Life-Cycle Carbon from Waste Wood Used in District Heating and Other Alternatives

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Abstract

Using wood wastes provides an opportunity to avoid fossil carbon emissions from the combustion of natural gas or other fossil fuels. Using a life-cycle assessment, a new biomass boiler sourced by forest residuals, sawmill residuals, and clean demolition material (CDM) was compared with an existing natural gas boiler for supplying heat to a large-scale district heating system. Potential alternative uses of these feedstocks, such as recycled or reprocessed products, and landfill alternatives were also evaluated for their relative impact on carbon emissions. We found a reduction in emissions from natural gas of 0.62 unit of carbon for every unit of carbon in the wood combusted. Temporary losses of forest carbon after initiating the collection of forest residuals were minimal over a short interval. These losses were more than offset by the joint production of wood products displacing fossil emissions. Carbon mitigation in the Pacific Northwest was increased from 5.5 metric tons/ha/y from the production of forest products with no collection of forest residuals to 6.5 metric tons/ha/y after completing the first rotation, an 18 percent reduction in fossil emissions per hectare of forest. The potential to recycle CDM into wood products may ultimately raise the efficiency in avoiding carbon emissions by 40 to 60 percent, although available wood quality and logistics currently favor use of CDM as biofuel feedstock. In the absence of any ''incentives'' or value for carbon mitigation, feedstock collection costs relative to low-cost fossil fuel will substantially limit the use of waste woods for biofuel or recycling alternatives.

A broad, although not universal, agreement exists that releases of greenhouse gases from fossil fuels are warming our planet, which could potentially have serious environmental and social consequences (Intergovernmental Panel on Climate Change [IPCC] 2007a). Combustion of woody biomass has been considered to be carbon neutral, because the carbon absorbed from the atmosphere by tree growth is simply returned to the atmosphere upon combustion or forest decomposition when sustainable forest management is practiced (IPCC 2007b, Beauchemin and Tampier 2008, Fernholz et al. 2009, Malmsheimer et al. 2011). Under sustainable management, the rate of wood removed from the forest is not allowed to be greater than the rate of net forest growth. This two-way flow of carbon from the atmosphere, when using woody biomass for fuels, displaces the one-way flow of fossil carbon from ancient, deep pools to the atmosphere.

Some studies have focused on biogenic carbon emissions at the time of combustion, suggesting that carbon must first be absorbed during new tree growth before the bioenergy from that tree contributes to reducing emissions (Manomet Center for Conservation Sciences [MCCS] 2010, Biomass Energy and Research Center [BERC] 2012). As the demand for biofuels increases, other concerns have been raised about reductions in forest carbon as a consequence of excessive removals (Schulze et al. 2012). On the other hand, biomass resources have been reported to be largely underutilized for the production of fuels (Gan and Smith 2006, US Department of Energy 2011). In spite of some loss of forestland to urban development, forest inventory information shows growth greater than removal in all US regions and potential growth per acre substantially greater than current growth (US Department of Agriculture [USDA] 2011). Greater rates of wood accumulation through forest growth compared with rates of wood removal from harvest

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and all other activities (USDA 2011) suggest that opportunities exist to displace fossil-intensive products and fuels by using more wood, not just in the Pacific Coast region, the focus of the present article, but in other regions as well. In the Pacific Coast region, potential growth exceeds current growth by more that 60 percent, whereas current growth exceeds removal by more than 50 percent. A biomass assessment for Washington State (Jamison et al. 2012) estimated that a volume of forest residuals equivalent to 40 percent of the volume of merchantable logs could be considered potentially marketable with favorable prices. Pre-existing woody material (dead trees and downed material) varied widely but could still provide additional biomass volume for bioenergy use.

The burning of wood residue in boilers for heat generation has historically been restricted to those industries in which biomass or ''hogged fuel'' is readily available as a by-product, primarily in the forest products industry. Converting boilers from fossil fuels to renewable biomass is relatively new. The Seattle Steam Company (SSC) has recently installed a biomass boiler to substantially reduce its use of natural gas (NG) and carbon emissions. The SSC is using a mix of purchased mill residuals, forest residuals, and clean demolition material (CDM) as biofuel feedstock. Concerns have been raised about the effectiveness of its use of waste wood relative to other potential uses, providing a useful case study to evaluate the impact of alternative uses for different waste wood biofuel feedstocks.

Quantifying Carbon

Life-cycle measures

Life-cycle assessment (LCA) is necessary to compare the impacts of using wood waste as a biofuel feedstock to displace NG. Although standards for life-cycle studies exist (International Organization for Standardization [ISO] 2006), different approaches have been taken for quantifying carbon changes in the forest, leading to different conclusions. Bird et al. (2011), Cherubini et al. (2011), Helin et al. (2012), and Guest et al. (2013) concluded that forest growth and forest residual decomposition must be considered when quantifying changes in forest carbon based on a 100-year-rotation boreal forest. However, these studies did not consider the impact of phasing in such a strategy over a uniformly aged forest (made up of stands at each age class from 0 to 100 y). Under sustainable management, forests are restored annually to the same mixture of stand conditions as existed during the previous year. When the management strategy changes, such as with the introduction of collecting forest residuals that were previously left to decompose, a change in forest carbon also occurs, progressing across the rotation as more and more wood is removed and the previous forest residuals are collected to displace fossil fuels. To fully account for the carbon transitions, a forest landscape with stands at every age class must be considered in the model.

Efficiency measures for reducing fossil carbon emissions

Use of wood products to substitute for different nonwood products, such as steel and concrete building materials, has a substantial range of impacts on carbon mitigation. A meta-analysis of published wood product substitution studies averaged 2.1 units of carbon (C; or CO_2) reduced for every unit of C (or CO_2) in the wood used (i.e., 2.1 C:C; Sathre and O'Connor 2010). This provides an average efficiency metric when wood products substitute for more fossil-intensive nonwood products. The impact of introducing the production of biofuels derived from the joint production with wood products introduces a strategic management alternative to displace even more carbon emissions while increasing forest removals. Emission reductions from the use of biofuels to displace fossil fuels is much lower than that for products, ranging from 0.4 to 0.7 (C:C) for a range of biofuels displacing NG or gasoline (Lippke et al. 2012). Concerns have been raised that biofuel use may not displace more emissions than they produce.

Biofuel Feedstock Alternatives

Mill residues

Forest management is designed to produce wood useful for the production of long- and short-lived wood products. Most sawmill residues from industrial lumber-processing facilities have been used for many years in heat generation to reduce the cost of drying lumber or other solid-wood products (Milota et al. 2005, Puettmann et al. 2010). At these sawmills, wood residues are practically a ''no-cost'' energy source. The cost to sawmills for disposal would likely be larger than the cost of using the waste to produce energy at the sawmill. Small-scale and secondary manufacturing plants closer to metropolitan centers or sawmills cutting only for green lumber may not be able to effectively use their residues but can dispose of them to other users within a competitive hauling distance. A market, albeit at a low price, can exist for residues that are effectively a waste to the producer of wood products. Sawmill residues may be suitable for mulch or biofuel feedstock. The carbon emission impacts when producing biofuels are largely limited to the collection and preparation of the waste (transport, loading, and any preprocessing), with the opportunity to displace fossil fuel emissions.

Clean demolition material

Woody feedstocks that have other valuable uses or may have environmental advantages over use as a biofuel need careful consideration in such trade-offs. CDM could potentially be recycled directly into wood products, reprocessed into composite building panels, collected for biofuel feedstock, or landfilled with or without fuel recovery. Oriented strandboard (OSB) provides a large-volume product used in composite structural panels that can be produced from reprocessing wood as well as other fiberboards, although because of the high use of resins, reprocessing may require three times more energy than the production of lumber products. Composite panels have a higher carbon displacement value than use of the biomass for biofuel and may result in a price premium for collecting CDM over use as a biofuel. Notably, CDM can extend the life of the carbon that has been stored in a product for a considerable period of time (Winistorfer et al. 2005). Forest residuals and even disposal in the landfill raise more complex carbon trade-offs and are evaluated in more detail.

Collection of forest residuals as a biofuel feedstock

There are many underutilized wood waste streams, such as waste piles after harvesting (forest residuals) and precommercial thinnings. By collecting forest residuals for conversion to fuels, another marketable product is produced from the forest that displaces fossil fuels but decreases forest carbon. The availability of forest residuals that might be collectable for biofuel feedstocks was taken from a recent study for the Washington Department of Natural Resources (Jamison et al. 2012). The study showed that forest residuals were equivalent in volume to 59 percent of the merchantable logs processed for solid wood products, with 40 percent collected and moved to the log landing. Less than 20 percent of this volume is currently being used. The report also noted that with higher prices or incentives that increase carbon values or fossil fuel prices, most of these residuals could be collected for use in biofuels.

Previous economic modeling suggests that it will take a significant increase in the value of carbon (about 3%/y for 100 y) to significantly reduce the rate of carbon accumulation in the atmosphere (Nordhaus 2007). If and when the value of carbon increases, it is projected to substantially change the motivation to use wood and wood wastes to displace nonwood products and fuels. The National Research Council (2011) also concluded that even with a crude oil price of US$111 per barrel, there is a price gap of over US$50 per dry ton that will have to be closed by incentives or even higher oil prices to reach federal targets for increased use of biofuels. We used the Jamison et al. (2012) estimate of collecting 40 percent of the forest residuals for our scenario to assess their impact on displacing NG emission, acknowledging that it represents future potential requiring higher carbon or fossil fuel prices.

The carbon in wood residuals left in the forest to decay may initially contain more carbon than the avoided fossil emissions from using them for energy production. While referred to as a forest carbon gap, in just a few years the carbon in the decaying residuals will fall below the carbon emissions avoided by burning it for energy. Others have suggested that the forest carbon must regrow before the stand can be considered as an offset to emissions from using the wood (MCCS 2010, Cherubini et al. 2011, BERC 2012, Helin et al. 2012, Guest et al. 2013). Ignoring the biogenic carbon absorption across a sustainably managed forest, but accounting for the carbon releases from the manufacture and use of wood products and biofuels from that forest, results in a critical error in carbon accounting under life-cycle thinking and could lead to false conclusions (Lippke et al. 2011).

While the prevailing practice in western Washington State involves piling and then burning forest residuals without recapturing any energy potential, not burning the piles provides temporary carbon storage in the forest. The practice of piling and burning is motivated by its contribution to better forest regeneration and the high cost of removing the biomass for use as a bioenergy feedstock. The practice of burning slash piles does not produce a forest carbon gap like that created by leaving the residuals in the forest; however, it does produce more methane emissions than burning wood waste in a controlled boiler for heat or power (Johnson et al. 2012).

Objective

The objective of this study was to evaluate life-cycle impacts for several different waste wood feedstocks used to provide heat to a localized business district and to evaluate other potentially competitive uses of the feedstock. The focus was on the permanency and timing of forest carbon as an area of concern. Other potential uses of woody feedstocks that were evaluated include recycling or reprocessing demolition wood that may eventually ‘‘compete’’ with using wood as a biofuel feedstock and landfill disposal options. This article is a companion to Puettmann and Lippke (2013), which documents the LCA of a district heating system using both woody biomass and NG.

Methods

Data sources

The SSC operates both NG and biomass direct fired boilers that produce heat for 200 buildings in the Seattle downtown business district. The SSC provided a direct source of measured data as the case study for comparing the environmental impacts of wood biofuels relative to NG using several wood waste streams as feedstock (Puettmann and Lippke 2013). The LCA models for the wood and NG boilers were developed using TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts; Bare 2011) with SimaPro 7 LCA software (PRé Consultants 2012). Life-cycle inventory (LCI) processes for US fuel and electricity production, including modes of transportation, were obtained from the US LCI Database (National Renewable Energy Laboratory 2012). Additional LCI data for jointly produced forest products and forest residual collection, CDM, and sawmill residual collection were obtained from Kline (2005), Milota et al. (2005), Perez-Garcia et al. (2005), and Johnson et al. (2012). Information regarding fuels used for electricity generation was obtained from Seattle City Light.

Each stage of LCI (e.g., fuel production, combustion, forest growth, biomass collection, and transportation) was tracked over time to reveal the differences between collection and use strategies (Lippke et al. 2011). Sawmill processing data were developed from primary surveys covering Pacific Northwest sawmill products and representative forest inventory data for the private sector (Johnson et al. 2005, Milota et al. 2005, Oneil et al. 2010) and projected forward using the Forest Vegetation Simulator growth model calibrated to the region (Wykoff 1986). The impact of a change in strategy to initiate collection of forest residuals was tracked across the harvesting of sustainable forest stands for each age class to and beyond completion of a rotation, thereby capturing both temporary and permanent changes in forest carbon and fossil fuel displacement.

The collection of forest residuals is unlikely to occur in the United States if not a part of a sustainably managed commercial harvest, which brings most of the nonmerchantable biomass material to log landings, thus lowering the cost of biofuel feedstock collection and transportation. Hence, we evaluate the biofuel impacts as a joint production process along with the carbon impacts from the removal of logs that are merchandised into lumber or other solid-wood products from successive forest rotations. Collection of forest residuals with the initial harvest and of CDM at the end of product life, estimated at 80 years for quality wood construction (Winistorfer et al. 2005), were assessed relative to the burning of discarded wood at the end of life or landfill disposal. Recycling or reprocessing CDM includes the transportation before softwood product manufacturing and mill residuals as shown within the boundaries of the analysis in Figure 1, but it does not involve the collection of forest residual biomass or any change in forest carbon.

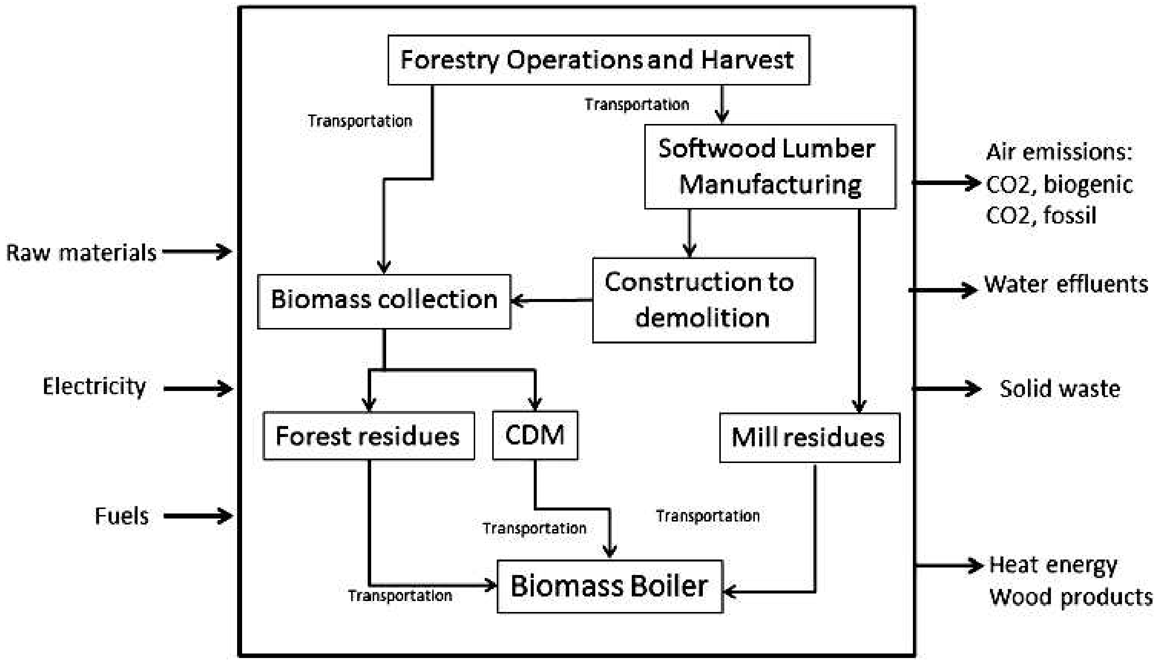

Figure 1.—Cradle-to-grave system boundary for feedstocks serving biomass boilers and alternative feedstock uses. CDM = clean demolition material.

We have primary LCI data from mill surveys for most all structural products as well as (LCI) data for particleboard, medium-density fiberboard, and resins (Johnson et al. 2005; Kline 2005; Milota et al. 2005; Wilson and Dancer 2005; Wilson and Sakimoto 2005; Wilson 2010a, 2010b, 2010c), but do not have data collected at the mill for recycled or reprocessed products. However, the primary data that we do have for producing lumber use process stages very similar to those for recycling CDM to lumber (Milota et al. 2005). Similarly, reprocessing CDM to OSB uses process steps very similar to those for producing OSB (Kline 2005). We use these data sources as proxies for fairly direct recycling or reprocessing of CDM.

Although the amount of carbon in the soil is significant, sustainable harvesting has not been found to reduce carbon (Johnson and Curtis 2001, Sterner and Elser 2002, Yanai et al. 2003, Cleveland and Liptzin 2007, Yang and Luo 2010) and therefore is not considered in the present analysis.

System boundaries

The cradle-to-grave system boundary for the production of heat generation from biomass includes upstream processes for each woody feedstock (forest residuals, mills residuals, and CDM; Fig. 1). Included within the boundaries is the joint production of merchantable wood products with biofuels. We internalize the use of pulp chips for their energy value in the same way that mill residuals produce heat for wood product manufacturing. We estimate the impact of solid waste to the landfill outside the boundary but then include the carbon impact for total carbon mitigation impacts.

GWP accounting

Tree growth, production of wood products and fuels, fuel combustion, and final disposal result in various fluxes of CO_2. The appropriate methodology for assessing these fluxes is the global warming potential (GWP). Values are factored to kilograms of CO_2 equivalents. GWP compares the amount of heat trapped by a certain mass of the gas in question to the amount of heat trapped by a similar mass of CO_2. GWP is an indicator that reflects the relative effect of greenhouse gases in terms of climate change. When linked to forest management alternatives, it is useful to convert from emission reductions to the carbon stored in the forest, stored in the products, or displaced fossil emissions.[1]

Carbon is emitted to the atmosphere as biogenic CO_2 or fossil CO_2 depending on the fuel combusted. All calculations for CO_2 absorption were based on 50 percent carbon content for dry woody feedstocks representative of the dominant softwood inventory near the SSC facility.

Scenarios considered

Eight scenarios were used to evaluate potential uses of woody feedstocks, such as recycling or reprocessing, that may ‘‘compete’’ with their use as biofuel feedstocks. A base-case comparison of the SSC biomass boiler emissions to the NG boiler system established the boiler conversion efficiency for these scenarios.

Base-case biomass and natural resource boiler GWP from heat production.—Puettmann and Lippke (2013) provided a comparison of the net GWP for annual heat production between the SSC design boiler and the existing NG boiler system (Table 1). This is used as the starting point for evaluating the impact of feedstock alternatives. The SSC's annual heat output of 1,329,075 GJ (1,259,723 MMBtu) produces 56 percent of the heat from the biomass and 44 percent from NG. The SSC biomass boiler blend of wood wastes (10% forest residuals, 55% sawmill residuals, and 35% CDM) is evaluated in more detail to show each feedstock's impact on forest carbon.

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[1] To convert from CO_2 to carbon, multiply CO_2 emissions by 0.273.

Table 1.—Net annual carbon emissions (global warming potential [GWP]), as metric tons of CO_2 (tCO_2) or metric tons of CO_2 equivalents (tCO_2e), for the production of 744,282 GJ of biomass heat.[a]

Boiler fuel	100% natural gas	56:44 biomass:natural gas (SSC)	Difference
tCO_2 absorbed from the atmosphere	−29	−93,700	−93,671
tCO_2e released	99,600	136,000	36,400
Net GWP emissions (tCO_2e)	99,500	42,300	−57,200
Wood displacement efficiency: fossil CO_2 displaced per CO_2 in wood used			0.62

[a] Seattle Steam Company (SSC) annual biomass production; 56 percent of their total energy production.

The biomass/NG boiler emits (cradle to grave) 136,000 metric tons of CO_2 equivalents (tCO_2e) annually, compared with 93,700 tCO_2 in the wood used, resulting in 42,300 tCO_2e net GWP (Table 1). To produce the same amount of heat energy as from 100 percent NG results in a release of 99,600 tCO_2e. Because the NG boiler stored only 29 tCO_2e, the net GWP was 99,500 tCO_2e, resulting in a 57 percent reduction in GWP from the 100 percent NG system. The efficiency of displacing NG is important and derived in Table 1 for the SSC design boiler system. This cradle-to-grave assessment showed an avoided emission rate of 0.62 CO_2 avoided per 1.0 CO_2 (0.62 C:C) in the woody feedstocks used, including the derived efficiency of the SSC biomass boiler.

Forest residual scenarios.—Two forest residual scenarios were used:

- Scenario 1: Sustainable management across a uniformly aged forest focusing only on the collection of forest residuals, not including merchantable logs. In this scenario, we introduce the collection of forest residuals from one harvest to the next across the first rotation displacing NG emissions compared with no collection. We include the impact of initiating the collection of residuals as well as the growth in stands not yet harvested and the decay in the forest residuals left from previous treatments assuming the residuals were not burned. The rate of forest residual decay varies with climatic conditions. There is generally minimal dead wood remaining at the end of a rotation, consistent with decay rates of 10 percent per year and a 1 percent residual over a 45-year Pacific Northwest rotation (Prescott 2010). We show three efficiencies of wood energy to characterize how efficiency changes the timing of how long it takes for the displaced NG to reduce emissions more than the carbon decomposing in previously uncollected forest residuals:

  a. Fossil emission displacement efficiency of 0.62 C:C (Puettmann and Lippke 2013),
  b. A high displacement efficiency of 0.75 C:C, typical of sawmill use of the forest residuals (Puettmann and Lippke 2012), and
  c. A low displacement efficiency of 0.4 C:C, such as when producing ethanol to displace gasoline (Budsberg et al. 2012, Daystar et al. 2012).

  Note that because the most common practice is burning the slash piles in the field, any carbon left in the slash that was not collected will be released by burning and hence will result in no change in forest carbon (i.e., no carbon gap if the collectable material was previously burned).
- Scenario 2: Sustainable trends beyond the introduction of collecting forest residuals to displace NG. This scenario includes displacement of fossil energy from the joint production of wood products using the meta-average impact of wood products substitution of 2.1 C:C and the displacement of NG from the collection of forest residuals (using the Scenario 1a conversion efficiency). The carbon gap analyzed in Scenario 1 produces a one-time reduction in forest carbon from the collection of forest residuals assuming that slash piles were not burned and their slow release of carbon from decomposition temporarily offsets some of the avoided NG emissions.

CDM scenarios.—Carbon is measured at the end of each rotation just before harvest when short-lived products and forest residuals are minimal. Six CDM scenarios were used:

- Scenario 3: Base-case products using the meta-average impact of wood products substitution and CDM burned (no recovery). This scenario provides a no waste-wood recovery base case.
- Scenario 4: Direct reuse of CDM with minimal reprocessing adding to wood products. This scenario provides a high recycling efficiency for reusing high-quality CDM in products.
- Scenario 5: Reprocessing CDM into composite wood panels. This scenario provides a relatively high recycling efficiency for somewhat lower-quality CDM but requires more energy for reprocessing.
- Scenario 6: CDM burned in a boiler. This scenario avoids the use of NG and its emissions and can process lower-grade CDM than required for the direct reuse or reprocessing alternatives.
- Scenario 7: CDM landfilled with gas recapture for energy. This scenario allows the CDM to decompose in the landfill, but the methane emissions are recaptured and used for energy. Estimates of the carbon emission reductions for disposal in the landfill depend heavily on conversion efficiency and recovery assumptions that remain uncertain (Barlaz 2006). We used the US Environmental Protection Agency (US EPA) decomposition rates in the landfill as reviewed by Skog (2008).
- Scenario 8: CDM landfilled with gas flared. This scenario allows the CDM to decompose in the landfill and be flared to convert the methane to less harmful CO_2 emissions.

Results

Scenario 1: Collecting forest residuals

Focusing on the use of forest residuals that otherwise might be left to decay in the forest versus the reduction in NG emissions, Figure 2 tracks the impact of such a change in strategy over time. Sensitivity to three displacement

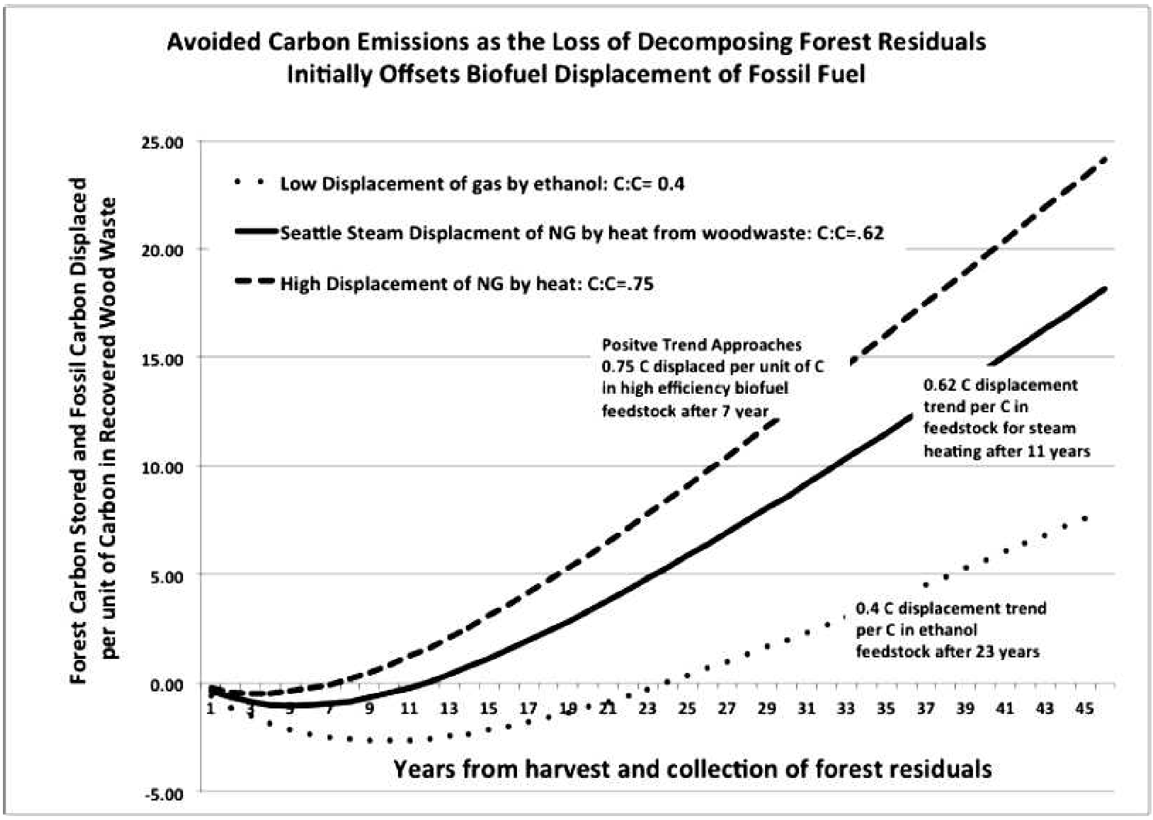

Figure 2.—Temporary loss in avoided carbon emissions from biofuels, a carbon gap when forest residuals that were not previously collected or burned exceed the carbon from displaced fossil energy. NG = natural gas.

efficiencies of 0.62, 0.75, and 0.4 C:C are shown over 45 years of residual collection after harvest.

The displaced NG does not provide an immediate, full offset for carbon that may have previously been left in the forest to decay, resulting in a temporary carbon gap until the NG emission displacement exceeds the decaying forest carbon residuals (Fig. 2). As sustainable harvesting progresses from stand to stand across a rotation, the natural decomposition in the forest residuals ultimately falls below the avoided fossil fuel emissions. The carbon gap is both small and short lived (approximately 11 y). Sensitivity analysis on other fuels from wood feedstocks showed a much lower displacement of gasoline emissions by use of ethanol from forest residuals, with a displacement rate of only 0.4 C:C (Fig. 2). With this lower displacement efficiency, the carbon gap is more significant, and it takes 23 years for the sustainable rate of carbon displacement to surpass the short-lived decay of forest residuals.

Scenario 2: Joint production of wood products and biofuels

Wood products and biofuel feedstock from the forest are generally joint products produced from the same hectare of land. Figure 3 simulates the temporary carbon gap across a 45-year forest rotation simultaneously with the impact of producing products that substitute for fossil-intensive products. Forest carbon decreases for several decades as collection of forest residuals is initiated with each harvest, but this is of little consequence compared with the emission reductions from wood products displacing nonwood construction products and the sustained growth in displaced fossil fuels.

The average carbon across the forest is reduced slightly from a change in strategy to remove forest residuals rather than leaving them to decompose. Once the forest residuals have decayed, the forest carbon remains stable as the harvest moves from one stand to another, and the sustainable trend of avoided fossil emissions from the production of the biofuel and wood products continues. Noteworthy in Figure 3 is the large amount of carbon displaced by solid wood products relative to the fossil fuel avoidance from the use of biofuel. Hence, no temporary carbon gap occurs with joint production. The production of woody biofuels, in this case from the collection of 40 percent of waste residuals, contributes approximately 10 percent to the emission reductions from solid wood products given the lower efficiency of conversion from biofuel versus wood products. The end of solid wood product life after approximately 80 years will reduce the rate at which wood products accumulate carbon unless the wood is recovered and reused. Focusing on the potential forest carbon gap when first collecting forest residuals for a biomass feedstock fails to consider the importance of sustained carbon mitigation from sustained forest management and production of products.

Scenarios 3 through 6: Clean demolition material

Several comparisons for recovered wood uses are shown in Table 2, with the total carbon impacts shown in Figure 4. Table 2 provides LCI data for each stage of the process,

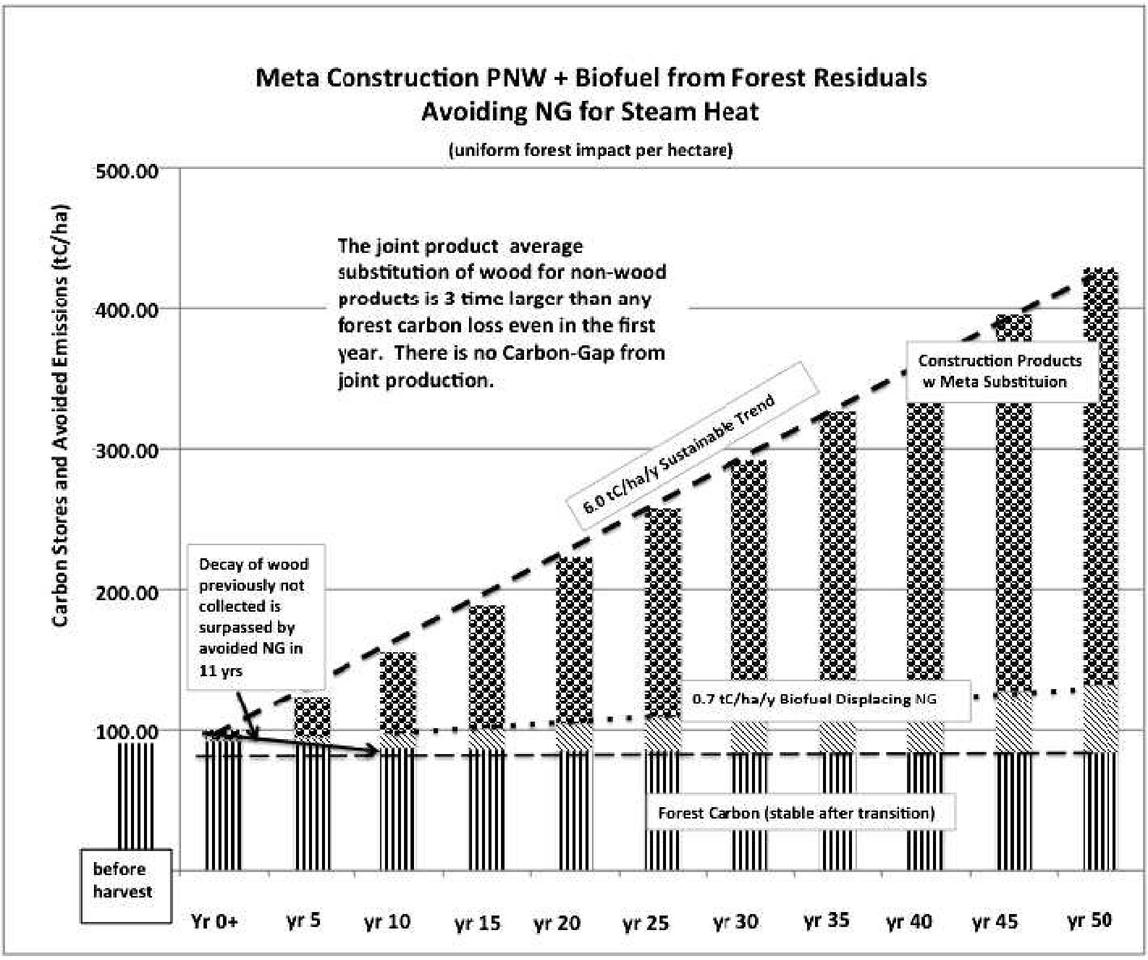

Figure 3.—Total sustainable carbon trend increase from jointly produced wood products and heat from woody biofuel. PNW = Pacific Northwest; NG = natural gas; tC = metric tons of carbon.

including forest management (by rows), a base case with no product recovery (Column 1), and five different uses of CDM material (Columns 2 through 6).

Scenario 3 assumes conventional production of wood products and their substitution for fossil-intensive products and co-products that reduce the need for fossil fuels in product manufacturing. Total carbon in the forest is shown in the top rows of Table 2 at the time of harvest, totaling 243 metric tons of carbon per hectare (tC/ha). Average forest carbon across the forest is less than half as much as at harvest given the many younger and less mature stands in the mix. The carbon for products from the stem includes that of long-lived wood products with useful lives longer than the rotation, short-lived products that are shown after harvest but are decomposed by the end of a rotation, processing energy required (negative carbon), and the energy offset from internal mill residuals used as biofuel, including the portion of pulp chips consumed as biofuel. In this case, internalizing the energy produced from pulp chips results in a biofuel surplus and avoided fossil fuel. The net carbon storage in products at the end of a rotation, which excludes short-lived products, is 92 tC/ha.

Using the meta-average substitution for all wood products of 2.1 CO_2 reduced per 1.0 CO_2 in the wood used (3.85 CO_2 reduced per 1.0 metric ton of wood used) results in 176 tC/ha from substitution (avoided fossil emissions) and, like net carbon stored in products, contributes to total carbon. Forest carbon makes up the rest of total carbon. By measuring total carbon in the stand just before harvest, we eliminate the short-term carbon impacts in products and forest residuals that make no contribution to the sustainable trend in carbon stored or avoided. Total sustainable carbon (Table 2, bottom row) increases from the initial forest carbon, which is restored with each rotation, by the cumulative impacts of substitution and the carbon stored in products for their useful life. The sustainable trend increase in total carbon (Table 2, bottom row) is 4.6 tC/ha/y for the base case (Table 2, Column 1).

When high-quality CDM is recovered and reused directly (Scenario 4; Table 2, Column 2), there are no short-lived products, and the processing energy requirement is much less. However, there will be negligible mill residuals, still resulting in 78 tC/ha from the CDM and 176 tC/ha from substitution, raising the trend rate of increase of total carbon to 7.9 tC/ha/y (72% above the no-recovery base case; Table 2, Column 2 vs. Column 1).

Being able to reuse CDM with minimal processing requires high-quality CDM, which is currently very limited. Although not a useful comparative metric for other practical alternatives, it does establish a high potential for the ideal use of recollected wood material after primary use.

Table 2.—Recovered demolition wood product use alternatives modeling carbon back to the land source from a Pacific Northwest (PNW) stand.[a]

Carbon in forest, products processing, and fossil avoided	Column 1 Base products, no CDM recovery	Column 2 CDM products reused	Column 3 CDM reprocessed into composite panels	Column 4 CDM burned to avoided NG	Column 5 CDM in landfill, gas to energy	Column 6 CDM in landfill, gas flared
C in forest (tC/ha)						
Stem and bark	133					
Crown and other nonmerchantables	77					
Roots	33					
PNW forest C at 45-y rotation	243					
C in stem products (tC/ha)						
Long-lived wood products	84	84	59	0	0	0
Short-lived products	35	0	0	0	0	0
Processing energy	−18	−5	−38	−1	−2	−1
Biofuel + other avoided NG	26	0	15	84	0	0
Fossil fuel used	8	−5	−23	−1	−2	−1
Net C store except landfill (tC/ha)	92	78	36	−1	−2	−1
Landfill C (tC/ha)						
Landfill at 135 y					61	48
Landfill at 180 y					92	64
Landfill at 225 y					105	70
Substitution (avoided) (tC/ha)	176	176	123	52		
Total C in products, substitutes, and the landfill (tC/ha)						
Total C products at 135 y	452	706	611	503	511	499
Total C products at 180 y	636	1,134	871	738	723	658
Total C products at 225 y	820	1,416	1,181	973	919	887
Total C pools vs. time (tC/ha)						
Forest at 45 y	243	243	243	243	243	243
All pools at 90 y	511	511	511	511	511	511
All pools at 135 y (reuse at 125 y)	695	950	854	746	754	742
All pools at 180 y (+ reuse at 170 y)	879	1,304	1,114	981	965	925
All pools at 225 y (+ reuse at 215 y)	1,063	1,659	1,424	1,217	1,168	1,130
Total C trend (tC/ha/y)	4.6 (base)	7.9 (+72%)	6.6 (+44%)	5.4 (+19%)	5.1 (+/−)	4.9 (+/−)

[a] CDM = clean demolition material; NG = natural gas; C = carbon; tC = metric tons of carbon; 45 y = year of rotation. +/− = much greater uncertainty.

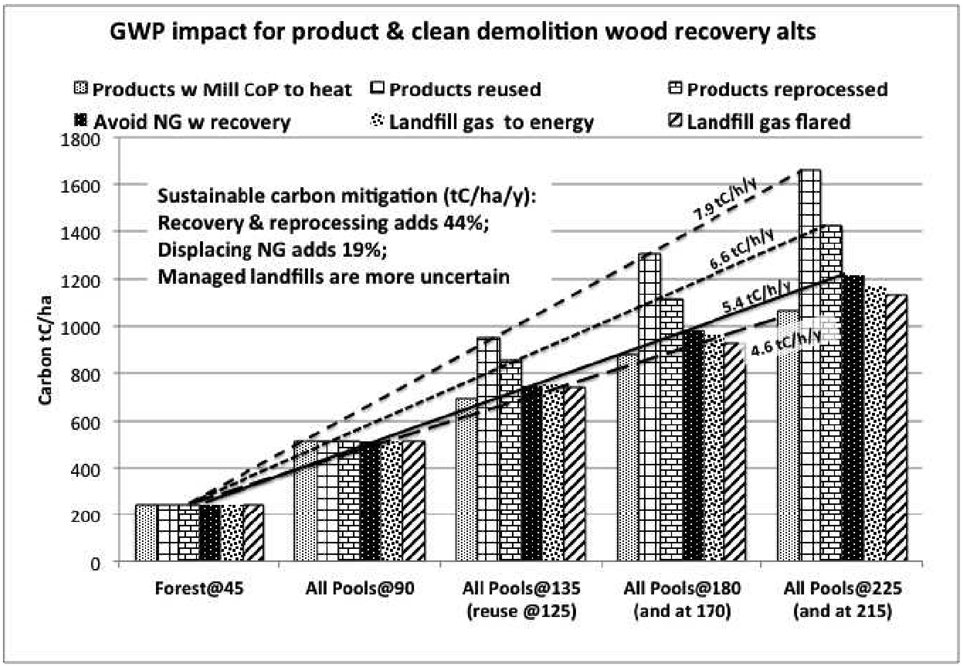

Figure 4.—Assessments of sustained carbon mitigation for alternative uses of recovered wood from a Pacific Northwest forest stand. GWP = global warming potential; CoP = co-product; NG = natural gas; tC = metric tons of carbon.

Reprocessing CDM to composite panels (Scenario 5; Table 2, Column 3) reduced the yield of long-lived products, increased the energy used substantially, and reduced the biofuel energy source, resulting in a net product carbon store of 36 tC/ha. The rate of substitution was also reduced by the reduced product yield. The trend rate of increase of total carbon was reduced to 6.6 tC/ha/y, still 44 percent over the no-recovery case in spite of much higher processing energy (Table 2, Column 3 vs. Column 1).

When recovered CDM is used as a source of heat to offset the use of NG (Scenario 6; Table 2, Column 4), the processing energy (transportation and chipping) is low, but it uses fossil fuel. The carbon in the biomass displaces NG with an efficiency of 0.62 C:C, resulting in 52 tC/ha displacement of NG (Table 2, Substitution row). The substitution impact from reused or reprocessed products is much higher by displacing fossil-intensive products rather than fossil fuels but requires the highest quality of CDM.

Using recovered wood for heat to displace NG does not have the high leverage of product substitution for fossil-intensive products, but it still increases the sustainable carbon mitigation trend from 4.6 to 5.4 tC/ha/y, a 19 percent increase over the no-recovery case. Recovering wood to be used as a fuel, such as replacing NG with biofuel for producing heat, may be the most practical option requiring minimal reprocessing of lower grades of recovered wood for boiler feedstock.

Scenarios 7 and 8: Landfill alternatives

An alternative for most CDM is disposal in landfills. Disposal of CDM raises a similar problem to the carbon store in the forest, because the decomposition of wood in the landfill depends heavily on the quality of the material and the management methods in place at the landfill. In particular, the oxygen-deprived decomposition in landfills produces methane, which has a 25 times more powerful impact on global warming than CO_2. Short-lived products, such as paper wastes, in landfills are known to produce substantial amounts of methane, resulting in more emissions than burning the waste before landfilling. Lower grades of wood waste can have somewhat similar impacts. CDM wastes will take much longer to decompose and, with a higher lignin content, will not likely release all the carbon through decomposition. Again, so long as the wood is left to decompose, it cannot displace the use of fossil fuels, although it may produce a partial carbon storage offset in the landfill for a longer period of time than decaying forest residuals. Landfills that are being designed to flare their emissions can decompose methane to CO_2 but lose the opportunity to avoid the use of fossil fuels for energy. Landfills that are upgraded to capture methane emissions for energy are an alternative form of waste recovery similar to generating heat.

Directly burning landfill emissions for steam heat serving the needs of a business district is unlikely given their different and non-compatible locations. Burning landfill emissions for energy has been exclusively for electricity usage to date, with much lower conversion efficiencies. Landfill leakage and other efficiency losses are also uncertain. The estimates shown in Column 5 of Table 2 assume the US EPA's 49-year half-life for solid wood decomposition rates in the landfill and an ultra conservative conversion efficiency only 10 percent less than that of a boiler used for producing heat. Even with conservative assumptions, landfills are likely to be less competitive where business district heating is feasible and alternative biomass supply is available. The total carbon growth trends for landfills that recapture methane emissions or flare them are better than burning the CDM but lower than using the CDM for heat energy to avoid NG emissions.

Discussion

Life-cycle impact assessment for a forest under sustainable management considers not only the wood volume harvested for products and fuels but also the carbon absorption from the atmosphere from growth of the forest simultaneously with the fuels used for management and harvesting, the carbon stored in the final product, and the decay of forest residuals. The result is a net impact, best measured by GWP in CO_2 equivalents applied to the total forest and its uses. LCAs directly compare the difference between alternatives but do not consider indirect effects, such as changes in land use or in supply from substitution, which involve sensitivity to economic changes. Sustainably managed forests are not subject to land use changes from waste collection activities given the relatively low price of biofuels compared with wood products.

Studies that model the impact of carbon at the stand level but omit the carbon absorption in the forest are inconsistent with life-cycle methods (ISO 2006) and acceptable carbon accounting procedures (IPCC 2007a, US EPA 2011). Studies that consider the decay of forest residuals for an individual stand simultaneously with the regrowth of that stand omit the carbon growing across the sustainably managed forest. Life-cycle analysis must include all parts of the system (ISO 2006), which for the short term requires measuring forest impacts rather than just individual stand impacts.

Forest residual collection depends upon periodic harvesting, at which time there will be wood product substitution for fossil-intensive products as well as forest residual biofuels displacing fossil fuels. The displacement of fossil emissions by wood products substantially exceeds any temporary carbon gap when the carbon in forest residuals has not yet been offset by the displacement of NG emissions. The use of forest residuals has the potential to significantly improve the reduction of carbon emissions, but the cost of collecting woody biofuel feedstock limits the opportunities to very-low-cost situations or those supported by other incentives, such as increased fossil fuel costs or value placed on reducing carbon emissions.

Leaving waste wood in the forest does not have the substitutional benefit of a sustainable reduction in the use of fossil fuel. The avoidance of fossil fuel, however, results in a permanent reduction in the one-way flow of carbon from ancient fossil fuel pools to the atmosphere. The carbon in forests is removed from the atmosphere during the life cycle of the forest. If this wood is not utilized, it will decompose without contributing to any fossil emission reduction. The trade-off that exists is only an issue of timing. If the forest residual waste is not pile burned, the result is a temporary time delay in forest carbon decomposition. In contrast, when the wood waste is used as a biofuel, it creates a permanent reduction in avoided fossil fuels that accumulates with each harvest and use of the feedstock.

Purchase of mill residues provides a low-cost waste feedstock with only the cost of transportation. These feedstocks do not impact forest carbon or promote land use change and are an attractive option; however, the supply may be limited.

Collection of CDM can provide options to extend the life and carbon stored in products as well as to provide additional displacement of fossil-intensive products and fuels. The use of CDM for boiler feedstocks to displace NG provides the most practical alternative, resulting in similar displacement efficiencies as producing lumber mills get from mill residuals (Puettmann and Lippke 2012).

The landfill alternatives for CDM are more difficult to evaluate because the emission measurements and the quantity of methane released are uncertain. While progress in managing landfills to capture and flare methane emissions or capture the energy is advancing, for landfill management to challenge the efficiency of a boiler to produce heat under current practices appears to be problematic.

Conclusions

Energy use, greenhouse gas emissions, and carbon storage are major concerns that have resulted in national priorities to reduce carbon emissions and US dependence on fossil fuels. Increasing the use of renewable (bio-based) products and fuels will directly reduce the one-way flow of fossil carbon emissions to the atmosphere, an opportunity that could be substantially enhanced by greater use of waste wood as well as greater use of wood products to displace the most fossil-intensive nonwood products.

There is a fundamental difference between storing wood in the forest and using wood products to displace fossil-intensive nonwood products or woody biomass fuels to displace fossil fuels. The displacement options reduce the one-way flow of carbon emissions from ancient pools to the atmosphere. Increasing the wood stored in the forest cannot be sustained without using more land, and ultimately, the carbon stored in the forest returns to the atmosphere through decomposition. While storing nonmerchantable waste wood in a commercial forest supports a small, one-time increase in the carbon averaged over the forest compared with pile burning of waste wood, it does not contribute to displacing fossil emissions like that achieved by using wood to substitute for fossil fuels or fossil-intensive products.

The SSC provides district heating for downtown businesses. The NG that is being displaced at the plant producing 56 percent of the energy needs from biomass result in a 57 percent reduction in the carbon emissions produced from using all NG. Collecting forest residuals within the region accessible by the SSC could result in an increase from 5.5 tC/ha/y from the use of the merchantable wood to 6.2 tC/ha/y (a 13% increase in carbon mitigation productivity) by collecting and using the forest residuals as well. The trend increases to 6.5 tC/ha/y (an 18% per y increase) after the 45-year rotation when there is no further reduction in forest carbon.

Collection of demolition wood occurs long after forest residuals have decayed or have been removed and are not a contributor to any temporary carbon gap. The frequent interest in increasing forest carbon misses the objective of sustainable carbon mitigation. Only by collecting and using wood products and biomass feedstock to directly displace fossil emissions is there any reduction in the one-way flow of fossil carbon emissions to the atmosphere. The same statement applies to landfill alternatives, because landfilling wastes does not reduce the one-way flow of fossil emissions to the atmosphere. However, landfilling wastes does store the carbon from products that have reached the end of their useful life through slower decomposition for a longer period of time than if left in the forest. If methane emissions from a landfill are collected for energy, they can avoid fossil emissions much like using the waste for biofuels. This benefit will be delayed by the much slower rate of decomposition in an oxygen-deprived landfill, and will reflect the uncertainty in the efficiency of capturing and using methane to produce energy.

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