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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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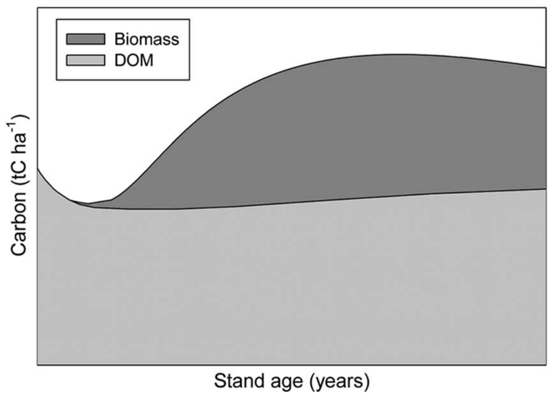

Figure 1. Typical change in forest carbon stocks after stand harvest (modified from Ter-Mikaelian et al. 2014a). Dark and light gray areas represent carbon stocks in live biomass and dead organic matter (DOM), respectively.

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.

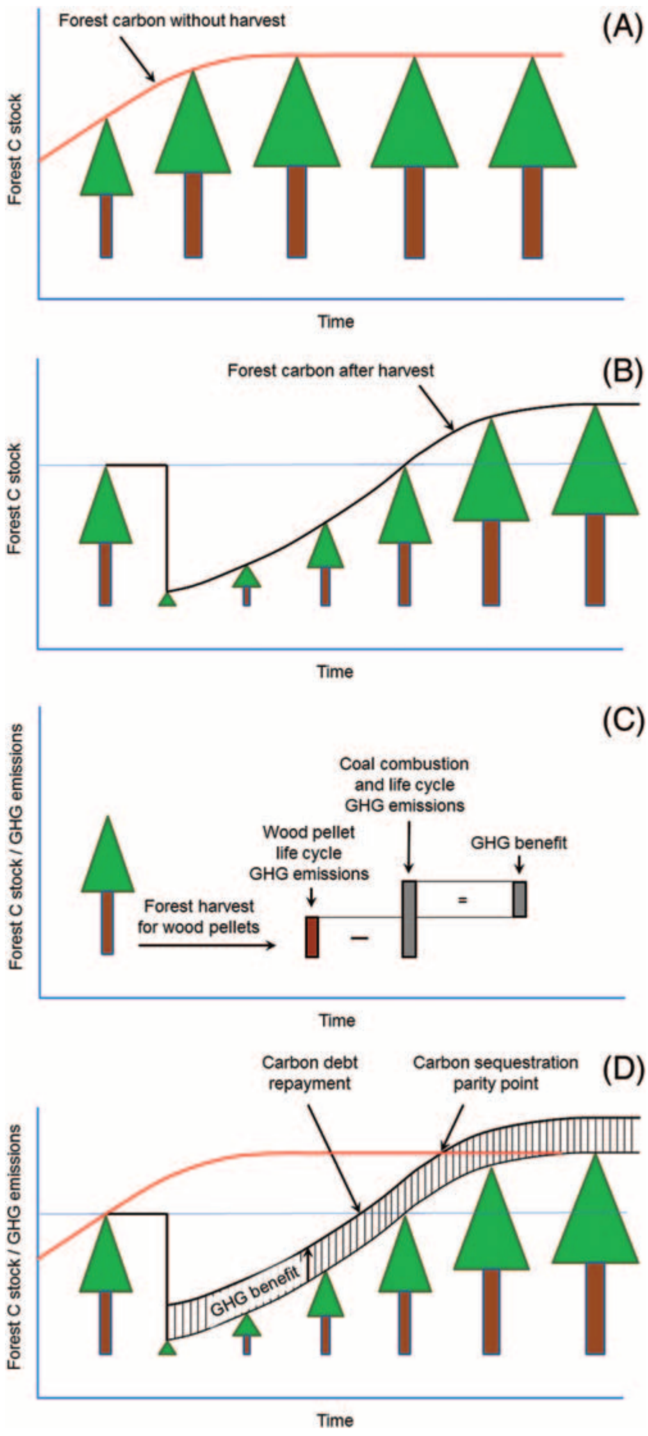

Figure 2. Effect of harvest for bioenergy used to replace coal on forest carbon stock changes and total greenhouse gas (GHG) emissions (stand level, from Ter-Mikaelian et al. 2014b). A. Accumulation of carbon in an unharvested forest stand. B. Carbon in the stand regenerating after harvest. C. Harvested 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

$$\text{Total GHG emissions} = \text{Change in forest carbon stocks} + \text{GHG benefit of replacing fossil fuel with forest bioenergy} \quad (1)$$

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).

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.

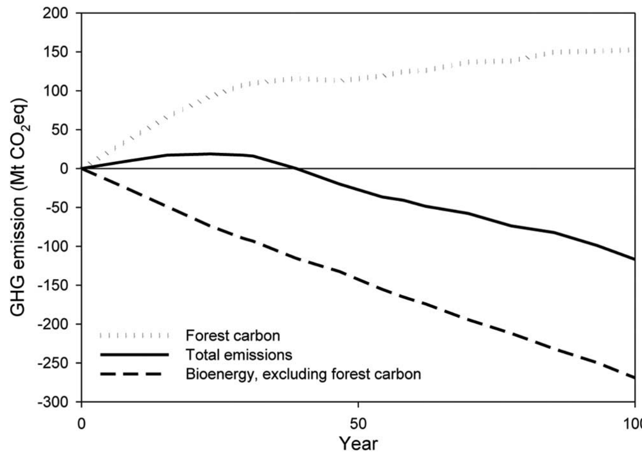

Figure 3. Changes in forest landscape carbon stocks (dotted line), cumulative total GHG emissions (solid line), and GHG benefits (dashed line) from displacing coal with bioenergy generated from harvest of standing live trees (modified from McKechnie et al. 2011). Positive values correspond to emissions, whereas negative values show removals (sequestration) of carbon from the atmosphere.

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 broadscale 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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