Comparing Life-Cycle Carbon and Energy Impacts for Biofuel, Wood Product, and Forest Management Alternatives*

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Abstract

The different uses of wood result in a hierarchy of carbon and energy impacts that can be characterized by their efficiency in displacing carbon emissions and/or in displacing fossil energy imports, both being current national objectives. When waste wood is used for biofuels (forest or mill residuals and thinnings) fossil fuels and their emissions are reduced without significant land use changes. Short rotation woody crops can increase yields and management efficiencies by using currently underused land. Wood products and biofuels are coproducts of sustainable forest management, along with the other values forests provide, such as clean air, water, and habitat. Producing multiple coproducts with different uses that result in different values complicates carbon mitigation accounting. It is important to understand how the life-cycle implications of managing our forests and using the wood coming from our forests impacts national energy and carbon emission objectives and other forest values. A series of articles published in this issue of the *Forest Products Journal* reports on the life-cycle implications of producing ethanol by gasification or fermentation and producing bio-oil by pyrolysis and feedstock collection from forest residuals, thinnings, and short rotation woody crops. These are evaluated and compared with other forest product uses. Background information is provided on existing life-cycle data and methods to evaluate prospective new processes and wood uses. Alternative management, processing, and collection methods are evaluated for their different efficiencies in contributing to national objectives.

Sustainably managed forests remove carbon from the atmosphere during their growth cycle, transferring that carbon by harvesting and processing to product carbon stores or fuels that displace fossil fuel–intensive products and fuels. The increasing storage of carbon in products extends the carbon stored in the forest to growing carbon pools outside of the forest, offsetting some fossil fuel–intensive product and fuel emissions. The use of wood products and biofuels to substitute for fossil fuel–intensive nonwood products or fossil fuels directly reduces the one-way flow of fossil fuel carbon emissions to the atmosphere. Wood products and wood-based biofuels are coproducts of

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sustainable forest management along with the other values forests provide such as clean air, water, and habitat. Producing multiple coproducts with different uses that result in different values complicates carbon mitigation, accounting for both policy and investment decision makers, especially because so many of the values, including carbon, have no clear market value, thereby increasing the risk of investing in biofuels production.

The potential to divert feedstock to uses that may produce unintended consequences is an ever-present risk, such as burning wood for fuel when it might result in significantly greater carbon mitigation if used in engineered wood products that also use low-valued resources. The different ways to produce and use wood result in a hierarchy of carbon and energy impacts that can be characterized by their efficiency in using wood to reduce carbon emissions and/or to reduce fossil energy imports. Effective policy and investment decisions must consider how forest management and wood use impact fossil energy use and carbon emissions. Using life-cycle inventory (LCI) measurements for every input and output for every stage of processing followed by life-cycle assessments (LCAs) of key human health and ecosystem risks provides consistent comparisons between alternative materials, processes, and engineering designs in search of environmental improvement opportunities. The focus of this article is on characterizing the hierarchy of alternative uses of biomass that reduce global warming potential (GWP) measured by greenhouse gas emissions (GHG) in units of CO_2 or C equivalence and on characterizing the impact of liquid biomass fuels that can also directly reduce energy dependence.

Comparisons of interest include biofuels from lower grades of wood that are not substituting for fossil fuel–intensive products but can still substitute directly for fossil fuels, including liquid fuels that are being imported, contributing to energy dependence. Producing ethanol from short rotation woody crops such as willow provides both the benefits of higher yield per acre, shorter rotations, productive use of marginal agricultural land, and less forest waste, while contributing directly to energy independence as well as carbon mitigation. Collecting forest residuals left to decompose because the cost of removing them may exceed their market value provides the opportunity to displace emissions from fossil fuels. Thinning stands to improve wood quality or reduce fire risks can also contribute substantially to biomass feedstock for carbon mitigation and energy independence goals.

Alternative Scenarios Spanning the Range of Impacts on Carbon Mitigation and Energy Independence

To reduce the number of wood and biofuel use alternatives to a manageable range that would reveal the hierarchy of wood uses and improvement opportunities, the US Forest Service sponsored the Consortium for Research on Renewable Industrial Materials (CORRIM 2010) to assemble a workshop of experts to develop a research plan. The series of articles published in this issue of the *Forest Products Journal* reports on life-cycle assessments for the biofuels and their feedstocks selected for the research plan along with comparisons to other wood uses. The options selected included three liquid fuel alternatives: pyrolysis bio-oil from whole trees (thinnings or restoration) compared with residual fuel oil (RFO), ethanol from thermochemical gasification from forest residuals, and biochemical fermentation from a short rotation woody crop (willow) compared with gasoline. Pyrolysis was selected as the conversion process that might be economical on a smaller scale that could better match local supply regions. Fermentation was selected as the likely best use for high yield, high moisture short rotation crops. Gasification was considered more likely able to handle variation in the quality of the forest residual feedstock. These alternatives were compared with the prior LCI/LCA evaluations for wood product uses. Biofuels are usually a jointly produced coproduct with wood products requiring analysis of the integration back to the managed forest to assess impacts on total carbon.

These recent studies of the life-cycle implications of biomass collection and biofuel processing opportunities provide the data needed to extend the evaluation of potential benefits from products to fuel use and to identify those options that produce improvements that would contribute to the national goals of carbon mitigation and energy independence as promulgated by the Energy Independence and Security Act (Sissine 2007). The LCI/LCA data used in this article for biofuel feedstock collection and production were developed and are published in the series of articles in this issue of the *Forest Products Journal*. The findings were extended in this article to include the integration from forest management through feedstock collection, product processing, and end use. Various wood products and biofuels are compared with alternative nonwood products and fuels in order to identify best options to effectively improve environmental performance while acknowledging the lack of polices that promote carbon values in the US market relative to fossil fuel taxes in Europe and carbon taxes in British Columbia.

To gain perspective on the carbon benefits for various uses of wood, the highly leveraged impact of using wood products to substitute for energy-intensive steel products, such as the carbon impact of substituting engineered wood product (EWP) I-joists for steel joists in residential floors, is introduced first. There is a hierarchy of wood uses, with some uses having a much higher impact on reducing fossil fuel emissions than others. The comparison between alternatives relies on using LCI data for each stage of processing and time event with conservative end of life assumptions, i.e., the finally discarded wood products for this example are burned with no energy recovery. Lippke et al. (2011) demonstrated that substituting EWP I-joists for steel floor joists produced one of the higher leveraged carbon mitigation opportunities, although only indirectly contributing to energy independence. Life-cycle data have been collected over the last decade for most primary products, providing a database to make carbon emission/carbon storage comparisons between wood and nonwood products. Data for each type of steel and wood product are available from the US LCI database (National Renewable Energy Laboratory 2012). These data are representative of national markets that are served by regional exports. With the newly collected life-cycle data on biofuel collection and processing options reported in this issue of *Forest Products Journal,* the product alternatives now include pyrolysis of woody feedstocks to bio-oil and thermochemical gasification or biochemical fermentation to ethanol. Life-cycle data on each stage of processing are linked to the time profile for growing trees, harvesting, transporting, wood processing

Table 1.—Carbon impacts for each stage of processing comparing high leveraged engineered wood product (EWP) I-joists with steel, average wood substitution, and biochemical ethanol from willow biomass crops.

	Pacific Northwest (PNW) 45-y rotation (metric tons C/ha)						Willow 3.3-y rotation (metric tons C/ha)		
	EWP I-joist	Steel I-joist	EWP-steel net	Wood construction	Meta substitution	Wood-meta net	Biochemical ethanol	Gasoline	Ethanol-gasoline net
Carbon in forest (before harvest)									
a. Stem and bark	132	0	132	132	0	132	24	0	24
b. Crown	24	0	24	24	0	24	7	0	7
c. Roots	32	0	32	32	0	32	7	0	7
d. Forest biofuel	0	0	0	0	0	0	0	0	0
e. Total (a–d)	188	0	188	188	0	188	38	0	38
Carbon in wood products (after harvest)									
f. Long-lived	84	0	84	84	0	84	0	0	0
g. Short-lived	34	0	34	34	0	34	0	0	0
Carbon in wood processing									
h. Processing and transport	−51	0	−51	−20	0	−20	−16	−1	−15
i. Mill biofuel avoided natural gas	8	0	8	8	0	8	24	0	24
j. Short-lived avoided energy	17	0	17	17	0	17	0	0	0
k. Mill fossil fuel (h+i+j)	−26	0	−26	5	0	5	8	0	8
l. Net product and processing (f+k)	58	0	58	89	0	89	8	−1	9
Carbon in other processing									
m. Other processing	0	−403	403	0	−177	177	0	0	0
n. Other biofuel use	0	0	0	0	0	0	−7	−7	0
Product, processing, and avoided carbon (total carbon except forest carbon)									
o. (l+m+n)	58	−403	461	89	−177	266	2	−8	10
Substitution									
p. Wood used/stored	84	0	84	84	0	84	24	0	24
q. Fossil displaced	0	−403	403	0	−177	177	2	−8	10
r. C_subs/(C_used)			4.8			2.1			0.4
s. C_subs/(wood use)			9.6			4.2			0.8
Total carbon accumulated with time measured just before harvest (after decay and end of short lives)									
Year 45 rotations: 1 PNW; 13 willow	188	0	188	188	0	188	59	−103	162
Year 90 rotations: 2 PNW; 27 willow	246	−403	649	277	−177	454	81	−215	295
Year 135 rotations: 3 PNW; 41 willow	304	−805	1,109	367	−354	721	103	−326	429
Year 180 rotations: 4 PNW; 55 willow	278	−1,208	1,485	372	−531	903	125	−437	562
Total carbon mitigation trend (tC/ha/y)	0.7	−8.9	9.6	1.4	−3.9	5.3	0.5	−2.5	3.0
Forest removal yield (tC/ha/y)	2.9	0	2.9	2.9	0	2.9	7.5	0	7.5

including energy production, wood use, recycling, and final demolition/discard, hence providing ''cradle-to-grave'' environmental footprint comparisons for many alternatives.

Method of Analysis

The total carbon emissions resulting from the production and use of each product and process, e.g., EWP I-joists, is first computed from its LCI profile generated from primary survey data from producing mills; then the emissions resulting from the production and use of an alternative product, e.g., steel floor joists, are computed, with the difference between the two alternatives providing a direct measure of the impact when substituting one product for the other (Table 1). Indirect impacts that may result from the changes in markets to support this substitution, such as land use changes (referred to as consequential LCAs), are not included in this direct comparison (Lippke et al. 2011).

Forest carbon is derived by simulating representative sustainable forest growth rotations with periodic harvests of stem and bark as a primary input to life-cycle measures derived from mill surveys (or processing models in the absence of operating mills) applied to all inputs and outputs for every stage of wood processing. LCI data are derived as a snapshot for every stage of process under current (fixed) technology for a specific range of uses. International standards allow simulations of changing technologies but require transparent differentiation from LCI analysis. Alternatives are used to define and compare different technologies. The LCI data in Table 1 are limited to current (fixed) technologies using different alternatives to characterize regional product and process differences.

Each product/process alternative is characterized by a column in Table 1, with the LCI data for each specified stage of process provided in rows. When the LCI for one alternative is directly compared with another, such as substitution of one for another, the net comparison provides an LCA between the two alternative footprints. Row titles identify each stage of processing or an aggregation of several stages. Generally used stages of processing proceed from forest pools and forest activities to processing and use for any given alternative.

Stem and bark at harvest: Measure of forest carbon removed for products.

Crown: Measure of aboveground carbon left in the forest after harvest.

Roots: Measure of carbon in roots left in the forest; soil carbon is considered stable and is not included (Lippke et al. 2011).

Forest biofuel feedstock: Thinnings that are either unrecovered or recovered whole tree.

Long-lived wood products: Carbon in long-lived products such as housing with 80 years life (Winistorfer et al. 2005). These products result in a decrease in carbon mitigation after 80 years of product life with the ultraconservative assumption that discarded wood is burned, returning carbon to the atmosphere.

Short-lived wood products: Carbon in products expected to be decomposed by the end of a 45-year rotation, e.g., chips for pulp and paper.

Processing and transport: Carbon emissions from forest management, harvesting, transportation to mill, and wood processing.

Mill biofuel avoided natural gas: Partial offset of processing energy by the use of mill residues to avoid natural gas use, e.g., providing 50+ percent of the thermal energy needed for product drying by combusting mill residues.

Short-lived avoided energy: Avoided energy in pulp and paper production from the portion of wood chips used for energy.

Mill fossil fuel and avoided natural gas: Sum of processing and transport, mill biofuel avoided natural gas, and short-lived avoided energy.

Net product and processing: Sum of long-lived wood products, carbon storage net of carbon emitted from mill fossil fuels plus short-lived avoided fossil fuels.

Other product processing: Emission impact of substitute products or fuels.

Other biofuel or vehicle end use: Emissions from combustion of biofuels or fossil fuels.

Product, processing, and avoided carbon: Sum of net product and processing, other product processing, and other biofuel or vehicle end use, e.g., total net carbon except forest carbon.

Total carbon accumulated with time measured just before harvest: Sum of carbon in forest at harvest plus total product processing and avoided carbon that survived to the end of rotation. All short-lived impacts are insignificant, because forest carbon uptake offsets their emissions such that they have no impact on sustained carbon mitigation.

Total carbon mitigation trend: Total carbon emissions avoided by sustainable management and wood use (measured in C units per hectare per year).

Forest removal yield: Forest carbon removals per hectare per year over a rotation for comparison to total carbon growth (e.g., lower than total carbon from high leveraged displacement of fossil fuel–intensive products).

Results

Results from high leveraged wood product substitution

When EWP I-joists produced in the Pacific Northwest (PNW) from sustainably managed forests substitute for steel floor joists in the US market, a sustainable reduction in emissions to the atmosphere occurs by the avoided fossil fuel–intensive steel product emissions (Table 1, column ‘‘EWP-steel net’’). The carbon in the wood products is also stored, offsetting fossil fuel emissions over the product's useful life. The EWP I-joist does, however, use much more energy to produce the product than using dimension lumber in wood construction (Table 1, column ‘‘EWP I-joist’’ vs. column ‘‘Wood construction,’’ impact difference in row h ‘‘Processing and transport’’), suggesting that the use of processing energy by itself is not a useful performance metric because it leaves out the impacts of how the wood is used and what nonwood options are available. GHGs (or C equivalence in Table 1) contributing to GWP provide a more robust environmental impact burden for emission comparisons.

For example, the substitution of wood joists for steel joists across multiple forest rotations results in the total carbon mitigation trend growing sustainably at the rate of 9.6 metric tons of carbon per hectare per year (tC/ha/y) or 35.2 tCO_2/ha/y of reduced emissions from sustainably managed PNW forests. The PNW region of the United States supports the highest rate of carbon going into long-lived products (Fig. 1 and Table 1, first three columns).

When measuring carbon related to PNW forestland, C units are directly measured, resulting in about 0.5 metric tons C for every bone dry metric ton of wood. The equivalent CO_2 is 3.67 times greater than a unit of C.[1] While not an upper bound for carbon mitigation from managing forests, the EWP I-joist substituting for steel floor joist does provide a high leverage carbon mitigation opportunity to contrast with other alternatives, demonstrating that there is a hierarchy of emission reduction potentials across the range of products, their uses, and the resources available.

Results from average product substitution of wood products for nonwood products

The more typical use of wood framing in housing as an alternative to wall construction using concrete results in a 1.3-tC/ha/y increase over concrete framing (Lippke et al. 2011). The dominant reason that the carbon mitigation is so low is that the substitution of wood frame for concrete only covers a small share of the wood used in the building, and the carbon stored in wood products that is not a part of framing barely offsets the emissions from producing the nonwood materials used in the house. Only 8 percent of the nonwood materials in the house (by weight) are displaced by wood framing substitution relative to concrete (Perez-Garcia et al. 2005). Much of the carbon stored in wood products becomes an offset to other fossil fuel–intensive materials used in wood or concrete framed structures even if they are not direct substitutes. In contrast, the substitution of EWP I-joists for steel floor joists provides a very direct substitution not involving significant amounts of other materials. Similarly, when a biofuel substitutes for a fossil fuel, the substitution results in a direct displacement of fossil fuel emissions.

A generalized product substitution comparison has been quantified by using a meta-analysis derived from many substitution studies. Sathre and O'Connor (2010) evaluated all available substitution studies and concluded that while there was a wide range of results from different substitution

[1] The forest C is converted to CO_2 equivalent by multiplying by their molecular weight ratio of 44/12 or 3.67. CO_2 per unit of wood is obtained by multiplying C by 3.67 times 0.5 for the carbon in the wood used, or 1.835.

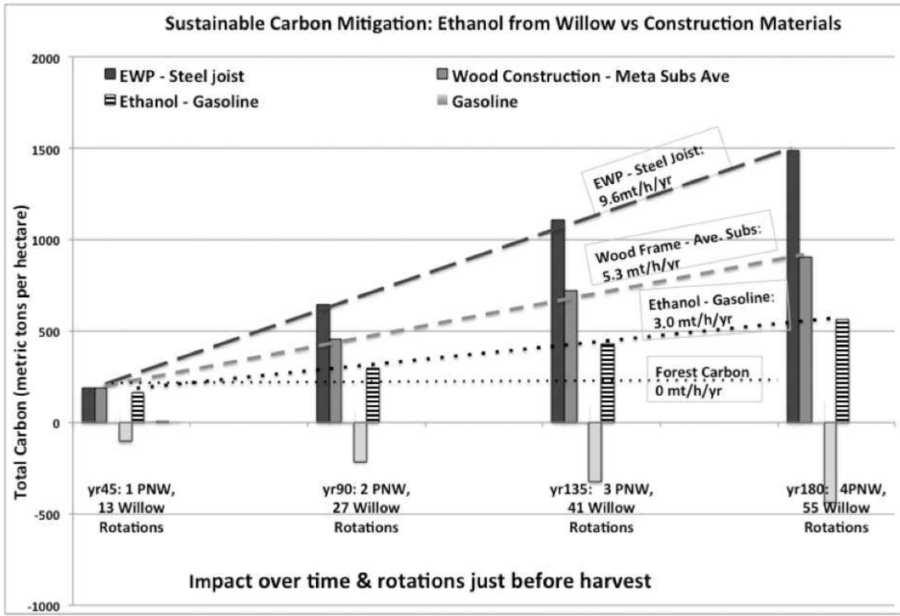

Figure 1.—Sustainable forest carbon mitigation from average (Ave) to high leveraged product substitution (Subs) contrasted with biochemical ethanol from short rotation willow substituting for gasoline. EWP = engineered wood product; PNW = Pacific Northwest.

alternatives, the average of their meta-analysis resulted in 2.1 tC reduction in emissions for every 1.0 tC in the wood used. A base management case for wood construction using this average rate of product substitution from the same PNW land base grows sustainably at 5.3 tC/ha/y (Table 1, columns ''Wood construction,'' ''Meta substitution,'' and ''Wood-meta net''). The meta-analysis reflects an average rate of wood substitution of roughly one-half that of high leveraged products such as the EWP I-joist comparison. Other processing assumptions include considering the energy value from the wood in chips for pulp, a coproduct output as avoided energy (i.e., half the short-lived products were used as a conservative estimate of the biofuel in producing pulp, avoiding the need for fossil fuel). The variation across different pulp mills is, however, large. There are insufficient data available to estimate the substitution benefits of paper as an addition to the avoided fossil energy. The other half of the fiber in the short-lived products was assumed to decompose within the rotation, although the potential exists to collect that waste material for its energy value, or alternatively when landfilled it may contribute to carbon stores or emissions from the methane releases resulting from oxygen-deprived decomposition.

Results from a no-harvest alternative compared with sustainable management

The carbon in sustainably managed PNW forest stands is restored across each 45-year rotation at time of harvest. The total forest remains carbon neutral because under sustainable management, removals are set to be not larger than net growth. Unharvested forests in the region tend to reach their carrying capacity limits within the next 100 years. Once this carrying capacity is reached, there is no significant contribution to carbon mitigation or energy independence, since any growth in forest carbon is offset by mortality. Analysis of federal lands in western Washington, where the sample of old forests is adequate to estimate the impact of increasing mortality in aging stands, showed little net growth beyond 100 years. A no-harvest alternative produces no CO_2 mitigation after about 100 years because the forest stand reaches its productive carrying capacity. In contrast, the sustainable carbon mitigation trends demonstrated in Figure 1 when substituting wood for nonwood products produces 5.3 tC/ha/y (19 tCO_2/ha/y) for the average rate of substitution. There are exceptions in some areas, such as forests in peat bogs where the dead wood from the old forest does not decompose rapidly, resulting in an increasing pool of carbon in the forest floor over time, not unlike the increasing store of carbon in products.

Some have questioned the carbon impacts of management, noting that harvesting often leaves considerable waste in the forest to decompose, with the forest carbon stocks substantially lower following harvest. In such cases the sum of the carbon in products and the forest can be less than a no-action alternative of not harvesting for a period of time. But that leaves out the substitution of wood replacing nonwood. The impact of wood products substituting for nonwood products more than offsets the shortfall in product carbon relative to the no-harvest alternative immediately. When the objective is sustainable carbon mitigation, achieved by using the wood removed from forests to displace fossil intensive products and fuels as well as to store carbon in products outside the forest, the dead wood left in the forest or short-lived products are of no concern. Both the dead wood and short-lived products decay as the forest is restored. For sustainable carbon mitigation, one only needs the time points just before harvest where these short-term carbon impacts have expired because they do not influence the sustainable substitution of carbon stored in wood products that displaces the emissions from nonwood products and fuels.

Results from biochemical ethanol displacement of gasoline using short rotation willow crop feedstock

Using biochemical ethanol produced from willow biomass crops grown in the Northeast to displace gasoline

(Budsberg et al. 2012) addresses a large market demand and is estimated to result in a 3.0-tC/ha/y (11-tCO_2/ha/y) trend increase in carbon mitigation (last three columns of Table 1 and Fig. 1). Burning surplus lignin for electricity in the biochemical ethanol production offsets the fossil energy needed for harvesting and feedstock collection. Because of the surplus energy contributing to avoided emissions, biochemical ethanol processing can be better than carbon neutral, resulting in a 100+ percent reduction of the fossil fuel emissions when displacing gasoline (Table 1, in the column ''Biochemical ethanol,'' LCI row ''Processing and transport'' [h] is more than offset by ''Mill biofuel avoided natural gas'' [row i]).

The ratio of fossil carbon reductions per unit of carbon in the wood used (C:C or CO_2:CO_2) provides a measure of wood's efficiency in reducing emissions. This displacement ratio is 4.8 when EWP replaces steel joists (not counting the forest carbon, which is not changing, or the carbon stored in the product) compared with only 0.40 for displaced gasoline emissions per unit of carbon used in biofuel. The meta-average from building product substitution studies produced a 2.1-tC displacement for every 1.0 tC of wood used, substantially higher than when using wood as a biofuel, but requires higher grade solid wood feedstock sourced by much slower growing species. High biomass growth rates from short rotation woody crops offset much of the relatively low carbon displacement efficiency from producing ethanol.

A growth scenario assumption of 7.5 tC/ha/y (27.5 tCO_2/ha/y) was used for willow feedstock based on early experience with field plots (Volk et al. 2011). The forest carbon growth in removals yield for the PNW was 2.9 tC/ha/y, somewhat lower than the trend growth in carbon across all products, which is enhanced by the benefits of high leverage product substitution. The willow crop yield at 7.5 tC/ha/y is higher than the sustainable mitigation trend, 3.0 tC/ha/y, as a consequence of the low carbon displacement efficiency in producing ethanol. The differences in forest/crop yield are also impacted by regional and species productivity differences.

Results from thermochemical ethanol displacement of gasoline using forest thinnings in the US SE

Advances in forest management technology are resulting in increasing investments to raise the volume and quality of wood available to forest products. Precommercial thinnings are used frequently in the Southeast (SE), resulting in a large volume of biomass waste from the thinnings. A midrange estimate of management intensity and site class productivity (Johnson et al. 2005, 2012) is used here to provide a comparison of the impacts of whole tree collection of thinnings for use as a biofuel. As a management activity, thinning is justified by the increased value of the final harvest. Therefore precommercial thinnings for biofuel are only allocated the fossil fuel emissions from the collection and delivery of the thinning material to the biofuel facility as other forest management emissions are allocated to the uses of the final harvest.

Forest management in the US SE is substantially different from management in the PNW, with much shorter rotations (25 y SE vs. 45 y PNW) and a much larger portion of the harvest directly serving pulp and paper uses rather than wood product uses. With the life-cycle data for average intensity sites from Johnson et al. (2005) and the lumber mill data for the production of wood products from Milota et al. (2005), a carbon tracking profile for SE forests similar to that developed for the PNW is produced including biofuel from collection of whole tree thinning treatments. The biomass from thinnings at age 17 years is collected but the forest residuals left behind at final harvest are not because the collection of whole tree thinning can be much less costly than attempting to collect postharvest slash. The volumes are roughly one-third in whole tree thinnings for biofuel, one-third pulp logs direct to paper mills, and one-third to lumber mills, with 55 percent of that volume ending up in solid wood products or composite products, 32 percent in pulp chips, and 13 percent in mill residuals for drying. While only 32 percent of the harvest is used for pulp in the PNW, in the SE about 66 percent goes to pulp without collection of thinnings and 77 percent including thinnings.

The impact of thermochemical gasification from thinnings for SE forests (Daystar et al. 2012) is compared with and without the production of ethanol: (1) the base case uses the meta-average substitution for building products and avoided energy for paper production, while leaving the thinnings to decompose rather than producing ethanol and (2) the alternative includes the collection of thinnings and production of ethanol (Table 2).

The base case produces a sustainable carbon mitigation of 0.8 tC/ha/y (2.9 tCO_2/ha/y) without the production of ethanol. The collection of thinnings and production of ethanol increases the sustainable carbon mitigation by 50 percent to 1.2 tC/ha/y (4.4 tCO_2/ha/y). This is less than the rate of carbon growth in the young forests (2.5 tC/ha/y) because so much of the product is being used for paper. Including postconsumer paper collection and recycling would increase the sustainable carbon mitigation rate. Paper disposed of in landfills could increase the rate if the methane emissions from oxygen-deprived decompositions are captured for their energy value, or the trend could be reduced if the methane leaks from the landfill.

It is noteworthy that the decomposing dead wood from precommercial thinnings provides enough forest carbon to more than offset the emission reductions from using ethanol at the time of the first rotation but not beyond. The transition from not removing thinnings to using them to displace gasoline results in more carbon in the forest when thinnings are not collected than the avoided emissions from substitution until the dead wood has decayed to a level less than the displaced emissions from using the biofuel.

Results from producing thermochemical ethanol from forest residuals

Short rotation woody crops require dedicated land to the production of a biofuel. In contrast, forest residuals from sustainably managed forests can be collected to produce biofuel requiring no change in land use area. There are a number of studies on how much of the forest residuals left behind after harvest or forest thinnings might be available for bioenergy feedstock.

For an example case of using forest residuals for biofuel, the collection of 45 percent of the aboveground forest residuals is analyzed in Table 3 based on a study that sampled 2,000 slash piles in eastern Washington with a subsample measured after grinding at the cogeneration facility (Johnson et al. 2012). The percentage of residuals that are recoverable can be higher with whole tree chipping

Table 2.—*Carbon impacts for each stage of processing producing ethanol from southeast (SE) thinnings with construction and paper products from final harvest.*

	SE wood use with and without thinning for ethanol (metric tons C/ha)	
	Base case: building materials and paper without ethanol	Building materials and paper with ethanol
Carbon in forest (before harvest)		
a. Stem and bark	42.2	42.2
b. Crown	13.0	13.0
c. Roots	14.5	14.5
d. Unrecovered thinnings at 17 y	0	2.5
e. Whole tree thinning at 17 y	0	21.0
f. SE forest total at 25 y (a–c)	69.7	69.7
g. SE forest + thinnings at 25 y	80.1	
Carbon in products (after harvest)		
h. Long-lived wood products	9.9	9.9
i. Short-lived (chips for paper)	5.7	5.7
j. Short-lived pulpwood for avoided energy	24.2	24.2
k. Mill biofuel for avoided natural gas	2.4	2.4
l. Total carbon used (h+i+j+k)	42.2	42.2
Carbon in wood processing		
m. Processing and transport	−2.7	−2.7
n. Short-lived avoided energy	14.9	14.9
o. Forest thinnings to ethanol	0	8.0
p. Mill fossil fuel + avoided (k+m+n+o)	14.6	22.6
Total product, processing, and avoided carbon (total carbon except forest carbon)		
q. Long-lived product net processing (h+p)	24.5	32.5
Substitution		
r. Wood used/stored	42.2	63.2
s. Fossil fuel displaced	24.5	32.5
t. C_subs/(C_used)	1.7	1.9
Total carbon accumulated with time measured just before harvest (after decay and end of short lives)		
Year 25: 1 SE forest + 1 ethanol sub	80	78
Year 50: 1 SE forest + 2 ethanol subs	94	110
Year 75: 1 SE forest + 3 ethanol subs	119	143
Year 100: 1 SE forest + 4 ethanol subs	143	175
Year 125: 1 SE forest + 5 ethanol subs	158	198
Total carbon mitigation trend (tC/ha/y)	0.8	1.2
Forest removal yield (tC/ha/y)	1.7	2.5

on flatlands or lower in mountainous terrain where collection is more difficult, but we consider leaving 55 percent of the slash and/or leaving trees for ecosystem functions to be a reasonable estimate.

If we assume the collection of 45 percent of the forest residuals converted to ethanol by thermochemical processing, then the carbon mitigation from using wood products is raised by only 9.5 percent from 5.3 tC/ha/y (19 tCO_2/ha/y) to 5.8 tC/ha/y (21 tCO_2/ha/y). The collection of 45 percent of forest residuals does not contribute to the high leverage in reducing carbon emissions that products do because the carbon efficiency to produce ethanol is only about one-fifth as great as substituting wood for fossil fuel–intensive products (0.38 tC displaced compared with 2.1 tC displaced).

Results from pyrolysis of whole tree forest residuals compared with ethanol alternatives

Pyrolysis provides another processing option resulting in the ability to operate on a smaller scale, making use of forests that lack the capacity to serve large-scale ethanol biofuel facilities. However, the fuel is not suitable as a direct substitute for gasoline without further refinement. The bio-oil produced can be used as a substitute fuel for RFO, a lower grade of liquid fuel than ethanol that is used in large utilities for heat and power. The emissions from producing bio-oil displacing RFO (Steele et al. 2012) are compared with the several alternatives for producing ethanol to displace gasoline. The comparisons (Fig. 2) show common characteristics. Each of the wood-based fuels produces fewer emissions than their fossil fuel alternative, resulting in a substantial reduction in carbon emissions when displacing the fossil fuel by a wood-based fuel. Each also exceeds the 60 percent reduction of the fossil energy emissions required by the US Environmental Protection Agency (US EPA).

Discussion of Results

When producing ethanol, about 0.4 metric tons of C (or CO_2) are displaced for every metric ton of C (or CO_2) in the biofuel feedstock used (Fig. 3). While displacement of RFO by the bio-oil from pyrolysis is about 20 percent higher than from ethanol, it is not an acceptable transportation fuel. Further processing in order to make it acceptable would

Table 3.—Carbon impacts for each stage of processing producing ethanol from 45 percent recovery of forest residuals.

	Pacific Northwest product use and forest residual recovery to biochemical ethanol (metric tons C/ha)			
	Wood construction-meta substitution net	Residuals (45%) to ethanol	Gasoline	Ethanol-gasoline net
Carbon in forest (before harvest)				
a. Stem and bark	132	132	0	132
b. Crown and slash	84	84	0	84
c. Roots	32	32	0	32
d. Forest carbon total (a–c)	248	248	0	248
Carbon in wood products (after harvest)				
e. Long-lived	84	84	0	84
f. Short-lived	34	34	0	34
Carbon in wood processing				
g. Processing and transport	−20	−20	0	−20
h. Mill biofuel avoided natural gas	8	8	0	8
i. Short-lived avoided energy	17	17	0	17
j. Mill fossil fuel + avoided (g+h+i)	5	5	0	5
k. Net product and processing (e+j)	89	89	0	89
Carbon in other processing				
l. Substitution + ethanol and gas	177	110	−31	140
m. Residuals recovered	0	59	0	59
Product processing and avoided carbon (total carbon except forest carbon)				
n. (k+l+m)	266	258	−31	289
Substitution				
o. Wood used/stored	84	143	0	143
p. Fossil displaced	177	169	−31	200
q. C_subs/(C_used)	2.1	1.2		1.4
Total carbon accumulated with time measured just before harvest (after decay and end of short lives)				
Year 45 forest carbon (FC)	248	248	0	248
Year 90 FC + meta subs + ethanol subs	514	506	−31	537
Year 135 FC + 2 meta subs + 2 ethanol subs	780	764	−61	826
Year 180 FC + 2 meta subs + 3 ethanol subs	963	938	−92	1,030
Total carbon mitigation trend (tC/ha/y)	5.3	5.1	−0.7	5.8
Forest removal yield (tC/ha/y)	2.9	4.2	0	4.2

reduce the emission reductions as well as carbon displacement efficiency somewhat. Fossil carbon emission displacement by ethanol produces only about one-fifth of the 2.1 tC average rate of displacement by wood products; however,

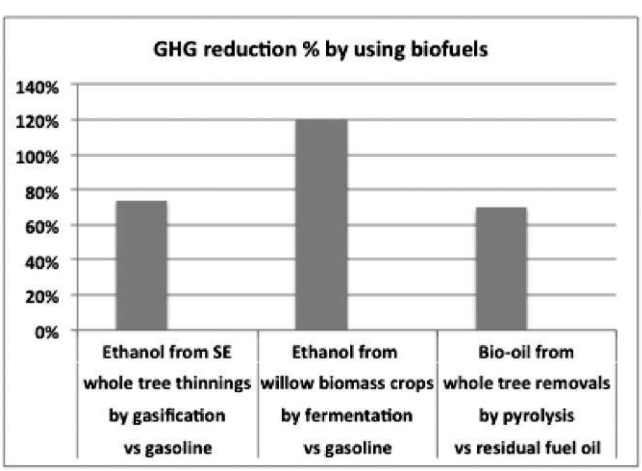

Figure 2.—Emission reductions using biofuels: (1) thermochemical ethanol versus gasoline, (2) biochemical ethanol versus gasoline, (3) pyrolysis bio-oil versus residual fuel oil. GHG = greenhouse gas; SE = Southeast.

the ethanol is derived from residues that are generally not suitable for producing wood products.

In effect these comparisons show that where it is possible to produce wood of sufficient quality to produce wood products, they provide the most effective opportunities to sustainably reduce carbon emissions. While using wood for products is more effective at carbon mitigation, the liquid fuels substitute directly for imported fossil fuels and contribute to energy independence as well as carbon mitigation. While the efficiency to produce liquid fuels per unit of wood used is low, the value of reducing energy dependence may be high enough to offset the low efficiency. Reducing the nation's energy dependence on petroleum imports reduces a hidden tax on the domestic economy in terms of lost jobs, economic activity, and tax revenue along with the increased national security costs. In economic terms, the value of energy independence is much higher than carbon mitigation alone. Producing cellulosic biofuels from short rotation crops can reduce emissions and energy dependence better than corn ethanol, current grass, shrub, or low-value crop uses (US EPA 2009).

Evaluating the relative efficiency of these options in contributing to either carbon mitigation or energy independence objectives is further complicated by establishing values for the different metrics, i.e., reduced energy imports

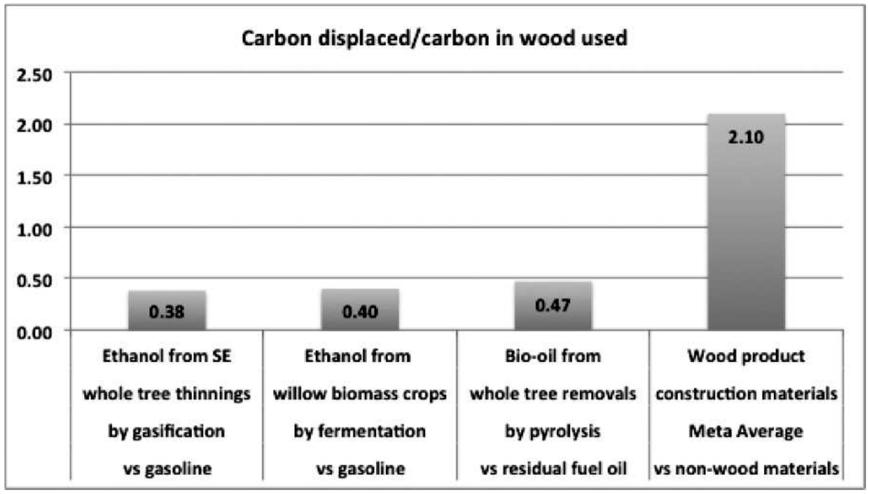

Figure 3.—Carbon equivalent emission reductions per unit of carbon in the wood used. SE = Southeast.

versus reduced emissions. The fact that existing policies do not directly consider the benefit in value terms of reducing emissions versus reducing energy dependence complicates any determination of what method is best and where it is best applied. Incentives such as the ethanol tax credit provided by the US Congress or carbon emissions taxes being used in British Columbia, Canada, create relative cost advantages for wood uses over fossil fuels. Direct taxes on fossil fuels such as practiced in Europe have increased the cost of fossil fuels and hence the collection of biomass to displace them (Fouche 2008, Lippke et al. 2011). Carbon exchanges that provide a monetary value for some sources of carbon may or may not alter the relative cost of biobased products and fuels to fossil sources. They may even be counterproductive to carbon objectives, for example, paying for forest carbon stores by not harvesting increases the use of fossil fuel–intensive products and fuels.

While in the United States there may not be many situations where collecting the feedstock for biofuels will economically break even in competition with natural gas or gasoline prices or until there is a carbon tax or other incentives, the potential to contribute to carbon mitigation is still very real. The $13 per metric ton of CO_2 ($48/tC) as valued in the European Climate Exchange (Cozijnsen 2012) a several year average could contribute $24 (bone dry equivalent) toward the cost of collecting wood if the markets were not otherwise restricted, thus monetizing the value into products proportional to their carbon value, thereby offsetting about half of the cost of delivering forest residuals. The carbon emitted in collecting the feedstock, even though higher than hauling merchantable logs, is usually only 1 to 3 percent of the carbon available to produce fuel. Cost of collection is a substantial barrier that will be reduced if and when the value of carbon is internalized in markets, whether through carbon taxes or incentives. The emissions from collection are small and will not have a significant impact on the cost of collection. If the incentive derives from higher fossil fuel costs, such as fossil fuel carbon taxes, markets will seek out the most efficient response to cover the cost of collection. Regardless of the uncertainty in the value of different alternatives, understanding the relative efficiencies of different collection and processing options is an essential first step.

It does not appear that thermochemical gasification processing produces significantly different carbon displacement efficiency than biochemical fermentation. Thermochemical processing could divert lignins to electricity production, offsetting fossil fuel uses in collection and hauling, much like the biochemical fermentation example, and become carbon neutral. However, these fuels are substantially different in other aspects, such as sensitivity to wet or dry wood, because as a dry process gasification benefits from dry wood, whereas biochemical fermentation uses water and benefits from wet wood.

Using fast-growing short rotation woody crops can produce a significant reduction in carbon emissions, while at the same time contributing to energy independence, with much of the lower displacement efficiency by not substituting for wood products offset by the much faster growth of short rotation woody crops. While the displacement efficiency in the willow example is only 43 percent less than the average for wood product substitution, this difference will be directly related to the productivity potential of the sites, in addition to processing efficiency differences. While the LCI data include all of the purchased inputs needed to support willow biomass crops, they do not include impacts of any land use change, which will require a more extensive land use analysis for any land that is converted from other productive uses. Conversion of unproductive land to willow will most likely increase the below-ground carbon stored in the crop but does not change soil carbon levels over successive rotations (Pacaldo et al. 2010, 2011).

There is, however, substantial natural variation in site-specific forest growth conditions such that any attempt to scale results up to national potentials would require a more detailed regional modeling effort linked to processing models and collection methods that model local differences.

To gain insight into the benefit of using liquid fuels to reduce emissions, they can be compared with the emissions from an auto averaging about 12,000 miles of use per year with 24 miles per gallon efficiency, which would consume 500 gallons of gasoline per year, producing 4 metric tons of CO_2. The average rate of wood product substitution for nonwood products offsets 19 metric tons of CO_2 per year per hectare, such that the emissions from almost five auto years are offset by 1 hectare of sustainable forest used to reduce nonwood construction materials. Using the willow biomass crop offsets 11 metric tons of CO_2 per year, equivalent to 2.8 autos per year. Using the feedstock from thinnings in the SE or collecting 45 percent of the forest residuals in the west contributed about 0.5 tC/ha/y (1.8 tCO_2/ha/y), thus adding about half an auto per year per hectare to the much larger production alternatives. These waste residuals are otherwise left to decompose or burned in piles.

Conclusions

The analysis of alternative uses of wood for products and fuels suggests that there are many feedstock sources for biofuel, including forest residuals, thinnings, and short rotation crops, that can directly substitute for fossil fuels, reducing their one-way flow of emissions to the atmosphere. Biofuels are not as effective as wood products in reducing carbon emissions, because wood products tend to substitute for more fossil fuel–intensive products, resulting in much higher efficiency to displace fossil fuel emissions per unit of wood used. However, producing cellulosic biofuels from wood resources that are currently wasted or are not of adequate quality to produce wood products can still substantially reduce emissions by substituting for transportation fuels that also have a disproportionately larger impact on reducing energy dependence.

These differences create a hierarchy of wood uses and processes for reducing carbon emissions and energy dependence. High leverage products like EWP I-joists substituting for steel joists provide large opportunities for reducing carbon emissions by penetrating light commercial structures. The current average of displacement from product substitution studies remains far above the displacement efficiency of biofuels. But biofuels make use of materials not suitable for products and can have a disproportionately large impact in reducing imports, which provide considerable added benefits to the domestic economy.

It is important to note that the sustainability of reducing carbon emissions or fossil fuel imports flows directly from using wood to displace fossil fuel–intensive products and fuels, forest rotation after rotation. Carbon stored in the forest or wood products may offset fossil fuel carbon emissions for a period of time but do not displace them. Carbon stores can only be increased by using the harvest to produce items that store carbon. Increasing carbon stores in existing forests that could otherwise be used for products or biofuels ultimately reduces opportunities to displace fossil fuel emissions.

Since the primary barrier for collecting lower quality waste woods for biofuels is their relatively high cost compared with fossil fuels, incentives such as a tax on carbon emissions that raise the cost proportional to the carbon being displaced would effectively avoid diverting feedstock to less valuable end uses and could enable a substantial competitive market for biofuel production. The opportunities to increase sustainable carbon mitigation and energy independence are significant if and when the financial barriers are reduced through a higher value for carbon stores or higher cost for carbon emissions. Designing incentives that are not counterproductive, such as misdirecting feedstock to lower leveraged carbon mitigation uses, is however difficult, and without LCA built into the criteria, it is likely to be counterproductive. Opportunities for improvement will be sensitive to site and regional conditions as well as scale.

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