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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 CO₂ 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 CO₂ 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, CO₂ removal is assumed to occur via bioenergy combined with technology to capture and store CO₂ bioenergy (known as 'bioenergy with CO₂ 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 CO₂ 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

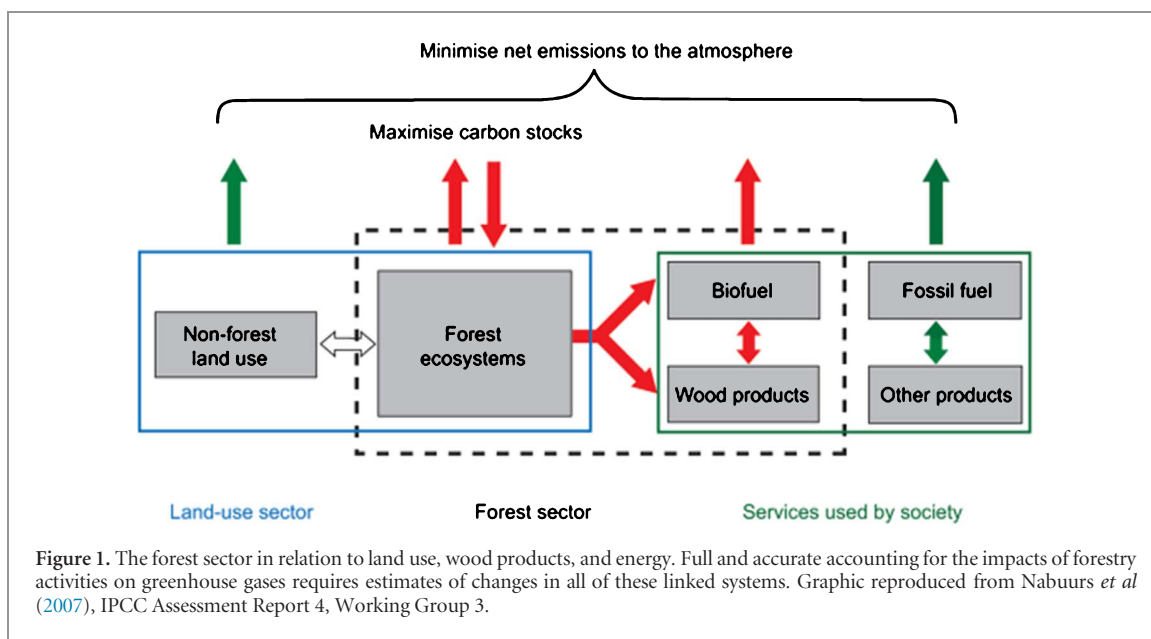


Figure 1. The forest sector in relation to land use, wood products, and energy. Full and accurate accounting for the impacts of forestry activities on greenhouse gases requires estimates of changes in all of these linked systems. Graphic reproduced from Nabuurs *et al* (2007), IPCC Assessment Report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

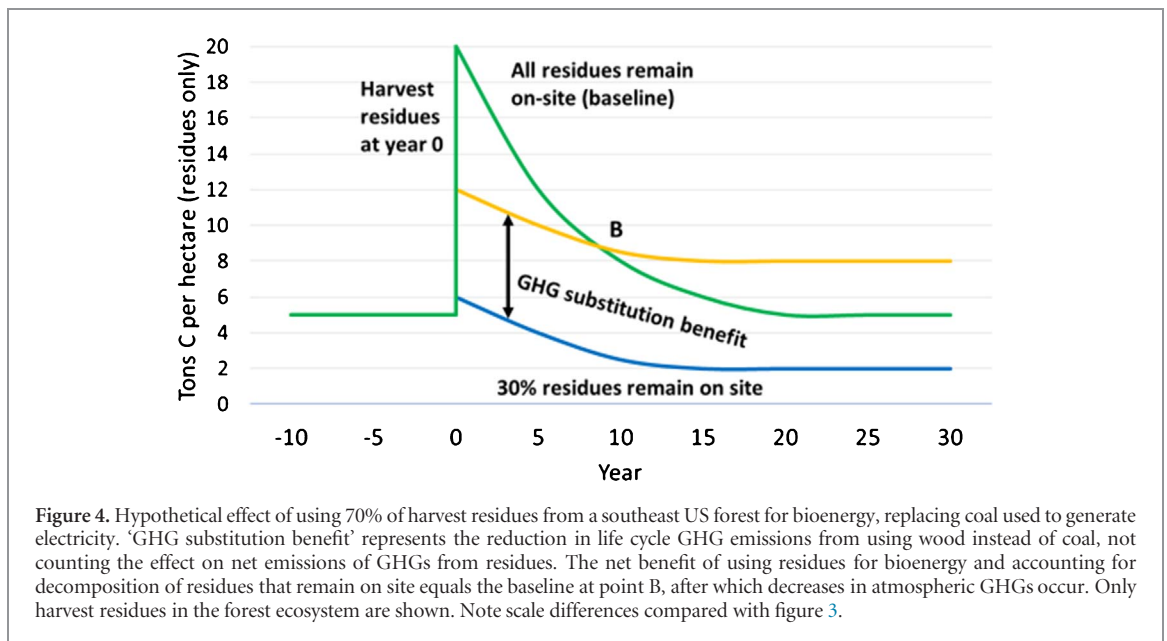
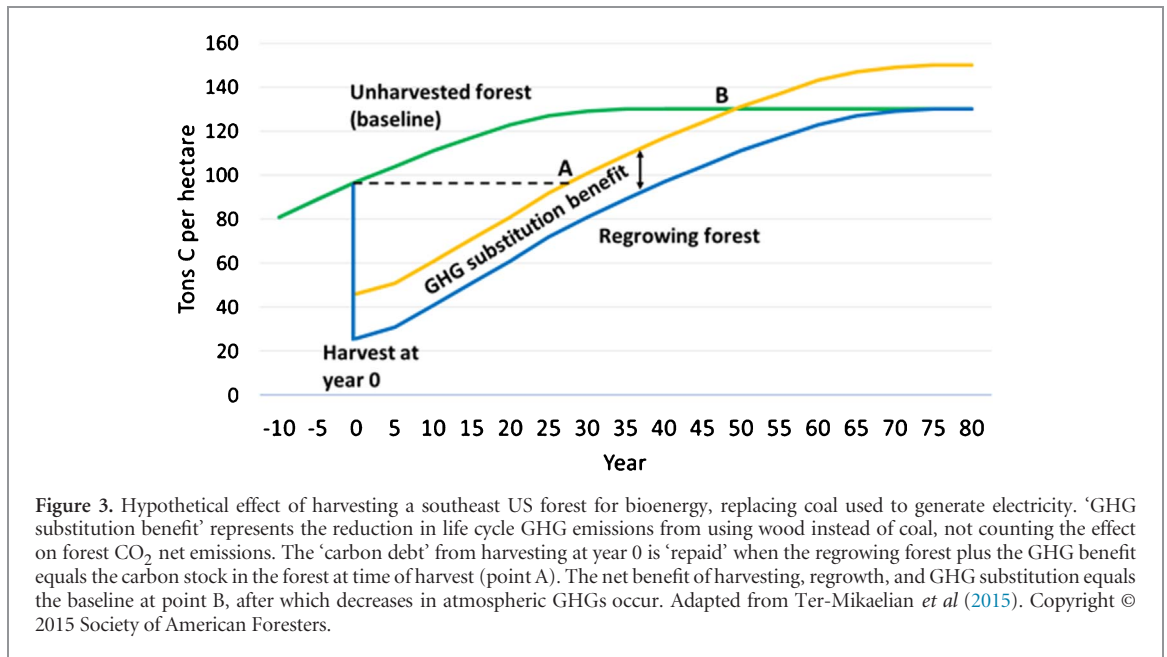
Accounting element	Definition
1. Forest ecosystem	Net change in CO ₂ emissions (sources + sinks) of the baseline (no removal of biomass) or from the activity (removal of live or dead biomass for fuel)
+	
2. Supply chain	CO ₂ emissions from harvesting, transporting, and processing wood biomass for use 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 CO₂ 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 CO₂ (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).



If harvesting live trees for bioenergy, the loss of stored biomass has been considered a ‘carbon debt’ that needs to be re-paid, and the ‘carbon payback period’ is the time required to recover the CO₂ 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 CO₂ 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-Mikaelian *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 CO₂. 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 CO₂ emissions per unit of energy produced (Environmental Protection Agency 2014). For example, emissions of CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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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