intended to provide a C-neutral energy source to substitute for fossil fuels (Parikka, 2004; Richter *et al.*, 2009; Buford & Neary, 2010), yet such harvests can arrest the C sequestration of many forests far short of their full potential (Harmon *et al.*, 1990; Canadell & Raupach, 2008; Pan *et al.*, 2011). Much of the world's

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forested land area stores far less C than it potentially could (House *et al.*, 2002; Canadell & Raupach, 2008), and foregoing future harvest/s could provide a more rapid amelioration of atmospheric CO_2 then bioenergy production. A recent study conducted in US West Coast forests examined the C storage/bioenergy production trade-offs of many ecosystems and found that the current C sink for most ecosystems is so strong that it cannot be matched or exceeded through substitution of fossil fuels by forest bioenergy over the next 20 years. However, due to its reliance on existing field data instead of simulation models, it could not extrapolate these results beyond the 20-year period (Hudiburg *et al.*, 2011). Another recent study that addressed these trade-offs is the so-called 'Manomet' study, which modeled bioenergy production systems for different forest types in Massachusetts and found that utilizing forests for bioenergy production reduces C storage without providing an equitable substitution in the near-term (Walker *et al.*, 2010). However, the approach taken by the 'Manomet' study dealt short-term repayment in C Debts at the stand level, while our approach focuses on the C Debt that is incurred as a result harvesting forests for bioenergy production over the long-term at the landscape level. We provide further description of our concept of C Debt *sensu* Fargione *et al.* (2008) by contrasting it with what we refer to as the C Sequestration Parity, which we outline in the discussion below.

Carbon debt

Compared to fossil fuels, woody biomass yields a lower amount of energy per unit mass of C emitted. Since biomass harvesting reduces C storage but does not produce the same amount of energy that would be obtained from an equal amount of C emissions from fossil fuel combustion, recouping losses in C storage through bioenergy production may require many years. We refer to this recoupment as the *C Debt Repayment*, calculated as the change in C storage resulting from bioenergy harvests and associated C substitution, demonstrated in Fig. 1. A mathematical representation is given below in Eqn (1), where $C^{\mathrm{m}}_{\mathrm{storage}(t)}$ is the amount of C stored in a managed forest at time t, $C^{\mathrm{m}}_{\mathrm{storage}(0)}$ is the amount of C stored in a managed forest at $t = 0$ (before bioenergy harvests have begun), and $C^{\mathrm{m}}_{\mathrm{harvest}(t)}$ is the amount of C biomass harvested from a managed forest at time t, which is multiplied by the bioenergy conversion factor $\eta_{biomass}$:

$$C^{\mathrm{m}}_{\mathrm{debt}(t)} = C^{\mathrm{m}}_{\mathrm{storage}(t)} - C^{\mathrm{m}}_{\mathrm{storage}(0)} - \sum_{t=1}^{n} C^{\mathrm{m}}_{\mathrm{harvest}(t)} \times \eta_{\mathrm{biomass}} \tag{1}$$

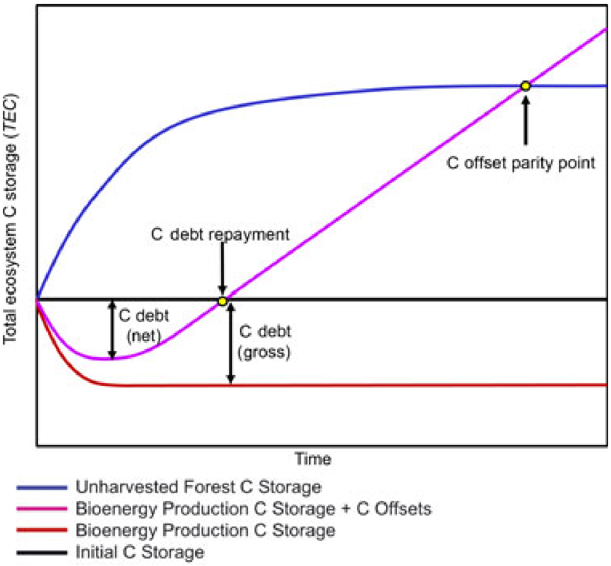

Fig. 1 Conceptual representation of C Debt Repayment vs. the C Sequestration Parity Point. C Debt (Gross) is the difference between the initial C Storage and the C storage of a stand (or landscape) managed for bioenergy production. C Debt (Net) is C Debt (Gross) + C substitutions resulting from bioenergy production.

Carbon sequestration parity

A repayment of the C Debt does not necessarily imply that the forest has been managed for maximal amelioration of atmospheric CO_2. If a forest is managed for the production of bioenergy to substitute for traditional fossil fuel energy as part of an effort to ameliorate atmospheric CO_2 concentrations, such a strategy should be gauged by the climate change mitigation benefits that would accrue by simply leaving the forest unharvested. Ascertaining the point at which a given strategy provides the maximal amount of climate change mitigation benefits requires accounting for the amount of biomass harvested from a forest under a given management regime, the amount of C stored under a given management regime, and the amount of C that would be stored if the forest were to remain unharvested (Schlamadinger & Marland, 1996a,b,c; Marland & Schlamadinger, 1997; Marland *et al.*, 2007). It is expected that a forest that is continuously managed for bioenergy production will eventually produce enough bioenergy to 'recoup' the associated loss in C storage (the so-called carbon debt) through the substitution of bioenergy for fossil fuel energy. However, the ultimate effectiveness of this strategy should be determined by the amount of time required for the sum of the total ecosystem C storage and bioenergy C substitution to exceed the amount of C that would be stored if that same forest were to remain unharvested (Fig. 1). We refer to this difference as the C sequestration differential ($C^{m}_{\mathrm{differential}(t)}$), illustrated in Eqn (2) below:

$$C^{m}_{\mathrm{differential}(t)} = C^{u}_{\mathrm{storage}(t)} - C^{m}_{\mathrm{storage}(t)} - \sum_{t=1}^{n} C^{m}_{\mathrm{harvest}(t)} \times \eta_{\mathrm{biomass}} \tag{2}$$

where $C^{u}_{\mathrm{storage}(t)}$ is the amount of C stored in an *unmanaged* forest at time *t*. We refer to the crossing of this threshold as the point of *C Sequestration Parity*. Thus, we make a distinction between the amount of time required for the bioenergy production system to recoup any reductions in C storage resulting from bioenergy production (C Debt repayment) and the amount of time required for the bioenergy production system to equal the C than would be stored if the forest were to remain unharvested (C Sequestration Parity Point), as the latter represents a more ambitious climate change mitigation strategy (Fig. 1).

Materials and methods

We simulated the growth and harvest of woody biomass using a significantly updated version of the ecosystem simulation model LANDCARB (Harmon, 2012). LANDCARB is a landscape-level ecosystem process model that can simulate a full spectrum of potential harvesting regimes while tracking the amount of material harvested, allowing one to simulate ecosystem C storage while tracking the amount of fossil fuel C that could be substituted by using harvested materials as biomass fuels. LANDCARB integrates climate-driven growth and decomposition processes with species-specific rates of senescence and mortality while incorporating the dynamics of inter- and intra-specific competition that characterize forest gap dynamics. Inter- and intra-specific competition dynamics are accounted for by modeling species-specific responses to solar radiation as a function of each species' light compensation point and assuming light is delineated through foliage following a Beer-Lambert function. By incorporating these dynamics the model simulates successional changes as one life-form replaces another, thereby representing the associated changes in ecosystem processes that result from species-specific rates of growth, senescence, mortality, and decomposition.

LANDCARB represents stands on a cell-by-cell basis, with the aggregated matrix of stand cells representing an entire landscape. Each cell in LANDCARB simulates a number of cohorts that represent different episodes of disturbance and colonization within a stand. Each cohort contains up to four layers of vegetation (upper tree layer, lower tree layer, shrub, and herb) that each have up to seven live pools, eight dead pools, and three stable pools. For example, the upper and lower tree layers are comprised of seven live pools: foliage, fine-roots, branches, sapwood, heartwood, coarse-roots, and heart-rot, all of which are transferred to the appropriate dead pool following mortality. Dead sapwood and dead heartwood can be either standing or downed to account for the different microclimates of these positions. Dead pools in a cell can potentially contribute material to three, relatively decay-resistant, stable C pools: stable foliage, stable wood, and stable soil. There are also two pools representing charcoal (surface and buried).

Our modeling approach with LANDCARB was designed to account for a broad range of ecosystem characteristics and initial landscape conditions of a forest, both of which are influential in determining rate of C debt repayment and the time required for C sequestration parity. Forests with high productivity can generate fossil fuel substitutions more rapidly than forests with low productivity. Conversely, forests with high-longevity biomass raise the C storage of the ecosystem (Olson, 1963), which has implications for C debt and C sequestration parity. Furthermore, forests can contain a wide range of C stores even within a fixed range of productivity and C longevity (i.e., lower rates of mortality and decomposition; Smithwick *et al.*, 2007), yet we know of no study to date that has examined the impact of forest productivity and biomass longevity on C Debt repayment or C Sequestration Parity. Furthermore, we know of no previous study that examines a sufficiently large range of forest management strategies and land-use histories to ascertain exactly what sort of situation/s might provide for an efficient utilization of forest biomass for bioenergy production.

To provide a more comprehensive evaluation of the effectiveness of utilizing forest bioenergy as a substitute for fossil fuels, we performed our analysis across a wide range of ecosystem properties by simulating three levels of forest growth and three levels of biomass longevity, resulting in nine distinct ecosystems (Table 1). Levels of longevity were drawn from published rates of bole growth efficiency, mortality, and decomposition (growth and biomass Harmon *et al.*, 2005). The upper and lower bounds of these parameters were intended to cover the range of these processes for most of the world's temperate forests. Our parameters are largely drawn from forests of the US Pacific Northwest, but the extreme values of bole growth efficiency, mortality, and decomposition could be considered extreme values of other forests as well, thereby giving our results maximal applicability.

We ran each of our nine simulated ecosystems under four sets of initial landscape conditions: afforesting post-agricultural land (age = 0), forest recovering from a severe disturbance (age = 0), old-growth forest (age > 200 years), and a forest harvested on a 50-year rotation (mean age ~25 years). Each combination of ecosystem characteristics and land-use history was simulated with seven different management strategies (Table 2), which included one unharvested control group as well as three biomass harvest frequencies (25, 50, 100 years) applied at two different harvest intensities (50% harvest of live stems, 100% harvest of live stems). We assumed that our post-agricultural landscape did not have any legacy C storage apart from a small amount of soil C, thus our post-agricultural simulation did not have any spin-up simulation. However, simulations of the other land-use histories all had a 500-year spin-up simulation were run to establish initial live, dead, and soil C stores. Additionally, for the two simulations that were recovering from harvests and prior disturbance (recently disturbed and rotation forest) we tracked the respective C stores from these events. To simulate a landscape that had previously been harvested on a 50-year rotation, we simulated an annual clearcut on 2% of the landscape throughout the 50 years prior to the

Table 1 Table of selected growth, mortality, and decomposition characterstics for each of our nine ecosystems. Classifications G1, G2, and G3 represent increasing growth rates, represented by the Site Index. L1, L2, and L3 represent increasing biomass longevities. The group with the lowest potential C storage had the lowest growth rate (G1) combined with the highest rates of mortality and decomposition that yielded the lowest rates of biomass longevity (L1). The upper and lower bounds of our rates of growth and longevity were intended to cover the range of these processes for most of the world's forests, thereby giving our results maximal applicability. Thus, the group referred to as G1-L1 is the group with the lowest potential C storage, while the group referred to as G3-L3 has the highest potential C storage. Also note that L1 and L3 values represent extreme values of mortality and decomposition, whereas L2 represents a median value, rather than a midpoint between L1 and L3. $\text{Mortality}_{\text{MAX}}$ is the maximum rate of mortality, while k_{Foliage} and $k_{\text{Heartwood}}$ are decomposition constants for foliage and heartwood. Potential C Storage is the mean amount of C storage of an old-growth stand under these characteristics, as measured over a 500 year interval

Group	Bole growth efficiency +ΔMg Stem C/+ΔMg Leaf C)	$\text{Mortality}_{\text{MAX}}$ (yr^{-1})	k_{Foliage} (yr^{-1})	$k_{\text{Heartwood}}$ (yr^{-1})	Potential C storage (Mg C ha^{-1})
G1-L1	0.35	0.03	0.25	0.1	212
G1-L2	0.35	0.02	0.2	0.02	230
G1-L3	0.35	0.01	0.15	0.01	296
G2-L1	0.54	0.03	0.25	0.1	359
G2-L2	0.54	0.02	0.2	0.02	492
G2-L3	0.54	0.01	0.15	0.01	621
G3-L1	0.84	0.03	0.25	0.1	645
G3-L2	0.84	0.02	0.2	0.02	757
G3-L3	0.84	0.01	0.15	0.01	954

Table 2 List of all bioenergy production system characteristics simulated. We incorporated four land-use histories, three levels of biomass accumulation, three levels of biomass longevity, three different harvest frequencies and two levels of harvest intensity

Land-use histories	Growth rates	Biomass longevities	Harvest frequencies	Harvest intensities
Post-agricultural (age = 0)	G1*	L1*	100 (100Y)	50% (050H)
Recently disturbed (age = 0)	G2*	L2*	50 (50Y)	100% (100H)
Rotation forest (age ~25)	G3*	L3*	25 (25Y)	
Old-growth (age > 200)				

*See Table 1 for details.

completion of the spin-up. In accordance with a prior framework for harvested C decomposition, we assumed that 60% of the harvested C would go directly into long-term C storage mediums (i.e., houses, buildings) that decayed at the rate of 1% per year (Harmon & Marks, 2002). The remaining 40% of the harvested C was assumed to be lost to the atmosphere during manufacturing (Harmon & Marks, 2002). Landscapes were first harvested for bioenergy production in the year following the completion of the spin-up.

Initial conditions of our disturbed forest were analogous to those of a severe pine beetle outbreak. To simulate this condition, we initiated a total mortality of all trees at the end of the spin-up, prior to the biomass harvests. We then simulated an annual salvage logging on 5% of the landscape for each of the 5 years following the simulated pine-beetle disturbance (25% of the landscape was salvage logged). We assumed that 75% of all salvageable biomass was removed in each salvage logging. Salvageable materials harvested in the first 5 years following disturbance were assumed to be stored in wood products and subject to the same decomposition scheme outlined above for the 50-year Rotation Harvest. Such conditions are fairly similar to those in a landscape subject to a high-severity, stand-replacing wildfire, though a landscape subject to a pine beetle infestation will initially have more C storage than one experiencing a high-severity wildfire. However, this difference is temporary and would have a minimal effect on the long-term effects of biomass harvesting, thus this set of initial conditions could also be considered as a proxy for the initial conditions that would follow a high-severity wildfire.

Wildfire

Our analysis also incorporates wildfires in all simulations, not only because they are naturally occurring phenomena in many forest ecosystems, but also because amount of harvestable biomass in an ecosystem can be altered by the event of wildfire, which needs to be accounted for. In the LANDCARB model, fire severity controls the amount of live vegetation killed and the amount of combustion from the various C pools, and is influenced by the amount and type of fuel present. Fires can increase (or decrease) in severity depending on how much the weighted fuel index a given cell exceeds (or falls short of) the fuel level thresholds for each fire severity class (T_{light}, T_{medium}, T_{high}, and T_{max}) and the probability values for the increase or decrease in fire severity (P_i and P_d). For example, a low-severity fire may increase to a medium-severity fire if the fuel index sufficiently exceeds the threshold for a medium-severity fire. Fuel level thresholds were set by monitoring fuel levels in a large series of simulation runs where fires were set at very short intervals to see how low fuel levels needed to be to create a significant decrease in expected fire severity.

The fire regime for low-growth forests (G1) is characterized by a low-severity, high frequency fire regime, with a mean fire return interval (MFRI) of 16 years (Bork, 1985), similar to the fire regime in a Ponderosa pine forest, also a low-growth rate forest. Fire regimes for the medium and high-growth forests (G2, G3) consisted of high-severity, low frequency (MFRI = 250 years) fire regimes, similar to that of a Douglas-fir or Sitka spruce forest (Cissel *et al.*, 1999). We generated exponential random variables to assign the years of fire occurrence (Van Wagner, 1978) based on literature estimates (Bork, 1985) for mean fire return intervals (MFRI) for each ecosystem. The cumulative distribution for our negative exponential function is given in Eqn (1) where X is a continuous random variable defined for all possible numbers x in the probability function P and λ represents the inverse of the expected time for a fire return interval given in Eqn (2).

$$P\{X \leq x\} = \int_0^x \lambda e^{-\lambda x} \mathrm{d}x \tag{1}$$

where

$$E[X] = \frac{1}{\lambda} \tag{2}$$

Fire severities in each year generated by this function are cell-specific, as each cell is assigned a weighted fuel index calculated from fuel accumulation within that cell and the respective flammability of each fuel component, the latter of which is derived from estimates of wildfire-caused biomass consumption.

Bioenergy conversion factors

Previous studies on the mitigation potential of bioenergy have yielded conflicting conclusions about the potential for bioenergy production from woody biomass (Schlamadinger & Marland, 1996a,b,c; Marland & Schlamadinger, 1997; Marland *et al.*, 2007; Walker *et al.*, 2010). Differences in these conclusions are due, in part, to the different assumptions regarding the efficiency of bioenergy utilization. Energy is required for transporting biomass and powering bioenergy conversion facilities, and some is lost due to inefficiencies in the conversion process (Hamelinck *et al.*, 2005; Walker *et al.*, 2010). Thus, it is difficult to provide a one-size-fits-all estimate of bioenergy conversion efficiency. Rather than using one value, we will evaluate a range of bioenergy conversion efficiencies, ranging from 0.2 to 0.8, to ascertain the sensitivity of C offsetting schemes to the range in variability in the energy conversion process. We estimate the *average* bioenergy conversion factor for woody biomass ($\eta_{biomass}$) to be 0.51, meaning that harvesting 1 Mg of biomass C for bioenergy production will substitute for 0.51 Mg fossil fuel C since less energy per unit C emissions is obtainable from biomass compared to fossil fuel. Calculations for this conversion factor ($\eta_{biomass}$) are in the Supporting Information. A conversion factor of 0.8 represents a highly efficient utilization of bioenergy, though such a conversion efficiency is likely not realistic. Conversely, a conversion factor of 0.2 represents a highly inefficient method of energy utilization, though some bioenergy facilities and conversion processes do operate at this low level of efficiency (Walker *et al.*, 2010).

We ran our analysis across 252 distinct scenarios, as we had nine distinct ecosystems (based on three levels of forest growth for three levels of biomass longevity), four initial types of initial landscape conditions, and seven treatment groups (one control, plus three treatment frequencies applied at two levels of intensity). Output from the 252 distinct modeling scenarios was analyzed using seven different bioenergy conversion factors, meaning that our analysis had 1764 combinations of ecosystem properties, initial landscape conditions, harvest frequencies, and bioenergy conversion factors. Our analysis quantifies the degree to which the harvesting and utilization of forest-derived bioenergy alters the landscape-level C storage and bioenergy production in order to calculate (1) the time required for the C mitigation benefits accrued by forests managed for bioenergy production to repay the C Debt incurred from the harvest, and (2) the time required for the C mitigation benefits accrued by forests managed for bioenergy production to achieve C Sequestration Parity, the point at which the sum of forest C storage and bioenergy C substitution equals or exceeds the C mitigation benefits of a comparable forest that remained unharvested.

Results

Times required for repayment of the carbon debts

Most Post-Agricultural landscapes repaid their C debts within 1 year because their initial live C storages were low to begin with and did not require any waiting period for the repayment of their C Debt (Fig. 2). Thus, by undergoing a conversion from a Post-Agricultural landscape to a bioenergy production landscape, there was a repayment of the C Debt as well as an increase in landscape C storage. Similarly, Rotation Harvest landscapes harvested for bioenergy production every 100 years increased their C storage, as they were previously harvested at a frequency of 50 years. Most of the Rotation Harvest landscapes repaid their C Debt in a year due to their initially low live C storage, as their average stand age is ~25 years. However, some of these landscapes that were clear-cut every 50 or 25 years required much longer to repay their C Debt. Harvesting with greater frequency and intensity lowers C storage and prolongs the time needed for repayment of the C Debt; clear-cut harvests performed on Rotation Harvest landscapes every 25 years required 100 to over 1000 years to repay their C Debt. Once a landscape requires several years to repay its C Debt, it may then exhibit sensitivity to the bioenergy conversion efficiencies used to calculate rate at which it can substitute for C emissions from fossil

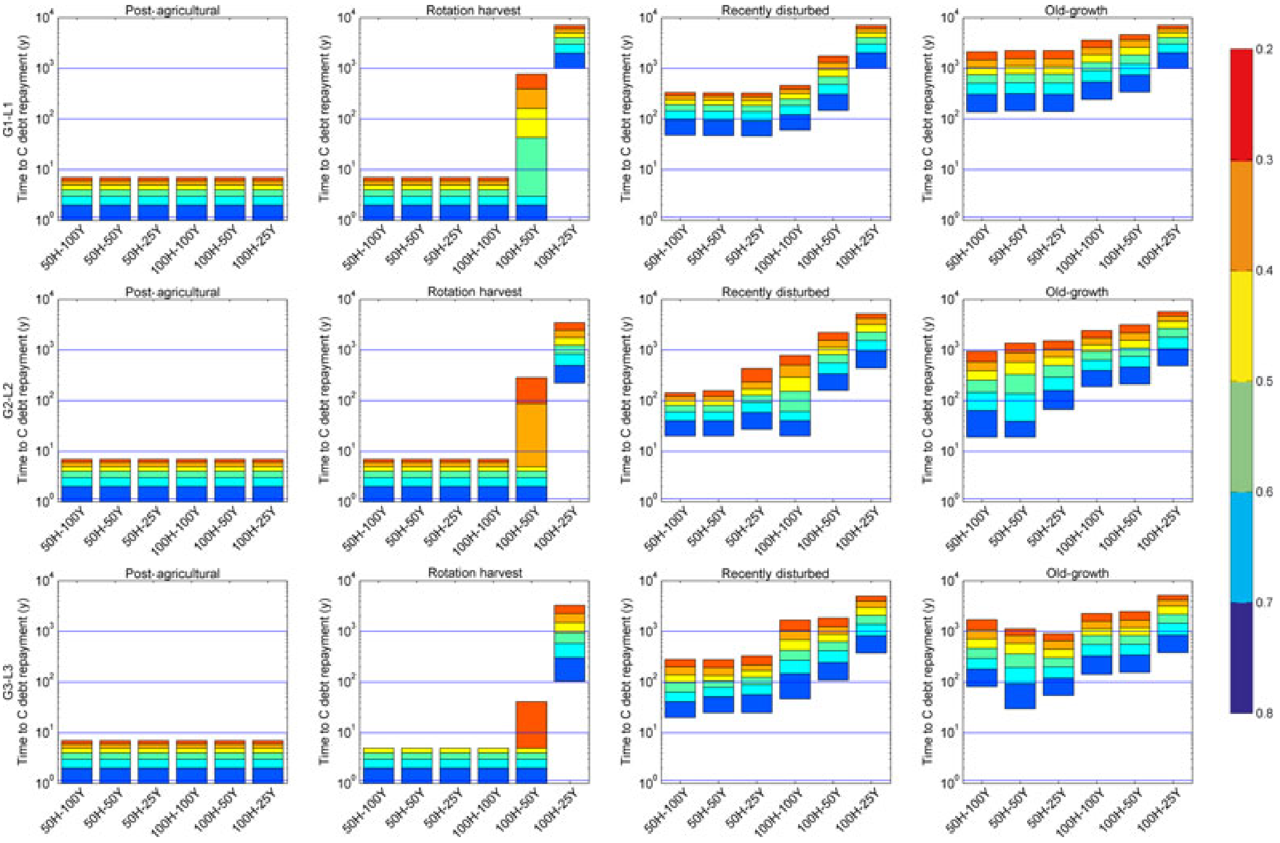

Fig. 2 Comparisons of the time required for a repayment of the C Debt Repayment among three of our nine ecosystem types, each with six biomass harvesting regimes and four land-use histories. Note that times are represented on a log scale. Different harvesting regimes are indicated on the *x*-axis, with 50% and 100% harvesting intensity represented as 50H and 100H, respectively. Harvest frequencies of 25, 50, and 100 years are represented as 25Y, 50Y, and 100Y.

fuels. Recently Disturbed landscapes required more time for a repayment of the C Debt and were much more sensitive to harvest frequency, harvest intensity, and bioenergy conversion efficiencies (Fig. 2). Following disturbance, these landscapes can store high amounts of dead C that can persist for decades. Due to low net primary production following disturbance, recovery to pre-disturbance levels of C storage can take many years, ranging from 20 to over 1000 years. Old-growth landscapes usually took the longest amount of time to repay their C debts because their initial C storages were so high, ranging from 19 to over 1000 years.

Times required to reach carbon sequestration parity

The amounts of time required for C Sequestration Parity were usually longer than the amounts of time required for a repayment of the C debt. In general, Old-Growth landscapes achieved C Sequestration Parity at a faster rate than other categories of land-use history since they have more initial biomass available for bioenergy production (Fig. 3). Recently Disturbed landscapes were the second fastest, followed by Rotation Harvest landscapes, though differences between these two categories of land-use history are relatively minor. Post-Agricultural landscapes took longer than the other categories of land-use history, due to of a lack of initial biomass available to harvest for bioenergy production.

Times required to reach C Sequestration Parity were longest for the low-productivity ecosystems and shortest for the high-productivity ecosystems (Fig. 3), indicating that high productivity ecosystems were able to more quickly recoup their substantial reductions in C storage compared to the rates at which low-productivity ecosystems were able to recoup their considerably smaller reductions in C storage. Within each respective grouping of ecosystem productivity (G1, G2, G3), there were significant effects of different biomass longevities (L1, L2, L3) on the amount of time required for C Sequestration Parity. Increased biomass longevity (i.e., lower rates of mortality and decomposition) increased

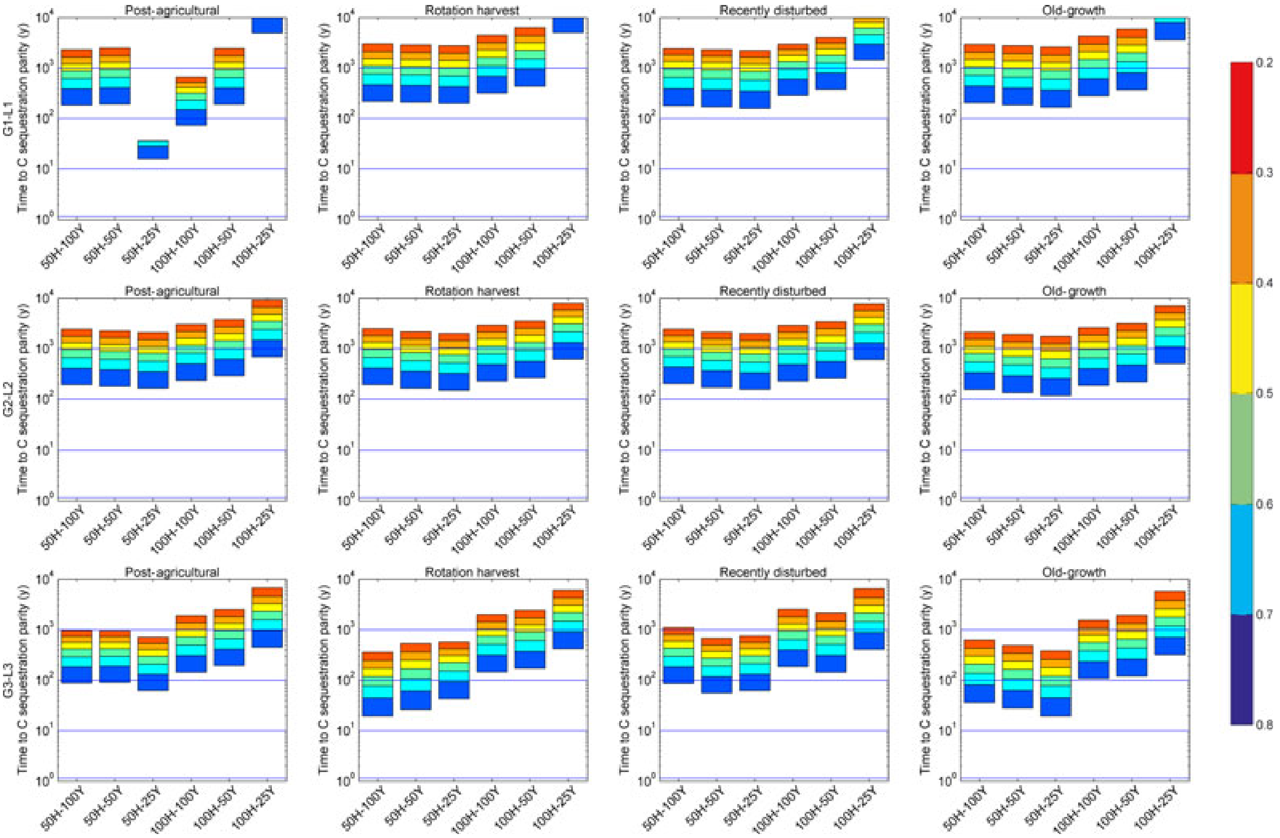

Fig. 3 Comparisons of the time required for a repayment of the C Sequestration Parity among three of our nine ecosystem types, each with six biomass harvesting regimes and four land-use histories. Note that times are represented on a log scale. Different harvesting regimes are indicated on the *x*-axis, with 50% and 100% harvesting intensity represented as 50H and 100H, respectively. Harvest frequencies of 25, 50, and 100 years are represented as 25Y, 50Y, and 100Y.

the times required to reach C Sequestration Parity, a trend which was consistent across all three rates of ecosystem productivity.

Regardless of land-use history and ecosystem characteristics, most scenarios required well over 100 years to reach C Sequestration Parity. Simulations with total harvests performed every 25 years often required more than 1000 years for C Sequestration Parity. Some scenarios achieved C Sequestration Parity in < 50 years, but most of these were scenarios with relatively high bioenergy conversion efficiencies. Harvests performed at lower frequency (50, 100 years) and intensity (50% harvest) required less time; partial harvests (50% harvest) performed every 25 years appeared to reach C Sequestration Parity more rapidly than any other management regime. Harvesting frequency and intensity appeared to affect all ecosystems similarly. Without exception, performing a clear-cut every 25 years resulted in the greatest reduction in C storage and required the longest periods to achieve C Sequestration Parity, suggesting that attempts to generate bioenergy from forests would be most effective in substituting for fossil fuels when managed for moderate amounts of production over a long time scale.

Discussion

Delays in the time required for a net benefit of a substitution of bioenergy for fossil fuels are caused by two factors. First, harvesting materials for bioenergy increases the C losses from the forest over the losses caused by mortality and decomposition, thus, increasing the amount of biomass harvest for bioenergy production will increase the C Debt. Second, since there is less potential energy per unit of C emissions in biomass energy compared to fossil fuels, substituting biomass for fossil fuels does not result in a 1 : 1 substitution of energy per unit of C emission. Consequently, ecosystems that are capable of quickly repaying their C Debts were those that had little C storage to begin with.

Our simulations demonstrated that initial landscape conditions and land-use history were fundamental in determining the amount of time required for forests to repay the C Debt incurred from bioenergy production.

While Recently Disturbed and Old-Growth landscapes required considerable time to repay their C Debts, Post-Agricultural and Rotation Harvest landscapes were capable of repaying their C Debt in relatively short time periods, often within 1 year. However, a quick repayment of the C Debt and an increase in C storage does not imply a high degree of bioenergy production; it merely indicates that more C is being stored in a bioenergy production system. Post-Agricultural landscapes undergoing afforestation have minimal initial C storage, and managing them for an appreciable yield of bioenergy production would require a considerable waiting period. Furthermore, the conversion of an agricultural field to a forest could have short-term climatic warming effects while the afforesting landscape is in the early stages of succession, since a decrease in landscape albedo resulting from afforestation could yield climatic warming effects that would overshadow any climatic cooling effects associated with an uptake of atmospheric CO_2 (Jackson *et al.*, 2008; Anderson *et al.*, 2011), as the latter would be relatively small during the early stages of forest succession. By contrast, a Rotation Harvest system would not undergo a significant change in albedo during a transition to a landscape managed for bioenergy production. However, Rotation Harvests have a much different legacy than a Post-Agricultural landscape, since a history of harvesting on the landscape implies that there is additional wood being stored in wood products which are slowly decomposing (see Methods). Consequently, the ongoing decomposition of previously harvested materials lowers terrestrial C storage.

The times required for Old-Growth landscapes to repay C Debt were similar to the times required for them to achieve C Sequestration Parity, since the initial C storage of an old-growth landscape is at or near the level of C that could be stored in the landscape if it were to remain unharvested. Consequently, Old-Growth landscapes required long periods of bioenergy production to achieve C Debt Repayment and C Sequestration Parity. For the three other land-use histories, reaching the point of C Sequestration Parity requires much more time than a repayment of C Debt. Trends were quite consistent among the Recently Disturbed, Rotation Harvest, and Old-Growth landscapes and most simulations required at least 100 years to reach C Sequestration Parity (Fig. 3).

Times required for C Sequestration Parity were longest for the low-productivity ecosystems and shortest for the high-productivity ecosystems. Similarly, the effects of biomass longevity were quite consistent among the Recently Disturbed, Rotation Harvest, and Old-Growth landscapes (Fig. 3). Within each respective grouping of ecosystem productivity (G1, G2, G3), there were significant effects of different biomass longevity rates (L1, L2, L3) on the amount of time required to reach a point of C Sequestration Parity. Higher rates of biomass longevity (i.e., lower rates of mortality and decomposition) resulted in longer times required for C Sequestration Parity, a trend which was consistent across all three rates of ecosystem productivity (Fig. 3). Such a result may seem counterintuitive at first, but the net effect of lowering mortality and decomposition rates is that potential C storage is increased. Since ecosystems with lower mortality and slower decomposition have higher potential C storage, more bioenergy substitutions must be produced to exceed the amount of C stored in a forest that is allowed to grow without harvest. Annual biomass harvest varied little among our different levels of longevity. Therefore, higher rates of biomass longevity raised the target for C Sequestration Parity without resulting in a comparable increase of bioenergy production. We note that biomass longevity is largely a function of the environmental factors that control rates of biomass decomposition, such as temperature and moisture, and is governed by catastrophic disturbances to a lesser degree. Our simulations reiterate previous findings (Mitchell *et al.*, 2009; Campbell *et al.*, 2012) about the limited impact that wildfires have on biomass longevity; wildfires may temporarily lower the C storage of the landscape but most of the losses that occur are among unharvestable components of the forest, such as leaf litter and fine woody debris. Most of the harvestable biomass remains unconsumed even by high-severity wildfires and can either be salvage harvested shortly thereafter or persist on the landscape for decades (Mitchell *et al.*, 2009; Campbell *et al.*, 2012).

However, C storage is not the only way that vegetation affects climate, as different levels of surface reflectance (albedo) and evapotranspiration result in different levels of heat absorbance in the terrestrial biosphere (Jackson *et al.*, 2008; Anderson *et al.*, 2011). Utilizing degraded agricultural lands for the production of bioenergy via non-woody plant species (i.e., switchcane, switchgrass, etc.) could both reduce heat absorbance in the terrestrial biosphere and produce bioenergy to serve as a substitute for fossil fuels. A recent study by Beringer *et al.* (2011) estimated that, by 2050, the cultivation of bioenergy crops on degraded agricultural land could produce 26–116 EJ yr^{-1}, 3–12% of projected global energy demand. Additional energy may be obtained from secondary sources, such as residues from agriculture and forestry, municipal solid waste, and animal manures, and the combined production potential could potentially be around 100 EJ yr^{-1} by then (Ifeu, 2007; Iea, 2009; Wbgu, 2009; Haberl *et al.*, 2010), thereby generating an additional 10% of projected global energy demand (13–22% total). However, it is unclear what proportion of degraded agricultural lands would be better utilized for climate change mitigation via reforestation, rather than by non-woody bioenergy production. Non-woody bioenergy crops would need a sufficiently high surface reflectance if their climate change mitigation benefits were to exceed the mitigation benefits of afforestation, but the studies conducted on this topic have yielded conflicting results. Some studies have suggested that land cover types with high albedos could yield a greater cooling to the atmosphere than temperate forests (Diffenbaugh & Sloan, 2002; Oleson *et al.*, 2004; Bala *et al.*, 2007) while other studies have shown the opposite (DeFries *et al.*, 2002; Jackson *et al.*, 2005; Juang *et al.*, 2007), indicating that further research on these tradeoffs is needed.

Further research is also needed to ascertain the potential conversion efficiencies of woody biomass. Our findings indicate that an accounting of the C emissions that are necessary for the harvest, transport, and firing of woody biomass must be performed if forest bioenergy is to be utilized without adding to atmospheric CO_2 concentrations in the near-term. Many of our combinations of forest productivity, biomass longevity and harvesting regimes required more than 100 years to achieve C Sequestration Parity, even when the bioenergy conversion factor was set at near maximal level. A consideration of stand characteristics and land-use history may also prove to be imperative for any bioenergy production system to be effective. Competing land-use objectives make it highly unlikely that forests will be managed purely for C mitigation efforts, and many of the current management objectives within existing forests will undoubtedly prevent them from reaching their full C storage potential. Achieving the maximal C mitigation potential of what remains becomes all the more imperative, as mean global temperatures, sea-level rise, or the melting of ice sheets may continue long after any future stabilization of atmospheric CO_2 and other greenhouse gases (Jones *et al.*, 2009). Managing forests for maximal C storage can yield appreciable, and highly predictable, C mitigation benefits within the coming century, while managing forests for bioenergy production will require careful consideration if they are to provide a C neutral source of energy without yielding a net release of C to the atmosphere in the process.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Times for Carbon Debt Repayment for all Post-Agricultural landscapes.

Figure S2. Times for Carbon Sequestration Parity for all Post-Agricultural landscapes.

Figure S3. Times for Carbon Debt Repayment for all Rotation Harvest landscapes.

Figure S4. Times for Carbon Sequestration Parity for all Rotation Harvest landscapes.

Figure S5. Times for Carbon Debt Repayment for all Recently Disturbed landscapes.

Figure S6. Times for Carbon Sequestration Parity for all Recently Disturbed landscapes.

Figure S7. Times for Carbon Debt Repayment for all Old-Growth landscapes.

Figure S8. Times for Carbon Sequestration Parity for all Old-Growth landscapes.

Appendix S1. Energy Conversion Calculations.

9. Ana Repo, *et al.*, *Sustainability of Forest Bioenergy in Europe: Land-use-related Carbon Dioxide Emissions of Forest Harvest Residues*, GCB Bioenergy, (Mar, 2014).

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Sustainability of forest bioenergy in Europe: land-use-related carbon dioxide emissions of forest harvest residues

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Abstract

Increasing bioenergy production from forest harvest residues decreases litter input to the soil and can thus reduce the carbon stock and sink of forests. This effect may negate greenhouse gas savings obtained by using bioenergy. We used a spatially explicit modelling framework to assess the reduction in the forest litter and soil carbon stocks across Europe, assuming that a sustainable potential of bioenergy from forest harvest residues is taken into use. The forest harvest residue removal reduced the carbon stocks of litter and soil on average by 3% over the period from 2016 to 2100. The reduction was small compared to the size of the carbon stocks but significant in comparison to the amount of energy produced from the residues. As a result of these land-use-related emissions, bioenergy production from forest harvest residues would need to be continued for 60–80 years to achieve a 60% carbon dioxide (CO_2) emission reduction in heat and power generation compared to the fossil fuels it replaces in most European countries. The emission reductions achieved and their timings varied among countries because of differences in the litter and soil carbon loss. Our results show that extending the current sustainability requirements for bioliquids and biofuels to solid bioenergy does not guarantee efficient reductions in greenhouse gas emissions in the short-term. In the longer-term, bioenergy from forest harvest residues may pave the way to low-emission energy systems.

Keywords: carbon debt, indirect emissions, logging residues, RED, soil carbon, sustainability criteria

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Introduction

Bioenergy plays a crucial role in plans to achieve climate and energy policy targets agreed in the European Union (COM, 2010; Beurskens & Hekkenberg, 2011; Szabó *et al.*, 2011). The annual demand for bioenergy is estimated to increase from the present 5.7 to 10 EJ by 2020 (Bentsen & Felby, 2012). According to the National Renewable Energy Action Plans (NREAPs) of the EU countries, the use of biomass for heating and cooling will double between 2005 and 2020 to account for 80% of the total in the EU-26 countries. Correspondingly, the use of biomass in electricity generation will triple during the same time period to represent 19% of the total renewable electricity.

One option to fulfil the growing need for bioenergy is to increase the use of forest harvest residues for energy production. The residues are comprised of branches, nonmerchantable tops, stumps and other residual biomass from forestry operations that are traditionally left in the forest after timber harvesting (UNECE, 2008; Mantau *et al.*, 2010; Díaz-Yáñez *et al.*, 2013).

Estimates of energy potential in forest harvest residues range from 0.4 to 2.3 EJ yr^{-1}, and additional fellings may expand this range from 0.8 to 10.6 EJ yr^{-1} in Europe (EEA, 2006, 2007; Ericsson & Nilsson, 2006; Alakangas *et al.*, 2007; Asikainen *et al.*, 2008; UNECE, 2008; Anttila *et al.*, 2009; Haberl *et al.*, 2010; de Wit & Faaij, 2010; Bentsen & Felby, 2012). The range of the estimates is wide depending on whether the studies approximated theoretical, technological or economic potentials and which constraints they applied (Rettenmaier *et al.*, 2010; Offermann *et al.*, 2011; Bentsen & Felby, 2012). Other reasons for the wide range are differences in applied conversion factors, in definitions of biomass fractions, and in temporal and geographical scopes (Bentsen & Felby, 2012). In addition, some studies used demand-driven approaches, whereas others applied resource-focused ones (Offermann *et al.*, 2011).

Intensification of biomass removals from forests has raised concerns about the environmental effects on

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forest productivity, biodiversity, soil quality, and climate change mitigation potential of forest bioenergy (Lattimore *et al.*, 2009; Walmsley & Godbold, 2010; Thiffault *et al.*, 2011; Agostini *et al.*, 2013; Fritsche & de Jong, 2013). The estimates for the sustainable potential of forest bioenergy have taken into account some of the possible effects (e.g., EEA, 2006, 2007; UNECE, 2008). However, the environmental constraints considered have mainly been related to site productivity, biodiversity, erosion, water regulation, and soil properties (EEA, 2006, 2007; Böttcher *et al.*, 2010; Verkerk *et al.*, 2010, 2011). In some cases, the sustainable levels of forest harvests are seen to guarantee the sustainability of forest bioenergy (de Wit & Faaij, 2010).

The European Renewable Energy Directive (RED) defines sustainability criteria for biofuels and bioliquids (2009/28/EC). The RED mandates that greenhouse gas (GHG) emission savings from the use of biofuel over the life-cycle shall be at least 60% compared to the use of fossil fuels from 2018 onwards. In addition, the raw material shall not be obtained from land with high biodiversity value or high carbon stock (2009/28/EC). Although the RED does not mandate sustainability criteria for solid biomass, there is an ongoing discussion on defining sustainability requirements also for solid and gaseous biomass used in electricity generation, heating and cooling (COM, 2010; Fritsche & de Jong, 2013). It is currently foreseen that the criteria will be linked to the existing criteria for biofuels and bioliquids (COM, 2010; Lamers *et al.*, 2013). The government of the United Kingdom has already introduced national sustainability criteria for the solid biomass used for electricity generation (OFGEM, 2011).

One motivation for defining the sustainability criteria for biofuels in the EU is the effort to avoid bioenergy-related emissions from direct and indirect land-use changes (EC, 2009; COM, 2013). This is because converting forests to energy crop cultivations or land clearing for delocalised food production often reduce carbon stocks of biomass, soil, or both (Fargione *et al.*, 2008; Searchinger *et al.*, 2008, 2009; Melillo *et al.*, 2009). The reductions in the carbon stocks may offset some or all of the emission savings of bioenergy (Fargione *et al.*, 2008; Searchinger *et al.*, 2008, 2009).

The emissions resulting from the reductions in the carbon stocks are not limited to land-use change but can occur within the same land use, as a consequence of altered management, for example, when harvesting of forest biomass is intensified (Melin *et al.*, 2010; Lindholm *et al.*, 2011; McKechnie *et al.*, 2011; Repo *et al.*, 2011; Zanchi *et al.*, 2011; Domke *et al.*, 2012). Increasing forest residue harvesting reduces litter input to the soil, and consequently reduces the carbon stock and sink of the soil (e.g., Schlamadinger *et al.*, 1995; Palosuo *et al.*, 2001; Hope, 2007; Sievänen *et al.*, 2014). Even small changes in the soil carbon stocks may have significant effects on the climate (Peng *et al.*, 2008), because soil contains two to three times as much carbon as the atmosphere or the terrestrial vegetation globally (Peng *et al.*, 2008; Pan *et al.*, 2011). Despite of this probable importance, previous studies estimating the sustainable forest harvest residue potentials have not considered the effects of intensified biomass harvesting on the European litter and soil carbon stocks or analysed the amount of GHG emissions that can be avoided by exploitation of the otherwise environmentally compatible forest bioenergy potential (EEA, 2006).

The objectives of this study were to (i) investigate the change in the European litter and soil carbon stocks assuming that a sustainable bioenergy potential of forest harvest residues is taken into use; and (ii) estimate the CO_2 emission reductions achievable with forest harvest residue bioenergy in different EU countries. We used a spatially explicit modelling framework to investigate the reduction in the carbon stocks, and contrasted these simulated reductions with the amounts of energy produced from the forest biomass to estimate the land-use-related CO_2 emissions of forest harvest residue bioenergy across Europe.

Materials and methods

Approach

We developed a framework that links spatially explicit information on forest biomass and harvests to litter and soil carbon stocks in Europe. The framework consisted of two models: the Global Forest Model G4M (Kindermann *et al.*, 2013) estimating the development of standing stem volume under changing forest management and environmental conditions, and the Yasso07 soil carbon model simulating the corresponding changes in litter and soil carbon stocks (Tuomi *et al.*, 2008, 2009, 2011a,b). We conducted the calculations by 25 × 25 km grid cells across our study area.

Biomass carbon stocks

The development of the European forests over the 21st century was simulated with the G4M model (Tietjen *et al.*, 2010). We assumed harvesting according to the current practices and the climate change following the IPCC SRES A1B emission scenario (Tietjen *et al.*, 2010). In our simulations, we used the medians of the different model outputs (Mitchell & Philip, 2005; Tietjen *et al.*, 2010).

The initial growing stock of stem wood in each grid cell was based on a forest biomass map (Kindermann *et al.*, 2008). Forest growth was estimated according to a map of the potential Net Primary Productivity (NPP) (Cramer *et al.*, 1999). The climate change affected the NPP estimates over our simulation period (Tietjen *et al.*, 2010), and consequently our simulated estimates of forest growth. The estimates of initial stem wood stock and the NPP-based yield level estimates determined the forest rotation length in each grid cell (Kindermann *et al*., 2008). We assumed an even distribution of age classes and a fixed harvesting age over the time period studied in each grid cell.

The G4M estimates of the stock and harvests of stem wood were converted to total tree biomass and litter input to the soil according to a calculation scheme shown in Fig. 1. The biomasses of branches, foliage, roots, and stumps were estimated from stem biomass with biomass equations that used diameter at breast height (DBH) and tree height as explanatory variables (Table 1, DBH and height calculation described in Kindermann *et al*., 2013). We applied these equations to determine the ratios of foliage/stem, branch/stem, stump/stem, and roots/stem, and thus the estimates of the stocks of foliage, branch, stump, and root biomass in each grid cell. The annual litter flow to the soil consisted of litter from standing biomass, harvest residues and harvest losses (Fig. 1). The litter input to the soil from living trees was estimated by applying tree-compartment-specific turnover rates separately for coniferous and broadleaved species groups (Liski *et al*., 2002). The carbon input to the soil from the harvest losses was calculated as the difference between stocking stem wood and harvested logs.

Litter and soil carbon stock

The changes in the litter and soil carbon stocks were simulated using the dynamic soil carbon model Yasso07. This model has been shown to give unbiased estimates for the decomposition of nonwoody and woody litter (Tuomi *et al*., 2009, 2011a). The validity of the Yasso07 model has been tested on global (Tuomi *et al*., 2009; Thum *et al*., 2011), national (Rantakari *et al*., 2012; Ortiz *et al*., 2013), and site scales (Karhu *et al*., 2011; Lu *et al*., 2013). Based on these studies, the Yasso07 is suitable for estimating the decomposition rate of litter, the carbon stocks of litter and soil, and the changes in these stocks in this study.

The Yasso07 model describes the litter decomposition and the soil carbon cycle based on the chemical quality of the organic matter and climatic conditions (Tuomi *et al*., 2009). The decomposition of woody litter depends also on the physical size of the litter (Tuomi *et al*., 2011a). The model is based on more than 15 000 measurements of litter decomposition and soil organic carbon stocks across the globe, and the parameter values are determined from these measurements using Bayesian inference (Tuomi *et al*., 2009, 2011a). To avoid overparameterization, the Bayesian model comparison has been used in the development of the model (Tuomi *et al*., 2009, 2011a).

The Yasso07 model divides nonwoody and woody litter into four chemically distinguishable fractions that decompose at their unique rates. The fractions are (i) water soluble (W); (ii) ethanol soluble (E); (iii) acid hydrolysable (A); and (iv) neither soluble nor hydrolysable (N). In addition, there is a humus (H) fraction consisting of more recalcitrant compounds formed of the decomposition products of the A, W, E, and N fractions. We derived the chemical composition of the litter for the simulations from various earlier studies (Table 1). Diameters applied in the simulations were 2 cm for branches and roots, 7 cm for harvest losses and 35 cm for stumps.

The initial litter and soil carbon stocks for each cell were estimated by running the Yasso07 model for 10 000 years to a steady-state with a constant average litter input of the years 2011 to 2015 and a constant average climate of a period from

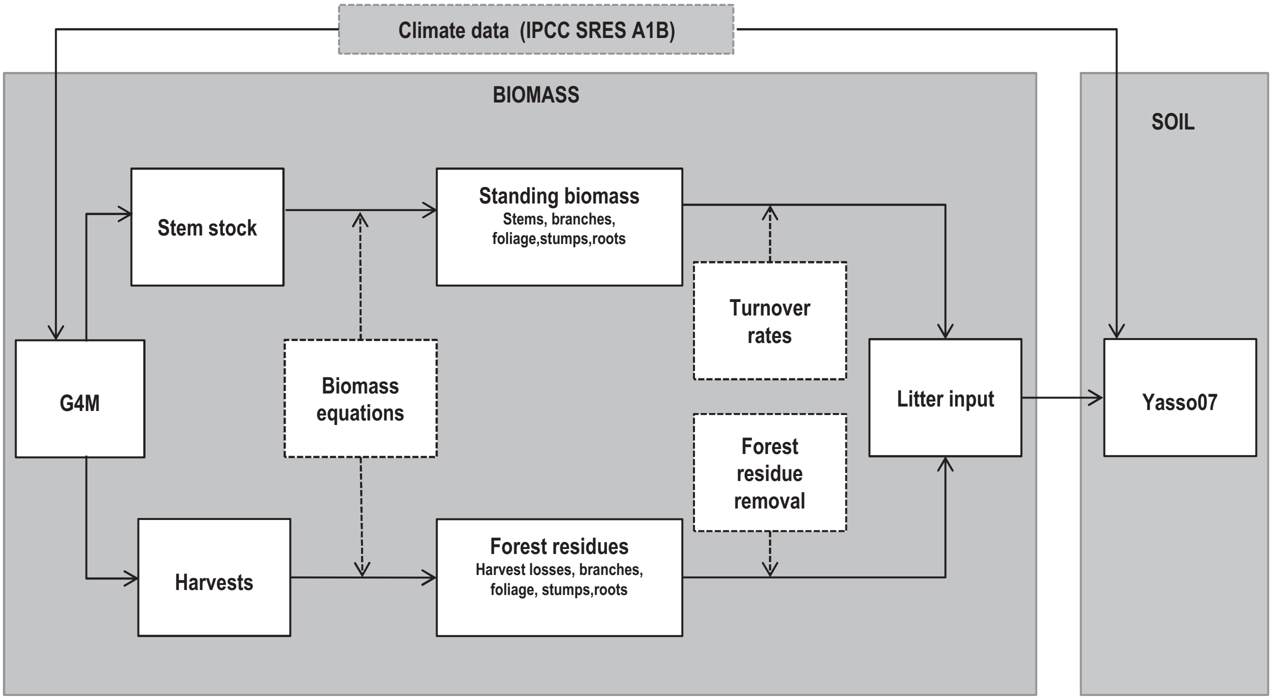

Fig. 1 Calculation scheme to estimate the effects of forest harvest residue removals on the carbon stocks of litter and soil across Europe.

Table 1 Biomass equations applied to estimate tree biomass and the chemical composition of litter used in the decomposition simulations in terms of the shares of acid hydrolysable compounds (A), water soluble compounds (W), ethanol soluble compounds (E) and compounds neither soluble nor hydrolysable (N)

Species group	Biomass equations	Tree part	A	W	E	N
Temperate broadleaved evergreen	aboveground biomass dbh < 30 cm [1] dbh > 30 cm [2] stump-root biomass[3]	Stem, branch, roots, stump[6]	0.76	0.01	0.01	0.22
		Foliage, fine roots[7,8]	0.49	0.15	0.08	0.29
Temperate broadleaved summergreen	aboveground biomass dbh < 30 cm [1] dbh > 30 cm [2] stump-root biomass[4]	stem, branch, roots, stump[9]	0.76	0.01	0.01	0.22
		foliage, fine roots[9-12]	0.39	0.09	0.05	0.47
Boreal broadleaved summergreen	above- and belowground biomass[4]	stem, branch, roots, stump[9]	0.76	0.01	0.01	0.22
		foliage, fine roots[9-12]	0.39	0.09	0.05	0.47
Temperate coniferous	above- and belowground biomass[5]	stem, branch, roots, stump[9]	0.68	0.02	0.01	0.29
		foliage, fine roots[9-12]	0.51	0.13	0.10	0.26
Boreal coniferous	above- and belowground biomass[5]	stem, branch, roots, stump[9]	0.68	0.01	0.05	0.26
		foliage, fine roots[9-12]	0.50	0.09	0.05	0.36

References: 1) Bartelink (1997), 2) Cienciala *et al.* (2005), 3) Goff & Ottorini (2001), 4) Repola (2009), 5) Repola (2008), 6) Pettersen (1984), 7) Gholz *et al.* (2000), 8) Trofymow (1995), 9) Hakkila (1989), 10) Berg *et al.* (1984), 11) Berg and Wessén (1984), 12) Berg *et al.* (1991).

1980 to 2010. The time period of the litter input values used was rather short to account for temporal variability in litter input caused by varying harvesting levels. In our approach, this problem was compensated by the fact that each grid cell contained forests of different age classes and tree species groups.

We evaluated the reliability of our approach by comparing the results to independent estimates of biomass, litter production and soil carbon stocks (see Data S1). Our estimates of aboveground tree biomass, total litter input, and soil carbon stocks were comparable to data compiled by FAO (2010) and earlier estimates calculated using the European Forest Information Scenario Model EFISCEN (Sallnäs, 1990; Schelhaas *et al.*, 2007). These comparisons supported the adequacy of our approach for the present study.

Sustainable forest bioenergy potential

To estimate an annual sustainable bioenergy potential from forest harvest residues, first, we calculated the total quantity of the residues in each European country in the year 2011 using the G4M model. Second, we calculated the share of the total forest harvest residues that equalled the sustainable potential as proposed by Elbersen *et al.* (2011). This potential has been calculated for the EU-27 countries using methods described in detail by Verkerk *et al.* (2010, 2011). It follows a scenario assuming that regulations and practices enabling or restricting forest operations will be similar to those today, and takes into account several environmental, technical and social constraints, including requirements of workforce, forests not available for wood supply, site productivity and soil erosion risk (Verkerk *et al.*, 2010, 2011).

The sustainable share of forest harvest residues ranged from 2% to 44% depending on the country. In our simulations the proportions of branches, harvest losses and stumps were equal and did not change over time. For the non-EU-27 countries, we assumed that 15% of forest residues were harvested, which corresponds the median value among the EU-27 countries. The 15% share was applied also for Ireland and the United Kingdom because the G4M estimate of the total forest harvest residue potential was lower than the constrained potential proposed by Elbersen *et al.* (2011). Cyprus and Malta were excluded from the analysis because of lack of information.

In the forest carbon simulations the sustainable share of the forest harvest residues was allocated to bioenergy production from each grid cell and year starting from the year of 2016. The sustainable share was constant, whereas the total quantity varied annually according to the harvest level. To estimate the effect of forest harvest residue removal on litter and soil carbon stocks, we simulated the development of the forest carbon stocks with and without forest residue harvesting between 2016 and 2100 and contrasted the results with each other.

Emission reductions with bioenergy from forest harvest residues

We estimated the CO_2 emission savings achievable by using bioenergy from forest harvest residues taking into account the reductions in the carbon stocks of litter and soil. We calculated the average litter and soil carbon loss resulting from the removal and energy use of forest harvest residues in each country and year by summing up the amount of carbon remaining in the decomposing forest harvest residues if they were left in the forests. This cumulative carbon loss was divided by the cumulative energy obtained from the collected forest harvest residues each year to calculate emissions per energy unit (Repo *et al.*, 2011, 2012). Following the European Commission requirements for the sustainability for solid and gaseous fuels in electricity, heating and cooling (COM, 2010) we applied a fossil fuel comparator equal to 198 g CO_2eq MJ^{-1} for electricity generation and a comparator equal to 87 g CO_2eq MJ^{-1} for heating and cooling. To include energy conversion losses we assumed a 25% electrical and a 85% thermal conversion efficiency (COM, 2010). The carbon content of the biomass was assumed to be equal to 44% of dry wood (m/m), wood density 400 kg fresh ton^{-1}, and the energy content 19 MJ kg^{-1}(dry) (Nurmi, 1997; Alakangas, 2000).

Results

Harvesting the sustainable amount of forest residues decreased the simulated carbon stocks of litter and soil on average by 3 t C ha^{-1} by the end of this century in the European forests (Fig. 2). The largest carbon losses per a hectare of forest land occurred in Germany, the United Kingdom, Czech Republic, and Denmark (Fig. 3). On the other hand, the largest losses per country were found in Sweden, Finland, and Germany (Table 2). On average the harvesting of the forest residues decreased the carbon stocks of litter and soil by 3% between 2011 and 2100 in Europe. The relative carbon loss was the highest in the United Kingdom (9.7%) and the lowest Lithuania (0.3%) (Table 2).

The carbon loss was mainly dependent on the amount of forest residues harvested, the availability of forest land for the residue harvesting, and the climatic conditions. The large potential of available forest harvest residues explained the considerable carbon loss in Germany, Finland, and Sweden. The sustainable bioenergy potentials from forest harvest residues differed only little between Germany and Finland, but the carbon loss per a hectare of forest land was larger in Germany because the residues were harvested from a smaller forest area. The high intensity of forest residue harvesting from a small forest area resulted in considerable carbon loss also in the United Kingdom, Denmark, and the Netherlands. The differences in the carbon loss due to climatic conditions were visible within some countries. For example, in the cooler climate conditions of northern Finland, the decomposition of stumps and branches was slower than in southern Finland, and consequently forest residue harvesting reduced the carbon stocks more in the northern than in the southern Finland (Fig. 2).

Because of these variations in the carbon loss, the CO_2 emissions of forest harvest residue bioenergy per produced energy unit differed among the European countries. Consequently, the CO_2 emission savings from fossil fuel substitution varied (Figs 4 and 5). Electricity generation from forest harvest residues caused even larger CO_2 emissions than electricity generation from the reference fossil fuel for the first 5 years in many countries, and in some countries for the first 20 years (Fig. 4). On the other hand, heat production reduced emissions already within a few years in most European countries. The emissions of forest harvest residue bioenergy decreased over time because the rate of carbon loss reduced, as the residues would decompose even if left to decay in forest (Fig. 3). Nevertheless, the 60% reduction in the CO_2 emissions, compared to fossil fuels, required by the current EU RED directive after 2018 was achieved with a continuous forest bioenergy use for heat production in most European countries only after 60 years. Correspondingly, it took more than 80 years to reach to the 60% target in electricity generation (Fig. 5). The emissions decreased slower in Northern European countries than in Southern European countries as a result of lower decomposition rate of the forest harvest residues.

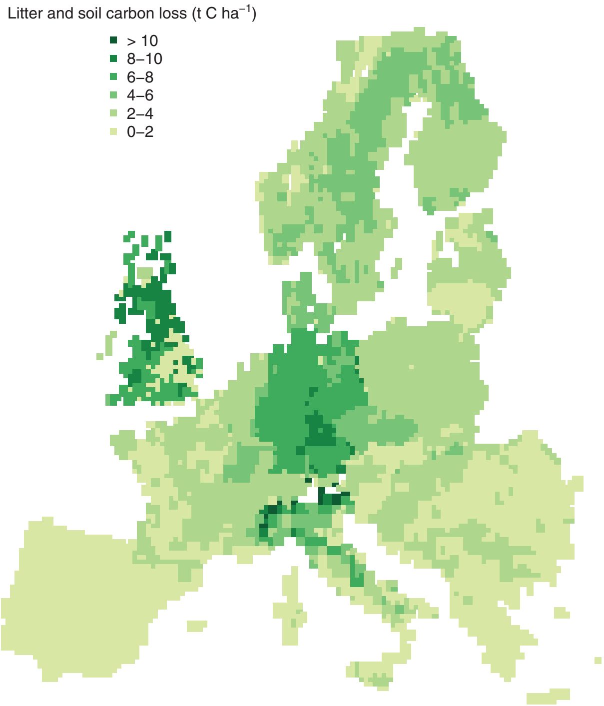

Fig. 2 Loss of litter and soil carbon between 2016 and 2100 resulting from sustainable removals of forest harvest residues.

Heat and power generation from forest harvest residues caused the highest emissions per energy unit in the Netherlands, Ireland, Finland, and Sweden (Figs 4 and 5). In the Netherlands and Ireland, the high emissions resulted from the small forest area available for forest residue harvesting, whereas the combination of a cool climate and a large amount of available felling residues explained the high emissions in the Northern European countries. The emissions per energy unit produced were the lowest in Portugal and Slovenia.

Discussion

An intensification of forest residue harvests and energy use reduced the simulated carbon stocks of litter and

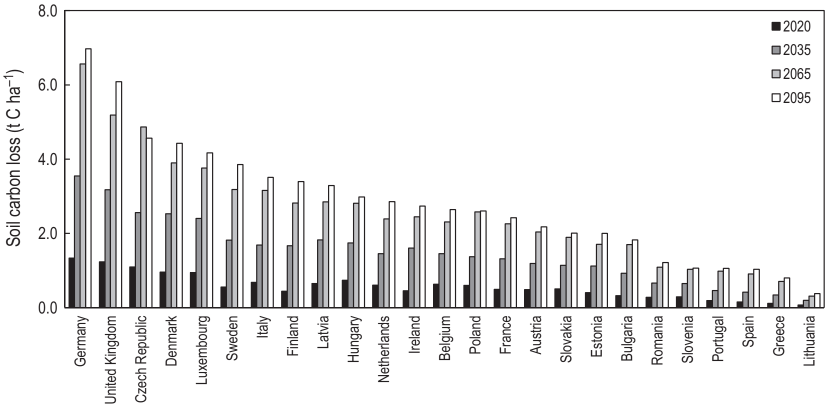

Fig. 3 Development of the average litter and soil carbon loss on forest land resulting from sustainable removals of forest harvest residues since 2016 in the selected EU countries.

Table 2 Loss of litter and soil carbon from between 2016 and 2100 resulting from sustainable removals of forest harvest residues in the studied countries

	Carbon loss (Mt C)	Share of soil carbon stock
Austria	12.6	1.3%
Belgium	1.8	2.6%
Bulgaria	8.2	2.5%
Czech Republic	14.6	2.6%
Denmark	1.3	3.7%
Estonia	3.6	1.1%
Finland	84.4	2.1%
France	37.4	3.6%
Germany	75.3	5.0%
Greece	2.5	3.4%
Hungary	4.8	2.7%
Ireland	<0.1	3.6%
Italy	45.0	8.1%
Latvia	8.2	2.0%
Lithuania	0.6	0.3%
Luxembourg	0.4	3.4%
Netherlands	0.7	2.9%
Poland	21.7	1.6%
Portugal	5.3	3.5%
Romania	13.0	1.1%
Slovakia	5.6	1.3%
Slovenia	1.6	0.9%
Spain	20.1	3.3%
Sweden	130.0	2.4%
United Kingdom	5.7	9.7%

soil across Europe. This reduction was small compared to the size of these carbon stocks but significant when related to the amount of energy produced. As a result of the forest carbon loss, replacement of fossil fuels with forest bioenergy did not result in immediate emission reductions, as has also been shown in previous studies (Walker *et al.*, 2010; McKechnie *et al.*, 2011; Repo *et al.*, 2011; Zanchi *et al.*, 2011; Schulze *et al.*, 2012). According to our study it would take 60 to 80 years to achieve the 60% emission reduction with forest harvest residue bioenergy in heat and power generation in most European countries. This result supports the finding of earlier studies applying the current RED calculation guidelines for liquid biofuels, the minimum GHG emission reduction target of 60% is difficult to achieve if the changes in the carbon stocks of litter and soil are accounted for (Holma *et al.*, 2013; Koponen *et al.*, 2013).

The achievable emission reductions with forest harvest residue bioenergy, and their timings, differed among the European countries. For example, the production of one unit of heat or electricity from forest harvest residues caused 7% higher CO_2 emissions in Finland and Sweden than it did in Slovenia in the year of 2020. In the year of 2095, the corresponding emissions per energy unit were significantly lower in each country because the forest harvest residues would also release CO_2 if left to decompose in forest (Repo *et al.*, 2011). Nevertheless, in the year of 2095, the production of one unit of energy caused as much as 79% higher emissions in the Nordic countries compared to Slovenia. The Nordic countries have the largest potentials of forest bioenergy but the carbon loss, and the consequent land-use-related emissions are also the largest in Europe. The differences between countries may pose a burden sharing issue, how to define mandatory emission reduction criteria given the discrepancy between countries?

Comparisons of our estimates to independent data supported the adequacy of our approach for this study. We assessed the reliability of our results by comparing the estimates of our different calculation steps to independent data because similar studies have not been conducted at a national scale earlier. The country-level estimates of the aboveground biomass in the year of 2011

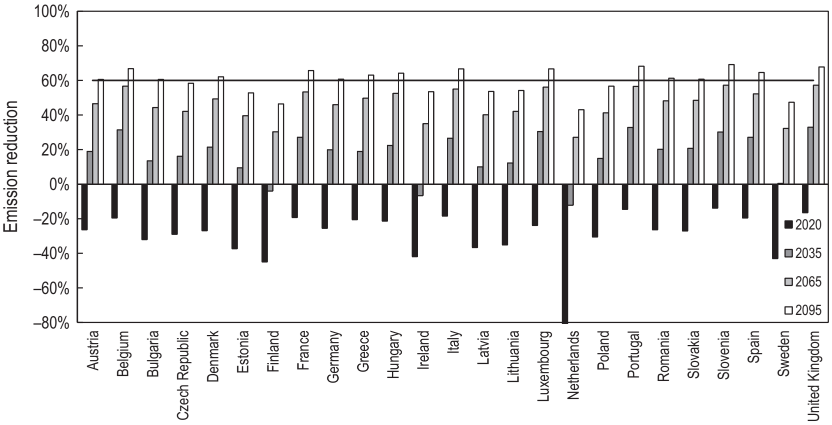

Fig. 4 Development of CO_2 emission reductions when producing electricity from sustainable removals of forest harvest residues since 2016 compared to a reference fossil fuel (EC, 2010). The horizontal line indicates the 60% emission saving limit of the EU RED.

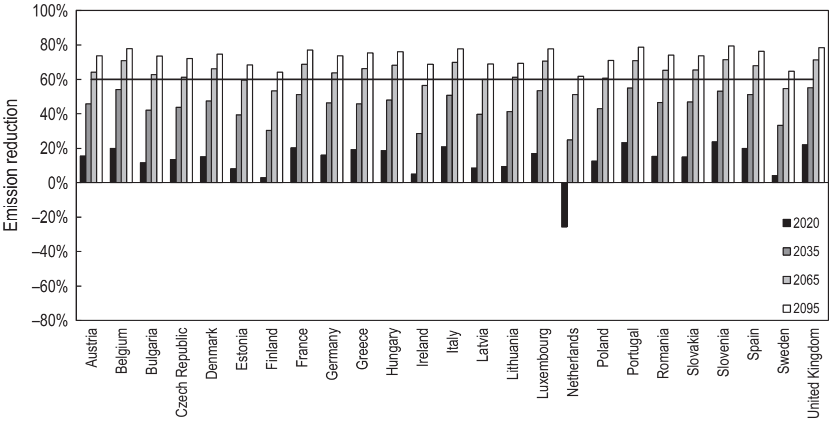

Fig. 5 Development of CO_2 emission reductions when producing heat from sustainable removals of forest harvest residues since 2016 compared to a reference fossil fuel (EC, 2010). The horizontal line indicates the 60% emission saving limit of the EU RED.

were consistent with the FAO (2010) data. Generally, the largest sources of uncertainty in the simulated changes of soil carbon stocks are litter input estimates (Ortiz *et al.*, 2013). Especially, the litter production of fine roots and branches is poorly known (Peltoniemi *et al.*, 2006; Monni *et al.*, 2007). In this study, the total litter input estimates were comparable to those of the EFISCEN model (see Data S1). However, our estimate consisted of more coarse woody litter and less foliage compared to the EFISCEN. These differences in the size distribution may explain our larger initial soil carbon stock estimates, especially in Northern and Eastern Europe. Since the diameter affects the decomposition of woody litter in the model we used (Tuomi *et al.*, 2011a), a better knowledge of the diameter distribution of litter input would decrease the uncertainty of our results. Nevertheless, the general conclusions of our study are not sensitive to these uncertainties. The estimates of forest harvest residue energy potentials in the EU-27 countries differ between studies because of differences in the applied methodologies and constraints (Bentsen & Felby, 2012). The country-specific potentials of this study were of the same order of magnitude compared to previous estimates (Asikainen *et al.*, 2008; Böttcher *et al.*, 2010; Elbersen *et al.*, 2011). These comparisons indicate that our results may be uncertain for individual countries but they support the validity of our results for Europe in general. The possible effects of CO_2 fertilization, species composition changes or changes in forest management were excluded from the analysis.

The emission savings estimated in this study depend on the fossil fuel comparators and the energy conversion efficiencies. The emissions from electricity generation using different fossil fuels vary between 160 and 380 g CO_2eq MJ^{-1} and those from heating between 66 and 127 CO_2eq MJ^{-1} if the conversion efficiency for electricity is 25–35% and that for heating and cooling 75–85% (IPCC, 2006a). Natural gas results in the lowest emissions and coal the highest. The fossil fuels comparators used in this study were in lower end of the ranges.

However, these comparators represent the fossil fuel mixes for electricity generation and heating and cooling in the EU-27 countries (COM, 2010). Thus, they may offer a basis for more realistic estimation of emission savings than either end of the ranges. The largest emissions savings are achieved with forest residue bioenergy by replacing carbon intensive fossil fuels and by deploying energy conversion technologies of high efficiency.

There are concerns that forest residue harvesting may increase the decomposition of organic matter in soil and reduce forest productivity. Soil disturbance, caused by stump harvesting, has been observed to increase CO_2 efflux from the soil (Johansson, 1994; Lundmark-Thelin & Johansson, 1997; Jandl *et al.*, 2007; Walmsley & Godbold, 2010). However, studies on the magnitude, duration and significance of this effect compared to traditional site preparation methods are scarce (SLU, 2009; Strömgren & Mjöfors, 2012; Strömgren *et al.*, 2012), and the long-term impacts are still poorly known (Strömgren *et al.*, 2012). Forest residue harvesting has often negative short and medium-term effects on forest productivity because of increased nutrient removal (Thiffault *et al.*, 2011; Wall, 2012). Accounting for the possible effects of the soil disruption and the decreased forest productivity would reduce the emission savings achieved with forest harvest residue bioenergy compared to the estimates given in this study.

Over the next decades climate change is likely to affect biomass growth, litter production and litter decomposition. The G4M and the Yasso07 are both models driven by climate variables, and can thus account for the effect of the projected changes in climate. The chosen SRES A1B scenario describes a more integrated world with a balanced emphasis on all energy sources. We chose this scenario as one of many likely scenarios to account for the fact that the climate is not going to be stable over the period of 100 years. We found that there was a clear gradient in the total carbon losses that could be partially attributed to climate. In our study, the potential carbon losses resulting from forest residue harvesting tended to be higher in Northern Europe compared to Southern Europe because of the slower decomposition rates in the northern forest ecosystems. In general, the IPCC projections suggest a more intensive warming in higher latitudes (IPCC, 2013). Therefore, the future climate change may affect the emissions from the energy use of forest harvest residues more in northern countries compared to other regions of Europe. An acceleration of decomposition (Brovkin *et al.*, 2012) in the northern forests would lead to higher reference emissions of the forest harvest residues left in the forest, and could therefore reduce the emissions of this bioenergy option compared to the current climate. A more detailed analysis, which is, however, beyond the scope of this paper, should address uncertainties of these emissions associated with climate change. Such analysis would help to better identify regions of high risk of net emissions from an intensified employment of forest harvest residue bioenergy, and regions where biomass extraction could be prioritized.

The timing of the emissions is important for the mitigation of climate change. Substantial reductions in GHG emission are required already in the near future to limit the global warming to less than 2 °C above the pre-industrial temperatures (IPCC, 2007). In previous bioenergy studies, the emissions and the carbon sequestration of ecosystems have been followed over time or they have been assumed to take place at the same time (Lamers & Junginger, 2013). Traditional life-cycle assessments (LCA) of bioenergy do not account for the timing of the emissions (Helin *et al.*, 2012), but recent studies have proposed methods for inclusion of the temporal information (e.g., Levasseur *et al.*, 2010). In the RED sustainability criteria, emissions from land-use change are annualized by dividing the total emissions equally over a 20 year period (2009/28/EC). The same approach is used in many voluntary initiatives for the sustainability certification of bioenergy (Scarlat & Dallemand, 2011). Approaches based on dynamic modelling, like the one we used, make it possible to follow the actual emissions and carbon sequestration from year to year.

The sustainability criteria are set to ensure that increasing bioenergy utilization will deliver significant reductions in GHG emissions, and that it does not lead to biodiversity loss (2009/28/EC). Increasing forest biomass harvests in order to meet the national targets under the EU renewables directive decreases forest carbon sink at the national levels (Kallio *et al.*, 2013; Sievänen *et al.*, 2014), at the EU level (Böttcher *et al.*, 2011) and globally (Schulze *et al.*, 2012). Additional forest harvests cut the carbon sink of biomass and soil, whereas increasing forest residue harvesting reduces mainly litter and soil carbon stocks (Sievänen *et al.*, 2014). Our results support the conclusions of previous studies that applying the current RED calculation rules to forest harvest residues used in biofuel production or heat and electricity generation overestimates the achievable emission savings (Soimakallio & Koponen, 2011; Koponen *et al.*, 2013). This is because the current RED sustainability criteria for biofuels and bioliquids accounts only for carbon stock changes associated with land-use change (2009/28/EC). There is no change in land-use category when forests are managed sustainably (IPCC, 2006b).

Ensuring the sustainability of bioenergy from forest harvest residues requires accounting for reductions in all carbon pools. Firstly, in addition to acting as carbon reservoirs, soil carbon and organic matter have numerous functions in amending soil structure, water regulation, nutrient cycling, site fertility and biological activity (e.g., Schils *et al*., 2008; Agostini *et al*., 2013). Carbon loss resulting from forest residue harvesting may pose a risk to these functions. Secondly, the inclusion of all carbon stock changes allows a more reliable estimation of the emissions and the potential climate impact of forest bioenergy (Helin *et al*., 2012; Pingoud *et al*., 2012; Repo *et al*., 2012). Comprehensive carbon accounting is crucial because forest-based biomass is estimated to form over 50% of the biomass supply for energy until 2020. The increased demand of forest biomass may be satisfied directly from forest with additional fellings and forest residue harvesting because the available waste wood and wood industry residues are already used for energy production (Fritsche & de Jong, 2013; Scarlat *et al*., 2013).

Currently, the sustainability criteria are set only to biofuels and bioliquids, but the extension of the sustainability requirements to solid and gaseous bioenergy is being planned (COM, 2010; Fritsche & de Jong, 2013; Lamers *et al*., 2013). We show that the current sustainability requirements do not guarantee efficient savings of GHG emissions with forest harvest residue bioenergy. In the long-term forest bioenergy may pave the way for low-emission energy systems, whereas in the short-term, it may even increase GHG emissions because of reductions in forest carbon stocks. These reductions may be compensated by changes in forest management and harvesting practices (Routa *et al*., 2011, 2012; Repo *et al*., 2012; Sathre & Gustavsson, 2012). A regional prioritization of harvest residue extraction, site-specific thresholds for maximum outtake volumes of forest harvest residues and definitions for no-go-areas may decrease risks related to soil productivity and biodiversity (2009/28/EC; Fritsche & de Jong, 2013; Lamers *et al*., 2013). Nevertheless, comprehensive carbon accounting and reliable climate impact estimates of forest bioenergy are needed to determine the amount of additional emission reductions in other sectors to efficiently mitigate climate change.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1. Comparison of the estimates from different calculation steps to independent data.

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INVITED EDITORIAL

Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral

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Abstract

Owing to the peculiarities of forest net primary production humans would appropriate ca. 60% of the global increment of woody biomass if forest biomass were to produce 20% of current global primary energy supply. We argue that such an increase in biomass harvest would result in younger forests, lower biomass pools, depleted soil nutrient stocks and a loss of other ecosystem functions. The proposed strategy is likely to miss its main objective, i.e. to reduce greenhouse gas (GHG) emissions, because it would result in a reduction of biomass pools that may take decades to centuries to be paid back by fossil fuel substitution, if paid back at all. Eventually, depleted soil fertility will make the production unsustainable and require fertilization, which in turn increases GHG emissions due to N_2O emissions. Hence, large-scale production of bioenergy from forest biomass is neither sustainable nor GHG neutral.

Keywords: bioenergy, biomass, ecosystem function, forestry, greenhouse gas emission, human appropriation of net primary production

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Climate change impacts resulting from fossil fuel combustion challenge humanity to find energy alternatives that would reduce greenhouse gas (GHG) emissions. One important option in this context is bioenergy. There is a wealth of literature on actual yields of different energy crops and production systems (WBGU, 2009; NRC, 2011). Beringer *et al.* (2011) estimate that 15–25% of global primary energy could come from bioenergy in the year 2050. A prominent recent assessment suggested that bioenergy provision could even be up to 500 EJ yr^{-1}, more than current global fossil energy use (Chum *et al.*, 2012) and that GHG mitigation could be sustained under future climate conditions (Liberloo *et al.*, 2010).

Western and developing countries are on a course to increase bioenergy production substantially. For example, the United States enacted the Renewable Fuels Standard as part of the 2005 Energy Policy Act and amended it in 2007, mandating the use of renewable fuels for transportation from 2008 to 2022 and beyond. In addition, 20% of all EU energy consumption is to come from renewable sources by 2020 with bioenergy as a focal point in this effort (COM, 2006a). In 2005, the European Commission adopted the Biomass Action Plan (COM, 2005) and in 2006 the Strategy for Biofuels (COM, 2006b), both of which aim to increase the supply and demand for biomass. Strategies that could substantially diminish our dependence on fossil fuels without competing with food production include substitution with bioenergy from forests (Tilman *et al.*, 2009), either by direct combustion near the source or by conversion to cellulosic ethanol. There are important questions about GHG reduction, economic viability, sustainability and environmental consequences of these actions.

Greenhouse gas reduction

The general assumption that bioenergy combustion is carbon-neutral is not valid because it ignores emissions due to decreasing standing biomass and contribution to the land-based carbon sink. The notion of carbon-neutrality is based on the assumption that CO_2 emissions from bioenergy use are balanced by plant growth, but

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this reasoning makes a 'baseline error' by neglecting the plant growth and consequent C-sequestration that would occur in the absence of bioenergy production (Searchinger, 2010; Hudiburg *et al.*, 2011), and it ignores the fact that fossil fuels are needed for land management, harvest and bioenergy processing.

Recent life cycle assessments cast doubt on the existence of emission savings of bioenergy substitution from forests. In the Pacific Northwest United States, policies are being developed for broad-scale thinning of forests for bioenergy production, with the assumed added benefit of minimizing risk of crown fires. This includes forests of all ages and thus timeframes of biomass accumulation. However, a recent study suggests that more carbon would be harvested and emitted in fire risk reduction than would be emitted from fires (Hudiburg *et al.*, 2011). Furthermore, policies allow thinning of mesic forests with long fire return intervals, and removal of larger merchantable trees to make it economically feasible for industry to remove the smaller trees for bioenergy. These actions would lead to even larger GHG emissions beyond those of contemporary forest practices (Hudiburg *et al.*, 2011).

Increased GHG emissions from bioenergy use are mainly due to consumption of the current carbon pool and from a permanent reduction of the forest carbon stock resulting from increased biomass harvest (Holtsmark, 2011). When consumption exceeds growth, today's harvest is carbon that took decades to centuries to accumulate and results in a reduction of biomass compared to the current biomass pool (Holtsmark, 2011; Hudiburg *et al.*, 2011). Hence, it is another example of 'slow in and fast out' (Körner, 2003). Consequently, reduction in forest carbon stocks has been shown to at least cancel any GHG reductions from less use of fossil fuel over decadal time spans (Haberl *et al.*, 2003; Mc-kechnie *et al.*, 2011). Boreal forests with relatively low carbon sequestration potential may take centuries before permanent reduction of the carbon stocks resulting from increased bioenergy harvest is repaid by reduced emissions from fossil fuels (Holtsmark, 2011). For more productive temperate regions, an infinite payback time was found implying that lower GHG emissions are achieved through C-sequestration in forests rather than through bioenergy production (Hudiburg *et al.*, 2011).

Recent studies of the differences in timing of CO_2 emissions from bioenergy production and forest carbon uptake (Cherubini *et al.*, 2011a,b) suggest that the 'upfront' CO_2 emitted during biomass harvest and combustion stays in the atmosphere for decades before the CO_2 is removed by the growing forest. It results in a 'pulse' of warming in the first decades of bioenergy implementation. This contrasts calls for a rapid reduction of the growth rate of climate forcing (Friedlingstein *et al.*, 2011) required to achieve the policy of limiting warming to 2 °C.

The initially reported emission savings from forest bioenergy are based on erroneous assumptions in the accounting schemes. Studies that corrected these errors suggest that forest management that reduces the current biomass pool is unlikely to result in the envisioned emissions savings at all, and certainly not over the next decades.

Economic viability

Emerging technologies such as biofuel refineries and combined heat and power plants have to compete against established technologies applied in coal, gas and nuclear power plants. In the United States, a recent National Research Council report concluded that only in an economic environment characterized by high oil prices (e.g. >$191 per barrel), technological breakthroughs (cellulosic ethanol) and at a high implicit or actual carbon price would biofuels be cost-competitive with petroleum-based fuel (NRC, 2011). Hence, incentives favouring bioenergy (i.e. production quota, subsidies, tax cuts) will be needed to complement or even replace fossil fuel-based technologies (Schneider & Kaltschmitt, 2000; Ryan *et al.*, 2006; Ahtikoski *et al.*, 2008; NRC, 2011).

Schemes favouring the economics of one practice or technology over another often lead to unanticipated side-effects. For example, side-effects have been documented for the Common Agricultural Policy of the European Union (Macdonald *et al.*, 2000; Stoate *et al.*, 2001), and forest-based bioenergy production would seem to be similar. In Germany, where bioenergy is subsidized, the market price for woody biomass increased from 8 to 10 € m^{-3} in 2005 to 46 € m^{-3} for hardwood and 30–60 € m^{-3} for coniferous wood in 2010. Prices for woody biomass for bioenergy now reach 60–70% of saw log prices (Waldbesitzerverband, 2010; wood sales by one of the authors). Such prices discourage the production of quality timber and make root extraction and total tree use attractive options despite the documented unfavourable effects on soil carbon, soil water and nutrient management (Johnson & Todd, 1998; Johnson & Curtis, 2001; Burschel & Huss, 2009; Peckham & Gower, 2011).

For the German example, the price increase is driven by the installation of distributed bioenergy plants and the competitive market of other uses for biomass, such as wood for production of cellulose. Although the details will differ among regions and countries, increasing imports by developed nations is the most likely response to an increasing wood demand (Seintsch, 2010), because total wood harvest has not substantially changed in the developed world (i.e. ~1.4×10^9 m^3

between 1990 and 2010 in Europe and North America, FAO, 2010). Increased imports are likely to be met through land-use (intensity) change in other regions (lateral transfer of emissions). In the case of increased imports, these are most likely met by harvesting previously unmanaged forests or forest plantations. Thus, similar to crop-based production systems, forest-based bioenergy requires additional land, contrary to previous expectations (Tilman *et al.*, 2009). Increased wood imports, thus, represent a global footprint of local energy policies and should be accounted for in life cycle assessment of wood-based bioenergy.

Reduced manufacturing residue losses and other technological advances such as glued wood-based elements initiated a trend towards shorter rotations and thus younger forests. However, the economics of bioenergy production supported by existing subsidy schemes is expected to reduce rotation length to its lowest limit and promote questionable management practices and increased dependency on wood imports. Further, high prices for biomass will discourage forest owners from investments in long rotations, resulting in a shortage of quality timber. Given the time required to produce high-quality timber, such shortage cannot be remedied by short-term (economic) incentives.

Environmental consequences

Homogeneous young stands with a low biomass resulting from bioenergy harvest are less likely to serve as habitat for species that depend on structural complexity. It is possible that succession following disturbance can lead to young stands that have functional complexity analogous to that of old forests; however, this successional pathway would likely occur only under natural succession (Donato *et al.*, 2011). A lower structural complexity, and removal of understory species, is expected to result in a loss of forest biodiversity and function. It would reverse the trend towards higher biomass of dead wood (i.e. the Northwest Forest Plan in the United States) to maintain the diversity of xylobiontic species.

Cumulative impacts of bioenergy-related management activities that modify vegetation, soil and hydrologic conditions are likely to influence erosion rates and flooding and lead to increased annual runoff and fish habitat degradation of streams (Elliot *et al.*, 2010). Young uniform stands with low compared to high standing biomass have less aesthetic value for recreation (Tahvanainen *et al.*, 2001) and are less efficient in avalanche control and slope stabilization in mountains owing to larger and more frequent cutting (Brang, 2001). A potential advantage is that younger forests with shorter rotations offer opportunities for assisted migration, although there is great uncertainty in winners and losers (species, provenances, genotypes) in a future climate (Larsen, 1995; Millar *et al.*, 2007; Pedlar *et al.*, 2011). Plantations, however, largely contribute to pathogen spread, such as rust disease (Royle & Hubbes, 1992).

Forests offer several important ecosystem services in addition to biomass and some would be jeopardized by the bioenergy-associated transition from high to low standing biomass. Agriculture provides a visible example for abandoning most ecosystem services except biomass production (Foley *et al.*, 2005); communities in intensive agricultural regions often rely on (nearby) forested water sheds for drinking water, recreation and offsetting GHG emissions from intensive agriculture (Schulze *et al.*, 2009).

Sustainability

From a historical perspective, a transition from forest biomass burning to fossil fuels literally fuelled the industrial revolution, and consequently, caused rapid climate change. However, the collapse of biomass use enabled the recovery of largely degraded forest ecosystems (Gingrich *et al.*, 2007). Partly due to recovery from previous (mis)use, C-sequestration is especially strong over Europe (Ciais *et al.*, 2008; Luyssaert *et al.*, 2010) and the United States (Williams *et al.*, 2011). As such, C-sequestration can be considered a side-effect of the transition of energy sources from wood to fossil fuels (Erb *et al.*, 2008). Industrial-scale use of forest biomass for energy production would likely reverse this trend or at least reduce the carbon sink strength of forests (Haberl *et al.*, 2003; Holtsmark, 2011; Hudiburg *et al.*, 2011). The historical forest resource use in Europe and the United States is the present day situation in Africa. For example, southern African *miombo* forests have been degraded into shrubland as a result of charcoal production, where charcoal is the main energy source for rural communities even at a very low level of total energy consumption (Kutsch *et al.*, 2011).

A widespread misconception is that the most productive forests are necessarily the strongest carbon sinks. Actually, net primary productivity of forests is typically negatively correlated with the cumulative amount of carbon stored in biomass (Fig. 1). In reality, old forests show lower NPP but store the largest amount of carbon (Luyssaert *et al.*, 2008; Hudiburg *et al.*, 2009; Bugmann & Bigler, 2011) because slow growing forest live longer than fast growing forest (Schulman, 1954; Bigler & Veblen, 2009). Hence, on areas currently forested, any fast rotation management and use for fossil fuel substitution is reducing forest carbon sequestration. At regional scales, a permanent increase in annual wood harvest results in a permanent reduction in the amount of

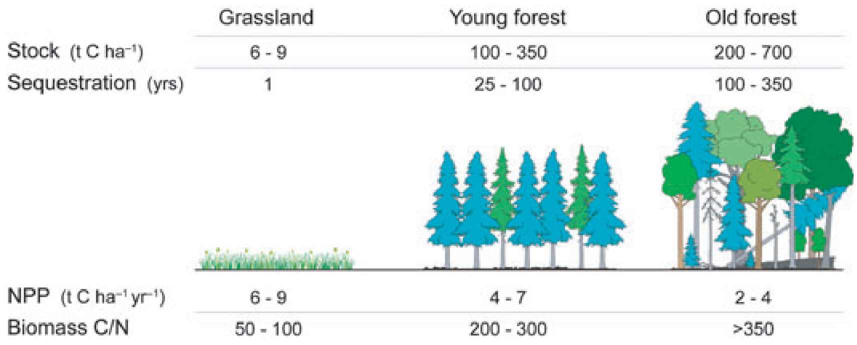

Fig. 1 Land management trade-off: maximizing productivity vs. carbon stocks. Given fixed resource availability, land managers can maintain highly productive ecosystems with a low standing biomass such as grasslands. The dominant tissues are leaves and roots with a low C/N ratio (~50). The same resources could be used to grow forest. With time forest accumulate considerable amounts of carbon in their biomass but forest that grow old have a lower net primary production than young forest and grasslands. Woody biomass has high C/N ratios (~400) and with an increasing share of woody biomass in the total biomass, the C/N ratio of the ecosystem decreases. Consequently, the time integral of productivity will be lower for an old forest compared with grassland, but at the same time, the time integral of nitrogen export will be lower for an old forest (closed nitrogen cycle) compared with a grassland (open nitrogen cycle). Hence, increasing the biomass pool size is the sustainable way of capitalizing from forests in the C-sequestration vs. C substitution debate. Ranges in the figure are for temperate ecosystems based on (Van Tuyl *et al.*, 2005; Luyssaert *et al.*, 2007, 2008; Schulze *et al.*, 2009; Keith *et al.*, 2009).

carbon stored in forests at the regional scale due to a lower average stand age (Körner, 2009; Holtsmark, 2011).

Globally, ~7% of global forest net primary production (NPP) outside wilderness areas is used by humans annually (Haberl *et al.*, 2007a). In Europe, human appropriation of forest NPP reaches ~15% (Luyssaert *et al.*, 2010). Thus, even in the absence of industrial production of wood-based bioenergy, humans already seize a remarkable share of forest production. To produce 20% of current primary energy consumption from wood-based bioenergy, as suggested by policy targets, it would require more than doubling the global human appropriation of NPP (HANPP) to 18–21% (Table 1; ratio of row 1 and 6). Such an increase in human appropriation would have serious consequences for global forests. Due to its nature, much of forest NPP cannot be harvested, e.g. fine root NPP, NPP for mycorrhizal associations and NPP in volatile organic emissions. Further, forests are harvested after decades of growth; hence, much of the NPP is already consumed by herbivores, added to the litter pool or decomposed in the detritus food chains long before harvest, e.g. leaves, fruits, fine

Table 1 Global HANPP in forests in the year 2000 and future HANPP that would result from providing 20% of world primary energy from forest harvest. NPP denotes net primary production and HANPP the human appropriation of net primary production. Using a gross caloric value of 19 kJ g^{-1} forest biomass or 38 kJ g^{-1} biomass carbon and a net caloric value of 41.9 GJ for 1 ton of oil equivalent. Conversion from net to gross calorific value was based on the following multipliers (gross/net): coal 1.1, oil 1.06, natural gas 1.11 and biomass 1.1 (Haberl *et al.*, 2006)

	Global C-flux (PgC yr^{-1})	Energy equivalent (EJ yr^{-1})	Source
(1) Current NPP of forest ecosystems	27–29	1030–1100	Haberl *et al.* (2007a) and Pan *et al.* (2011)
(1a) Belowground NPP (40%)	10–11	–	Luyssaert *et al.* (2007)
(1b) Leaf + twigs NPP (30%)	8.4–8.7	–	Luyssaert *et al.* (2007)
(1c) Aboveground woody NPP (30%)	8.4–8.7	330	Luyssaert *et al.* (2007)
(2) Primary energy use in 2006–2008	–	550	IEA (2008) and BP (2009)
(3) Global fossil energy use in 2006–2008	6–7	450	IEA (2008) and BP (2009)
(4) Additional fuel wood to produce 20% of primary energy	2.3	87	From 3 and 5
(5) NPP lost in harvest (10–30%)	0.5–1.4	19–53	From 2 and 6
(6) New HANPP level in forests	4.4–5.3	170–200	From 2, 6 and 7

roots, mycorrhiza and plants in early succession stages. Last, part of the NPP could be harvested but typically has no economic value, e.g. perennials, mosses and lichens. Consequently, the maximum HANPP is about 30% of the total NPP; hence, the proposed HANPP of 18–21% already represents ca. 60% of the global increment of woody biomass (Table 1; ratio of rows 1c and 6). Note that our maximum level of harvestable increment of woody biomass is most likely overestimated because the estimate did not account for economic (e.g. distance to population centre), logistic (e.g. steep mountain slopes) and legal (e.g. conservation areas) constraints on harvest. In addition to the increased GHG emissions that would result from such a programme due to reduced biomass stocks (see above), this increase in human appropriation of forest production would likely contribute to forest biodiversity loss, according to recent evidence on the correlation between HANPP and species richness (Haberl *et al*., 2005, 2007b).

Typically, the most fertile lands are in urban and agricultural use (Scott *et al*., 2001), leaving the poorer soils for forest use. The industrial-scale of envisioned forest bioenergy production would export substantial amounts of nutrients, further depleting the soil nutrient stock, particularly if wood removal includes relatively nutrient-rich biomass residues (slash) and root stocks (Peckham & Gower, 2011) as for total tree use. Nutrient and cation losses would have to be compensated for by fertilization, which in turn increases GHG emissions and increases N and P levels in nearby rivers leading to eutrophication of aquatic ecosystems (for a crop related example see Secchi *et al*., 2011).

A persistent 60–70% appropriation of woody biomass increment for bioenergy production from forest harvest over decades will erode current biomass pools, lower average stand age, deplete soil fertility and could thus only be sustained by amendments to nitrogen and phosphorous-depleted soils, activities that also produce GHG (N_2O) emissions.

Conclusion

Although bioenergy from forest harvest could supply ~20% of current energy consumption, this would increase human appropriation of NPP in forests to ~20% which is equivalent to 60–70% of the global increment in woody biomass. We argue that the scale of such a strategy will result in shorter rotations, younger forests, lower biomass pools and depleted soil nutrient capital. This strategy is likely to miss its main objective to reduce GHG emissions because depleted soil fertility requires fertilization that would increase GHG emissions, and because deterioration of current biomass pools requires decades to centuries to be paid back by fossil fuel substitution, if paid back at all. Further, shorter rotations would simplify canopy structure and composition, impacting ecosystem diversity, function and habitat. In our opinion, reasonable alternatives are afforestation of lands that once carried forests and allowing existing forests to provide a range of ecosystem services. Yet, on arable or pasture land, such a strategy would compete with food and fodder production. Society should fully quantify direct and indirect GHG emissions associated with energy alternatives and associated consequences prior to making policy commitments that have long-term effects on global forests. Reasonable alternatives for reducing GHG emissions on the order of the proposed bioenergy substitution include increased energy efficiency and reduced waste of energy via technological improvements and behaviour modification. There is a substantial risk of sacrifying forest integrity and sustainability for maintaining or even increasing energy production with no guarantee to mitigate climate change.

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Carbon debt repayment or carbon sequestration parity? Lessons from a forest bioenergy case study in Ontario, Canada

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Abstract

Forest bioenergy can contribute to climate change mitigation by reducing greenhouse gas (GHG) emissions associated with energy production. We assessed changes in GHG emissions resulting from displacement of coal with wood pellets for the Atikokan Generating Station located in Northwestern Ontario, Canada. Two contrasting biomass sources were considered for continuous wood pellet production: harvest residue from current harvest operations (residue scenario) and fibre from expanded harvest of standing live trees (stemwood scenario). For the stemwood scenario, two metrics were used to assess the effects of displacing coal with forest biomass on GHG emissions: (i) time to carbon sequestration parity, defined as the time from the beginning of harvest to when the combined GHG benefit of displacing coal with biomass and the amount of carbon in regenerating forest equalled the amount of forest carbon without harvest for energy production; and (ii) time to carbon debt repayment, defined as the time from the beginning of harvest to when the combined GHG benefit of displacing coal with biomass and the amount of carbon in the regenerating forest equalled forest carbon at the time of harvest. Only time to carbon sequestration parity was used for the residue scenario. In the residue scenario, carbon sequestration parity was achieved within 1 year. In the stemwood scenario, times to carbon sequestration parity and carbon debt repayment were 91 and 112 years, respectively. Sensitivity analysis showed that estimates were robust when parameter values were varied. Modelling experiments showed that increasing growth rates for regenerating stands in the stemwood scenario could substantially reduce time to carbon sequestration parity. We discuss the use of the two metrics (time to carbon sequestration parity and time to carbon debt repayment) for assessing the effects of forest bioenergy projects on GHG emissions and make recommendations on terminology and methodologies for forest bioenergy studies.

Keywords: biomass, carbon neutral, coal, electricity, forest carbon, greenhouse gas emissions, harvest residue, renewable energy, slash pile, standing trees

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Introduction

Current interest in forest bioenergy can be attributed to factors such as increasing energy demand, climate change, and greenhouse gas (GHG) emissions from combustion of fossil fuels. Forest biomass-derived energy can be a renewable alternative to traditional fossil fuel-based energy sources, and as such has been proposed for large-scale use to reduce demand for fossil fuels and dependence on foreign sources of these fuels (Richter *et al.*, 2009). Although nonhydro renewable sources, including bioenergy, are the fastest growing sources of electricity (IEA, 2011), current biomass use is often substantially below the available potential. For example, Parikka (2004) estimated sustainable worldwide woody biomass energy potential at about 12.5% of total global energy consumption, with less than 40% of this potential currently utilized. (For a review of studies on the contribution of woody biomass to the future global energy supply, the reader is referred to Berndes *et al.*, 2003).

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Substitution of fossil fuels with forest bioenergy to reduce GHG emissions was identified as one of four forest sector climate change mitigation options (IPCC, 2007). However, not every source of forest bioenergy immediately reduces atmospheric GHG (Lamers & Junginger, 2013). Assessments of the GHG emission reduction potential of any forest bioenergy fuel must include the following components: (i) life cycle analysis (LCA) of GHG emissions associated with producing forest bioenergy; (ii) analysis of forest carbon stock changes caused by biomass extraction compared to a baseline scenario; and (iii) LCA of GHG emissions associated with a reference energy scenario if forest biomass displaces a fossil fuel. An LCA of bioenergy production [Component (i)] includes GHG emissions related to both producing the bioenergy (including standing tree harvest and related forest operations such as regeneration, road construction and maintenance) and its use in place of fossil fuel alternatives (Ter-Mikaelian *et al.*, 2011). It includes noncarbon dioxide (CO_2) emissions from biomass combustion but not CO_2 emissions which are accounted for in forest carbon stock changes [Component (ii)]. This avoidance of double counting, as prescribed by the Intergovernmental Panel on Climate Change (IPCC), has led some to erroneously consider bioenergy to be 'carbon neutral', an error acknowledged in IPCC documents (see http://www.ipcc-nggip.iges.or.jp/faq/faq.html, accessed 1 May 2013).

Analysis of forest carbon stock changes [Component (ii)] is required to assess CO_2 emissions to the atmosphere or lost capacity for CO_2 sequestration from the atmosphere resulting from extracting biomass from the forest relative to a baseline scenario. The need to account for forest carbon stock changes relative to a baseline was discussed by Searchinger *et al.* (2009) and Haberl *et al.* (2012), who criticized flaws in international policies for bioenergy accounting. Although Searchinger *et al.* (2009) and Haberl *et al.* (2012) were primarily concerned with biomass produced from harvesting standing live trees, their arguments apply equally to all forest biomass sources, including harvest residue (Law & Harmon, 2011).

Two metrics used in recent literature on climate change mitigation potential of bioenergy include 'time to carbon sequestration parity' and 'time to carbon debt repayment' (Mitchell *et al.*, 2012). *Time to carbon sequestration parity* is the time between biomass harvest and when the overall carbon balance offsets the loss of carbon that would have been stored if the biomass were not harvested (Mitchell *et al.*, 2012). Here, overall carbon balance refers to the combined effect of biomass accumulation after harvest and reduced GHG emissions because of fossil fuel displacement.

Time to carbon debt repayment is the time between biomass harvest and when overall carbon balance of bioenergy use offsets the loss of carbon stored in biomass at time of harvest (Mitchell *et al.*, 2012). Time to carbon debt repayment may be relevant to forest bioenergy projects involving biomass harvest from purpose-grown plantations for which continued growth and accumulation of forest carbon in the absence of harvest for bioenergy seems unlikely (Lamers & Junginger, 2013). Difference between the two metrics is illustrated in Figure S1 (see Supporting Information). Time to carbon sequestration parity is a more commonly used metric than carbon debt repayment (Lamers & Junginger, 2013). Time to carbon sequestration parity is also referred to as carbon offset parity period (e.g. Jonker *et al.*, 2013) or break-even period (e.g. Ter-Mikaelian *et al.*, 2011), while carbon debt repayment is elsewhere called carbon payback period (e.g. Jonker *et al.*, 2013). We discuss both metrics later in this article.

Studies without a reference energy scenario [i.e. no Component (iii)], in which GHG emissions associated with forest bioenergy production are compared only with carbon losses from forest harvest relative to a baseline forest scenario, are relatively uncommon (e.g. Domke *et al.*, 2012). Most studies include a reference energy scenario (i.e. they assume that forest bioenergy is used to displace a fossil fuel), in which case GHG emissions resulting from the use of this fossil fuel [Component (iii)] are compared with GHG emissions from producing bioenergy [Component (ii)] and changes in forest carbon relative to a baseline scenario [Component (i)]. Studies with reference energy scenarios include traditional types of fossil fuels such as coal (McKechnie *et al.*, 2011; Holtsmark, 2012; Repo *et al.*, 2012; Jonker *et al.*, 2013; Lamers *et al.*, 2014), natural gas (Domke *et al.*, 2012; Repo *et al.*, 2012) and oil (Repo *et al.*, 2012). Although the geographical location and source of forest biomass for energy vary in these studies, common conclusions were that (i) forest bioenergy increases GHG emissions for a period of time relative to fossil fuels; and (ii) it may take decades (e.g. McKechnie *et al.*, 2011) or centuries (Holtsmark, 2012; Mitchell *et al.*, 2012) for associated net increases in GHGs to be reduced.

Most studies of GHG emissions from forest bioenergy use coal-produced energy as the reference scenario: biomass typically mitigates comparatively more CO_2 emission when used to replace more carbon-intensive fuels (Gustavsson *et al.*, 2011), and coal/lignite has the highest average GHG emissions per KWh of electricity produced, followed by oil and natural gas (Weisser, 2007). Coal also remains the main fuel for electricity generation globally and is the largest source of GHG emissions: coal accounted for 41% and 43% of electricity generation, and 73% and 78% of CO_2 emissions worldwide and in North America, respectively, in 2008 (IEA, 2011).

In Ontario, interest in forest biomass as a substitute for coal coincided with the decision to eliminate coal-fired energy generation by the end of 2014 (http://news.ontario.ca/mei/en/2009/09/ontarios-coal-phase-out-plan.html; accessed 12 December 2012). In 2012, Ontario operated four coal-fired generating stations with a combined capacity of 3347 MW. Forest bioenergy is one of the fuel-switching alternatives to coal considered by the Ontario Power Generation that would allow continued use of the existing generating station infrastructure beyond 2014. In McKechnie *et al.* (2011), net forest life cycle GHG emissions for a forest biomass-derived energy pathway for the Nanticoke (Ontario) Generating Station were compared to those for coal and were found to result in no net reduction in GHG emissions for 16 years (harvest residue) and 38 years (standing trees) if coal was displaced with wood pellets.

In this article, we examine GHG emissions resulting from displacing coal with forest biomass at the Atikokan Generating Station, located in Northwestern Ontario, Canada. The station has one coal-fired generating unit using low-sulphur lignite coal with 211 MW maximum generating capacity (http://www.opg.com/power/thermal/atikokan.asp, accessed March 2013). This work is part of a larger study in which LCA was applied in a real-life bioenergy case study to assess its usefulness for making policy decisions about energy choices. In the GHG component of the LCA, the carbon implications of retrofitting the Atikokan Generating Station for forest biomass use were analysed. In this study, we considered (i) harvest residue from ongoing harvest for traditional wood products (residue); and (ii) harvest of stemwood (standing live trees) as a biomass source to produce wood pellets. The objectives of the study were to:

1 Develop a temporal profile of GHG emissions resulting from the use of forest biomass for energy,
2 Estimate times to carbon debt repayment and carbon sequestration parity,
3 Assess sensitivity of the study results to assumptions and parameter values, and
4 Test the effects of growth rate of regenerating forest on carbon sequestration parity period after the harvest of stemwood for bioenergy.

We compare our results with those of similar studies and discuss the suitability of selected metrics (time to carbon debt repayment, time to carbon sequestration parity) for assessing the GHG emissions reduction potential of forest bioenergy projects.

Materials and methods

Forest data

All of Ontario's forests that are managed for fibre are divided into forest management units (FMUs). Forests available for harvest in each FMU are described using the Ontario forest resource inventory, an aerial survey describing the extent, species composition and age-class structure of the forest. Individual forest stands in the forest resource inventory are classified into forest units, defined as an aggregation of forest stands in 10 year age classes and with similar species composition that developed in a similar manner and are managed under the same silvicultural system. Forest units are further assigned natural disturbance rates based on regional disturbance history, natural succession rules defining transition of stands from one forest unit and/or age class to another with and without disturbance, and yield curves (Penner *et al.*, 2008). Forest management planning in individual FMUs is based on processed forest resource inventory (with forest land classified into forest units and age classes with assigned disturbance rates, succession rules and yield curves), on silvicultural rules and prescriptions (e.g. harvesting eligibility based on stand age or volume, renewal methods), and on management objectives and environmental constraints.

We used forest resource inventory for four FMUs (Crossroute Forest, Dog River-Matawin Forest, Sapawe Forest and Wabigoon Forest; Fig. 1), and the most recent forest management plan for each FMU (developed in 2007, 2009, 2010 and 2008,

Fig. 1 Boundaries of Ontario's forest management units (FMUs) with the study area highlighted in grey: 1 – Crossroute Forest, 2 – Dog River-Matawin Forest, 3 – Sapawe Forest, 4 – Wabigoon Forest, A – Atikokan Generating Station, B – Fort Francis. Inset: map of Canada, with province of Ontario highlighted in grey.

respectively). The four FMUs were selected because their proximity makes them logical sources of forest biomass for the Atikokan Generating Station, which is located in the eastern part of the Crossroute FMU (Fig. 1). Total forested area in the four FMUs is 2.41 million ha, with 2.21 million ha of forest available for fibre production. Dominant species included black spruce [*Picea mariana* (Mill.) B.S.P.], jack pine (*Pinus banksiana* Lamb.) and trembling aspen (*Populus tremuloides* Michx.). Average annual harvest from 1990 to 2008 was 2.61 million m^3, ranging from 2.22 million m^3 in 1990 to 3.70 million m^3 in 2000.

Locations of forest stands identified for harvest in the current forest management plans were provided by the Ontario Ministry of Natural Resources (R. Spaans, OMNR, personal communication, 2011). Together, the stands comprise the maximum forest area and wood volume that can be harvested while meeting targets for other aspects of sustainability of forest ecosystems. In practice, maximum volumes are rarely harvested because of factors such as low market demand and cost of harvesting/lack of access to remote stands. Ratios of actual harvested volumes to the maximum allowed in forest management plans were estimated for each individual forest unit based on historical harvest data for each FMU (J. Maure, OMNR, personal communication, 2011). These ratios were used to estimate area and wood volume within the maximum harvest targets specified in forest management plans that, based on historical average harvest volumes, would not be harvested for traditional wood products and thus would be available for harvesting for bioenergy.

Biomass collection and baseline scenarios

Two biomass sources were considered for producing wood pellets: (i) harvest residue from planned harvest operations for traditional wood products (e.g. construction lumber, pulp), resulting in production of 'brown' wood pellets (residue scenario); and (ii) stems of standing live trees from increased harvest of forest stands that otherwise would not be harvested for traditional wood products, resulting in production of 'white' pellets (stemwood scenario). The difference between brown and white pellet grades is based on ash content, which is related to proportions of bark, leaves and inorganic contaminants: the premium grade (white pellets) is produced from debarked wood but the commercial grade (brown pellets) includes a large amount of bark. The scenarios therefore represented contrasting sources of biomass for energy production: in the residue scenario, biomass was collected from existing harvest operations (i.e. no additional harvest of standing trees); in the stemwood scenario, biomass was collected from harvest of standing trees beyond planned harvest operations, without collection of any harvest residue.

Baseline scenarios were used to track the fate of forest carbon stocks without biomass collection for bioenergy. In the residue scenario, the baseline was controlled burning of a fraction of the residue in the forest (without energy production) to reduce fire hazard, with the remainder left to decay ('no residue collection' baseline). The fate of carbon stocks in standing trees was not included in the baseline for the residue scenario because these trees were scheduled for harvest for traditional wood products regardless of potential collection of harvest residue for bioenergy. The baseline for the stemwood scenario assumed a continued successional trajectory in which stands that would be harvested for biomass undergo natural changes such as growth, natural disturbances, changes in species composition, and dead organic matter decay ('no harvest' baseline). Stands harvested for traditional wood products are assumed to be harvested at the same rate in both the 'no harvest' baseline and biomass collection scenarios. Biomass collection and baseline scenarios are presented in Table 1.

Stands harvested for traditional products were selected from those eligible for harvest based on proximity to existing forestry roads, and harvest volume targets were estimated using historical ratios of actual-to-planned harvest for each FMU; these stands constituted the biomass source for the residue scenario. The forest stands remaining after those identified for harvest for traditional wood products were removed constituted the potential source of biomass in the stemwood scenario. Although harvest of new trees also generates harvest residues, this residue source was not included in the stemwood scenario to avoid production of mixed grade wood pellets.

Table 1 Description of biomass collection and baseline scenarios used in the study

Bioenergy scenario	Biomass source	Baseline scenario	Stand type	Pellet type	Reference scenario	Carbon metric
Residue	Harvest residue (slash piles)	Harvest residue at roadside burned (19–55%) or left to decay (45–81%), depending on FMU	Predominantly softwood	Brown pellets	Coal	Time to carbon sequestration parity
Stemwood	Stemwood (standing live trees) from additional harvest of underutilized stands; harvest residue left at roadside to decay (not burned)	No harvest: Stands continue to change, subject to natural processes (growth, decay, natural disturbance)	Predominantly hardwood	White pellets	Coal	Time to carbon sequestration parity Time to carbon debt repayment

Analysis framework

Total GHG emissions resulting from displacing coal with forest biomass were assessed using the analysis framework developed by McKechnie *et al.* (2011). The framework combines two components: (i) life cycle inventory analysis (LCIA) to quantify GHG emissions from energy produced using forest biomass; and (ii) forest carbon modelling to quantify the effect of biomass harvest on forest carbon stocks over time. Life cycle inventory analysis includes GHG emissions related to all phases of producing energy from forest biomass, such as collecting biomass (standing tree harvest or collection of harvest residue), regenerating harvested stands, constructing and maintaining roads, transporting biomass to the pellet facility, pelletizing, transporting pellets to the generating station, and using biomass in place of coal. Changes in forest carbon stocks following biomass harvest are not included in the LCIA and are treated as a separate component as in McKechnie *et al.* (2011). Total GHG emissions equal the sum of contributions to GHG emissions resulting from the life cycle inventory analysis and from changes in forest carbon stocks.

For a one-time collection of forest biomass to produce energy occurring at time T_0, total GHG emissions at time t after collection ($\mathrm{GHG_{Total}}$; t $\mathrm{CO_2eq}$, tonnes of $\mathrm{CO_2}$ equivalent) can be calculated as:

$$\mathrm{GHG_{Total}}(T_0+t) = \Delta\mathrm{FC}(T_0+t) + Z(T_0)P_{\mathrm{bio}}(\mathrm{GHG_{LCAbio}} - \mathrm{GHG_{LCAcoal}}) \quad (1)$$

where ΔFC is change in forest carbon resulting from biomass collection (t $\mathrm{CO_2eq}$), $Z(T_0)$ is the amount of biomass collected to produce energy (odt, oven-dry tonnes), P_{bio} is the energy produced by one odt of biomass (MWh odt^{-1}), $\mathrm{GHG_{LCAbio}}$ is life cycle emissions from producing forest biomass energy but excluding $\mathrm{CO_2}$ combustion emissions (t $\mathrm{CO_2eq}$ MWh^{-1}), and $\mathrm{GHG_{LCAcoal}}$ is life cycle emissions from producing the same amount of energy using coal (t $\mathrm{CO_2eq}$ MWh^{-1}). GHG variables in Eqn (1) are presented in tonnes of $\mathrm{CO_2}$ equivalent (one tonne of carbon is equivalent to 3.667 tonnes of $\mathrm{CO_2}$) to account for non-$\mathrm{CO_2}$ GHG emissions, which require conversion into $\mathrm{CO_2eq}$ using global warming potential multipliers. To express changes in forest carbon stocks in the same units as GHG emissions, ΔFC was also converted to t $\mathrm{CO_2eq}$. The difference ($\mathrm{GHG_{LCAbio}} - \mathrm{GHG_{LCAcoal}}$) is the GHG emission benefit of producing one unit of energy from forest biomass instead of coal, while the entire second term in Eqn (1) is the total GHG emissions benefit from using $Z(T_0)$ biomass instead of coal to produce energy.

To assess the GHG emission effect of forest bioenergy scenarios, we used two metrics that differ in calculation of the term ΔFC in Eqn (1). For the first metric, time to carbon sequestration parity, change in forest carbon resulting from biomass collection (ΔFC) equals the difference between forest carbon stocks after collecting biomass and those in the baseline scenario:

$$\Delta\mathrm{FC}(T_0+t) = \mathrm{FC_{base}}(T_0+t) - \mathrm{FC_{pc}}(T_0+t). \quad (2)$$

Here, $\mathrm{FC_{pc}}$ (T_0+t) is forest carbon stock (t $\mathrm{CO_2eq}$) at time t after biomass collection and $\mathrm{FC_{base}}$ (T_0+t) is forest carbon stock (t $\mathrm{CO_2eq}$) at time t if residues were not collected or stands were not harvested for bioenergy. Time to carbon sequestration parity (T_{parity}), is the time t after biomass collection at which $\mathrm{GHG_{Total}}$ in Eqns (1) and (2) equals zero. This is the time required for the GHG benefits of displacing coal with biomass to offset losses of forest carbon, taking into account changes in forest carbon that would have occurred in the absence of biomass collection. Time to carbon sequestration parity was estimated for both residue and stemwood biomass collection scenarios.

For the second metric, time to carbon debt repayment, the change in forest carbon from biomass collection (ΔFC) is calculated from:

$$\Delta\mathrm{FC}(T_0+t) = \mathrm{FC_{base}}(T_0) - \mathrm{FC_{pc}}(T_0+t). \quad (3)$$

Eqn (3) quantifies changes in forest carbon only relative to its amount at the time of harvest T_0. Time to carbon debt repayment (T_{debt}) is the time t after biomass collection at which $\mathrm{GHG_{Total}}$ in Eqns (1) and (3) equals zero. This is the time required for the GHG benefits of displacing coal with biomass to offset losses of forest carbon that occurred at the time of biomass collection. Time to carbon debt repayment was estimated only for the stemwood scenario.

For continuous biomass collection to produce energy, Eqn (1) is integrated over time starting from the first year of biomass collection for both residue and stemwood scenarios. The GHG emissions associated with collecting biomass and displacing coal and its effect on forest carbon stocks were estimated for 100 years, with biomass collection beginning in 2015. Forest management plans do not indicate the harvest eligibility of forest stands beyond the first 10 years of the plan and therefore the analysis was completed for forest stands identified for the first 10 years, and then repeated nine times at 10 year intervals (i.e. availability of stands for harvest during the first 10 year term was assumed to be the same in all consecutive 10 year terms).

GHG emissions

In the stemwood scenario, biomass available for producing wood pellets was estimated using yield curves from forest management plans. For the residue scenario, only roadside slash was considered as a source of biomass. Roadside slash is produced when stands are harvested using full-tree harvesting, the most prevalent system in Northwestern Ontario (Pulkki, 2013). The amount of available biomass in the residue scenario was estimated using the Biomass Opportunity Supply (BiOS) model. In this model, allometric equations developed by Lambert *et al.* (2005) are applied to estimate the potentially available biomass, which is modified using a technical feasibility factor that is based on validation trials conducted by FPInnovations (Ralevic *et al.*, 2010).

Estimating changes in forest carbon stocks in the residue scenario [term $\Delta\mathrm{FC}(t)$ in Eqn (2)] requires projecting the amount of carbon in the baseline scenario. The fraction of biomass burned in roadside slash piles and the natural decay rates of the unburned fraction of the piles were compiled from forest management reports for the study area and from literature on down woody debris decomposition (see Supporting Information).

In the stemwood scenario, forest carbon stocks after biomass collection for bioenergy [term FC_{pc} (T_0+t) in Eqn (2)] equal the sum of carbon stocks in the regenerating forest plus the carbon content of harvest residue at time t after biomass collection. Stands harvested in the stemwood scenario are in addition to normal harvest rates and therefore we assumed that harvest residue produced in the stemwood scenario was left to decay (i.e. none was burned in slash piles). This assumption was based on the fact that estimated historical average fractions of burned slash piles were less than 100% in all four FMUs in the study, indicating either operational difficulties or a lack of capacity precluding forest companies from completing the burning of all roadside slash.

Forest carbon stocks for the stemwood scenario are estimated at the time of harvest T_0 [term FC_{base} (T_0) in Eqn (3)] and projected into the future in the absence of biomass collection [term FC_{base} (T_0+t) in Eqn (2)]. Carbon stocks in a given forest stand and their projection over time were estimated using the algorithms and parameter values in FORCARB-ON (Chen *et al*., 2010). FORCARB-ON is a large-scale forest carbon budget model developed to project forest carbon stocks under various management scenarios. The model estimates forest ecosystem carbon stocks in seven pools: live trees, standing dead trees, down woody debris, understory vegetation, forest floor, soil and black carbon resulting from wildfires; estimation of carbon stocks in the eighth pool, slash piles, was done outside of the model as described above. Input data required by FORCARB-ON (growth and yield curves, succession rules, and disturbance rates) were obtained from forest management plans. Simulation of regenerating stands also required information on postharvest renewal rules that specify allocation of regenerating areas to different silvicultural intensities, producing stands with different yield curves. Detailed descriptions of methods and parameter values used to estimate forest carbon pools are in Chen *et al*. (2010).

Life cycle emissions for energy produced from forest biomass and from coal (terms GHG_{LCAbio} and $GHG_{LCAcoal}$ in Eqn (1)) were developed using LCA methods consistent with ISO-14040/44 standards. The models provide GHG emissions associated with all phases of the use of a given energy source, from initial resource extraction through to the use of the fuels, including transportation and distribution. LCA studies do not usually include GHG emissions for roadside slash, other than its collection and comminution. For the residue scenario in this study, a mass balance allocation approach was used that attributed a percentage of GHG emissions to slash generation. In the stemwood scenario, life cycle emissions resulting from energy produced using forest biomass included emissions from constructing roads to access stands for harvest; proposed access roads were based on locations of specific stands and the existing forestry road network. Based on annual volumes of collected biomass, it was assumed that two pellet plants would be required to produce the resulting wood pellets. Fort Francis and Atikokan were selected as locations of hypothetical pellets plants, with collected biomass sent to the closest plant. All pellets were then assumed to be transported to the Atikokan Generating Station.

GHG emissions related to producing inputs (e.g. diesel, electricity) were included based on their cradle-to-grave activities. Specific emissions associated with each life cycle phase were estimated using the EcoInvent database (http://www.ecoinvent.ch/, accessed March 2012). EcoInvent data were supplemented with estimates by Zhang *et al.* (2010) and McKechnie *et al.* (2011). To avoid double counting, life cycle GHG emissions for forest biomass did not include CO_2 emissions from combustion of wood pellets because these were already accounted for in forest carbon stock change [term $\Delta FC(t)$ in Eqn (1)]. Methodologies for estimating life cycle GHG emissions associated with producing energy from wood pellets and coal are from Zhang *et al.* (2010) and McKechnie *et al.* (2011).

Sensitivity analysis and effect of regeneration rate

To assess the robustness of estimated GHG emissions to assumptions and parameters used in the analysis, we tested the effect of slash decomposition rate and GHG 'benefit' of displacing coal (i.e. reduction in GHG emissions resulting from displacement of coal with wood pellets) in both the residue and stemwood scenarios. In addition, the residue scenario was tested for the effect of slash pile burning ratio (i.e. fraction of slash piles, by area, burned within an FMU), and the stemwood scenario was tested for the effect of yield curves in regenerating stands. Slash combustion ratio (i.e. fraction of slash burned within a slash pile) was not included in the sensitivity analysis because its effect on estimated GHG emissions would be identical to that of the slash burning ratio. Parameters differed between the two scenarios because some were relevant to only one scenario (e.g. slash burning ratio had no effect on the stemwood scenario).

The effects were tested using factorial design as described by Saltelli & Annoni (2010) for the following response functions: time to carbon sequestration parity, time to carbon debt repayment (only for the stemwood scenario), and cumulative GHG emissions/reductions from displacing coal with wood pellets at years 50 and 100 from the start of biomass collection.

To further explore the effect of growth rate on total GHG emissions in the stemwood scenario, we conducted a series of modelling experiments in which yield curves (Fig. 2) were incrementally changed to simulate accelerated accumulation of stocks in postharvest regenerating stands (i.e. effect of more rapid regeneration and early growth rates). Modified yield curves were used to calculate forest carbon stocks, $FC_{pc}(t)$, in regenerating forest, and time to carbon sequestration parity was estimated using Eqn (1) for each set of modified yield curves. See Supporting Information for additional detail on sensitivity analysis and regeneration rates.

Results

Average annual harvest for traditional wood products (lumber and pulp) in the four FMUs was projected at 2.32 million $m^3\ yr^{-1}$, generating 443 900 odt yr^{-1} of harvest residue. Some 66 600 odt residue yr^{-1} were assumed to be used to generate heat during the

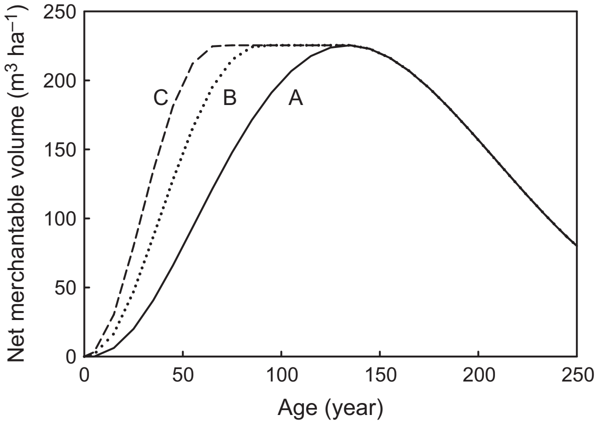

Fig. 2 Example of initial (A) and modified (B and C) yield curves used to simulate the effect of postharvest regeneration rate on time to carbon sequestration parity.

pelletization process, leaving 377 300 odt yr^{-1} to produce energy. This was estimated to generate 675 000 MWh of electricity annually (P_{bio} = 1.520 MWh odt^{-1}). In the residue scenario, we used the above estimated P_{bio} (for consistency) to calculate total GHG emissions in Eqn (1) for the total amount of residues collected (i.e. both for producing pellets and for burning at the Atikokan Generating Station) for life cycle GHG emissions.

The stemwood scenario generated 587 400 odt yr^{-1} of stemwood biomass for pellet production, increasing the ratio of actual/maximum allowed harvest from the historical levels of 84% to 95% for softwoods and from 51% to 95% for hardwoods. (Bark stripped from stems was assumed to be used to generate heat during pelletization and was not included in the 587 400 odt yr^{-1} estimate). This would generate 1 020 000 MWh of electricity annually (P_{bio} = 1.736 MWh odt^{-1}). All GHG emissions are expressed using a functional unit of 1 MWh yr^{-1} so that residue and stemwood scenarios can be compared. Conversion of results to this functional unit does not affect estimates of times to carbon sequestration parity or carbon debt repayment.

Table 2 Life cycle greenhouse gas (GHG) emissions (kg CO_2eq MWh^{-1}) associated with two bioenergy and coal reference scenarios

	GHG emissions (kg CO_2eq MWh^{-1})		
LCA category	Residue scenario	Stemwood scenario	Coal scenario
Commissioning*	8.55	5.63	4.50
Fuel procurement†	47.48	54.79	35.38
Power plant‡	21.99	21.83	1210.83
Total	78.02	82.25	1250.70

*Commissioning – coal plant construction (coal scenario) or pellet plant construction, retrofit of the Atikokan Generating Station, and construction of forestry access roads (biomass scenarios). GHG emissions associated with construction of plants were spread over life time of plants that was assumed to be 40 years.

†Fuel procurement – coal mining, processing and transportation (coal scenario) or biomass collection, comminution, forest regeneration, transporting biomass from forest to pellet plant, pelletizing, ash management and transporting pellets to power plant (biomass scenarios).

‡Power plant – fuel handling, combustion emission (CO_2 not included in biomass scenario) and ash management.

Estimated life cycle GHG emissions for the two biomass scenarios and the coal reference scenario are presented in Table 2. In the residue scenario, GHG emission reductions from displacement of coal outweighed losses of forest carbon from the beginning of biomass collection, resulting in a steady decrease in total cumulative emissions (Fig 3a). Carbon sequestration parity was achieved within the first year of biomass collection, with total GHG emissions reduced by 82.9 t CO_2eq after 100 years relative to coal. In the stemwood scenario, losses in forest carbon stocks were initially larger than the reduction in GHG emissions from displacement of coal by wood pellets (Fig. 3b and c). Accumulating carbon in regenerating forests reversed the trend in forest carbon by about 40 (Fig. 3b) and 50 (Fig. 3c) years from the beginning of biomass collection. The point of maximum loss in forest carbon stocks when using the time to carbon sequestration parity (Fig. 3b) occurs earlier than when using the time to carbon debt repayment (Fig. 3c) because without harvest forest carbon stocks would have decreased because of natural succession and disturbance. Carbon sequestration parity (T_{parity}) in the stemwood scenario was reached after 91 years of continuous biomass collection and total GHG emissions were reduced by 14.4 t CO_2eq after 100 years (Fig. 3b). Time to carbon debt repayment (T_{debt}) in the stemwood scenario was 112 years and total GHG emissions increased by 32.8 t CO_2eq after 100 years (Fig. 3c).

Effects of parameter variation on total cumulative GHG emissions after 50 and 100 years of continuous biomass collection and on times to carbon sequestration parity and carbon debt repayment are shown in Fig. 4. In the residue scenario, parameters tested had no effect on time to carbon sequestration parity, which remained at less than 1 year, and therefore are not shown in Fig. 4a. As with Fig. 3, changes in forest carbon stocks in the stemwood scenario were calculated for two metrics: time to carbon sequestration parity [Eqn (1); Fig. 4b] and time to carbon debt repayment [Eqn (3); Fig. 4c]. Effects of simultaneous variation in all pairs of parameters calculated using Eqn (S2) were negligible (less than 1% relative to response function's value at the

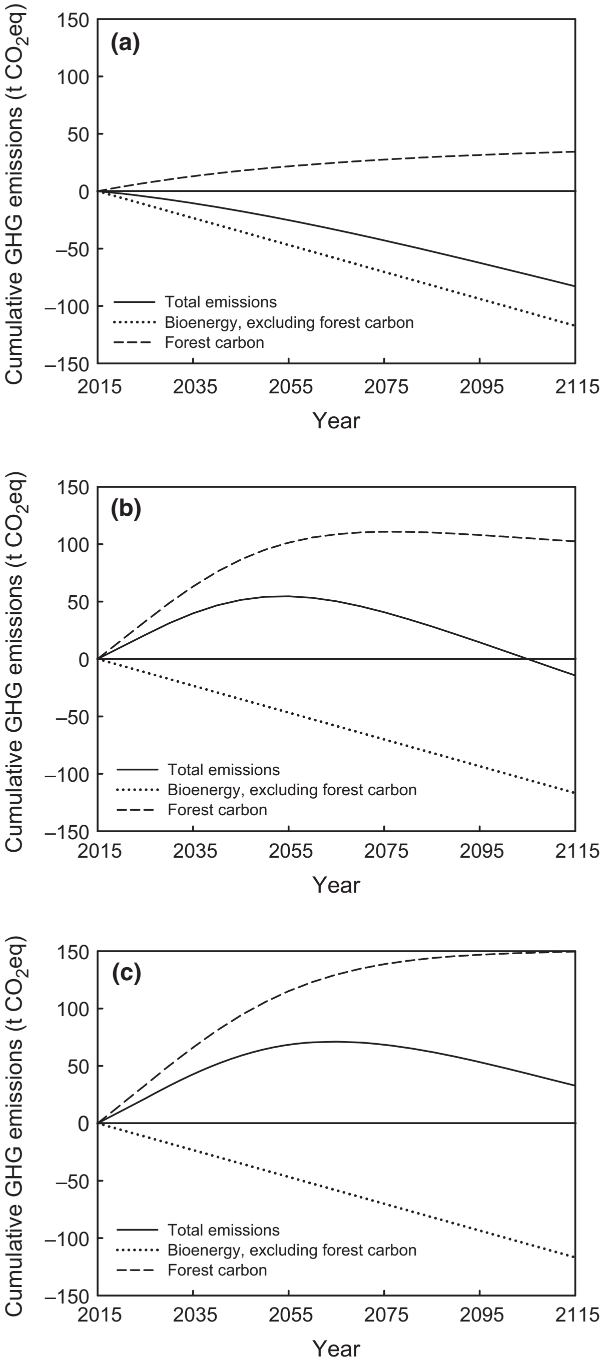

Fig. 3 Cumulative greenhouse gas (GHG) emissions (dotted line – from changes in forest carbon stocks; dashed line – from displacement of coal with wood pellets not including wood pellet combustion emissions; solid line – total) for (a) residue, and (b and c) stemwood scenarios. GHG emissions are presented for (a and b) time to sequestration parity, and (c) time to carbon debt repayment metrics. GHG emissions are presented as MWh yr^{-1}. Positive values indicate an increase in GHG emissions to the atmosphere.

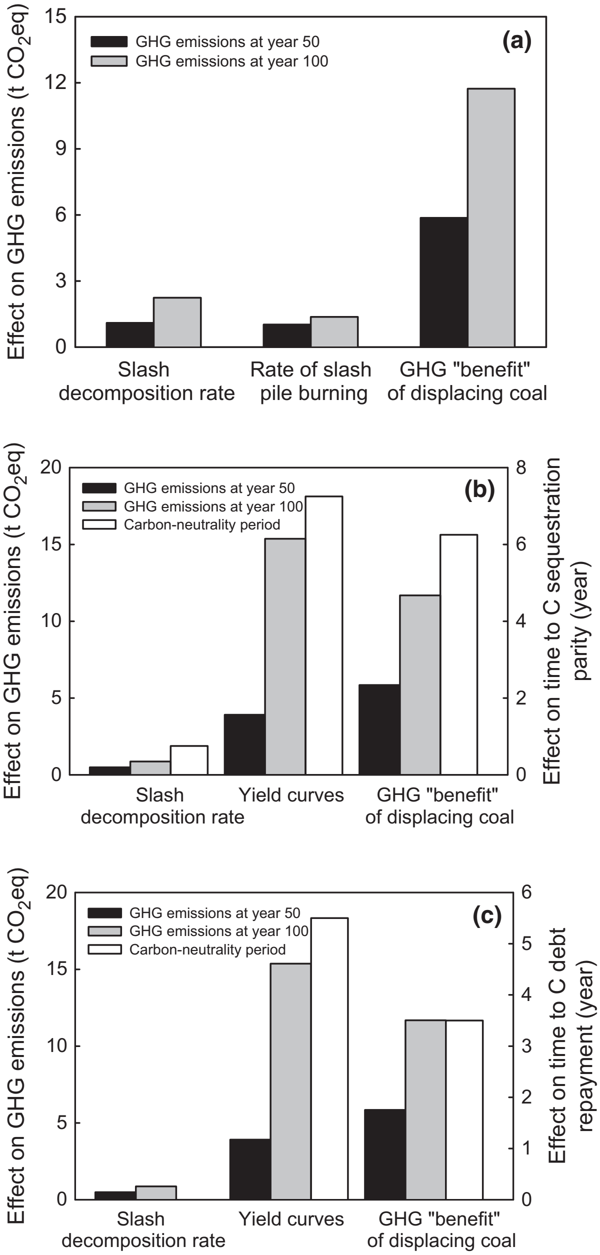

Fig. 4 Effect of model parameter variation on change in total cumulative greenhouse gas (GHG) emissions by year 50 and year 100 in (a) harvest residue, and (b and c) stemwood scenarios. The carbon neutrality period in (b) is time to carbon (C) sequestration parity, and in (c) is time to carbon (C) debt repayment. GHG emissions are presented as MWh yr^{-1}.

base value of parameters), indicating no interaction among parameters.

Time to achieve carbon sequestration parity in response to changes in growth rate of regenerating forest stands following biomass collection in the stemwood scenario decreased with increased growth rate of low productivity stands (Fig. 5).

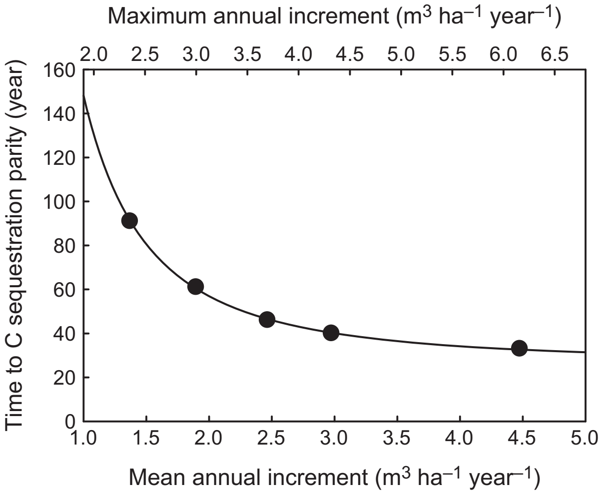

Fig. 5 Effect of growth rate of regenerating forest stands on time to carbon (C) sequestration parity in stemwood scenario. Dots are times to carbon sequestration parity estimated in modelling experiments; respective values of mean and maximum annual increment (m^3 ha^{-1} yr^{-1}) are shown on the bottom and top *x*-axes, respectively. The solid line illustrates the trend in times to carbon sequestration parity in response to increasing growth rate of regenerating stands.

Discussion

Estimates of residue availability and life cycle GHG emissions found in this study are consistent with those of others. For example, Froese *et al.* (2010) estimated available harvest residue from harvest operations in Michigan, USA, at 351 Gg yr^{-1} (351 × 10^6 kg yr^{-1}) for an average annual harvest of 1143 Gg. This is equivalent to 148 kg (oven-dry weight) of harvest residue for each cubic metre of wood harvested for traditional wood products (mass of annual harvest converted into volume using specific gravity of 480 kg m^{-3} as per Froese *et al.*, 2010). In our study, the amount of residue available from harvest operations was estimated to be 192 kg m^{-3}.

Life cycle GHG emissions associated with each energy production scenario (Table 1) were similar to worldwide estimates compiled by Weisser (2007). For lignite power plants, Weisser (2007) estimated the range of total GHG emissions to be 800–1700 kg CO_2eq MWh^{-1}, with a standard deviation around the mean of all estimates included in his review ranging from 950 to 1250 kg CO_2eq MWh^{-1}; estimates of total GHG emissions from wood-based fuels were 35 to 99 kg CO_2eq MWh^{-1} (total range) and 60 to 85 kg CO_2eq MWh^{-1} (standard deviation around the mean); our estimates (Table 1) were thus within 1 SD of the mean of those compiled by Weisser (2007). Also of note is that the product $P_{\mathrm{bio}}\cdot(\mathrm{GHG}_{\mathrm{LCAbio}} - \mathrm{GHG}_{\mathrm{LCAcoal}})$ in Eqn (1) is equivalent to the bioenergy conversion factor η_{biomass} used by Mitchell *et al.* (2012). In their simulations, Mitchell *et al.* (2012) used the range 0.2–0.8 for the bioenergy conversion factor (η_{biomass}), with a mean of 0.51. In our study, the product $P_{\mathrm{bio}}\cdot(\mathrm{GHG}_{\mathrm{LCAbio}} - \mathrm{GHG}_{\mathrm{LCAcoal}})$ in Eqn (1) was equal to 0.49 and 0.55 for the residue and stemwood scenarios, respectively, which are very close to the mean value used by Mitchell *et al.* (2012).

Results of our study are consistent with other analyses of the displacement of fossil fuels by forest biomass but direct comparison of results is often not straightforward for several reasons. First, studies on the use of forest biomass vary in methodology; some do not account for all phases of LCA (e.g. Domke *et al.*, 2012; Zanchi *et al.*, 2012) or the fate of forest carbon stocks in the absence of collecting biomass to produce energy (e.g. Yoshioka *et al.*, 2005; Gustavsson *et al.*, 2011). While methods employed in these studies met their specific objectives, they do not provide a comprehensive assessment of GHG emissions associated with the use of forest biomass to produce energy in place of fossil fuels. Second, studies differ in the reference fossil fuel considered, ranging from coal (e.g. McKechnie *et al.*, 2011) to natural gas (e.g. Domke *et al.*, 2012), oil (e.g. Repo *et al.*, 2012), automotive gasoline (e.g. Hudiburg *et al.*, 2011) or generic fossil fuel (Holtsmark, 2012). Third, life cycle GHG emissions for producing bioenergy and each reference fuel source reflect differences in the thermal efficiency of power plants and upstream emissions (Weisser, 2007). Finally, studies are specific to local forest conditions and management practices, as reflected in treatment of harvest residue and regeneration of harvested stands. Nevertheless, despite variations in methods and geography, the conclusions of our study are consistent with those of others on the use of forest biomass for energy generation: for scenarios involving use of harvest residue from ongoing forestry operations, an overall reduction in GHG emissions is achieved within the first few years of biomass collection (0–16 year range as per literature review by Lamers & Junginger, 2013), while increased harvesting of trees to produce energy leads to an initial increase in GHG emissions that may take decades or even centuries to offset (Holtsmark, 2012; Mitchell *et al.*, 2012).

Closest to this study in terms of methods and geography are those by McKechnie *et al.* (2011) and Ter-Mikaelian *et al.* (2011). McKechnie *et al.* (2011) also studied the use of harvest residue and stemwood but did so in Eastern Ontario for use in place of coal at the Nantikoke Generating Station. They estimated the time to carbon sequestration parity at 16 and 38 years from the start of continuous biomass collection for both the residue and stemwood scenarios, respectively (compared to 1 and

91 years in the present study, respectively). We hypothesize that differences in estimated times to carbon sequestration parity between the two studies are attributable to factors such as tree growth rates and average age of successional changes, treatment of harvest residue in the baseline scenario, and life cycle GHG emissions for the reference fuel scenario.

Sensitivity analysis showed that time to carbon sequestration parity was unaffected by variations in any parameter tested in the residue scenario. As seen from Fig. 4a, the GHG benefit of displacing coal with bioenergy (i.e. reduction in GHG emissions from using 1 odt of biomass to displace the amount of coal needed to produce the equivalent amount of energy) had the largest effect on total cumulative GHG emissions after 50 and 100 years. GHG benefit is an aggregated parameter that integrates all emission factors included in the life cycle analysis. Thus, in the residue scenario, the success of displacing coal with forest biomass in terms of reducing total GHG emissions depends mostly on life cycle emission factors associated with both energy sources, while slash decomposition rates and burning ratios had relatively small effects on total cumulative GHG emissions. In the stemwood scenario, yield curves had the largest effect on total cumulative GHG emissions and times to carbon sequestration parity and carbon debt repayment, followed closely by the GHG benefit of displacing coal with bioenergy, while the effect of slash decomposition rate was relatively small (Fig. 4b, c). Yield curves affect the rate at which regenerating stands accumulate carbon and offset carbon losses caused by harvest. Thus, applying more intensive regeneration silviculture treatments to harvested areas will reduce the time to carbon sequestration parity and debt repayment and increase the overall GHG benefits of displacing coal with forest biomass.

The sensitivity analysis suggested that since coal is a more carbon-intensive fossil fuel (Weisser, 2007), displacing other fuels such as oil and natural gas with forest bioenergy would likely yield longer time to carbon sequestration parity in both biomass scenarios and longer time to carbon debt repayment in the stemwood scenario. Second, a larger biomass supply area would likely change the estimated time to carbon sequestration parity in the stemwood scenario, with the sign of change dictated by changes in regeneration rates of postharvest stands.

The use of harvest residue to generate electricity, especially if the alternative is to burn the residue at roadside, results in atmospheric carbon benefits in relatively short time periods when substituted for coal. We estimate that ~5.8×10^6 MWh yr^{-1} can be generated from residue from current harvest operations in Ontario (based on estimates from this study and the average annual harvest volume in Ontario of ~20 million m^3 per year; 1998–2007 data). This is equivalent to ~3% of total energy output in Ontario (151×10^6 MWh yr^{-1} in 2012; IESO Monthly Market Report, January 2013, http://www.ieso.ca/imoweb/pubs/marketReports/monthly/2013jan.pdf, accessed 10 March 2013), compared to the 13% by 2018 commitment for power from nonhydro renewable sources (wind, solar and bioenergy) in Ontario's Long-Term Energy Plan (http://news.ontario.ca/mei/en/2010/11/energy-news-release-November-23-2010.html, accessed 9 March 2013). Stemwood is another potential source of forest biomass, but GHG emissions can be substantial before the benefits of replacing coal with biomass become apparent (Fig. 3b, c). However, several contrasting considerations are relevant to fossil fuel substitution with stemwood. On the one hand, the stemwood scenario emits carbon that is part of a biogenic cycle and will therefore be resequestered so long as stands regrow over the next rotation period, with only a small increase in net carbon in the biosphere–atmosphere system relative to coal because of the fossil fuels accounted for in LCA, and the lower energy density of biomass compared to coal. On the other hand, the time to carbon sequestration parity in slower-growing forests will likely occur after the time period in which efforts to avoid reaching critical atmospheric CO_2 concentration that could cause dangerous climate change must be achieved, especially if climate inertia is also taken into consideration (Tebaldi & Friedlingstein, 2013). The issue of the length of time before the net benefits of fuel substitution with stemwood are realized must be balanced against the fact that combustion of coal permanently increases the amount of carbon in the biosphere–atmosphere system. Overall, policy decisions should consider use of forest bioenergy within a context that includes differences in forest biomass sources, availability of other renewable energy sources, emerging carbon capture and storage technologies, energy conservation (including increasing energy conversion efficiencies), economic feasibility and ecological sustainability.

Time to carbon sequestration parity was substantially reduced by regenerating forests using practices that increased growth, resulting in higher mean annual increment (Fig. 5). The average area-weighted mean annual increment for regenerating forests used in this study was 1.37 m^3 ha^{-1} yr^{-1}. In their review of the effects of intensive silvicultural treatments on forest growth in Ontario, Park & Wilson (2007) reported mean annual increments of 6.0 (black spruce), 3.1 (jack pine), 16.0 (red pine) and 4.3 (black spruce) m^3 ha^{-1} yr^{-1}. These mean annual increments were estimated at age 40–50 from planting and require verification of how long such growth rates are sustained in these northern temperate forests. Also, time to carbon sequestration parity is likely somewhat longer than we estimated because we did not account for the additional GHG emissions incurred with more intensive silviculture. However, our results show the potential for reducing both time to carbon sequestration parity and short-term increases in total GHG emissions when stemwood is used as a source of biomass to replace energy produced using coal.

In the stemwood scenario, time to carbon sequestration parity was 91 years, nearly two decades less than the time to carbon debt repayment. In contrast, Mitchell *et al.* (2012) reported that time to carbon debt repayment was usually shorter than time to carbon sequestration parity. Our shorter time to sequestration parity likely reflects forest succession in Ontario, in which unharvested stands start losing carbon at a relatively younger age because of tree mortality during successional changes. This is particularly true for hardwood-dominated stands, which in this study constituted a large fraction of those harvested in the stemwood scenario; hardwood species in our study area have a shorter life span than conifers, and total carbon stocks in hardwood stands can start declining at age 100–120. The second factor contributing to the longer time to carbon debt repayment than to sequestration parity in our study is common in most boreal forests: a fraction of forest stands, if left unharvested, lose much of their aboveground carbon stock because of natural disturbances, such as fire. As a test, we conducted simulations in the stemwood scenario using hypothetical yield curves that remained constant after reaching the maximum net merchantable volume (i.e. we 'eliminated' losses of carbon resulting from stand senescence); although these hypothetical yield curves increased the time to carbon sequestration parity to 97 years, it was still more than a decade less than time to carbon debt repayment, which we attribute to carbon loss from forest fire.

The two metrics considered in this study, time to carbon sequestration parity and time to carbon debt repayment, differ in calculation of forest carbon stocks changes following biomass collection [term ΔFC in Eqn (1)]. The former metric (sequestration parity) accounts for projected changes in forest carbon stocks if biomass (residues or stemwood) was not collected for bioenergy, while the latter metric (carbon debt repayment) quantifies changes in forest carbon only relative to its amount at the time of biomass collection. Mitchell *et al.* (2012) note that carbon sequestration parity is the appropriate measure, as 'ascertaining the point at which a given strategy provides the maximal amount of climate change mitigation benefits requires accounting for the amount of biomass harvested from a forest under a given management regime, the amount of carbon stored under a given management regime, and *the amount of carbon that would be stored if the forest were to remain unharvested*' (italics added for emphasis.) From this point of view, the use of carbon debt repayment (i.e. comparing forest carbon stock changes to the amount of carbon at the time of collection) would be justified only for a baseline scenario that assumes constancy of forest carbon stocks in the absence of biomass collection [i.e. $\mathrm{FC}_{\mathrm{base}}\ (T_0 + t) = \mathrm{FC}_{\mathrm{base}}\ (T_0)$]. Such a baseline is clearly unsuitable for the harvest residue scenario: if not collected for bioenergy, residues would be burned without energy production or left to decay. The baseline is also inappropriate in forests being managed for multiple values (such as maintaining landscape age and species composition and providing wildlife habitat, in addition to producing fibre). In the absence of harvest for bioenergy, these forests would continue to change as a result of natural processes such as growth, mortality, changes in age structure and species composition due to succession, and natural disturbance.

Some authors propose that time to carbon debt repayment is an appropriate metric in the case of plantations managed on a sustainable yield basis (i.e. annual harvest of stemwood from a fraction of area is compensated by the growth of trees in the remaining part of plantation; e.g. Jonker *et al.*, 2013). However, such an approach overlooks several facts. First, plantations have usually been established on land that historically held natural forest, which either was converted directly to plantation forest or was deforested and converted to another land use before plantation forest was established on it. Second, notwithstanding a hypothetical case of plantations established specifically for bioenergy production, existing plantations have been established for fibre use for traditional wood products. In the latter case, the bioenergy scenario diverts fibre from traditional wood products, and GHG emissions from using biomass from these plantations for energy production must also account for the effects of lost carbon storage in traditional harvested wood products and the GHG emission effect of substituting these harvested wood products with other materials or wood from other sources. Finally, for plantations that become available for bioenergy due to lower fibre demand (e.g. pulp or timber) (e.g. Lamers & Junginger, 2013), a baseline scenario assuming continued growth would be a reasonable alternative that should be considered, especially if reduced GHG emissions is a land-use objective.

Overall, we submit that debating the appropriateness of either metric obscures the more important issue of selecting the appropriate baseline scenario. A baseline scenario justified in clear and convincing terms with the metric based on Eqns (1) and (2) provides the most complete estimate of the effects of displacing fossil fuels with forest bioenergy on total GHG emissions. In particular, a baseline scenario with constancy of forest carbon stocks in the absence of biomass collection would result in time to carbon sequestration parity equal to time to carbon debt repayment [note that Eqn (3) is a partial case of Eqn (2) for $FC_{base}(T_0 + t) = FC_{base}(T_0)$].

The results of this study were based on predictions of future forest conditions generated under the assumption that rates of forest growth, successional change, and natural disturbance all remain constant throughout the simulation period. The same assumptions were used in timber supply models from which availability of sources for continuous supply of biomass to produce energy was estimated. Changes to these assumptions caused by climate change or widespread natural disturbances may affect the predicted supply of biomass and forest conditions, and consequently alter estimates of forest carbon stocks. This emphasizes the need to develop large-scale timber supply and forest carbon models that account for the effects of changes in both climate and natural disturbance regimes.

In conclusion, literature on the effects of using forest bioenergy on GHG emissions is rapidly growing and patterns in the GHG emissions benefits of using specific sources of biomass to displace reference fossil fuel sources are becoming apparent. This literature exhibits the 'growing pains' typical of an emerging discipline; for example, there is a strong need for consistent terminology. Studies on GHG emissions from forest bioenergy projects use a variety of ambiguous terms such as carbon sequestration parity, carbon offset parity, carbon debt repayment, carbon payback and break-even period, sometimes interchangeably or without clear distinction. This can lead to misinterpretation and, in some cases, erroneous conclusions. Although in this study, we used the terms carbon sequestration parity and carbon debt repayment as defined by Mitchell *et al*. (2012), we note that the meanings of these terms are not self-evident.

The terms 'baseline scenario' and 'reference scenario' should also be clearly defined and differentiated. 'Baseline scenario' refers to the fate of forest carbon stocks when biomass is not collected to produce energy, whereas 'reference scenario' refers to the fossil fuel scenario to which a given forest bioenergy scenario is compared; combining the two under the single term 'baseline scenario' may lead to an unnecessary number of combinations of fates of forest carbon stocks and fossil fuel reference scenarios. Terms such as 'business-as-usual', 'counter-factual' or 'protection' used to describe baseline scenarios are vague, subject to misinterpretation and should be avoided (e.g. protection may refer to protection from harvest or natural disturbance or both).

Finally, this field of study will also benefit from use of more consistent methodologies. Studies on the effects of forest bioenergy on GHG emissions should include (i) life cycle analysis (LCA) of GHG emissions from forest bioenergy production; (ii) definition of and justification for a baseline scenario (i.e. what would happen to forest carbon stocks if biomass were not collected to produce energy) and the analysis of forest carbon stock changes caused by biomass collection relative to this baseline scenario; and (iii) definition of a reference energy scenario and its LCA of GHG emissions if it involves displacement of fossil fuels. Studies that include all these aspects of methodology will allow full assessment of GHG emission effects of forest bioenergy projects and their climate change mitigation potential.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1. Forest stocks and their changes in residue scenario, sensitivity analysis, and effect of regeneration rate on GHG emissions in stemwood scenario.

12. Michael Ter-Mikaelian, *et al.*, *The Burning Question: Does Forest bioenergy Reduce Carbon Emissions? A Review of Common Misconceptions About Forest Accounting,* Journal of Forestry, (Nov, 2014).

REVIEW ARTICLE

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harvesting & utilization

The Burning Question: Does Forest Bioenergy Reduce Carbon Emissions? A Review of Common Misconceptions about Forest Carbon Accounting

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Critical errors exist in some methodologies applied to evaluate the effects of using forest biomass for bioenergy on atmospheric greenhouse gas emissions. The most common error is failing to consider the fate of forest carbon stocks in the absence of demand for bioenergy. Without this demand, forests will either continue to grow or will be harvested for other wood products. Our goal is to illustrate why correct accounting requires that the difference in stored forest carbon between harvest and no-harvest scenarios be accounted for when forest biomass is used for bioenergy. Among the flawed methodologies evaluated in this review, we address the rationale for accounting for the fate of forest carbon in the absence of demand for bioenergy for forests harvested on a sustained yield basis. We also discuss why the same accounting principles apply to individual stands and forest landscapes.

Keywords: bioenergy, no-harvest baseline, reference point baseline, carbon sequestration parity, carbon debt repayment, dividend-then-debt, stand versus landscape, plantations

Interest in industrial-scale bioenergy production using forest biomass is part of a larger movement to reduce climate change by using renewable energy in place of fossil fuels. However, if climate change mitigation is indeed a driver for using forest bioenergy, then this energy source must be assessed for its effects on the greenhouse gas (GHG) concentration in the atmosphere. Misconceptions and errors in methodologies continue to affect this topic, both in the scientific and "gray" literature (e.g., magazines, reports, and opinion letters), despite having been addressed in prominent publications (e.g., Searchinger et al. 2009, Haberl et al. 2012). A common misconception is that forest bioenergy is immediately carbon neutral, with no net GHG emissions as long as the postharvest forest regrows to its preharvest carbon level. From a forest manager's perspective, this logic can be appealing because it appears to fit a sustained yield paradigm. But, as we shall show, this paradigm fails to account for other aspects of bioenergy use needed for proper assessment of its effect on GHG emissions.

The purpose of this review is to present the theory and principles for correctly assessing the GHG effects of forest bioenergy. We discuss common errors that appear in the forest bioenergy literature and explain why, in the absence of forest management to increase forest carbon before bioenergy harvesting, the use of forest bioenergy often increases atmospheric carbon dioxide (CO_2), at least temporarily.

Principles of Forest Bioenergy GHG Accounting

The primary consideration in GHG accounting for forest bioenergy is to accurately determine the fate of forest biomass in the absence of demand for its use to produce bioenergy. This theme will be repeated throughout this article, because failure to correctly address this consideration is the

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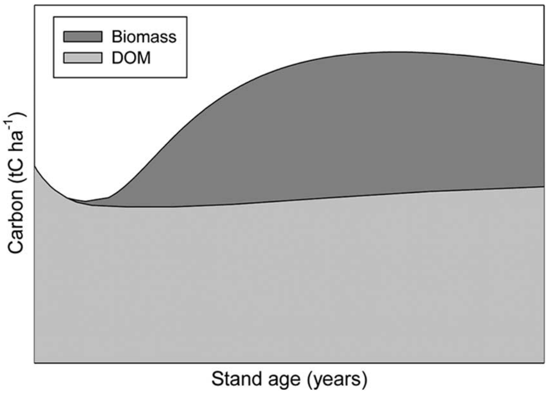

Figure 1. Typical change in forest carbon stocks after stand harvest (modified from Ter-Mikaelian et al. 2014a). Dark and light gray areas represent carbon stocks in live biomass and dead organic matter (DOM), respectively.

cause of most errors in forest bioenergy accounting.

When tree biomass is burned for energy production, sequestered carbon is released to the atmosphere, mainly as CO_2. Typical sources of forest biomass for biofuel production include standing live trees, harvest residue, biomass recovered during salvage operations, thinnings and residue from thinning operations, and mill processing residue (e.g., sawdust and wood chips); here and throughout the text, biofuel and bioenergy refer to fuel produced from live or dead biomass and to energy derived from burning of biofuel, respectively. Forest carbon is contained in live trees, understory vegetation, and in aboveground (standing dead trees, down woody debris, and forest floor) and belowground dead organic matter (mineral soil and dead roots). The processes determining changes in carbon pools include growth and mortality of live trees, decomposition of dead organic matter, and its combustion if burned. Tree growth and mortality are the main driving forces determining changes in carbon pools. Live trees transfer carbon to dead organic matter pools through self-pruning and mortality; in turn, dead organic matter pools release carbon to the atmosphere through decomposition. In temperate and boreal forests, the largest amount of carbon in a forest is typically contained in live trees and mineral soil, followed by forest floor, with other pools normally accounting for less than 15% of total forest carbon (Pan et al. 2011).

Given the large amounts of woody biomass that stands accumulate, it is intuitive that carbon accrues as they mature (Figure 1). After a stand-replacing disturbance, stand-level forest carbon stocks usually decrease, because carbon losses from decomposing dead organic matter are temporarily not compensated for by carbon sequestered by live trees that are still small. As trees grow, the pattern of net carbon accumulation is sigmoidal, characterized by initially rapid increases that slow as a stand reaches maturity (Figure 1). The slowdown in stand net carbon accumulation at maturity results from the death of individual trees with ongoing growth distributed among the remaining live trees.

Figure 2A shows the accumulation of carbon in live trees in the absence of harvest. Harvesting a stand for bioenergy removes most live tree carbon, leaving unutilized biomass on site, which in traditional harvesting includes stumps, branches and tops, and roots. In temperate and boreal forests, recovery of live tree carbon stocks takes decades because of slow stand regrowth after harvest (Figure 2B). Forest carbon stocks following harvest for bioenergy constitute a *forest bioenergy scenario* (black line in Figure 2B). Forest carbon in the absence of demand for bioenergy represents a *forest baseline scenario* (red line in Figure 2A and D); in some literature reports on forest bioenergy, the forest baseline scenario is referred to as either "business-as-usual," "counterfactual," or "protection scenario."

Forest bioenergy production involves the use of fossil fuels, resulting in GHG emissions that are estimated using life cycle analysis (LCA). An LCA accounts for emissions associated with all phases of bioenergy production and use (the so-called "cradle-to-grave" approach): silvicultural activities, use of logging equipment, transportation of harvested biomass to a biofuel processing facility, conversion of biomass into biofuel, transportation to the energy plant, and non-CO_2 products of combustion (e.g., Zhang et al. 2010). This is the GHG "cost" of producing and using forest bioenergy. The LCA of forest bioenergy does not include CO_2 GHG emissions from biofuel combustion, because these emissions are accounted for when the effects of bioenergy demand on carbon in forest stocks are evaluated (Figure 2C).

When forest bioenergy displaces energy from a fossil fuel, it eliminates GHG emissions from producing and burning the fossil fuel (the *reference fossil fuel scenario*). The LCA for a fossil fuel includes all GHG emissions from obtaining and processing the fuel, but, unlike bioenergy, the fossil fuel LCA also includes all GHG emissions from combustion (Figure 2C). The difference in LCA emissions between forest bioenergy and a fossil fuel constitutes the *GHG benefit* of displacing this fossil fuel with forest bioenergy (Figure 2C and D).

Management and Policy Implications

A growing market for energy produced from forest biomass has arisen because of the potential to mitigate climate change by replacing fossil fuel energy. However, managers who want to access this market should be aware that the benefits of forest bioenergy depend on evaluation of forest management options against a baseline scenario considering what happens to carbon stocks if biomass is not harvested for energy. Among the more favorable options are the use of residue from ongoing harvest operations for traditional wood products (lumber and pulp) and application of intensive silviculture to regeneration of harvested stands. Establishment of new bioenergy-designated plantations on abandoned/degraded lands requires more time for forest biomass to become available for harvest but has the advantage of a low carbon stock value baseline. The least favorable options include harvest of standing live trees, both in addition to and in lieu of ongoing harvest operations for traditional wood products. Policies for bioenergy use also need to recognize that accounting for emission benefits when fossil fuels are replaced requires accounting for forest carbon (either in forest or in traditional wood products) that would have continued to exist if fossil fuels were not replaced by bioenergy.

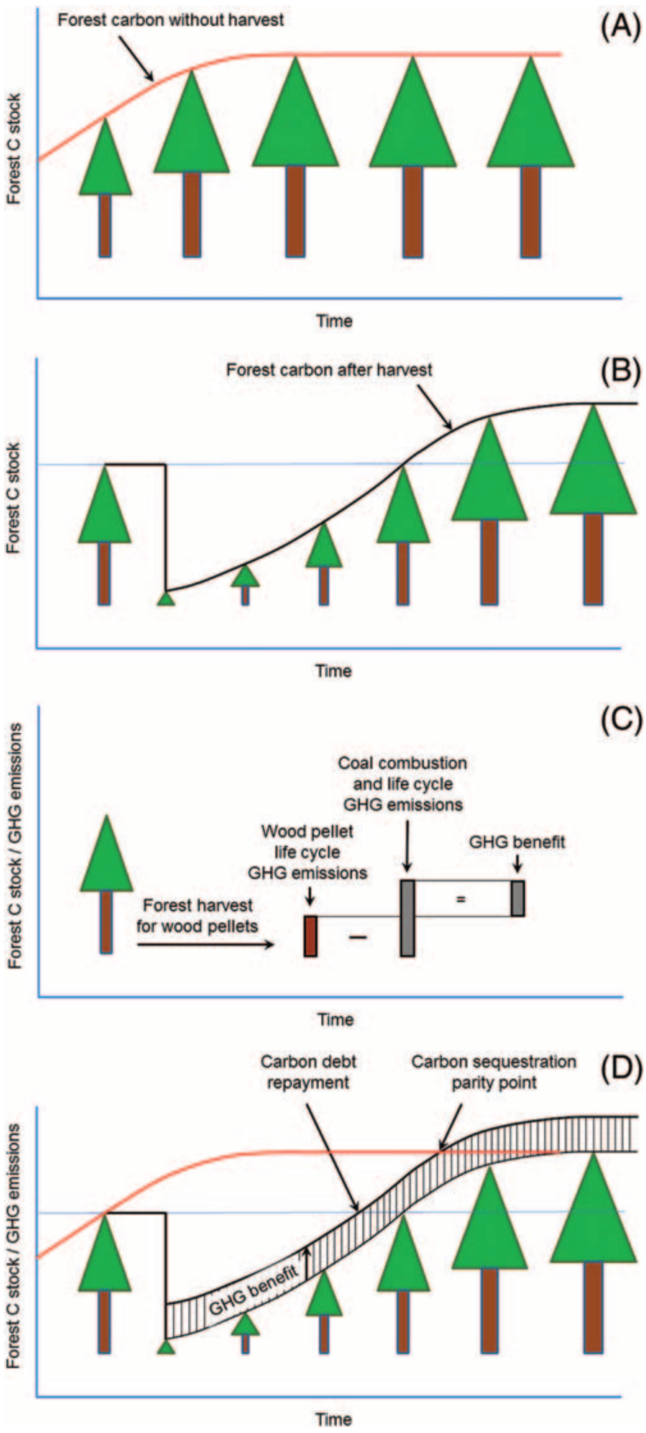

Figure 2. Effect of harvest for bioenergy used to replace coal on forest carbon stock changes and total greenhouse gas (GHG) emissions (stand level, from Ter-Mikaelian et al. 2014b). A. Accumulation of carbon in an unharvested forest stand. B. Carbon in the stand regenerating after harvest. C. Harvested biomass is used to produce wood pellets; life cycle GHG emissions from obtaining and producing wood pellets are lower than life cycle and combustion emissions of coal, resulting in a GHG benefit of using wood pellets to replace coal. D. Carbon sequestration parity is achieved when the sum of carbon in the regenerating stand and the GHG benefits of using wood pellets to replace coal reaches the amount of carbon in the stand if it had remained unharvested; carbon debt repayment is achieved when the sum of carbon in the regenerating stand and GHG benefits of using wood pellets to replace coal reaches the preharvest amount of carbon in the stand.

Thus, accounting for the GHG emission reduction potential of forest bioenergy must include the following:

A. Forest carbon following biomass harvest for energy production (the forest bioenergy scenario);
B. Forest carbon in the absence of demand for bioenergy (the forest baseline scenario);
C. Life cycle GHG emissions (upstream fossil fuel emissions) from producing forest bioenergy (excluding GHG combustion emissions); and
D. Life cycle GHG emissions (including those from combustion) for the fossil fuel displaced by forest biomass (the reference fossil fuel scenario).

Components A and B are required to assess CO_2 emissions to the atmosphere or lost potential CO_2 sequestration resulting from extracting biomass from the forest to meet the demand for bioenergy, relative to that without bioenergy demand (i.e., no harvest). Component C (LCA of bioenergy production) includes GHG emissions from producing the biofuel and its use in place of a fossil fuel; it includes non-CO_2 emissions from biomass combustion but not CO_2 emissions, which are accounted for in components A and B. Finally, component D (LCA of the reference fossil fuel) is required to assess the GHG emission benefits of displacing fossil fuel use with forest bioenergy.

Component A should include losses of forest carbon stocks due to the construction of access roads to harvest sites. Similarly, upstream emissions for fossil fuel-based energy (component D) may require accounting for changes in forest carbon stocks if extraction of fossil fuels is associated with forestland cover changes due to mining and road construction. While such losses of forested area in North America may be small at the regional and national scales (e.g., Sleeter et al. 2012, Natural Resources Canada 2013), their local effect on forest carbon stocks can be significant (e.g., Campbell et al. 2012, Drohan et al. 2012).

It should be noted that this review focuses primarily on solid biofuels used for combustion for heat and electricity generation. Although second-generation biofuels (e.g., bioethanol for vehicular use, and biogas) made from wood are currently not commercial energy sources (Naik et al. 2010, Bonin and Lal 2012), early research suggests that wood has a potential to become the main feedstock for production of liquid and gaseous biofuels (Hedegaard et al. 2008, Havlik et al. 2011). However, the principles for assessing the GHG effects of liquid and gaseous biofuels, in particular the methodology to account for changes in forest carbon stocks are the same as those described above.

The difference between components A and B constitutes the change in forest carbon stocks resulting from biomass harvest for bioenergy; the difference between components C and D indicates the GHG benefit of replacing a reference fossil fuel with forest bioenergy (Figure 2C). The estimated total GHG emissions caused by demand for bioenergy to replace fossil fuel are given by

$$\begin{aligned}&\text{Total GHG emissions}\\&\quad= \text{Change in forest carbon stocks}\\&\quad+ \text{GHG benefit of replacing fossil fuel with forest bioenergy}\end{aligned} \tag{1}$$

For a detailed mathematical form of Equation 1, see McKechnie et al. (2011). This numerical approach is used for an individual stand. The same approach is used for a forest landscape in which the annual biomass harvest is used to produce energy by integrating Equation 1 over time, starting from the first year of biomass collection.

The LCA of bioenergy and fossil fuel-based energy production usually includes emissions of CO_2 and two other GHGs: methane (CH_4) and nitrous oxide (N_2O) (Intergovernmental Panel on Climate Change [IPCC] 2006). Non-CO_2 GHG emissions are converted into CO_2 equivalents based on their global warming potential (GWP) (IPCC 2007). Despite growing criticism (e.g., Shine 2009, Fuglestvedt et al. 2010), GWP factors remain the standard approach for assessing the effects of GHGs on climate change (IPCC 2007). The amount of CH_4 and N_2O (in units of mass) released during combustion of biofuels and fossil fuels is several orders of magnitude lower than that of CO_2 (IPCC 2006). Release of these GHGs may also result from nitrogen fertilizer application (N_2O emissions) and organic matter decomposition in soil (CH_4 and N_2O emissions) (Cherubini et al. 2009).

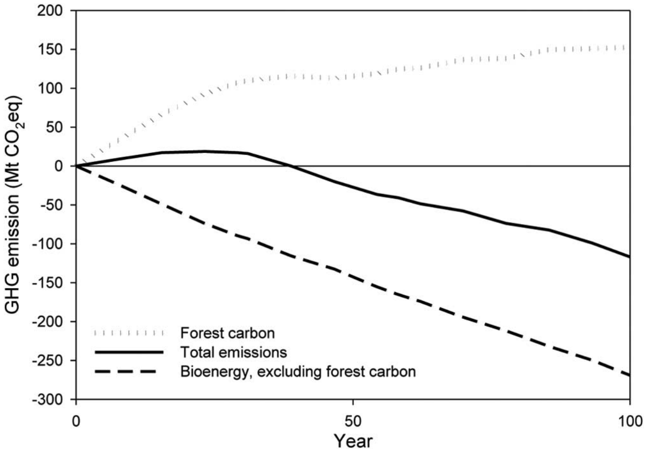

Figure 3. Changes in forest landscape carbon stocks (dotted line), cumulative total GHG emissions (solid line), and GHG benefits (dashed line) from displacing coal with bioenergy generated from harvest of standing live trees (modified from McKechnie et al. 2011). Positive values correspond to emissions, whereas negative values show removals (sequestration) of carbon from the atmosphere.

Accounting for changes in forest carbon stocks relative to the baseline scenario is paramount for proper assessment of bioenergy GHG emissions: without demand for bioenergy, harvesting either does not occur and the forest continues growing and sequestering additional carbon or it is harvested for traditional wood products (lumber and pulpwood). This is also true when bioenergy replaces fossil fuel energy: replacement of fossil fuels means harvest for bioenergy, whereas no replacement of fossil fuels means no harvest for bioenergy. This link results in an inextricable connection between the reference fossil fuel and forest baseline scenarios: accounting for GHG benefits when fossil fuels are replaced requires accounting for forest carbon losses (either in forest or in traditional wood products) that would *not* have occurred if use of fossil fuels continued.

At the onset of biomass harvesting for bioenergy, the total GHG emissions in Equation 1 are usually negative because the reductions in forest carbon outweigh the GHG benefits of displacing fossil fuel with forest bioenergy. Over time, however, net GHG emissions in the forest bioenergy scenario become smaller as harvested stands regenerate and sequester carbon (Figure 2D). The point at which the change in forest carbon (the difference between forest carbon in the bioenergy and baseline scenarios) equals the accumulated GHG benefit of using forest bioenergy in place of fossil fuel is called *carbon sequestration parity* (Mitchell et al. 2012). Consequently, the time from beginning biomass harvest to carbon sequestration parity is called *time to carbon sequestration parity.* Only after passing the time to carbon sequestration parity does forest bioenergy reduce atmospheric GHG compared with the reference fossil fuel scenario.

Time to carbon sequestration parity is also referred to as the "carbon offset parity point" (e.g., Jonker et al. 2014, p. 371), "break-even period" (e.g., Ter-Mikaelian et al. 2011, p. 644), or "time to carbon neutrality" (Domke et al. 2012, p. 146). We prefer the term carbon sequestration parity rather than carbon neutrality because the latter has been defined in a variety of ways (National Council for Air and Stream Improvement [NCASI] 2013).

Time to carbon sequestration parity depends on factors such as the source of forest biomass (e.g., standing live trees versus harvest residue), growth of regenerating stands after harvest, and emissions from the reference fossil fuel. The peer-reviewed literature contains many studies with estimates of time to carbon sequestration parity for forest bioenergy replacing coal (e.g., McKechnie et al. 2011, Ter-Mikaelian et al. 2011, Holtsmark 2012, Repo et al. 2012, Jonker et al. 2014, Lamers et al. 2014), natural gas (Domke et al. 2012), oil (Repo et al. 2012), and automotive gasoline (Hudiburg et al. 2011). These studies consistently show that harvesting live trees to produce bioenergy initially increases GHG emissions, which may take decades to centuries to offset. However, it has also been shown that intensive forest management of areas harvested for bioenergy may substantially reduce time to carbon sequestration parity (e.g., Jonker et al. 2014, Ter-Mikaelian et al. 2014b).

Figure 3 presents carbon stock changes and GHG emissions for the scenario of annual demand for bioenergy being met by harvesting standing live trees on a landscape scale to displace coal-fired power generation (from McKechnie et al. 2011). The study area covered a total of 52,494 km^2 in the Great Lakes-St. Lawrence forest region (Ontario, Canada); the supply of biomass came from clearcut harvesting of low-intensity managed stands composed of a mix of hardwood (sugar maple, yellow birch, and red oak) and softwood (jack pine, black spruce, and balsam fir) species. Emissions from reduced forest carbon stocks initially outweigh GHG benefits, resulting in positive GHG emissions overall (solid line above zero in Figure 3, indicating increased atmospheric CO_2). The trend is reversed by continued accumulation of GHG benefits from fossil fuel displacement and plateauing of landscape losses in forest carbon, although carbon sequestration parity (and net atmospheric reduction of GHG) is not reached until 38 years after harvesting begins (the time at which the solid line crosses below the zero line), beyond which total GHG emissions are negative (solid line below zero in Figure 3), indicating net removal of CO_2 from the atmosphere.

The approach we describe is based on counting carbon fluxes between the biosphere and atmosphere, referred to as a *mass balance* or *carbon balance* approach (Sathre and Gustavsson 2011). For approaches that enhance the mass balance approach by accounting for the timing of GHG emissions and radiative forcing, the reader is referred to Sathre and Gustavsson (2011), Cherubini et al. (2011), Repo et al. (2012), and Agostini et al. (2013).

Review Scope

Studies accounting for the GHG effects of forest bioenergy are characterized by spatial and temporal boundaries, type of LCA, and forest baseline and reference fossil fuel scenarios (Helin et al. 2013). This review pertains spatially to studies of forest landscapes managed for bioenergy production. We focus primarily on accounting for the carbon effects of harvesting standing live trees for bioenergy, because this biomass source has the greatest potential to produce large, long-lasting effects on the atmospheric carbon concentration. Nevertheless, the same basic premises for determining the atmospheric effects of bioenergy apply to other sources of biomass and are also discussed.

The spatial boundary used in bioenergy GHG accounting is interrelated with the issue of land-use change (LUC), which can be either direct or indirect (Berndes et al. 2010, Bird et al. 2011). Direct LUC involves changes on the land where bioenergy feedstock production occurs, such as a change from farmland to bioenergy plantation. Indirect LUC refers to changes in land use that take place elsewhere as a consequence of harvesting for bioenergy. An example of indirect LUC is conversion in another country of natural forest to farmland in response to the above direct LUC, where farmland in the study area was converted to a bioenergy plantation. Here, we focus on forest landscapes managed for bioenergy production; indirect LUC associated with forest bioenergy production is discussed in a section of this review devoted to that topic.

Bioenergy LCAs can be attributional or consequential (Brander et al. 2008, Lippke et al. 2011, Helin et al. 2013). An attributional LCA provides information about the direct effects of processes used for a given product (e.g., production, consumption, and disposal) but does not consider indirect effects arising from changes in the output of a product (Brander et al. 2008). Studies included in this review use a consequential LCA approach, because they assess the consequences of changes in the level of output of a product, including effects both inside and outside the life cycle of the product (Brander et al. 2008). Some reports (e.g., NCASI 2013) erroneously suggest that the consequential LCA approach is appropriate only for large-scale evaluations of forest carbon policies. In reality, all bioenergy studies reviewed here, regardless of their scale and objective, use a consequential LCA approach, at least partially. Indeed, it is most common to include reference fossil fuel scenarios to demonstrate the GHG benefits of using forest bioenergy. This inclusion automatically places such studies in the category of a consequential LCA approach, because fossil fuel displacement occurs as a consequence of forest bioenergy use.

This review considers three potential forest baseline scenarios: the *no-harvest baseline,* constituting the natural evolution of the forest in the absence of harvest for bioenergy; the *traditional wood products baseline,* in which forest in the absence of harvest for bioenergy is harvested for traditional wood products (lumber and pulpwood); and the *reference point baseline*, which will be introduced later in this review. Of the three baselines, the no-harvest baseline appears to be at the core of many misconceptions discussed in this review. This baseline is also referred to as an “anticipated future baseline” (e.g., AEBIOM 2013, p. 5), a “biomass opportunity cost baseline” (Johnson and Tschudi 2012, p. 12), and a “natural relaxation baseline” (Helin et al. 2013, p. 477). We prefer the term no-harvest baseline because it intuitively suggests what happens to the forest in the absence of harvest for bioenergy. Other baselines considered in the literature, such as the comparative baseline (US Environmental Protection Agency 2011) and the marginal fossil fuel baseline (Johnson and Tschudi 2012), combine forest and reference fossil fuel baselines to estimate net atmospheric balance.

As noted by Helin et al. (2013), there are no scientific criteria governing what the time frame for assessing GHG effects of forest bioenergy must be, because it depends on the aims of the assessment. Typically, studies cover at least one silvicultural rotation, with the time horizon ranging from several decades to hundreds of years. Unlike traditional LCA studies, in which results are presented as one estimate covering the entire time frame, studies on the GHG effects of forest bioenergy often provide a temporal profile of GHG emissions (Helin et al. 2013). It is worth noting, however, that short- and long-term effects of bioenergy emissions are likely to be different (Sedjo 2011). Miner et al. (2014) correctly point out that use of short time frames for assessing the GHG effects of bioenergy is inconsistent with application of GWP factors estimated over a 100-year period (GWP-100). Using a fixed time frame of 100 years is acceptable as long as it is clearly understood that such estimates of GHG effects will be realized 100 years after the beginning of bioenergy production. However, using only a 100-year time frame would obscure time to carbon sequestration parity, which is an important indicator of how long it takes forest bioenergy to start yielding climate mitigation benefits. In addition, the GWP factor for N_2O is reasonably constant over the first 100 years (e.g., GWP-20 and GWP-100 are equal to 289 and 298, respectively) (IPCC 2007). The GWP factor for CH_4 estimated over shorter periods would be higher than that for 100 years (e.g., GWP-20 and GWP-100 are 72 and 25, respectively) (IPCC 2007). However, the numerical error in estimating time to carbon sequestration parity introduced by applying GWP-100 to CH_4 is small because of the relatively low amounts produced during both bioenergy and fossil fuel energy production (e.g., Zhang et al. 2010; also see the sensitivity analysis in Ter-Mikaelian et al. 2014b). Next, we examine

Table 1. Main types of errors in approaches used to assess the carbon effects of forest bioenergy.

Category	Rationale for approach	Errors in approach
Renewable equals carbon neutral	Forest bioenergy is carbon neutral because harvested forest will grow back and compensate for carbon losses incurred during harvest	Disregards the length of time required for the forest to grow back and effects of elevated atmospheric carbon concentration during this period
Sustained yield equals carbon neutral	Carbon losses from harvesting a fraction of a sustainably managed landscape are compensated for by tree growth in the remaining landscape, removing the need to account for forest carbon stock changes	Fails to account for changes in forest carbon stocks in the absence of harvest for bioenergy (no-harvest baseline scenario) Commits a methodological error of using only "one-half" of the reference fossil fuel scenario
Direct diversion from traditional wood products	In the absence of demand for bioenergy, the forest would be harvested for traditional wood products, removing the need to account for forest carbon stock changes	Fails to account for lost carbon storage in traditional wood products and substitution of these products with more carbon emission-costly materials (traditional wood products baseline)
Dividend-then-debt	Harvest releases carbon previously sequestered from the atmosphere, therefore beginning the carbon accounting framework when the forest stand starts to grow "eliminates" the carbon deficit created by stand harvest (usually proposed in conjunction with sustained yield approach described above)	Disregards the fact that each stand is preceded by another stand and thus ignores carbon released by previous harvest, while crediting the current sequestration Also involves the errors outlined for the sustained yield approach (described above)
Plantations for bioenergy	Forest carbon stock changes need not be accounted for when plantations are established purposely for harvest for bioenergy	Currently associated with a largely hypothetical case in the United States; few plantations were established on nonforested land for bioenergy; also a partial case of the dividend-then-debt approach (see above)
Abandoned plantations carry no carbon debt	Forest carbon stock changes need not be accounted for when plantations established for traditional wood products are abandoned because of diminishing market demand for such products and would likely be deforested	Fails to consider the appropriate baseline scenarios that include either the no-harvest baseline scenario that could offer a better carbon emission mitigation option than harvest for bioenergy, or the deforestation scenario that includes a single harvest for traditional wood products/bioenergy and carbon stocks in deforested area
Carbon debt repayment (reference point baseline)	Changes in forest carbon stocks after harvest for bioenergy are compared with carbon losses at the time of harvest (often proposed in conjunction with sustained yield approach described above)	Fails to account for changes in forest carbon stocks in the absence of demand for bioenergy (no-harvest baseline scenario) Involves a methodological error of using only "one-half" of the reference fossil fuel scenario

common errors in forest bioenergy carbon accounting using live tree harvest for bioenergy, summarized in Table 1.

Common Errors in Accounting for Carbon When Using Forest Bioenergy

Renewable Equals Carbon Neutral

One of the earliest misconceptions about the effects of forest bioenergy is the erroneous conclusion that forest bioenergy is carbon neutral because forests harvested for bioenergy eventually grow back, reabsorbing carbon emitted during energy combustion. Although the flaw in this assumption has been identified repeatedly (e.g., Marland 2010, Agostini et al. 2013), some government documents, forest industry reports, and websites claim that forest bioenergy is carbon neutral because forests regrow. One such statement among many found on the worldwide web is as follows:

> The carbon dioxide (CO_2) emitted on combustion of biomass is taken up by new plant growth, resulting in zero net emissions of CO_2—bioenergy is considered to be carbon neutral (Sustainable Energy Authority of Ireland)[1]

Statements such as this one disregard the time factor for forests to achieve the same forest carbon level relative to the no-bioenergy demand scenario. Although the statement is generally correct in that the forest carbon deficit resulting from biomass harvest for energy might be eventually offset by carbon sequestration in regenerating forests, it is made implicitly incorrect by not acknowledging that decades to centuries are needed to erase this deficit. In the meantime, elevated levels of CO_2 in the atmosphere have numerous potential direct (independent of climate change) and indirect (through changes to climate) biological consequences (Ziska 2008).

Sustained Yield Equals Carbon Neutral

An assumption that bioenergy harvesting in forests managed on a sustained yield (also called sustainable yield) basis does not create a carbon deficit is one of the most common errors in forest bioenergy accounting. This argument is often presented as a "stand versus landscape" approach, implying that the accounting principles presented in the previous section of this review are valid for an individual stand but do not apply to forest landscapes managed for sustained yield. The stand versus landscape approach has been discussed in both the peer-reviewed (e.g., Lamers and Junginger 2013, Jonker et al. 2014) and non-peer-reviewed (e.g., Strauss 2011, 2013, Ray 2012, AEBIOM 2013) literature. The common argument is that because biomass removal from a fraction of the area in a sustained yield landscape is compensated for by growth in the remaining forest, harvesting causes no net loss of biomass, which leads to an incorrect claim that there is no carbon deficit from bioenergy harvest in a sustained yield landscape.

Although sustained yield harvesting is a valid approach in traditional forestry for providing a steady flow of wood, the claim that it is carbon neutral can only be made by ignoring the principles of carbon mass balance accounting (for examples of incorrect accounting, see Strauss and Schmidt 2012, AEBIOM 2013). To repeat these principles, to claim an emissions reduction from using forest biomass to produce energy in place of a fossil fuel, two scenarios must be accepted: one where fossil fuels are used and forests are not harvested for bioenergy; and the other where forests are harvested with the biomass used for energy generation. Stating that sustained yield management is carbon neutral is incorrect because it fails to account for the case involving no harvest for bioenergy in the reference fossil fuel scenario.

Furthermore, in a regulated forest, harvested biomass is maximized on a sustained yield basis when stands are harvested as they reach the maximum mean annual growth rate, which occurs before they attain maximum yield, i.e., if left unharvested the stand would gain more biomass and consequently increase live tree carbon stocks for a period of time (Cooper 1983). A stand may continue to accumulate carbon stocks even past the point of maximum fiber yield, because carbon from dead trees is transferred to dead organic matter pools, which, depending on climate, can have slow decomposition rates (Kurz et al. 2009). Therefore, increased harvest applied to an existing regulated (i.e., sustained yield) forest landscape results in a loss of potential carbon sequestration. This may also be the case in old-growth landscapes (Luyssaert et al. 2008), which may continue to increase total carbon stocks, albeit slowly, in the absence of harvesting. Thus, in a regulated forest landscape, any harvest (and harvest for bioenergy in particular) would in all instances result in increased atmospheric CO_2 for a period of time due to lost future carbon sequestration. Such increases in atmospheric CO_2 cannot be ignored simply because the landscape is being harvested on a sustained yield basis.

In summary, it is an error to conclude that bioenergy from a sustained yield forest is automatically carbon neutral, because, on the one hand, it accepts carbon emissions reductions associated with reduced fossil fuel use, but then fails to acknowledge the "other half" of the reference fossil fuel scenario; i.e., if fossil fuels are used, then forests are not harvested for bioenergy.

Diversion from Traditional Wood Products

An argument can be made that in the sustained yield approach the no-harvest baseline does not need to be considered if, in the absence of demand for bioenergy, forests would be harvested for traditional wood products (e.g., lumber and pulp). This argument may not be relevant, however, because bioenergy is one of the lowest value uses for forest biomass and market forces would be unlikely to result in bioenergy harvest in lieu of harvest for traditional wood products (Werner et al. 2010, AEBIOM 2013). Furthermore, even if the choice was made to harvest for bioenergy, this would shift the harvest for traditional wood products elsewhere (see the section on Indirect LUC), because many studies predict continued growth in demand for traditional wood products both at the national and global scales (Ince et al. 2011, Daigneault et al. 2012, Nepal et al. 2012, Latta et al. 2013).

If these issues were addressed and a legitimate case was made that forest biomass was diverted from harvest for traditional wood products to bioenergy, then the traditional wood products scenario is the correct forest baseline (Agostini et al. 2013). This would include accounting for the large and long-lasting stock of carbon that is retained in some traditional wood products (Chen et al. 2008, 2013). Retention of carbon in wood products is characterized by product "half-life": the time it takes half of a type of wood product to be removed from service. Estimates of wood product half-life range from 67 to 100 years for construction lumber in the United States and from 1 to 6 years for paper (Skog and Nicholson 2000). After wood product use ends, some carbon may be emitted to the atmosphere through decomposition or burning (with or without producing energy), or wood products may be recycled or disposed of in landfills. In landfills, a fraction of the carbon slowly releases to the atmosphere through decomposition, and the rest remains indefinitely due to its resistance to decomposition (Micales and Skog 1997). The traditional wood products baseline for building materials and other solidwood products should also include the displacement value from using wood compared with using more CO_2 emission-intensive materials (Richter 1998, Gustavsson et al. 2006), so that accounting for wood used for bioenergy in place of use in traditional wood products must include LCA emissions associated with substitution of wood by nonwood materials (Matthews et al. 2012).

Dividend-Then-Debt

Proponents of the dividend-then-debt approach to forest carbon accounting argue that studies on the effects of forest bioenergy are incorrect if they use the moment of harvest as the starting point for carbon cycle analysis (e.g., Strauss 2011, Ray 2012). As stated by Strauss (2013, p. 14),

> all of the studies that show that wood-to-energy adds to the carbon stock of the atmosphere assume a carbon debt is created that has to be repaid by new growth over 30–80 years (or more in some studies)

The dividend-then-debt approach is based on the idea that harvest does not create a loss of forest carbon because it merely returns CO_2 that was previously absorbed by the trees to the atmosphere. To quote, "carbon deficit is only real if you ignore the fact that the trees gobbled up carbon before they were harvested" (Ray 2012).

However, the dividend-then-debt approach ignores the fact that, in most cases, new stands replace previously harvested stands. Those stands were in turn preceded by other stands, and so on. Thus, moving the starting point of carbon accounting backwards in time to when carbon stocks in a given piece of land were low takes credit for the latest cycle of carbon accumulation but ignores the fact that over time, on average, forests contain substantial amounts of carbon. The point in question in dividend-then-debt comes down to the original natural state of the land, which, for most current forestland, was forest. In that case, it is incorrect to use dividend-then-debt accounting.

Plantations Used for Bioenergy Carry No Carbon Debt

Some studies conclude that forest bioenergy obtained from plantations that are already in a sustained yield state carries no carbon debt because the plantations were specifically established to be harvested for bioenergy, and, therefore, all the biomass in such forests can be considered to have been grown for the purpose of burning (e.g., AEBIOM 2013, Jonker et al. 2014). On this basis, it is argued that since carbon in such forests was sequestered for the purpose of burning, without a bioenergy market they would never have existed in the first place. Sedjo (2011) calls this a forward-looking approach:

> if trees are planted in anticipation of their future use for biofuels, then the carbon released on the burning of the wood was previously sequestered in the earlier biological growth process (Sedjo 2011, p. 4)

We contend that this is an acceptable interpretation, but only as long as such plantations were established on deforested land specifically to be harvested for bioenergy. However, we are unaware of large existing areas of plantations in the United States established specifically for bioenergy (short-rotation bioenergy plantations are not uncommon in Europe). For these reasons, the concept is largely hypothetical, and it is a mistake to apply this premise to plantations in general. Furthermore, plantations are usually established on land that historically held natural forest, which either was converted to plantation forest or was deforested and converted to another land use before the plantation forest was established. In such cases, bioenergy plantations would be subject to the criticisms made of the dividend-then-debt approach if they replace plantations for traditional wood products.

In conclusion, existing plantations used for bioenergy cannot be considered exempt from the need to account for carbon using the mass balance approach described in this review, although it may be the case in future for bioenergy plantations established on long-deforested land.

Abandoned Plantations Carry No Carbon Debt

Several studies (e.g., Lamers and Junginger 2013, Jonker et al. 2014) discuss plantations established for traditional wood products but "abandoned" due to diminishing fiber demand (referring primarily to the southeastern United States). They suggest that protection (no harvest) of such plantations is an unlikely scenario, and more realistic alternatives are conversion to agriculture or urban development. Lamers and Junginger (2013) argue that these plantations should therefore be considered a "free" source of bioenergy, since deforestation would be the baseline in the fossil fuel scenario, whereas Jonker et al. (2014) propose using the carbon debt repayment approach discussed later in this review. Here we note that such an approach is in error because it ignores the fate of forest carbon in the baseline scenario where there is no harvest for bioenergy.

Although production of certain traditional wood products (e.g., pulp and paper) has indeed been declining since 2000 (Hujala et al. 2013), the likelihood of there being large numbers of abandoned plantations contradicts national and global projections of increasing demand for traditional wood products (Ince et al. 2011, Daigneault et al. 2012, Nepal et al. 2012, Latta et al. 2013). If, however, there are plantations abandoned due to regional deviations from global trends for which the no-harvest baseline is an unrealistic scenario, then for such plantations the appropriate baseline for forest bioenergy scenario is deforestation followed by LUC. Because it is highly unlikely that the act of deforestation results in disposal of standing live trees as waste, the deforestation baseline should include a single harvest of standing live trees and their utilization for either traditional wood products or bioenergy, with carbon stocks in deforested areas determined by the new land use.

To conclude, the correct baseline scenarios for abandoned plantations are either the no-harvest scenario or, where this is deemed unrealistic, a deforestation scenario that accounts for the fate of forest biomass carbon due to deforestation and carbon stocks in deforested land.

Use of the Carbon Debt Repayment Approach to Carbon Accounting

The concept of carbon debt repayment (Mitchell et al. 2012, Jonker et al. 2014) calls for calculation of the forest carbon deficit relative to the amount of forest carbon at time of harvest. Unlike carbon sequestration parity, carbon debt repayment, referred to as "atmospheric carbon parity" by Agostini et al. (2013, p. 33), assumes that a forest carbon deficit created by harvest is completely repaid once the combined balance of carbon stocks in the postharvest forest and LCA benefits from substituting for fossil fuel equals carbon stocks in the preharvest forest (Figure 2D).

Recent defense of the carbon debt repayment approach was made in a report published by AEBIOM (2013). In its discussion of harvest for bioenergy of standing live trees in southeastern US forests, the no-harvest baseline is called "completely inappropriate" and "unrealistic" and is listed among the

> fundamental flaws in key assumptions and methodology that underlie prominent studies that have found forest-based bioenergy to be associated with significant carbon deficits (AEBIOM 2013, p. 5–6)

Instead, the report advocates using the so-called "reference point baseline" (p. 36), which is identical to carbon debt repayment.

Proponents of carbon debt repayment (such as AEBIOM 2013, Jonker et al. 2014) make the fundamental error of ignoring the fate of forests in the reference fossil fuel scenario. As noted earlier, in the fossil fuel scenario, when GHG emissions from fossil fuel combustion occur, they do so in lieu of bioenergy, and so carbon stored in forests increases over time. To claim emissions reductions from avoided fossil fuel use, it is logically required that forest growth be accounted for in the case where fossil fuels are used (no harvest for bioenergy is needed). Therefore, use of the carbon debt repayment method results in incorrect estimates of bioenergy GHG emissions.

Indirect LUC

As noted earlier, indirect LUC refers to changes in land use outside the area managed for bioenergy that occur as a consequence of harvesting for bioenergy (Berndes et al. 2010, Bird et al. 2011). For this reason, the spatial scale of bioenergy studies where indirect LUC is considered typically are regional or national in scope (for examples, see Abt et al. 2010, 2012, Ince et al. 2011, Galik and Abt 2012, Daigneault et al. 2012, Nepal et al. 2012, Sedjo and Tian 2012, Latta et al. 2013).

The above cited studies share in common the use of econometric models to analyze the effects of market prices and wood products and bioenergy demand scenarios on forest growing stock and/or carbon. Carbon accounting in these studies often has serious shortcomings; for example, some do not account for LCA emissions, whereas others do not consider forest carbon pools beyond those in harvested wood. Such shortcomings can potentially alter whether or when forest biomass produces a net atmospheric carbon benefit. Generally, and with these caveats in mind, such studies conclude that greater bioenergy demand would increase biomass supply and that growth in forest carbon due to indirect land use effects, such as increased planting or silviculture, may outpace forest carbon stock reductions caused by bioenergy harvest.

In the event that indirect LUC is accounted for, the estimation of GHG emissions attributed to forest bioenergy still requires quantification of forest carbon stocks in an appropriate forest baseline, as well as LCA emissions for the bioenergy and reference fossil fuel scenarios. This is because direct LUC associated with forest bioenergy (forest landscape managed for bioenergy) is "nested" in indirect LUC (changes to forest and/or nonforested areas outside of the landscape managed for forest bioenergy) (Berndes et al. 2010). In other words, inclusion of indirect LUC may alter the time to carbon sequestration parity for a given forestry system, but it does not alter the methodology of assessing the forest bioenergy contribution to GHG emissions from this system. In addition, it is important to verify that potential indirect LUC does in practice occur, taking note of Rabl et al. (2007), who recommend that emissions and removals of CO_2 be accounted for explicitly during each stage of the bioenergy life cycle. We consider the recommendation by Rabl et al. (2007)

key, given some highly uncertain potential consequences to indirect LUC resulting from increased bioenergy demand.

Other Sources of Forest Biomass

Residue from ongoing harvest operations is the second most common potential source of biomass considered in the literature on forest bioenergy. The GHG effects of using harvest residue for bioenergy have been studied by several authors (e.g., McKechnie et al. 2011, Domke et al. 2012, Repo et al. 2012). The key difference between assessing GHG effects of using harvest residue versus live trees as a source of biomass is in the baseline scenario: in the case of harvest residue, the baseline scenario must include a projection of the amount of carbon stored in harvest residue if it were not collected because of an absence of demand for bioenergy (an exception to the need to account for the fate of harvest residue is if it came from plantations established specifically for bioenergy production). Consequently, studies not including an analysis of a residue baseline scenario are bound to show shorter periods to reach a net reduction in GHG emissions (e.g., Yoshioka et al. 2005, Froese et al. 2010, Gustavsson et al. 2011).

Studies accounting for the fate of residues in the event they are not used for bioenergy are consistent in concluding that an overall reduction in GHG emissions is achieved within the first few years of biomass collection. Based on literature reports reviewed by Lamers and Junginger (2013), the time required to achieve the reduction in total GHG emissions ranges from 0 to 16 years from the onset of harvest residue collection for bioenergy. A variation in the time to overall GHG emission reduction is caused by assumptions about the fate of residue in the baseline scenario (e.g., decomposition rate and rate of slash burning) and the reference fossil fuel.

The assumption that harvest residue is a carbon "free" source of biomass for energy because otherwise it would be burned is an exaggeration of its fate (for example, in AEBIOM 2013, p. 18: "the majority of the biomass left following harvest is burned as a waste management measure"). The reality of the residue baseline scenario is more complex. First, in some regions, all harvest residue is left on site to decompose; i.e., none is burned (e.g., McKechnie et al. 2011). Decomposition varies by region, but it is not instantaneous. Second, even where harvest residue is burned, a substantial fraction does not get burned for logistical reasons (e.g., insufficient staffing and weather conditions). Analysis of annual forest management reports by Ter-Mikaelian et al. (2014b) revealed that fewer than 50% of slash piles were burned in northwestern Ontario, Canada. Differences in slash burning rates are also apparent among the administrative regions of British Columbia, Canada (Lamers et al. 2014). Even in the case of slash burning, the net effect of collecting it for bioenergy is not zero, contrary to the suggestion by Miner et al. (2014), because of incomplete combustion, with between 5 and 25% of residue in piles remaining after burning (e.g., Hardy 1996). Incomplete combustion of slash when burned produces black carbon, which resists biological and chemical degradation (Forbes et al. 2006). Although the black carbon pool is relatively small, its stability makes it an important component of total forest carbon. Thus, the baseline for harvest residue is not straightforward and should reflect local conditions and practices.

Sawmill residue (sawdust and wood chips), because it is a by-product of traditional wood products, has a substantially lower GHG baseline scenario compared with that of other sources of biomass because its LCA emissions include only those from production and transportation of biofuel and non-CO_2 GHGs from its combustion. However, according to Gronowska et al. (2009), in the United States about 98 and 60% of primary and secondary mill residue, respectively, is already used for energy or other value-added products; in Canada, 70% of mill residue is currently used. Properly assessing the GHG effects of mill residue used for bioenergy thus requires knowledge of the existing fate of mill residue to correctly define its baseline scenario in the absence of use for bioenergy.

Is Forest Bioenergy "Bad" for Climate?

The aim of this review is to promote accurate accounting of the atmospheric effects of bioenergy, not to argue against using forest biomass for energy generation. When correctly accounted for, GHG emissions from live tree forest biomass used for energy exceed those from fossil fuels for periods of a few years to more than a century, and the difference can be substantial, depending on the characteristics of the forest harvested and the fossil fuel replaced by bioenergy. Even when bioenergy from live tree biomass from temperate forests replaces coal, a CO_2-intensive fossil fuel, the time to obtain a net reduction in atmospheric CO_2 can be decades; if it is replacing a less CO_2-intensive fossil fuel, the time to achieve an atmospheric benefit may be more than 100 years.

Nevertheless, as correctly pointed out by AEBIOM (2013) and NCASI (2013), biomass combustion for bioenergy emits carbon that is part of the biogenic carbon cycle. Despite delays that may occur in achieving a net reduction in atmospheric carbon, as long as forests regrow, the total amount of carbon in the biosphere-atmosphere system remains approximately the same, with small increases due to consumption of fossil fuels to obtain, process, and transport the biofuel. It is considerably more damaging when energy is generated from fossil fuels because this increases total carbon in the biosphere-atmosphere system and is essentially permanent. We also note that the long-term GHG benefits of substituting fossil fuels with forest bioenergy will greatly surpass those of carbon sequestration in forests (e.g., see Miner et al. 2014) because net carbon accumulation in the no-harvest baseline scenario will slow substantially as forests reach maturity, whereas the benefits of substituting fossil fuels with forest bioenergy will keep accumulating at a steady pace. In addition, forest bioenergy may be needed as a stopgap until sufficient nonfossil fuel energy generation methods, with better atmospheric CO_2 consequences than forest biomass, can be implemented. Until then, even a century-long increase in atmospheric CO_2 caused by using forest bioenergy may be preferable to burning fossil fuels. As stated by Dehue (2013), mitigation of climate change may not be possible without broad-scale use of forest bioenergy; in other words, human society is probably going to require use of all available options to mitigate climate change, whether such options provide a short- or long-term GHG reduction benefit.

There may be reasons beyond climate change to harvest forests to produce bioenergy, such as the opportunity for forest landowners to receive economic benefits (as mentioned in AEBIOM 2013), the economic benefits to society overall of reducing dependence on imported fossil fuels (US Department of Energy 2013), or achievement of ecological objectives for which forest disturbance is necessary (Colombo et al. 2012). However, the rationale for using forest bioenergy should avoid the false promises of instant benefits to climate change mitigation. In this regard, we note that the principles of carbon accounting discussed in this review should not be confused with those described by the United Nations Framework Convention on Climate Change, the latter reflecting international carbon accounting entailing political compromises needed to reach agreement among participating parties (Prag et al. 2013).

In conclusion, some biomass sources used for forest bioenergy may indeed provide near-immediate GHG reduction, whereas others produce decades- to century-long increases in atmospheric GHGs. Our goal in this review was to support what we consider the use of scientifically sound knowledge for informed decisionmaking about using forest bioenergy for climate change mitigation and to help remove confusion caused by flawed approaches to bioenergy carbon accounting.

Endnote

1. For more information, see www.seai.ie/Renewables/Bioenergy/Introduction_to_Bioenergy/.

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NATURAL CAPITAL INITIATIVE AT MANOMET REPORT

BIOMASS SUSTAINABILITY AND CARBON POLICY STUDY

EXECUTIVE SUMMARY

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EXECUTIVE SUMMARY

BIOMASS SUSTAINABILITY AND CARBON POLICY

INTRODUCTION

This study addresses a wide array of scientific, economic and technological issues related to the use of forest biomass for generating energy in Massachusetts. The study team, assembled and directed by the Manomet Center for Conservation Sciences, was composed of experts in forest ecosystems management and policy; natural resource economics; and energy technology and policy. The Commonwealth of Massachusetts Department of Energy Resources (DOER) commissioned and funded the study.

The study provides analysis of three key energy and environmental policy questions that are being asked as the state develops its policies on the use of forest biomass.

1. What are the atmospheric greenhouse gas implications of shifting energy production from fossil fuel sources to forest biomass?
2. How much wood is available from forests to support biomass energy development in Massachusetts?
3. What are the potential ecological impacts of increased biomass harvests on forests in the Commonwealth, and what if any policies are needed to ensure these harvests are sustainable?

The goal of the report is to inform the development of DOER's biomass policies by providing up-to-date information and analysis on the scientific and economic issues raised by these questions. We have not been asked to propose specific policies except in the case where new approaches may be needed to protect the ecological functioning of forests. We do not consider non-forest sources of wood biomass (e.g., tree care and landscaping, mill residues, construction debris), which are potentially available in significant quantities but which have very different greenhouse gas (GHG) implications.

This Executive Summary highlights key results from our research and the implications for the development of biomass energy policies in Massachusetts. While certain of the study's insights are broadly applicable across the region (e.g., estimates of excess lifecycle emissions from combustion of biomass compared to fossil fuels), it is also important to recognize that many other conclusions are specific to the situation in Massachusetts—particularly greenhouse gas accounting outcomes that depend on the forest management practices of the state's landowners, which likely differ considerably from those in neighboring states. Nonetheless, the framework and approach that we have developed for assessing the impacts of wood biomass energy have wide applicability for other regions and countries.

SUMMARY OF KEY FINDINGS

Greenhouse Gases and Forest Biomass: At the state, national, and international level, policies encouraging the development of forest biomass energy have generally adopted a view of biomass as a *carbon neutral* energy source because the carbon emissions were considered part of a natural cycle in which growing forests over time would re-capture the carbon emitted by wood-burning energy facilities. Beginning in the 1990s, however, researchers began conducting studies that reflect a more complex understanding of carbon cycle implications of biomass combustion. Our study, which is based on a comprehensive lifecycle carbon accounting framework, explores this more complex picture in the context of biomass energy development in Massachusetts.

The atmospheric greenhouse gas implications of burning forest biomass for energy vary depending on the characteristics of the bioenergy combustion technology, the fossil fuel technology it replaces, and the biophysical and forest management characteristics of the forests from which the biomass is harvested. Forest biomass generally emits more greenhouse gases than fossil fuels per unit of energy produced. We define these excess emissions as the biomass *carbon debt*. Over time, however, re-growth of the harvested forest removes this carbon from the atmosphere, reducing the carbon debt. After the point at which the debt is paid off, biomass begins yielding *carbon dividends* in the form of atmospheric greenhouse gas levels that are lower than would have occurred from the use of fossil fuels to produce the same amount of energy (Figure 1). The full recovery of the biomass carbon debt and the magnitude of the carbon dividend benefits also depend on future forest management actions and natural disturbance events allowing that recovery to occur.

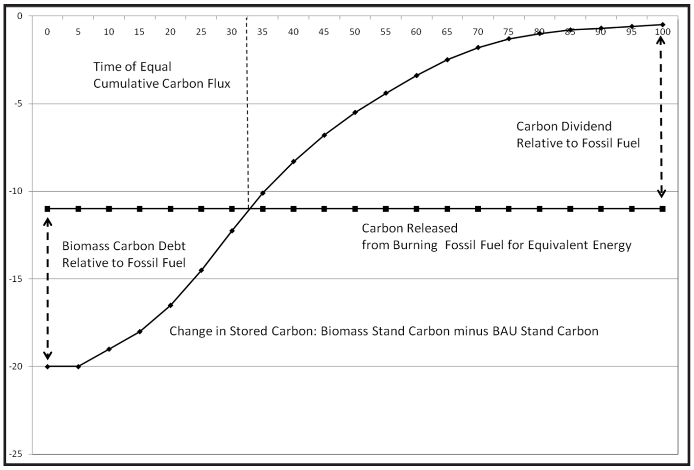

Figure 1 (tonnes of carbon). The schematic above represents the incremental carbon storage over time of a stand harvested for biomass energy wood relative to a typically harvested stand (BAU). The initial *carbon debt* (9 tonnes) is shown as the difference between the total carbon harvested for biomass (20 tonnes) and the carbon released by fossil fuel burning (11 tonnes) that produces an equivalent amount of energy. The *carbon dividend* is defined in the graph as the portion of the fossil fuel emissions (11 tonnes) that are offset by forest growth at a particular point in time. In the example, after the 9 tonnes biomass carbon debt is recovered by forest growth (year 32), atmospheric GHG levels fall below what they would have been had an equivalent amount of energy been generated from fossil fuels. This is the point at which the benefits of burning biomass begin to accrue, rising over time as the forest sequesters greater amounts of carbon relative to the typical harvest.

The initial level of the carbon debt is an important determinant of the desirability of producing energy from forest biomass. Figure 2 provides a summary of carbon debts, expressed as the percentage of total biomass emissions that are in excess of what would have been emitted from fossil fuel energy generation. Replacement of fossil fuels in thermal or combined heat and power (CHP) applications typically has lower initial carbon debts than is the case for utility-scale biomass electric plants because the thermal and CHP technologies achieve greater relative efficiency in converting biomass to useable energy. As a result, the time needed to pay off the carbon debt and begin accruing the benefits of biomass energy will be shorter for thermal and CHP technologies when the same forest management approaches are used in harvesting wood.

Figure 2: Carbon Debt Summary Table

Excess Biomass Emissions as % of Total Biomass Emissions				
Scenarios	**Coal**	**Oil (#6)**	**Oil (#2)**	**Natural Gas**
Electric	31%			66%
Thermal/ CHP		2%-8%	9%-15%	33%-37%

The absolute magnitude and timing of the carbon debts and dividends, however, is sensitive to how landowners decide to manage their forests. Since future landowner responses to increased demand for forest biomass are highly uncertain, we modeled the recovery of carbon in growing forests under a number of alternative management scenarios.

For a scenario that results in relatively rapid realization of greenhouse gas benefits, the switch to biomass yields benefits within the first decade when oil-fired thermal and CHP capacity is replaced, and between 20 and 30 years when natural gas thermal is replaced (Figure 3). Under comparable forest management assumptions, dividends from biomass replacement of coal-fired electric capacity begin at approximately 20 years. When biomass is assumed to replace natural gas electric capacity, carbon debts are still not paid off after 90 years.

Figure 3: Carbon Debt Payoff

Fossil Fuel Technology	Carbon Debt Payoff (yr)
Oil (#6), Thermal/CHP	5
Coal, Electric	21
Gas, Thermal	24
Gas, Electric	>90

Another way to consider greenhouse gas impacts of biomass energy is to evaluate at some future point in time the cumulative carbon emissions of biomass (net of forest recapture of carbon) relative to continued burning of fossil fuels. The Massachusetts Global Warming Solutions Act establishes 2050 as an important reference year for demonstrating progress in reducing greenhouse gas emissions. Figure 4, comparing 40 years of biomass emissions with 40 years of continued fossil fuel burning, shows that replacement of oil-fired thermal/CHP capacity with biomass thermal/CHP fully offsets the carbon debt and lowers greenhouse gas levels compared to what would have been the case if fossil fuels had been used over the same period—approximately 25% lower over the period under a rapid recovery scenario. For biomass replacement of coal-fired power plants, the net cumulative emissions in 2050 are approximately equal to what they would have been burning coal; and for replacement of natural gas cumulative total emissions are substantially higher with biomass electricity generation.

Figure 4: Cumulative Carbon Dividends from Biomass Replacement of Fossil Fuel

Biomass Cumulative % Reduction in Carbon Emissions (Net of Forest Carbon Sequestration)				
Year	**Oil (#6) Thermal/ CHP**	**Coal, Electric**	**Gas, Thermal**	**Gas, Electric**
2050	25%	-3%	-13%	-110%
2100	42%	19%	12%	-63%

Forest Biomass Supply: Future new supplies of forest biomass available for energy generation in Massachusetts depend heavily on the prices that bioenergy facilities are able to pay for wood. At present, landowners in the region typically receive between $1 and $2 per green ton of biomass, resulting in delivered prices at large-scale electricity facilities of around $30 per green ton. Under current policies that are influenced by the competitive dynamics of the electricity sector, we do not expect that utility-scale purchasers of biomass will be able to significantly increase the prices paid to landowners for biomass. Consequently, if future forest biomass demand comes primarily from large-scale electric facilities, we estimate the total "new" biomass that could be harvested annually from forest lands in Massachusetts would be between 150,000 and 250,000 green tons—an amount sufficient to support 20 MW of electric power capacity—with these estimates potentially increasing by 50%–100% when out-of-state forest biomass sources are taken into account (these estimates do not include biomass from land clearing or other non-forest sources such as tree work and landscaping). This is the amount of incremental biomass that would be economically available and reflects the costs of harvesting, processing and transporting this material as well as our expectations about the area of land where harvest intensity is likely to increase. Thermal, CHP, and other bioenergy plants can also compete for this same wood—which could support 16 typically sized thermal facilities or 4 typical CHP plants—and have the ability to pay much higher prices on a delivered basis; thus, they have more options for harvesting and processing forest biomass and can outbid electric power if necessary.

Paying higher prices to landowners for forest biomass could potentially increase forest biomass supplies significantly. For this to occur, electricity prices would need to rise, due to substantially higher fossil fuel prices or significant policy shifts. Thermal, CHP, and pellet facilities can already pay much higher prices for biomass at current energy prices, and would remain competitive if prices paid to landowners were to rise significantly. If these prices were to increase to $20 per green ton, we estimate that supplies of forest biomass from combined in-state and out-of-state sources could be as high as 1.2 to 1.5 million green tons per year. However, this high-price scenario is unlikely given current expectations of fossil fuel prices and existing renewable energy incentives.

Figure 5 shows the potential bioenergy capacity that could be supported from these estimated volumes of "new" forest biomass in Massachusetts. The upper end of the range for Massachusetts forest biomass supplies under our high-price scenario is approximately 885,000 green tons per year—this is close to the annual quantity of biomass that can be harvested without exceeding the annual net growth of the forest on the operable private land base. If additional forest biomass supplies that would be potentially available from out-of-state sources are taken into account, the biomass quantity and number of bioenergy facilities that could be furnished would be 50%–100% higher than shown in this table.

Figure 5: Potential Bioenergy Capacity from "New" Forest Biomass Sources in Massachusetts

	Green Tons per Year
Current Massachusetts Harvest *	325,000
Potential Forest Biomass Supply (Massachusetts only) **	
Current Biomass Prices	200,000
High-Price Scenario	800,000
	Number of Facilities
Electric Power Capacity: Number of 50 MW Plants	
Current Biomass Prices	0.4
High-Price Scenario	1.6
Thermal Capacity: Number of 50 MMBtu/hr Plants ***	
Current Biomass Prices	16
High-Price Scenario	62
CHP Capacity: Number of 5 MW/34 MMBtu/hr Plants ***	
Current Biomass Prices	4
High-Price Scenario	15

Notes: * *Average of industrial roundwood for 2001–2009.*
** *Based on mid-point of the range of volumes estimated for new biomass in Massachusetts.*
*** *Thermal plants are assumed to operate 1800 hours per year, while CHP plants operate 7200 hours per year.*

Forest Sustainability and Biomass Harvests: In Massachusetts, the possibility of increased harvesting of biomass for energy has raised a number of sustainability issues at both the landscape and stand levels. At the landscape scale, potential impacts to a broad range of societal values arise with increases in biomass harvesting. However, in our low-price scenario for biomass, we anticipate that harvested acreage will not increase from current levels—biomass will come from removal of logging residues and poor quality trees at sites that would be harvested for timber under a business-as-usual scenario. Furthermore, in this scenario the combined volume of timber and biomass harvests represents less than half of the annual net forest growth across the state's operable private forest land base. Under our high-price biomass supply scenario, although harvests still represent annual cutting on only about 1% of the forested lands in the state, the total harvest levels approach the total amount of wood grown each year on the operable private forest land base.

Under either price scenario, however, harvests for bioenergy facilities could have more significant local or regional impacts on the landscape. These might include aesthetic impacts of locally heavy harvesting as well as potential impacts on recreation and tourism and the longer-term health of the wood products sector of the economy. We have outlined four general options encompassing a wide range of non-regulatory and regulatory approaches that the state may wish to consider if it determines that further actions are needed to protect public values at the landscape scale.

- Option 1: Establish a transparent self-monitoring, self-reporting process for bioenergy facilities designed to foster sustainable wood procurement practices.
- Option 2: Require bioenergy facilities to purchase wood from forests with approved forest management plans.
- Option 3: Require bioenergy facilities to submit wood supply impact assessments.
- Option 4: Establish formal criteria for approval of wood supply impact assessments—possible criteria might include limits on the amount of harvests relative to anticipated forest growth in the wood basket zone.

At the stand level, the most significant sustainability concerns associated with increased biomass harvests are maintenance of soil productivity and biodiversity. Current Chapter 132 Massachusetts forest cutting practices regulations provide generally strong protection for Massachusetts forests, especially water quality; however, they are not currently adequate to ensure that biomass harvesting is protective of ecological values across the full range of site conditions in Massachusetts. Other states and countries have recently adopted biomass harvesting guidelines to address these types of concerns, typically through new standards that ensure (1) enough coarse woody debris is left on the ground, particularly at nutrient poor sites, to ensure continued soil productivity and (2) enough standing dead wildlife trees remain to promote biodiversity. While the scientific literature does not provide definitive advice on the appropriate practices for Massachusetts' forests, recent guidance from the Forest Guild and other states provides the State Forestry Committee with a useful starting point for developing additional stand level standards that ensure continued protection of ecological values in Massachusetts forests.

14. Giuliana Zanchi, *et al.*, *Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel*, GCB Bioenergy, (Nov, 2012).

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Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel

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Abstract

Under the current accounting systems, emissions produced when biomass is burnt for energy are accounted as zero, resulting in what is referred to as the 'carbon neutrality' assumption. However, if current harvest levels are increased to produce more bioenergy, carbon that would have been stored in the biosphere might be instead released in the atmosphere. This study utilizes a comparative approach that considers emissions under alternative energy supply options. This approach shows that the emission benefits of bioenergy compared to use of fossil fuel are time-dependent. It emerges that the assumption that bioenergy always results in zero greenhouse gas (GHG) emissions compared to use of fossil fuels can be misleading, particularly in the context of short-to-medium term goals. While it is clear that all sources of woody bioenergy from sustainably managed forests will produce emission reductions in the long term, different woody biomass sources have various impacts in the short-medium term. The study shows that the use of forest residues that are easily decomposable can produce GHG benefits compared to use of fossil fuels from the beginning of their use and that biomass from dedicated plantations established on marginal land can be carbon neutral from the beginning of its use. However, the risk of short-to-medium term negative impacts is high when additional fellings are extracted to produce bioenergy and the proportion of felled biomass used for bioenergy is low, or when land with high C stocks is converted to low productivity bioenergy plantations. The method used in the study provides an instrument to identify the time-dependent pattern of emission reductions for alternative bioenergy sources. In this way, decision makers can evaluate which bioenergy options are most beneficial for meeting short-term GHG emission reduction goals and which ones are more appropriate for medium to longer term objectives.

Keywords: bioenergy, biomass, carbon neutrality, consumption emissions, forest management, time-dependent

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Introduction

Increasing use of renewable energy is a key EU strategy for reducing its greenhouse gas (GHG) emissions and contributing to policy objectives within the next 40 years to maintain the global temperature rise below 2 °C. A substantial share of the total renewable energy needed to meet EU targets will come from biomass. According to projections on the deployment of renewable energy sources, energy from solid biomass and organic waste will constitute 58% of the total renewable energy generation in 2020 [140 million tonnes of oil equivalent (Mtoe) of 240 Mtoe] (Ragwitz *et al.*, 2009).

Under the current UNFCCC accounting systems, carbon dioxide (CO_2) emissions produced when biomass is burnt for energy are not accounted for in the energy sector, resulting in what is referred to as the 'carbon neutrality' assumption (UNFCCC, 2006). The convention is based on the assumption that the carbon (C) released when biomass is burnt will be recaptured by plant regrowth and that any excess of releases over regrowth will show up as a loss of C stock and will be accounted for in the land use sector. However, in practice, the current accounting system for the land use sector is incomplete. It was designed for a system in which all nations account for all C stock changes from land use, whereas only a limited set of countries currently account for a limited number of C stock changes.

Additional considerations arise from two issues. First, while in the case of annual crops emissions and regrowth occur within 1 year, there is a time delay between emissions and subsequent regrowth when woody biomass is burnt. Second, current harvest levels might be increased, for instance, to achieve renewable energy targets (Mantau, 2010). In this case, the overall C stock of forests might be lower than the C stock in the

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nonbioenergy scenario for the entire period when forest management is intensified, even in forests that are being sustainably managed. Where harvests are increased, C that would have been stored in the biosphere is burnt instead and released as CO_2 into the atmosphere. When these C stock changes are included in the emission profile of bioenergy, the question arises as to whether a nation will have more net emissions within the time frame of climate change policies aiming to achieve the 2 °C target if the biomass is extracted and used for energy or if fossil fuels are used.

This study builds up on research developed in the 1990s showing that emissions reductions that are achieved by substituting bioenergy for fossil fuels use are time-dependent, that is, they change over time and that bioenergy is not always carbon neutral (Schlamadinger & Spitzer, 1995; Schlamadinger *et al.*, 1995, 1997; Schlamadinger & Marland, 1996). Recent papers have confirmed those results, showing that the benefits of bioenergy use change according to the time frame that is considered. Initially, these studies considered a specific bioenergy source removed from a single stand and a one-time removal (Palosuo *et al.*, 2001). More recent studies have started to discuss the effect of adopting a landscape rather than a stand-level view (Walker *et al.*, 2010) and to compare different bioenergy sources (McKechnie *et al.*, 2011; Repo *et al.*, 2011). Other studies have used metrics that express the time-dependent emissions of bioenergy in terms of global warming potential (Cherubini *et al.*, 2011a,b; Sathre & Gustavsson, 2011). The assumptions and factors included differ among the studies, but the general conclusions are in agreement in stating that bioenergy is not always carbon neutral.

This study contributes to the discussion by comparing time-dependent emission benefits from different wood sources, thus helping to identify which bioenergy sources might be more beneficial to achieve near-term emission reduction targets. The study uses selected, illustrative examples to achieve this objective, showing the benefits over time of using wood from residues, additional fellings and new plantations.

Method

The benefits in terms of GHG emission reductions produced over time by using woody biomass for energy are assessed by comparing the bioenergy system to the fossil fuel system that is replaced.

Emissions in both systems can be classified as:

- Production chain emissions, that is, the emissions released to produce, transport, convert and distribute the fuel.
- Resource consumption emissions: the carbon (C) released when the mass of fuel – either biomass or a fossil fuel – is burnt.

This paper focuses only on the resource consumption emissions of different energy supply systems. In the case of bioenergy, these emissions are usually ignored under the assumption of carbon neutrality. In this study, a metric is defined that expresses benefits in terms of emission reductions resulting from using biomass rather than fossil fuel sources for energy.

As a first step biomass consumption emissions are determined:

1 Biomass consumption emissions, that is, emissions that are attributable to burning biomass to replace some fossil energy, are calculated as the difference between the forest C stock under the bioenergy scenario and the forest C stock under the fossil fuel scenario (i.e., when biomass is not extracted for bioenergy) at a given point in time:

$$\mathrm{Ec_B}(t) = (\mathrm{BC_B}(t) - \mathrm{BC_{FF}}(t)) \times 44/12. \tag{1}$$

$\mathrm{Ec_B}(t)$ is the consumption emissions from biomass at time t if a bioenergy system is implemented (tCO_2); $\mathrm{BC_B}(t)$ is the forest C stock under the bioenergy scenario at time t (tC); $\mathrm{BC_{FF}}(t)$ is the forest C stock under the fossil fuel scenario at time t (tC).

The forest C stock in both scenarios includes the C in tree biomass, litter and soil organic matter. This equation enables identification of the changes in forest C stocks attributable to bioenergy over time even in net-growing forests (Fig. 1). In practical terms, these emissions are the difference between C stocks under two different management regimes, one more intensive than the other. This stock difference usually decreases over time because growth rates differ under the two management regimes, with net annual increment usually higher under more intensive management. Other factors that might influence C stock levels, such as climate change and change of natural disturbance risk, are not considered in this study.

As a second step fossil fuel consumption emissions are determined:

2 Fossil fuel consumption emissions are equal to the C released when fossil fuel is burnt in the fossil-fuel scenario (baseline). In the bioenergy scenario, these emissions are

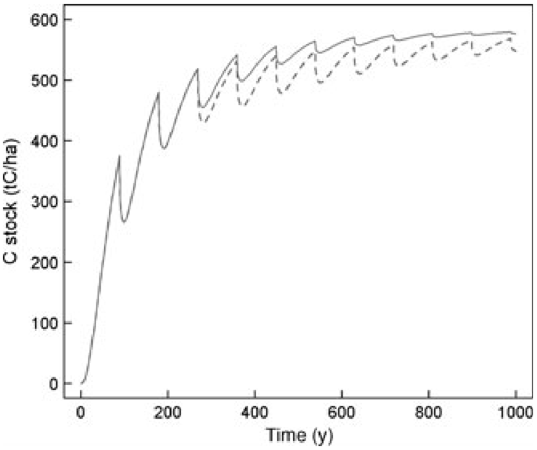

Fig. 1 C stocks in a forest parcel when a bioenergy system is implemented (dashed line) or in the reference system, when bioenergy is not used to replace fossil fuels (solid line).

avoided because fossil fuel is replaced by biomass. It can be assumed that there is a total loss of C to the atmosphere when fossil fuel is burnt, that is, no increase of fossil C stocks occurs in a time period of relevance due to the very long time required to create fossil fuel stocks. Similarly to the equation used for bioenergy emissions, the fossil fuel consumption emissions at time *t* ($\mathrm{Ec}_{\mathrm{FF}}(t)$, $t\mathrm{CO}_2$) are equal to:

$$\mathrm{Ec}_{\mathrm{FF}}(t) = (\mathrm{FC}_{\mathrm{FF}}(t) - \mathrm{FC}_{\mathrm{B}}(t)) \times 44/12. \tag{2}$$

$\mathrm{FC}_{\mathrm{FF}}(t)$ is the fossil C stock under the fossil fuel scenario at time *t* (*t*C); $\mathrm{FC}_{\mathrm{B}}(t)$ is the fossil C stock under the bioenergy scenario at time *t* (*t*C), $\mathrm{FC}_{\mathrm{FF}}(t)$ decreases over time more than $\mathrm{FC}_{\mathrm{B}}(t)$ by an amount equal to the fossil carbon that is replaced in the bioenergy scenario. Therefore, at year *t*, the fossil consumption emissions, $\mathrm{Ec}_{\mathrm{FF}}(t)$, are equal to the cumulative amount of fossil carbon burnt up to that year.

As a third step resource consumption emissions from the two scenarios are compared. The comparison of the biomass consumption emissions (Eqn 1) with fossil fuel consumption emissions (Eqn 2) determines the impact, in terms of emissions, of using biomass instead of fossil carbon for energy over time, production chain emissions excluded.

This impact of biomass use over time can be expressed as a factor. Carbon neutrality factors were first defined by Schlamadinger & Spitzer (1995) to quantify the extent to which use of biomass reduces emissions compared to a replaced fossil fuel over time. The factor CN(*t*) could cover both production chain and what we consider as consumption emissions, and is defined as follows:

$$\mathrm{CN}(t) = \frac{\mathrm{E}_{\mathrm{FF}}(t) - \mathrm{E}_{\mathrm{B}}(t)}{\mathrm{E}_{\mathrm{FF}}(t)} = 1 - \frac{\mathrm{E}_{\mathrm{B}}(t)}{\mathrm{E}_{\mathrm{FF}}(t)}, \tag{3}$$

where $\mathrm{E}_{\mathrm{FF}}(t)$ is the emissions from the fossil fuel system at year *t*; $\mathrm{E}_{\mathrm{B}}(t)$ is the emissions from the bioenergy system at year *t*.

This definition of CN factors leads to the following (Fig. 2):

1 CN < 0, where bioenergy system emissions are higher than those in the fossil fuel system.
2 CN = 0, where bioenergy system emissions equal those of the reference system.
3 0 < CN < 1, the bioenergy system produces less emissions than fossil fuels (e.g., if CN = 0.6, bioenergy produces 60% less emissions).
4 CN = 1, if the bioenergy system produces zero net emissions.
5 CN > 1, when the bioenergy system produces a C sink in the biosphere in addition to 100% emission reductions compared to the fossil fuel.

Under this system, a CN = 1 corresponds to the basic concept imbedded in viewing bioenergy as 'carbon neutral'. Under this definition, at points in time when a bioenergy system has a CN of 1, use of bioenergy reduces emissions by 100% compared to use of a fossil fuel.

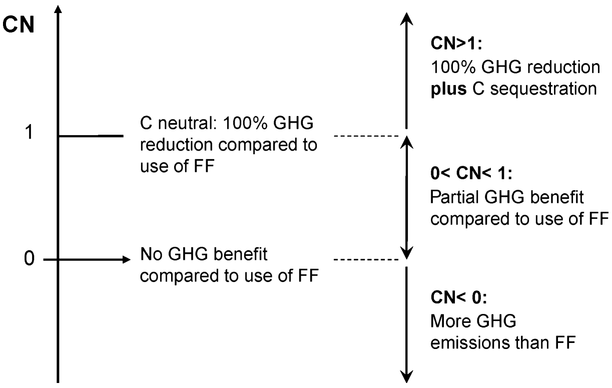

Fig. 2 Illustration of the CN factor value in relation to greenhouse gas (GHG) benefits. FF, fossil fuels.

Whereas a comprehensive analysis to assess the GHG emissions of bioenergy compared to fossil fuel should include production chain emissions, this study focuses only on the impact of resource consumption emissions. Therefore, if Eqn (3) is confined only to resource consumption emissions, it becomes equal to:

$$\mathrm{CN}(t) = \frac{\mathrm{Ec}_{\mathrm{FF}}(t) - \mathrm{Ec}_{\mathrm{B}}(t)}{\mathrm{Ec}_{\mathrm{FF}}(t)} = 1 - \frac{\mathrm{Ec}_{\mathrm{B}}(t)}{\mathrm{Ec}_{\mathrm{FF}}(t)}. \tag{4}$$

Case studies

To illustrate the emission reduction produced by the use of different biomass sources, we present three illustrative examples:

1 Additional fellings from a managed forest.
2 Extraction of harvest residues from a managed forest.
3 Bioenergy from new tree plantations.

It is assumed that each biomass source will be used to substitute coal, oil or natural gas. For purposes of the calculations in this paper, it is assumed that the coal and bioenergy systems have the same conversion efficiency and the same CO_2 emissions per unit of energy produced (Schlamadinger *et al.*, 1995). This is approximately the case where biomass is used to replace coal for electricity. It is also assumed that oil causes about 20% less C emissions per unit energy than coal, while natural gas produce about 40% less emissions than coal (Schlamadinger *et al.*, 1995; Sathre & Gustavsson, 2011). Therefore, where biomass is used to replace, for example, natural gas, benefits are lower, or take longer to emerge.

In the following examples, a modified version of the GORCAM model is used to simulate the effects of a change in management or land use against a baseline scenario (http://www.ieabioenergy-task38.org/softwaretools/gorcam.htm).

For simplicity and comparability of results, changes of management scenarios in managed forests are simulated for a single type of forest. The example is a typical stand of Norwegian Spruce (*Picea abies*) in the Austrian Alps near Bruck an der Mur, Austria. The stand has a rotation period of 90 years. The growth curve of the spruce forest is derived from the Austrian yield table for 'Spruce-Bruck/Mur', site class 10 (an index of site fertility equivalent to medium fertility) (Marschall, 1975). Merchantable volume is converted to total aboveground and below biomass based on the allometric equations by Wirth *et al.* (2004). Litter inputs are calculated as a percentage of the living biomass, and the litter decay is estimated using a temperature, precipitation and litter quality model (Moore *et al.*, 1999) (Table 1). Climate parameters are derived from data collected at the station in Bruck an der Mur (mean annual temperature and precipitation: T = 8.3 °C, P = 800 mm; ZAMG, 2011). The effect that climate change might have on the development of the C stocks in the baseline and in the bioenergy scenario is not included in this study. It is further assumed that the management changes entailed in the various biomass scenarios do not affect the natural disturbance regime. We consider a forest system of 90 ha of which one hectare is cut every year. The model assumes that prior to inauguration of the bioenergy scenario, there have been three complete rotations at harvest levels equal to those that occur under the baseline (e.g., no-bioenergy scenario). Changes of management to produce bioenergy occur after these three rotation periods. This assumption was introduced to simulate a change of management in forests that have been harvested in a steady manner for long periods.

In the following sections, the CO_2 emission reduction or increase of a specific biomass source compared to fossil fuels are represented by graphs that compare the biomass consumption emissions of bioenergy against the fossil fuel consumption emissions that would occur in the baseline. Graphs also show the development of the CN over time, that is, the relative advantage of bioenergy against fossil fuel. The graphs represent the replacement of coal and natural gas, while replacement of oil, the intermediate case, is discussed in the text. Production chain emissions are neither shown nor considered in the calculation of the CN factors presented in this paper.

The results presented in this study on the relative advantage of bioenergy against fossil fuels are independent of the size (areal extent) of the forest or plantation considered. This is because a full rotation system, not a single stand, has been used in the modeling. As a consequence, if a change of management to produce bioenergy is promoted on larger areas, the biomass consumption emissions and the fossil fuel consumption emissions would increase in absolute terms, but the ratio between the two, expressed by the CN factor, would remain the same. The management in other forest areas not included in the bioenergy system remains unchanged both in the baseline and in the bioenergy scenario and therefore no C gain or loss from these areas are or should be included in the calculations.

Results

Additional fellings

Increased demand for bioenergy could result in increased harvests from managed forests. According to

Table 1 Equations and parameters used in the forest carbon model

Biomass component (t d.m. ha^{-1})	Equations	Parameters
Aboveground	$B_{(t)} = B_{(t-1)}\left\{1 + \frac{R}{N}\left[1 - \left(\frac{B_{(t-1)}}{B_{\mathrm{MAX}}}\right)^{N}\right]\right\}$	$R = 0.0205$ $N = -0.5388$ $B_{\mathrm{MAX}} = 450\ \mathrm{t\ ha}^{-1}$
Roots	Total Root : $R_{(t)} = aB^{b}_{(t)}$ Fine roots : $FR_{(t)} = cR^{d}_{(t)}$	$a = 0.064$ $b = 1.257$ $c = 0.452$ $d = 0.632$
Litter	$L_{j_{(t)}} = L_{j_{\mathrm{Input}}} + L_{j_{(t-1)}}\mathrm{e}^{-1/K_j}$ $L_{j_{\mathrm{Input}}} = L_{j_{\mathrm{B(In)}}} + L_{j_{\mathrm{H(In)}}}$ $L_{j_{\mathrm{H(In)}}} = \mu \cdot Harv_{(t)}$	Foliage litter, $L_{1(t)}$: $L_{1\mathrm{B(In)}} = 0.08\mathrm{B}_{(t-1);}\ K_1 = 5.0$ Woody litter, $L_{2(t)}$: $L_{2\mathrm{B(In)}} = 0.0177\mathrm{B}_{(t-1)}$; $K_2 = 12.5$ Woody root litter, $L_{3(t)}$: $L_{3\mathrm{B(In)}} = 0.0177\mathrm{R}_{(t-1)}$; $K_3 = 12.5$ Fine root litter, $L_{4(t)}$: $L_{4\mathrm{B(In)}} = 0.641\mathrm{FR}_{(t-1)}$; $K_4 = 5.0$ $Harv_{(t)}$: amount of harvested $B_{(t)}$ μ: percentage of $Harv_{(t)}$ left on the forest floor or share of roots affected by harvest (based on root equations)
Soil	$S_{(t)} = S_{(t-1)}\mathrm{e}^{-1/K_5} + \varphi_1 \sum_{j=1}^{2}\left[1 - (L_{j_{(t-1)}}\mathrm{e}^{-1/K_j})\right]$ $+ \varphi_2 \sum_{j=3}^{4}\left[1 - (L_{j_{(t-1)}}\mathrm{e}^{-1/K_j})\right]$	$K_5 = 30.0$ $\phi_1 = 0.05$ $\phi_2 = 0.50$

a recent study (Mantau, 2010), the total demand for wood in Europe – consisting of the demand for material and energy uses – could increase by about 35% by 2020 compared to current levels. This demand could possibly be met domestically if the harvest levels are significantly increased beyond the current level of resource use. If the same additional amount of wood is taken out of the forests every year to provide a constant bioenergy supply, the forest C stock will develop differently than in a baseline scenario in which fellings are not increased and fossil fuels are burnt instead. Thus, it can be expected that the forest C stock in the bioenergy scenario will be smaller than in the baseline.

The following paragraphs illustrate a case study in which final fellings are increased beyond those in the baseline case to provide an annual wood supply for bioenergy. It is assumed that the entire increase in fellings is used to produce energy.

We consider two cases. In Case 1, a percentage of the net annual increment of the forest is removed. This simulates a sustainably managed forest, such as forests in Europe. The final fellings are increased from 60% (baseline scenario) to 80% of the forest net annual increment (Fig. 3a). The objective of such management is to maintain sustainable management over time by always cutting less than annual growth. Under this management scheme, the absolute amount of biomass that is extracted will decrease over time. The reason for this is that if less than full annual growth is removed, the forest tends to mature, a condition that is characterized by increasingly lower growth rates. Nevertheless, under these circumstances, the difference in forest C stock between the two scenarios will eventually decrease, because of higher growth rates under the more intensive management regime.

Case 2 represents what happens when the priority is to guarantee a constant biomass supply. In this case, a constant amount of biomass has to be extracted from the forest over time. To simulate this type of management, we modeled a bioenergy scenario in which the biomass extracted is increased from the 60% baseline to 80% of the aboveground biomass in the harvested parcel. Under this scenario, the amount of harvested wood can initially be greater than the forest net annual increment although at some point a new equilibrium will be reached. When the new equilibrium is reached, the difference between the two management scenarios stays constant (Fig. 3b).

Figure 4 shows the development of C stock changes in terms of CO_2 emissions from the forest ecosystem compared to the fossil fuel emissions over time. In both the cases where fellings are increased, the bioenergy system will produce more consumption emissions than the fossil fuel reference system for a long period. The use of bioenergy will start to produce some benefits, that is, CN ≥ 0, in:

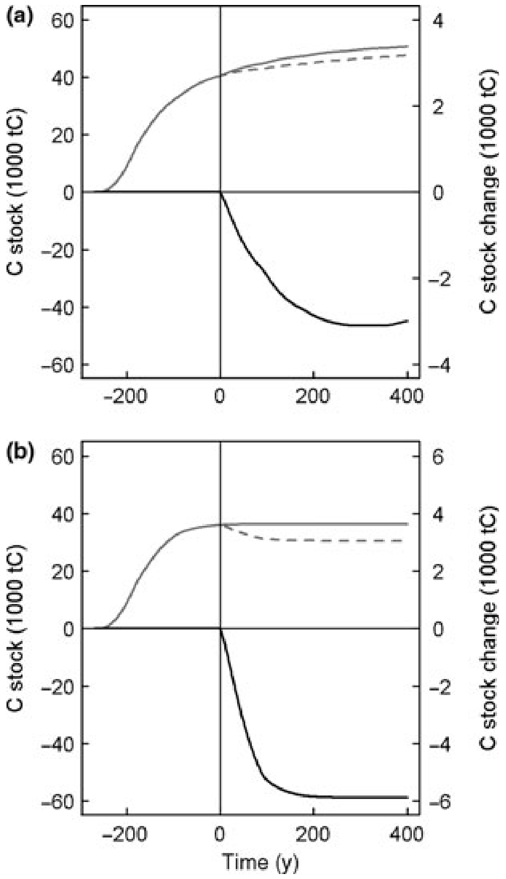

Fig. 3 Effect of additional fellings on the C stock in a rotation forest (living biomass, litter and soil). In graph a, fellings are increased from 60% to 80% of the net annual increment which decreases over time. In graph b, the fellings are increased from 60% to 80% of the aboveground biomass in the harvested parcel. The difference between the C stock in the bioenergy scenario (dashed, gray line) and the one in the fossil fuel reference system (solid, gray line) is represented by the C stock change curve (black line, plotted on the secondary y-axis). The point in time when management is changed is indicated by year 0.

- Case 1: after 175 years if coal is substituted and about 300 years if natural gas is substituted (Fig. 4, Case 1).
- Case 2: after about 230 years if coal is substituted and 400 years if natural gas is substituted (Fig. 4, Case 2).

Intermediate periods result if oil is substituted, that is, about 230 years in Case 1 and 295 years in Case 2.

According to these case studies, increasing fellings in already managed forest with fairly long rotation periods may produce emission reductions compared

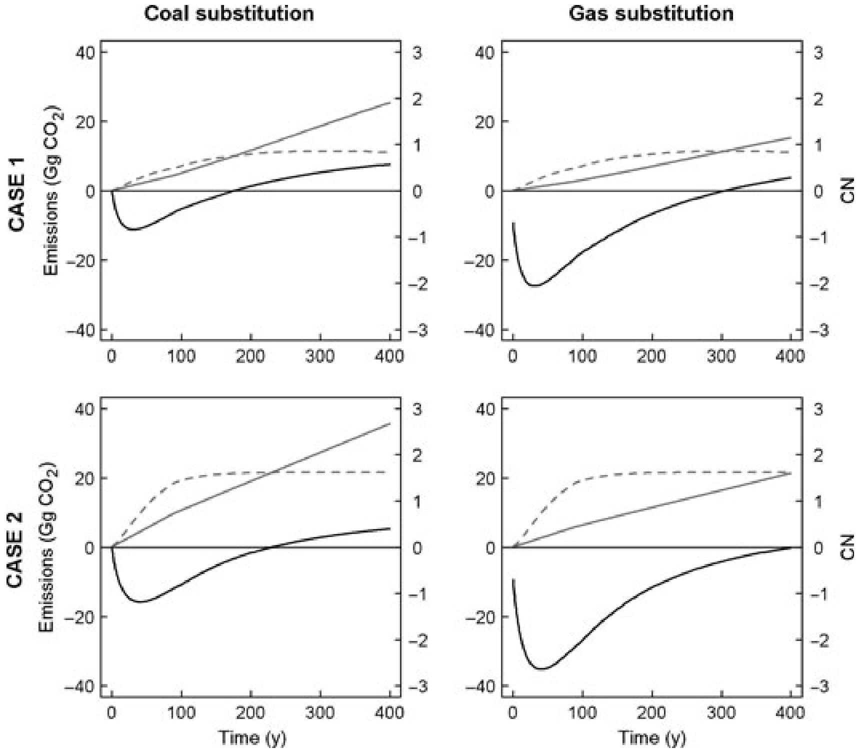

Fig. 4 Consumption emissions due to biomass use from additional fellings (dashed, gray line) compared to consumption emissions from use of an equivalent amount of fossil fuel (solid, gray line). The CN factor (black line, plotted on the secondary *y*-axis) shows when the consumption emissions due to change of forest management are higher (CN < 0) or lower (CN > 0) than the fossil fuel consumption emissions in the baseline. In Case 1, the final felling is increased from 60% to 80% of the net annual increment, which decreases over time, while in Case 2 the fellings are increased from 60% to 80% of the aboveground biomass in the harvested parcel. In each case, the graphs on the left represent bioenergy substituting coal, while the graphs on the right represent bioenergy substituting natural gas.

to continued use of fossil fuels only in the long term. In the short-to-medium term (20–50 years) relevant for current climate policies, additional fellings might result in more CO_2 emissions than continued use of fossil fuels.

The main reason of the initial negative values of CN is that not all the biomass affected by additional fellings is used for energy. In the illustrated cases, it is assumed that all residues from the additional fellings are left in the forest. Therefore, biomass such as roots and aboveground residues is left in the forest to decompose, resulting in a loss of C stock that does not contribute to substitution of fossil fuels. Under these circumstances, the bioenergy system is less efficient than the fossil fuel system. If the efficiency of biomass use is increased, that is, some portion of residues are used to produce energy instead of being left in the forest to decay, the period in which CN is negative is shortened. In Case 1, if the aboveground woody residues from the additional fellings are also removed to produce bioenergy, CN will be greater than zero after about 75 years instead of 175 years when coal is substituted and 200 years instead of 300 when natural gas is substituted.

This analysis does not take into account factors that could help maintain the total forest C stock unaffected under more intensive harvest regimes. Such factors could include management changes that improve the growth rate, such as fertilization, or lower disturbance risks from pests, storms and fires (Lindner *et al.*, 2008). Management strategies in European forests could also combine increased fellings for bioenergy in certain areas with afforestation and nature-oriented management in others. The result would be a compensation of C losses in intensified management areas by an increase of stocks in other areas (Nabuurs *et al.*, 2006).

Felling residues

One possible strategy to increase the biomass available for bioenergy is to collect forest residues usually left in the forest after harvest. Depending on the site, a certain amount of residues can be extracted without compromising soil fertility and therefore forest production

(EEA, 2006). If this amount of residues is utilized for bioenergy, emissions due to the management change are limited to the C stock changes in the dead wood, litter and soil pools (Schlamadinger *et al.*, 1995; Palosuo *et al.*, 2001; Repo *et al.*, 2011).

When residues are left on the forest floor, they gradually decompose. Most of the C contained in their biomass is released over time into the atmosphere, but a small fraction is transformed into humus and soil carbon. Thus, when residues are burnt for bioenergy, carbon that would have been gradually released from the dead wood and litter pools as well as carbon that would have been stored in the soil is released immediately to the atmosphere. This produces a short term decrease of the dead wood and litter pools that is later translated into a decrease of soil carbon.

In our example of a spruce forest, woody residues previously left on the forest floor at the end of the rotation period are collected to produce bioenergy that substitutes for fossil fuel. In the baseline scenario, 75% of aboveground biomass from fellings is used for forest products while the remaining 25% is left in the forest. According to allometric equations by Wirth *et al.* (2004), foliage accounts for an average of 11% of the aboveground biomass over a 90 year rotation period. It is assumed that the foliage is left is the forest in the bioenergy scenario to avoid loss of soil fertility. As a result, in the bioenergy scenario 14% of aboveground biomass left from felling operations (about 33 t ha^{-1} yr^{-1}) is removed to produce energy.

In this case, bioenergy starts to produce a benefit from almost the beginning when coal is replaced (Fig. 5). At time 0 the consumption emissions due to use of the biomass equals the loss of C in the litter. Since an equal stock of fossil fuel is replaced, biomass consumption emissions are equal to the fossil fuel consumption emissions and the CN factor starts at 0. In the cases where bioenergy substitutes for oil and natural gas, it takes few years before bioenergy starts to produce some benefits compared to fossil fuels, 7 and 16 years respectively. With time the soil and litter C pools tends to reach a new equilibrium – lower than in the baseline – while substitution of fossil fuel continues at a steady level. As a result, use of residues tends asymptotically toward 100% reductions compared to use of fossil fuels over time.

The results show that after 30 years the CN factor is about 0.6 in case of coal substitution and 0.3 in case of natural gas. This can be interpreted as meaning that use of biomass results in 60% or 30% less consumption emissions than use of fossil fuel by this point in time. In the case where coal is replaced, this could be correctly reflected in accounting by multiplying 60% of the bioenergy emissions by zero and assigning their full value (i.e., multiplying these CO_2 emissions by '1') to the other 40%. After 100 years, the CN factor is 0.76–0.85, that is, bioenergy from residues produces only 15–24% of the emissions that would have resulted from use of coal or natural gas, respectively.

Other authors have come to similar conclusions. (Schlamadinger *et al.*, 1995; Palosuo *et al.*, 2001; Repo *et al.*, 2011). Differences between their results and the results presented in this paper are a consequence of the different assumptions regarding management regimes and decomposition rates. As stated previously, this case study is based on data relevant to a Spruce forest in the Austrian Alps. Decomposition rates vary substantially for forests in other regions as well as by litter type. A review of litter decomposition rates shows that they increase with precipitation and temperature and are lower for coarse dead wood than for fine litter (Zhang *et al.*, 2008). When the residues are coarse dead wood

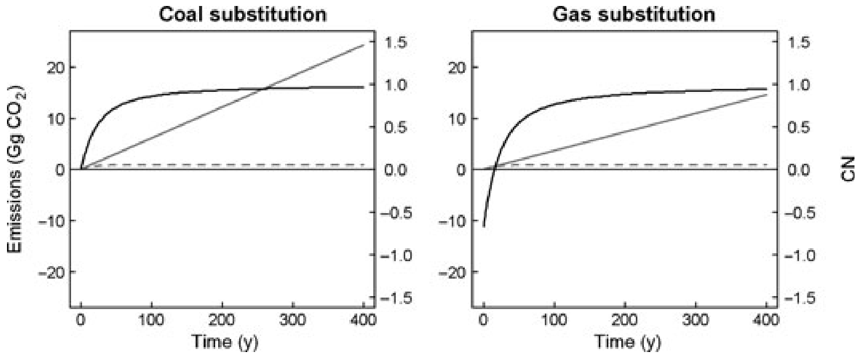

Fig. 5 Consumption emissions from the use of felling residues for energy (dashed, gray line) compared to consumption emissions from use of equivalent amount of fossil fuel (solid, gray, line). The carbon neutrality factor (CN, black line plotted on the secondary *y*-axis) shows to which extent bioenergy from residues produce greenhouse gas (GHG) emission reductions compared to fossil fuels. The graph on the left represents bioenergy substituting coal, while the graph on the right represents bioenergy substituting natural gas.

such as stumps, only a small fraction of the C decomposes in the forest within a year, for example, 0.05 yr^{-1} for coarse dead wood (Palosuo *et al.*, 2001). The rest remains as a C pool in the forest. When the stumps are removed and used for energy, their slower decomposition pattern must be taken into account. As a consequence, the CN of stumps used for bioenergy is likely to be significantly lower than CN values for fast decomposing residues after the same periods of time. Repo *et al.* (2011) report, for example, that emissions – production chain emission included – are 79% lower after 100 years of producing energy from combustion of branches instead of coal whereas emissions after 100 years are only 58% lower if stumps are combusted.

New plantations

Research studies show that marginal agricultural areas and degraded land could be used for afforestation or to grow energy crops, including short rotation plantations. Utilization of these areas for bioenergy has been advocated to reduce the risk of bioenergy competing with food demand and could contribute to rural development (Lu *et al.*, 2009; Mangoyana, 2009). It was estimated that 4.3 Mha in the EU-27 have been set-aside or fallowed as a result of incentives. An additional 4.2 Mha are fallow without subsidies. If 35% of the area under incentives were put to use, 1.5 Mha of new forests or short rotation plantations could be used to produce bioenergy (Hetsch, 2008).

Establishing new bioenergy plantations on lands with low initial C stocks, such as marginal agricultural land, has the clearest advantages in terms of emission reductions. Such plantations consist of C stocks accumulated above those in the baseline, when the baseline is a situation in which land remains marginal agricultural land. Under these conditions, the C stock accumulated in the plantations in the bioenergy scenario represents removals of CO_2 from the atmosphere additional to those in the baseline. Therefore, when the accumulated carbon is burnt to produce energy, the C stock returns to levels similar to those in the baseline and in addition there is has a benefit from reduction of emissions from fossil fuels.

However, as plantations can be established not only on fallow lands or cropland but also on forested lands, plantations can produce either positive or negative C stock changes during land conversion. In each case, the changes of C stock entailed in the land conversion must be included in calculations.

Three cases are considered below: a case where land with a low C stock, such as marginal agricultural land, is converted to a tree plantation and two cases where a forest is cleared and replaced with a plantation. In all the cases it is assumed that the C stock in the baseline (marginal agricultural land or forest) would have remained constant.

In Case A, where marginal agricultural land is converted, on site C losses are limited to soil C losses linked to site preparation. The temporary decrease of soil C stock, if any, is very soon recovered and followed by a net increase of soil carbon due to higher litter inputs from trees than from crops (Guo & Gifford, 2002). Aboveground and belowground live biomass stock is also higher in the tree plantations than in agricultural land.

The combination of the increased C stocks and the use of bioenergy leads to CN factors >1. In the beginning the CN is much >1 because the sequestered carbon is much greater than the emissions from the fossil fuel system that is substituted. However, the initial sink tends to a constant value while the cumulative emissions from fossil fuels in the baseline scenario constantly increase. As a consequence, the CN approaches 1, independently of which fossil fuel is substituted (Fig. 6, Case A).

If a forest area is clear cut and replaced by a tree plantation, the CN factor follows a significantly different trajectory. The CN factor will rise above zero only when the cumulative emissions from the conversion – including changes in the litter, soil and wood products' pools – are less than the cumulative fossil fuel emissions in the baseline case.

In Fig. 6, two further cases are illustrated in which bioenergy plantations replace a forest. In both cases it is assumed that about 50% of the wood extracted from the cleared forest is used for producing bioenergy and the rest for producing harvested wood products (HWPs) additional to the baseline. The aboveground biomass in the cleared forest is equal to 200 t d.m. ha^{-1}. We consider that the forest is replaced by a high productivity plantation of 10 year rotation period (Case B) and a low productivity plantation of 20 year rotation period (Case C). In both cases the new plantation is dedicated to bioenergy production that starts at the end of the first rotation period (10 or 20 years) and continues constantly on an annual basis. The aboveground biomass at the end of the rotation period is about 75 t ha^{-1} when productivity is low and about 160 t ha^{-1} when productivity is high (fast growing species).

In Case B, the initial C loss due to removal of existing forest biomass is repaid before the end of the second rotation period, or 17 years after the forest clear-cut when coal is replaced. After this initial period, the CN increases rapidly to 0.5 at 30 years after conversion and to about 0.9 after 100 years. The pay-back time is a bit longer when oil or gas is replaced, 20 and 25 year respectively. However, when

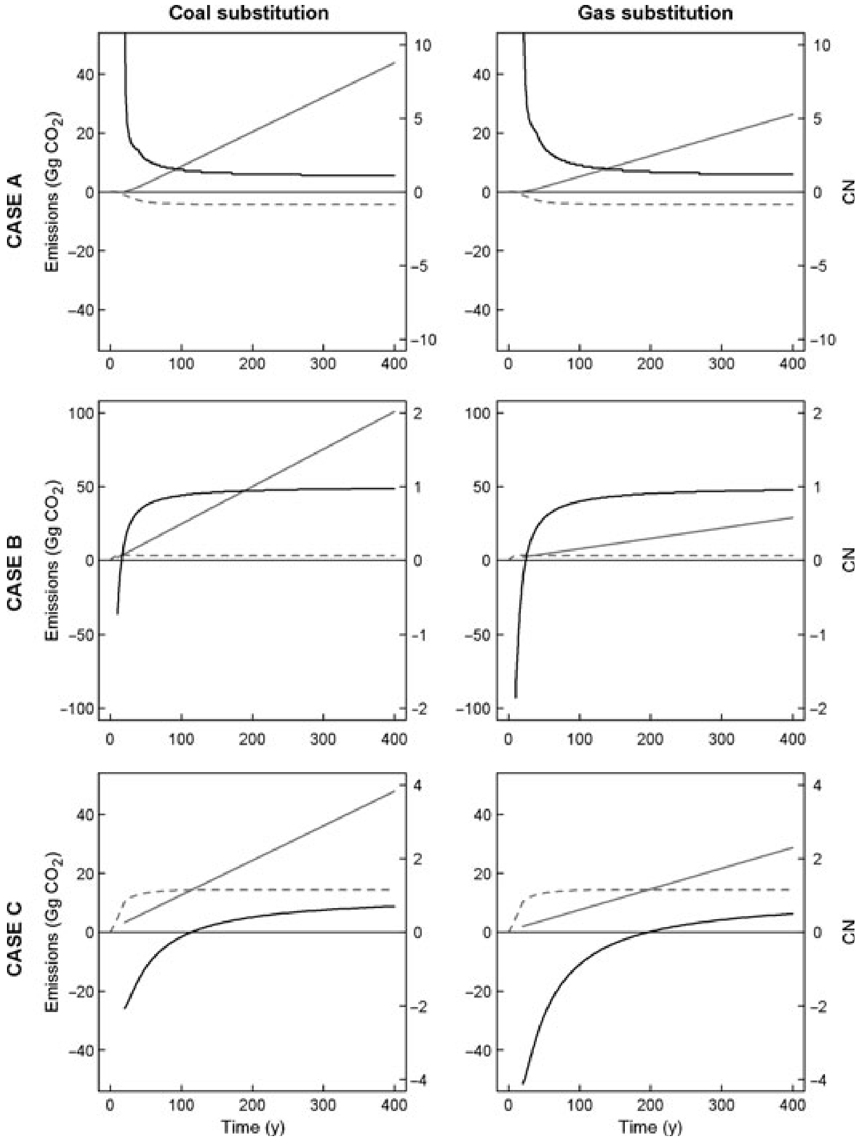

Fig. 6 Biomass consumption emissions from a new bioenergy plantation (dashed, gray line) compared to consumption emissions from substituted fossil fuel (solid, gray, line). In Case A, the plantation is established on marginal agricultural land and it produces a net C sink, resulting in a CN > 1 (black line, plotted on the secondary *y*-axis). In Case B and C, the new bioenergy plantation replaces a forest. Case B illustrates the establishment of a high productivity plantation, while Case C of a low productivity plantation. When the initial C loss is less than the cumulative fossil fuel emissions in the baseline case, CN > 0 and bioenergy starts producing emission reductions. In each case, the graphs on the left represent bioenergy substituting coal, while the graphs on the right represent bioenergy substituting natural gas.

HWPs from the cleared forest are long-lived products, the period in which bioenergy produces more emissions than fossil fuel is shortened because there is initially a smaller reduction in C stocks. In this case, the CN becomes greater than zero from the beginning when coal is substituted for and after an 8-year period if gas is replaced.

When productivity is low (Case C) it can take long periods to repay the initial C loss through fossil fuel substitution, because the amount of wood produced for fuel is relatively small compared to the initial C loss from the ecosystem. In the analyzed case, it takes almost six rotation periods to pay back the carbon lost from the ecosystem when coal is replaced (114 years). The payback time increases to 145 and 197 years, respectively, when oil and gas are replaced. In this case, the inclusion of long-lived products has no influence on the length of the payback time, because the contribution of the HWP stock to lowering the C stock decrease is not enough to compensate for the initial loss.

Results are strongly influenced by the assumptions made. If a forest with higher C stocks were converted to a plantation, the period needed to compensate for the biomass C loss is longer. The use of the biomass from the cleared forest can also have a strong influence on results. For instance, if the pre-existing forest is cleared with fire rather than harvested and used for a combination of bioenergy and HWPs, the payback times can be much longer. Altering the rotation period of plantations will also influence results. If, for example, the net annual increment is increased by decreasing the rotation period, the compensation period is shorter. Baseline assumptions can also influence the results. For instance, if marginal land in Case A would be afforested in the baseline instead of remaining agricultural land, emissions due to the loss of a potential forest would have to be taken into account.

This analysis can also be applied to indirect land use change to the extent that the indirect land use change connected to a new plantation can be identified. If new plantations are established on agricultural land and crops are displaced onto forest land, the effect is similar to a direct replacement of forest with bioenergy plantations.

Discussion and conclusions

The case studies presented in this paper are illustrative examples of different sources of woody biomass for bioenergy. These illustrative examples show that the capability of woody biomass to reduce the anthropogenic emissions in the atmosphere compared to continued use of fossil fuel vary widely depending on the source of biomass that is utilized and time horizon considered.

The paper also points out that the impact of consumption emissions varies substantially according to the assumptions made. Some of the key assumptions that influence the development of CN of woody bioenergy over time are: the productivity of stands; the extent to which management practices are changed (e.g., rotation period, change of harvest intensity); the previous land use; and baseline assumptions. In addition, the proportion of felled biomass that is used for bioenergy strongly influences the results. By increasing the amount of biomass that is used for energy, the period in which bioenergy produces more emissions than fossil fuel (CN > 0) is shortened.

It should also be kept in mind that a number of other factors contributing to consumption emissions were not included in this study. First, the illustrated case studies do not take into account the effect of natural disturbances on the forest C stocks. However, more intensive forest management regimes might reduce the risk of disturbances (Lindner *et al.*, 2008; Seidl *et al.*, 2008). Aging of forests is a current trend in some European regions and the older the forests, the higher is the risk of disturbances such as pests, windthrows and forest fires. Thus, it remains an open question whether it is a better strategy to store carbon in aging forests, while possibly increasing the risk of abrupt C stock losses, or to use these stocks to produce energy. Forest models that include projections of disturbance risks could help to better identify the trade-offs between C sequestration and bioenergy use and provide a more realistic assessment of the time horizons at which bioenergy would offer benefits over use of fossil fuels.

Second, climate change could affect both forest growth rates and natural disturbance risk and change results. However, climate change would have an influence on forest C stocks both in the bioenergy and the fossil fuel scenario and therefore the difference between the two scenarios might not be so relevant.

Third, as indicated in the Method section, the figures reported in this study do not take into account the emissions in the production chain and their effect on the overall mitigation potential of bioenergy. To serve as the basis for decision-making, comprehensive GHG emission profiles which include production chain emissions both in the bioenergy and the fossil fuel systems are needed.

Additional factors have to be taken into account when biomass is diverted from pulp, paper and other forest products to energy. Diversion from other uses might occur because of competition for biomass under increased demand for renewable energy (COM, 2008). First, when the biomass is used for energy rather than for HWPs such as paper and solidwood products, the saved emissions from replaced fossil fuels have to be compared to the loss of C stock in HWPs. Longer time frames are usually needed to produce the same amount of GHG benefits if wood is diverted from solidwood products to bioenergy, because of their longer life-time compared to paper products. Second, if wood is diverted from other uses, it is likely that these uses will be met either through other materials or by importing biomass from other countries. This raises the question of the emissions caused by use of other materials or by imports for paper, furniture or building. For a true picture of whether it is better to use woody biomass for products or bioenergy, all these emissions need to be assessed.

The strong influence of assumptions made and of the variability of conditions suggests that additional research is needed to allow drawing more realistic conclusions regarding the impact of consumption emissions on bioenergy GHG profiles. In particular, more in-depth analysis which includes all representative feedstocks and management regimes within a region or a country, natural disturbances and indirect effects on C stocks in other parts of the world is needed. By accounting for these factors, the impact of consumption emissions on the overall GHG profile could be smaller or greater than in the results presented here.

However, in agreement with other recent studies (Walker *et al*., 2010; Cherubini *et al*., 2011a; McKechnie *et al*., 2011; Repo *et al*., 2011), this study shows that the assumption that bioenergy always results in zero GHG emissions compared to continued use of fossil fuels, that is, that all biomass is carbon neutral, regardless of the time horizon considered is incorrect. Consequently, the current accounting approach in which no emissions are attributed to combustion of biomass is misleading in the context of the target compliance dates. While it is clear that all sources of woody bioenergy from sustainably managed forests will produce emission reductions in the long term, different bioenergy sources have various impacts in the short-medium term. Therefore, some sources of wood for bioenergy might make no contribution to reducing GHG emissions within the time frame of climate mitigation policies, whereas other sources may have this potential. The study shows that the use of forest residues that are easily decomposable can produce GHG benefits from the beginning of their use and that biomass from dedicated plantations that do not cause significant C stock losses through their establishment can be carbon neutral. On the other hand, the risk of short-to-medium term negative impacts is high when additional fellings are extracted to produce bioenergy and the proportion of felled biomass that is used for bioenergy is low, or when conversion of land to bioenergy plantations results in significant losses of C stocks.

The method used in this study allows tracing a time dependent GHG profile of bioenergy that highlights different impacts over time. Such a method provides an instrument to support the energy sources that are the most beneficial for GHG emission reduction according to time-dependent goals.

It is also shown that the concept of sustainable management does not always correspond to a concept of carbon neutrality. Biomass extracted from forests in which harvest is less than the net annual increment can still result in more GHG emissions than an alternative energy source within near-to-medium time horizons.

This study encourages further research to provide improved and comprehensive assessments of the mitigation potential of different bioenergy sources in comparison with continued use of fossil fuels. It also suggests that current accounting systems are not reflecting the impact that woody bioenergy can have on the atmosphere in the short-medium term.

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Disclaimer

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