Carbon Emission Reduction Impacts from Alternative Biofuels*

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Abstract

The heightened interest in biofuels addresses the national objectives of reducing carbon emissions as well as reducing dependence on foreign fossil fuels. Using life-cycle analysis to evaluate alternative uses of wood including both products and fuels reveals a hierarchy of carbon and energy impacts characterized by their efficiency in reducing carbon emissions and/or in displacing fossil energy imports. Life-cycle comparisons are developed for biofuel feedstocks (mill and forest residuals, thinnings, and short rotation woody crops) with bioprocessing (pyrolysis, gasification, and fermentation) to produce liquid fuels and for using the feedstock for pellets and heat for drying solid wood products, all of which displace fossil fuels and fossil fuel–intensive products. Fossil carbon emissions from lignocellulosic biofuels are substantially lower than emissions from conventional gasoline. While using wood to displace fossil fuel–intensive materials (such as for steel floor joists) is much more effective in reducing carbon emissions than using biofuels to directly displace fossil fuels, displacing transportation fuels with ethanol provides the opportunity to also reduce dependence on imported energy. The complex nature of wood uses and how wood fuels and products interact in their environments, as well as the methods needed to understand these impacts and summarize the relative benefits of different alternatives, are discussed herein. Policies designed to increase biofuel use by subsidies or mandates may increase prices enough to divert biomass feedstock away from producing products, such as for composite panels, resulting in increased emissions from fossil fuel–intensive substitutes. Policies that fail to consider life-cycle implications are discussed, identifying their unintended consequences.

The life-cycle inventory (LCI) data for the many different uses of wood reveal a hierarchy of different opportunities to reduce carbon emissions or increase energy independence, both being current national energy objectives. The Consortium for Research on Renewable Industrial Materials (CORRIM), composed of 17 research institutions, has developed LCI data for most of the US-produced wood products over the last decade (CORRIM 2005, 2010, 2012),

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which are publicly available in the National Renewable Energy Laboratory (NREL) life-cycle database (NREL 2012). Life-cycle data are becoming available[1] for forest residuals, thinnings, and high yield short rotation woody crops (SRWC) that are used as feedstock to produce bio-oil from pyrolysis and ethanol from gasification or fermentation processes. LCI data are also available for the impact of increasing the amount of forest waste used in sawmills for drying and densifying the biomass feedstock into pellets to improve the efficiency of combustion and long-distance hauling. Woody biomass feedstock is defined here as any wood or bark material that will be used to make heat, electric power, pellets, or liquid fuels.

As reported in other articles in this issue of the *Forest Products Journal,* the use of woody biofuels can reduce fossil CO_2 emissions per megajoule of energy used by 60 to over 100 percent compared with greenhouse gas (GHG) emissions per megajoule from gasoline (Budsberg et al. 2012, Daystar et al. 2012), which is a greater percent reduction in fossil fuel emissions than required by the standards set by the US Environmental Protection Agency (EPA) for federal use of synthetic fuels under the 2007 Energy Independence and Security Act legislation (Sissine 2007). Under EPA's standards, more than a 60 percent reduction is required for cellulosic ethanol, 50 percent for biomass diesel and advanced biofuels, and at least 20 percent for renewable fuels.

While the EPA fossil fuel emission standard was written to apply to nonfossil or synthetic fuels, cellulosic ethanol and other woody fuels are most often joint products along with wood products derived from the same source. As such, one must be aware of the different impacts and potential interactions of the joint products. Prior studies have shown a large variation in the fossil fuel emission reductions from wood products, although they generally reduce emissions much more per unit of wood used by displacing fossil fuel–intensive products than when wood is used to produce energy to displace fossil fuels directly (Lippke et al. 2011). Considering both long-lived wood products and woody biofuel feedstock uses produces a hierarchical range of opportunities to reduce emissions.

The production and use of biofuels have less of an impact for reducing emissions when compared with the production and use of solid wood products. On the other hand, liquid biofuels can displace fossil fuels (e.g., gasoline), which contributes directly to national energy independence goals as well as carbon mitigation goals. Energy independence provides domestic economic benefits that may be considered of higher value than just fossil fuel emission reduction benefits. Given the large trade deficit of the United States, which is exacerbated by petroleum imports, the economy would directly benefit from sustainable domestic production of cellulosic transport fuels rather than importing oil, resulting in an increase in income and rural jobs along with reduced deficit spending (Perez-Verdin et al. 2008, Pennock 2011). The production of biofuels from sustainably managed forests is not subject to the land-use change impacts that have been experienced by the increased production of corn ethanol (Fortenbery and Park 2008).

[1] LCI data on many biofuel collection and processing alternatives are reported on in this issue of the *Forest Products Journal* and cited throughout this article.

The objective of this article is to evaluate the comparative life-cycle impacts for a range of different biofuel alternatives on the reduction of fossil carbon emissions as well as the potential to reduce energy dependence and to understand how the use of biofuels can be most complementary to wood product opportunities for improvement.

Reductions in fossil carbon emissions from biofuel use are largely contingent upon sourcing the biofuel from sustainably managed forests that are carbon neutral. Under sustainable management, carbon absorption by regrowth of forests occurs at the same rate as biomass is removed and used, with no change in forest carbon. Carbon removed from the forest may be returned to the atmosphere when burned as a fuel, which displaces the need for and emissions from fossil fuels, or it may be stored in wood products even when they substitute for fossil fuel–intensive products displacing their emissions (Lippke et al. 2012). There have been studies, although not life-cycle studies, like the Manomet (2010) study, that did not consider sustainably managed forests along with the carbon neutrality definition. Forest carbon in this study is based on CORRIM's life-cycle analysis of all stages of processing (Lippke et al. 2011) and is consistent with the many studies that have challenged the Manomet perspective (Bowyer et al. 2011, Malmsheimer et al. 2011, Strauss 2011).

Methods

Emissions were derived from LCI data and evaluated for 12 biofuel alternatives to fossil fuels spanning the range from liquid fuel production to feedstocks used to reduce the need for natural gas in mills or to produce an electrical energy offset to that used by the mills (Table 1).

The LCI data include three biofuel feedstock collection alternatives: (1) forest residuals, (2) thinnings, and (3) SRWC serving three liquid bioprocessing alternatives—(A1) pyrolysis, (A2) gasification, and (A3) fermentation (Table 1). Comparisons are also made for five alternatives using more or less woody biofuel feedstocks in solid wood mills (A4 to A8), largely for drying energy, or using the feedstocks for electrical energy to offset fossil energy uses and their emissions. Four production alternatives for pellets and cordwood are also included (A9 to A12) covering a range of purchased and mill residual pellet feedstocks. The biofuel impacts are also compared with the impacts of wood products that substitute for fossil fuel–intensive materials, producing a hierarchy of high to low leveraged carbon reduction impacts. Each biofuel and fossil fuel alternative accumulates the emissions per unit of energy for each life-cycle stage of production and use, from forest management, extraction or harvesting, processing, avoided energy production, transportation, combustion, and carbon absorbed from the atmosphere that may be stored in products or returned to the atmosphere when used. Since there are not enough scale mills producing liquid fuels available, the LCI data for processing were obtained from processing model simulations contrasted with mill survey data for the wood product and mill residual alternatives.

Using the EPA's performance metric, the percent reduction of fossil fuel emissions is considered first. The EPA metric focuses directly on carbon emission reductions, rather than the effectiveness of using wood to reduce fossil fuel emissions. Using more wood as a feedstock for biofuel production to offset fossil fuel emissions can bias this metric exceeding 100 percent reduction in fossil fuel emissions. An

Table 1.—Biofuel alternatives to fossil fuels, feedstock inputs, and processing methods.[a]

Alternative	No.	Fossil fuel	Biofuel feedstock	Processing method	Source
Biofuel					
Ethanol	A1	Gasoline	SE whole tree thinnings	Thermochemical	Daystar et al. (2012)
Ethanol	A2	Gasoline	SRWC	Biochemical	Budsberg et al. (2012)
Bio-oil	A3	Residual fuel oil	SE whole tree thinnings	Pyrolysis	Steele et al. (2012)
Biofuel at sawmill					
INW mill survey: base case Electric grid	A4	Natural gas	Mill residues 56% + natural gas 44%	Boiler heat energy Electricity generation	Puettmann and Lippke (2012)
Forest residuals Electric grid	A5	Natural gas	Mill residues 56% + forest residuals 44%	Boiler heat energy Electricity generation	Puettmann and Lippke (2012)
INW mill survey: base case Forest residuals	A6	Natural gas	Mill residues 56% + natural gas 44% Forest residual	Boiler heat energy Electricity generation	Puettmann and Lippke (2012)
Electricity offset to base Mill residues	A7	Natural gas	Natural gas Mill residues	Boiler heat energy Electricity generation	Puettmann and Lippke (2012)
Pellets Electric grid	A8	Natural gas	Mill residues 56% + pellets 44%	Boiler heat energy Electricity generation	Puettmann and Lippke (2012)
Pellet at boiler					
Wood pellets: WI average	A9	Natural gas	WI survey average	Pelletization	Katers et al. (2012)
Cordwood: WI	A10	Natural gas	Cordwood average	NA	Katers et al. (2012)
Flooring wood pellets: SE	A11	Natural gas	Hardwood flooring waste: economic allocation	Pelletization	Reed et al. (2012)
Flooring wood pellets: SE	A12	Natural gas	Hardwood flooring residual: joint product mass allocation	Pelletization	Reed et al. (2012)
Feedstock collection alternatives	A1–A8		SE whole tree thinnings, SRWC, and forest residuals collection	NA	Johnson et al. (2012)

[a] SE = Southeast; SRWC = short rotation woody crops; INW = Inland Northwest; WI = Wisconsin; NA = not applicable.

alternative performance measure is calculated relating the reductions in fossil fuel emissions (change in fossil CO_2 equivalent output) to the input biogenic carbon (the CO_2 in the wood used). This C_{in}/C_{out} or ''C:C displacement ratio'' provides a direct measure of the efficiency to reduce fossil fuel emissions per unit of carbon in the wood used and is dimensionless whether units of C or CO_2 are used consistently. This C:C displacement ratio is far from a perfect performance measure because it will be affected by the variations in the quality of wood used as well as the input amount. For example, one could use the wood destined to produce solid wood products as a biofuel to reduce the emissions from using fossil fuels, although comparisons have shown this would not be nearly as effective for carbon mitigation as producing solid wood products to displace fossil fuel–intensive products (Lippke et al. 2011).

The efficiency of combustion chambers may also vary for different fuel types and designs while producing the same unit of energy. The range of efficiencies for residential heating units may differ from larger processing plants. Comparisons developed for this analysis assume equal efficiency in combustion between different fuels such that performance ratios (% fossil fuel emission reduction or the C:C displacement ratio) are not affected unless the combustion efficiency ratings differ by fuel type.

Emission Reduction Results

The apparently better applications for using wood are identified, and the different impacts of policy proposals targeted at the two objectives of reducing carbon emissions and increasing energy independence are then noted. While there are many feedstock and processing options that could be compared, the 12 alternatives (Alt) considered span the space of potentially high volume uses. Some of the alternatives produce better than 60 percent reduction in emissions per megajoule of energy produced compared with the fossil fuel alternative, the target threshold set by EPA for acceptable government use of cellulosic fuels. Some alternatives, such as pellets, fall short of the target, requiring an evaluation of the cause and consideration for other potential advantages. Table 1 delineates the 12 biofuel alternatives analyzed, the fossil fuel being displaced, feedstock inputs, processing methods, and data source references. Results for each alternative are provided in Figures 1 and 2.

Carbon emission reductions from three liquid biofuel alternatives

There is a substantial variation in the range of fossil fuel emission reductions resulting from different feedstock and processing alternatives. Simulated production of ethanol by gasification from whole tree thinnings substituting for gasoline (Daystar et al. 2012) resulted in a 74 percent reduction of fossil fuel emissions (Alt 1, in Fig. 1). Alternatively, when ethanol was produced by fermentation of willow (an SRWC) substituting for gasoline (Budsberg et al. 2012), a 120 percent reduction of fossil fuel emissions resulted (Alt 2, Fig. 1). The greater than 100 percent reduction is achieved when a portion of the woody feedstock (excess lignin) is used to produce electricity offsetting the emissions from the fossil fuels used in biomass collection and processing. Gasification options could also include using more wood for electric power to

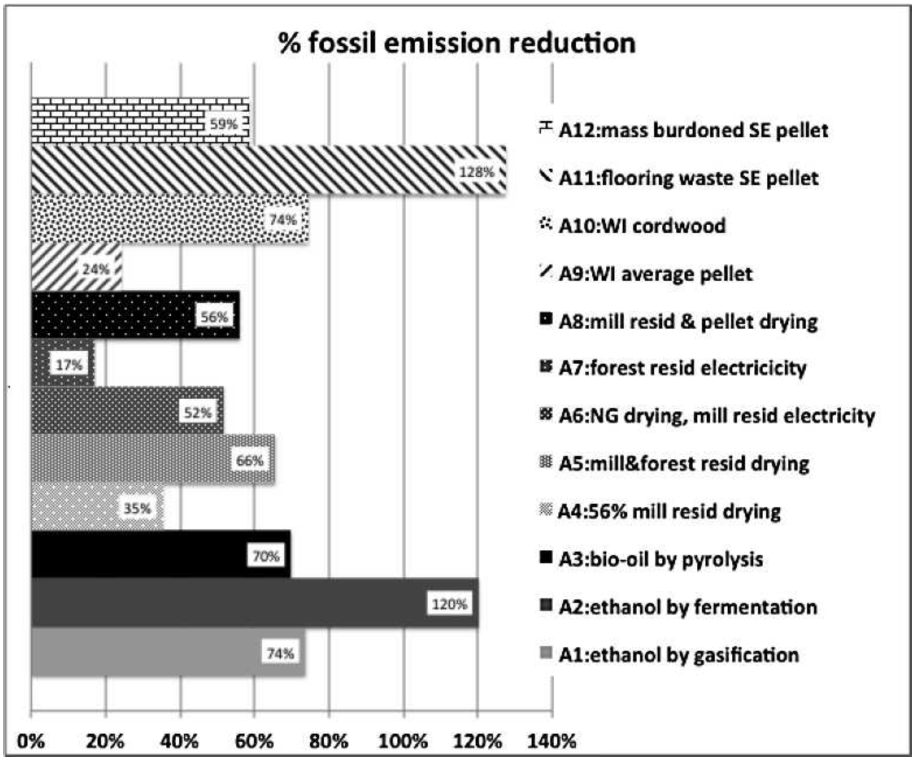

Figure 1.—Percent reduction of fossil fuel carbon emissions using biofuel alternatives.

offset collection and processing emissions, suggesting that the percent reduction in emissions relative to a fossil fuel is dependent upon the amount of wood used, not just how it is used.

Producing bio-oil from pyrolysis of whole tree thinnings in the US Southeast (SE; Steele et al. 2012) resulted in a 70 percent reduction of the fossil fuel emissions when displacing residual fuel oil (RFO; Alt 3, Fig. 1). All three liquid fuel options exceeded the EPA threshold reduction of 60 percent. RFO is not a transport fuel but is burned for heat and power in larger scale facilities and can be further refined to substitute for transport fuels, although it requires additional energy in the refinement process.

The alternative C:C displacement ratio that compares the reductions in fossil fuel emissions (the output) to the amount of carbon in the wood used (the input) is shown in Figure 2. The C:C displacement ratio is quite low for the liquid fuel alternatives such as 0.38 for wood gasification to ethanol versus gasoline (Alt 1), 0.40 for wood fermentation to ethanol versus gasoline (Alt 2), and 0.47 for bio-oil from pyrolysis versus RFO (Alt 3).

Carbon emission reductions from use of wood products

There is a substantial difference between the emission reductions possible from using biofuels to that possible when using wood products. While the substitution of engineered wood product (EWP) floor joists for steel floor joists results in a 5.3 C:C displacement ratio, many wood product uses produce lower levels of carbon emission reductions (Lippke et al. 2011). The C:C displacement leverage for EWP I-joists is high because the EWP I-joist uses much less fiber, with a strong and stiff vertical member, whereas steel floor joists require a high gauge of steel to reduce floor bounce in buildings. A meta-analysis of all available wood substitution studies produced a 2.1 C:C displacement ratio (Sathre and O'Connor 2010). While less than half that of the EWP I-joist substitution, the wood products meta-average is more than five times larger than the above results for liquid biofuels.

Nevertheless, the much lower carbon reduction from the production of wood-based ethanol contributes directly to increased energy independence and may be more important than reducing carbon emissions alone in conjunction with higher leveraged product substitution. Ethanol can also be produced from the lowest grades of waste wood, which otherwise may create GHG emissions through disposal and subsequent decomposition into methane, which has a much more potent GHG impact on global warming potential than CO_2.

Carbon emission reductions from five alternative uses of woody feedstocks for solid wood processing

The impacts of different ways to use forest residuals, mill residuals, and pellets were evaluated to find the best carbon options supportive of drying solid wood products (Puettmann and Lippke 2012). The surveyed fuel mix for drying wood in the Inland Northwest (INW), a base case, used 56 percent mill residuals and 44 percent natural gas (NG). Compared with the use of all NG for drying, the current mix reduces fossil fuel emissions by 35 percent, with a C:C displacement ratio of 0.72 (Alt 4, Figs. 1 and 2). The carbon displacement is almost twice as high as that from the liquid fuels, which require more processing. The carbon reduction is high since the mill residuals are essentially available as waste, partially dried and free of collection burdens. The

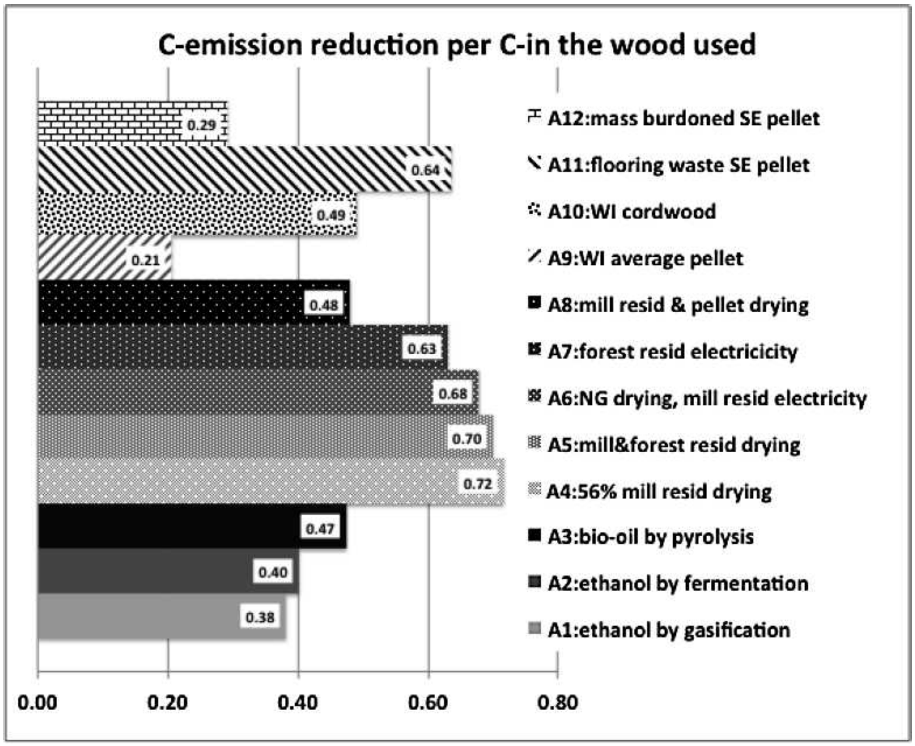

Figure 2.—Carbon emission reductions per unit of carbon in the wood used (C_{out}/C_{in}) for a range of biofuel alternatives.

percent fossil fuel emission reduction is low because NG is still providing nearly half of the fuel.

Collecting forest residuals could be used to displace the fossil fuel–intensive NG. Increasing the fuel mix for drying to 100 percent biomass using forest residuals to displace the 44 percent of energy provided by NG results in a 66 percent reduction in fossil fuel emissions, exceeding the EPA standard, and a C:C displacement ratio of 0.70 (Alt 5, Figs. 1 and 2), only slightly lower than for mill residuals because of the additional fossil energy used in collecting forest residuals.

In contrast, when the carbon uptake that is stored in the lumber product is included, fossil fuel emissions are reduced by 497 percent, because the carbon in the product is many times larger than the fossil processing emissions. Also the fossil carbon displacement ratio is much greater than 1.0, since the wood products substitute for fossil fuel–intensive products (Puettmann and Lippke 2012). Because both the mill residuals and forest residuals result from the production of solid wood products, their interdependence cannot be ignored. Other studies have assumed that the forest residuals when left in the forest will for a period of time be larger than the benefits of using the residuals for energy, producing a carbon gap (Manomet 2010). In reality, when the products and residual fuels are integrated coproducts, there is no gap in carbon benefits by using wood, and the addition of using biofuels increases the sustainable carbon mitigation trend.

At the other extreme, forest residuals could be used instead of NG to produce electricity while using mill residuals and NG for drying, resulting in a 52 percent reduction in fossil fuel emissions and a 0.68 C:C displacement ratio (Alt 6, Figs. 1 and 2). The C:C displacement ratio for producing electricity is only slightly lower than using the forest residuals to displace NG at the mill.

However, if the mill residuals are used to produce electricity relying on 100 percent NG for mill drying, the fossil fuel emission reductions drop to only 17 percent, while the C:C displacement ratio declines to 0.63 (Alt 7, Figs. 1 and 2), a 12 percent loss relative to the fuel mix used in current mills.

If pellets are used to displace the NG in mill drying instead of forest residuals, the reduction in fossil fuel emissions drops to 56 percent, a 15 percent decline, and the C:C displacement ratio declines to 0.48 (Alt 8, Figs. 1 and 2), a 33 percent decline. Pellets can be fossil fuel intensive in their production, substantially increasing fossil fuel emissions and reducing the displacement efficiency from the use of wood.

Carbon emission reductions from four pellet and cordwood alternative uses of woody feedstocks for heating

An extensive survey of pellet manufacturers in Wisconsin resulted in three different feedstocks—whole logs, wet residuals, and purchased predried residuals—the latter making up the largest share in the survey of mills (Katers et al. 2012). Using Wisconsin pellets for 100 percent of the feedstock for a boiler displacing NG only reduced fossil fuel emissions by 24 percent because the predried pellet feedstock was already fossil fuel intensive. The C:C displacement ratio was 0.21, only half that of the liquid fuel alternatives (Alt 9, Figs. 1 and 2).

Considering only a cordwood alternative, much like the whole logs that made up a small part of the Wisconsin pellet furnish, resulted in a 74 percent reduction in emissions displacing NG and a C:C displacement ratio of 0.49 (Alt 10, Figs. 1 and 2) or 32 percent lower than the result for the current mill fuel mix, although more than twice as high as the Wisconsin fossil fuel–intensive pellet mix of feedstocks (Katers et al. 2012).

Pellets can also be made of waste wood, which requires less fossil energy to produce (Reed et al. 2012). Using the waste from SE hardwood floor manufacturing for pellet production involves essentially no burdens associated with the waste, since the value of the waste would be insignificant relative to the value of the flooring. Considering the waste burden free in the production of pellets while using the pellets to produce heat, they reduce the emissions from an NG boiler by 128 percent with a 0.64 C:C displacement ratio (Alt 11, Figs. 1 and 2).

If, however, the fuels used in producing the flooring are allocated to both flooring and the wood waste proportional to their mass, a frequently used allocation method for joint products, the fossil fuel emission reductions are cut almost in half, to 59 percent, and the C:C displacement ratio is reduced to 0.29, less than half of the burden free waste alternative (Alt 12, Figs. 1 and 2). This demonstrates the problem of proper allocation of processing burdens. In cases where wastes are essentially free if not negative, such as when paying for disposal, mass allocation of burdens is not an appropriate allocation method.

Discussion of Alternatives

The percent fossil fuel emission reductions are quite similar across the alternative liquid fuels, exceeding 60 and 70 percent reductions and above the EPA target (Alts 1 through 3, Fig. 1). For the liquid fuels when more wood is used and diverted to electrical energy production, such as burning the lignin and generating electricity as an expansion of the fermentation process, it can offset the fossil fuel emissions used in collection and processing, producing more than 100 percent reduction in fossil fuel emissions. This system expansion could also be incorporated with the gasification process. The conversion process from woody feedstocks to ethanol (gasification or fermentation) results in significantly less carbon reduction efficiency (vs. gasoline) than producing bio-oil via pyrolysis (vs. RFO). However the reduction efficiency of converting woody feedstocks to a bio-oil and then to ethanol to substitute for gasoline would be lower than for producing bio-oil (Steele et al. 2012).

Current solid wood mills in the INW, as well as most of the Pacific Northwest, use only about 56 percent of the energy needed for drying from mill residuals, resulting in the need for a substantial supplement of NG. The mill residuals do reduce the fossil fuel emissions by about 35 percent compared with using all NG for drying energy or 66 percent when the use of NG is replaced by forest residuals (Alt 5, Fig. 1). The potential opportunity is to increase the woody feedstock share for drying by using forest residuals or other waste material sources.

If an electric utility was a coal-burning plant that converted to a woody feedstock biofuel, the C:C displacement ratio of reduced coal emissions to carbon in the wood used would have been close to 1:1, i.e., more efficiently replacing the fossil fuel emissions from coal by biogenic emissions than when replacing NG (Lippke et al. 2011). Because the dominant fuel source for producing electricity varies substantially across regions, consideration for which fuel is most likely to be displaced by an increase in supply can be important to the impact on emissions.

From a carbon perspective, using mill and forest residuals as biofuel feedstocks for drying rather than for electric power production results in a higher percent reduction in fossil fuel emissions and C:C displacement. But using waste wood feedstock for mill energy does not contribute directly to energy independence, since this fuel primarily displaces coal and other nontransportation fuels.

Producing pellets from multiple sources of woody feedstock can result in significant emissions assigned to the feedstock sources, resulting in substantially lower emission reductions and carbon displacement from the carbon in the wood used. The emissions to harvest and transport cordwood to produce electricity are similar to other biofuel feedstocks, e.g., ethanol by gasification or using mill and forest residuals (Alts 9 and 10; Katers et al. 2012). The survey of Wisconsin pellet mills produced the unexpected result that most of the feedstock came from predried sources and hence was quite fossil fuel intensive. The dried feedstock purchased by pellet producers required much more fossil fuel emissions than the wet wood they purchased and dried themselves using self-generated wood fuel. With the low cost of fossil fuels, pellet producers are not deterred from buying dry feedstock even though it required significant use of fossil fuels for drying.

In sharp contrast, making pellets from mill waste generated from producing hardwood flooring has low carbon emissions if the mill residue is considered a waste product carrying no emission burden. However, if the mill residuals are allocated a share of the collection and processing emissions with the flooring product, based on a mass-based burden allocation, the emission reductions are substantially reduced. Since the value of the mill residuals is generally much less than the flooring product, emissions allocated based on price would be close to the unburdened waste alternative (Alt 11; Reed et al. 2012). When the feedstock is functionally a waste product with minimal collection burdens in conjunction with lower moisture content, much higher emission reduction efficiencies can be achieved.

The carbon reduction potential from use of wood to produce wood products that substitute for fossil fuel–intensive nonwood products may be 10 times higher than the carbon reduction potential for the biofuel feedstock use alternatives (C:C from EWP of 5.3 vs. 0.4 for liquid fuels). However, there is much low-grade wood (e.g., forest residuals) that may only be usable as a biofuel feedstock. Using these feedstocks in wood product mills to displace NG for drying provides considerably greater carbon reduction potential than using them to produce liquid fuels.

The best biofuel use alternative depends on many factors. For a given national objective—decrease of oil imports or decrease in carbon emissions—the most efficient use of biofuels will vary with local conditions. The cost of collection is a significant factor and, in conjunction with the low cost of fossil fuel, it is the primary reason forest residuals have not historically been collected for biofuel use (Johnson et al. 2012). The fossil fuel emissions from collection are only 2 percent of the carbon in the feedstock that is used to displace fossil fuel emissions and not a barrier to the increased use of biofuels.

The Role of Incentives

The value of carbon emission offsets remains low in international carbon trading markets (the European Climate Exchange [ECX] 2011), and trading has been abandoned in the United States (the Chicago Climate Exchange [CCX] 2010). In effect there is no national mandate or sufficient incentive to reach emission reduction targets, which results in the market price from voluntary trades being too low to justify the transaction costs. States such as California are taking independent action, passing legislation requiring electric utilities to use more renewable energy and auction carbon credits in spite of their potential unintended consequences (http://www.climatechange.ca.gov/state/legislation.html).

Complex economic modeling undertaken to understand the optimum policy to reduce carbon emissions (Nordhaus 2007) supported an increasing trend in carbon prices (a tax or a fossil fuel price increase) of about 3 percent per y, reaching $270/ton C in 100 years. Such a trend would in just a few years make it economic to collect forest residuals for biofuel. However, many policies and procedures that do not involve taxing fossil fuel emissions have and are being considered that impact carbon emission reductions. Some that appear to reduce fossil fuel emissions may actually be counterproductive. Life-cycle assessment, which is used to track carbon across successive stages of processing, is essential to understand the impact of any policy or management change on the total carbon stock across multiple carbon pools. For example, while sustainably harvesting forests retains less carbon in the forest pool than not harvesting, the displacement of fossil fuel–intensive products by the substitution of wood products can more than offset the one-time reduction in forest carbon (Lippke et al. 2012). Using wood products and biofuels displaces fossil fuel–intensive products and fuels that otherwise provide a sustained one-way flow of carbon emissions into the atmosphere.

Neither mandated production nor existing tax subsidies for biofuel production results in a reduction of costs for fossil carbon emissions or incentives proportional to a product's fossil carbon content. Costs such as a carbon tax or incentives that are proportional to the carbon content would result in efficient market allocation of wood to reduce emissions. Otherwise the incentive may divert feedstock away from processes with higher leverage to reduce emissions and energy independence.

Setting policy to reduce emissions or increase energy independence cannot be successful without taking these sometimes-conflicting results into consideration, which requires life-cycle comparisons of the alternatives in order to reveal the impact across many processes. While the list of problematic policies is long, a few of those policies most directly exposed by the life-cycle comparisons across biofuel use are as follows:

- Recent policies that provided a tax credit for corn-ethanol production directly supported increased biofuel-based liquid fuel production while increasing the cost and price of alternative uses of the corn feedstock such as food production. Fortenbery and Park (2008) developed supply and demand models for corn markets showing that ethanol production has a positive impact on the national corn price and that the industrial demand for ethanol has a greater impact on the corn price than other demand categories, explaining corn's price behavior. US corn prices are almost triple what they were a decade ago, which is a major concern of the United Nations Food and Agriculture Organization (Ruitenberg 2012).
- Incentives (i.e., subsidies) directed at producing more bioenergy will increase demand and therefore prices that may pay for removing residuals or thinnings from the forest but will also bid up the price of mill residues and pulpwood feedstock. The same tax credit directed at biofuel production from forest biomass also creates the incentive to bid away the feedstock for composite panels, which have a larger impact on carbon emissions than biofuel use (Eilperin 2010). A decrease in composite panel production would increase emissions from fossil fuel–intensive substitutes, generating a counterproductive impact. Subsidies directed at the lowest valued wood producing the lowest impact on carbon inherently undermine the creation of products, resulting in greater impacts on carbon.
- Electric utility requirements to meet renewable energy standards can have a similar negative impact. The requirement to use renewable energy for a share of electric power or combined heat and power at whatever cost it takes to reach the required level will increase the price of feedstocks and also fragment the supply of biomass feedstock that will be needed to provide a sustainable supply for large-scale gasification or fermentation facilities (Mason et al. 2009, Tittmann et al. 2010). Focusing policy only on direct fuel uses for renewable resources could in the extreme disrupt all other uses of wood in spite of their greater ability to store carbon and reduce emissions by substitution.
- Incentives aimed at subsidizing the removal of forest residuals rather than producing liquid biofuels may avoid the diversion of feedstock that can result from incentives for the final product and increase the availability of feedstock but can result in difficult criteria for determining which residuals need to be eligible and which would be removed without the subsidy, a determination that gets more difficult with time and changing technology.
- Incentives aimed at growing and storing more carbon in forests can result in delayed harvests, reduced carbon stored in products, and decreased substitution for fossil fuel emission–intensive products. This curtails carbon emission reductions, which is counterproductive to carbon mitigation goals. The increased forest carbon is significantly less than the carbon in the wood products plus the emission reductions from displacing fossil fuel–intensive substitutes (Lippke et al. 2011).
- Providing subsidies to biofuel uses that provide the lowest fossil fuel emission reductions per megajoule or unit of carbon in wood used will be less effective in reducing emissions than supporting higher leverage substitution opportunities that are currently available.

Conclusions

Forest residuals and thinnings from sustainably managed forests producing both wood products and biofuels are coproducts of the same resource base. Biofuels provide an important opportunity to reduce fossil fuel emissions in a way that supplements the use of wood for products that can substitute for fossil fuel emission–intensive products. Wood that is not of sufficient quality to produce solid wood products can be used as biofuel. High yielding short rotation woody crops also provide biofuel feedstock potential. Processing feedstocks into ethanol to displace gasoline contributes directly to energy independence objectives, unlike most wood products. A goal to provide ethanol from biofuels as well as a goal to decrease carbon emissions increases the complexity in allocating wood to alternate uses, since current policies for these goals do not clearly establish a value for carbon or the value of biofuel-based transportation fuels to offset oil imports. When considering only carbon emission reductions, the production and use of wood products results in substantially larger GHG reductions. Using woody feedstocks to reduce NG for drying energy in solid wood mills reduces emissions about 80 percent more per unit of carbon in the wood used than does either gasification or fermentation conversion to ethanol. However, to the degree that the value of energy independence is greater because of its economic benefits, producing ethanol may be preferred.

Determining effective policy requires understanding the life-cycle impacts of different alternatives, of which there are many. Local conditions will differ such that general prescriptions for biofuel use will not fit all settings. Many conditions will influence what use is most competitive and effective in meeting carbon objectives, including the availability of biofuel supply, the cost of transportation and changing collection technologies, the life-cycle impacts of whether the source is waste or a coproduct with significant burdens, consideration for incentives and hidden subsidies, as well as locally competitive alternative fuels. Life-cycle data are essential for identifying wood uses that are best in providing carbon emission reductions, although the current low cost of fossil fuels and ineffective policies are significant barriers to the investment required to reach the national goals of reduced carbon emissions and greater energy independence.

Arguments that collecting forest residuals or thinnings from sustainably managed forests contribute to more emissions than leaving the carbon in the forest are without merit. Using wood as a fuel or in products that displace fossil fuels and fossil fuel–intensive products displaces the one-way flow of fossil carbon to the atmosphere. Storing more carbon in the forest may appear to contribute forest carbon as an offset to fossil fuel emissions, but sustainable management producing wood products and biofuels reduces emissions substantially more by displacing fossil fuels and fossil fuel–intensive products than is stored in the forest while sustainably contributing to fossil fuel emission reductions with each harvest.

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