Forests **2011**, *2*, 861-874; doi:10.3390/f2040861

OPEN ACCESS

forests

ISSN 1999-4907

www.mdpi.com/journal/forests

Article

Sustainable Biofuel Contributions to Carbon Mitigation and Energy Independence

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Received: 17 August 2011; in revised form: 25 September 2011 / Accepted: 27 September 2011 / Published: 19 October 2011

Abstract: The growing interest in US biofuels has been motivated by two primary national policy goals, (1) to reduce carbon emissions and (2) to achieve energy independence. However, the current low cost of fossil fuels is a key barrier to investments in woody biofuel production capacity. The effectiveness of wood derived biofuels must consider not only the feedstock competition with low cost fossil fuels but also the wide range of wood products uses that displace different fossil intensive products. Alternative uses of wood result in substantially different unit processes and carbon impacts over product life cycles. We developed life cycle data for new bioprocessing and feedstock collection models in order to make life cycle comparisons of effectiveness when biofuels displace gasoline and wood products displace fossil intensive building materials. Wood products and biofuels can be joint products from the same forestland. Substantial differences in effectiveness measures are revealed as well as difficulties in valuing tradeoffs between carbon mitigation and energy independence.

Keywords: biofuels; gasification; fermentation; sustainability; carbon mitigation; energy independence; LCI; LCA

1. National Objectives and Barriers

There has been a large research and development effort, an enormous amount of press coverage, and numerous professional conferences devoted to increasing the use of biomass, as a renewable energy source. Biomass materials derive from living or recently living organisms that can be grown sustainably. While there are many different sources of biomass, the focus of this work is on woody biomass. There is currently a substantial inventory of underutilized biomass in forests and wood wastes that could be processed into biofuels for the production of heat, power or transportation fuels. This interest in biofuels has largely been elevated by two primary policy goals, (1) to reduce carbon emissions and (2) to achieve energy independence (Energy Independence and Security Act 2007 [1]). However, these goals to date have not been supported by the necessary change in cost structure to motivate effective investments in un-subsidized bio-processing production capacity.

The low retail cost of US gasoline has historically precluded the economically competitive removal of currently unused woody biomass or the large-scale production of other sources of woody biomass for ethanol production, and the low cost of natural gas has precluded biomass from becoming the dominant feedstock for drying energy in solid wood processing mills. While one might speculate that the demand for biofuels should be increasing with substantial monetary rewards to the future participants, these low cost fossil fuels are a key barrier.

Evaluating the potential for sustainable biofuel production is quite complex. Some of the feedstock competes not only with low cost fossil fuels, but also with a wide range of wood products that are more effective than biofuel in reducing emissions [2]. Every stage of growth and processing has different impacts on carbon emissions. Comparing the effectiveness of biofuels to other uses of woody feedstock requires measurements across the total life cycle from biomass growth through processing. Growing more or less wood, producing higher or lower quality wood for different end uses, as well as different collection and manufacturing processes, result in many tradeoffs. Measuring every input and output for all processing stages provides the life cycle inventory (LCI) information necessary to analyze all significant direct impacts affecting each alternative. Comparing the impact of one process or product use on carbon emissions with other alternatives is referred to as a life cycle assessment (LCA) identifying alternatives for improvement. There are also potential indirect impacts of collecting biomass for biofuel production that may complicate the measurement of environmental effectiveness. Those impacts can directly involve other forest values and may indirectly affect land use changes [2].

There has been a substantial effort to develop credible LCI and LCA data over the last decade. Much of that information for North American forest resource operations and wood products production and utilization is synthesized in Lippke *et al.* [2]. This information will be used to contrast the impact of different biomass collection and processing options to produce biomass for competing product uses. Herein, we first demonstrate the carbon mitigation potential from sustainable production of traditional wood products and then analyze the degree to which that performance can be improved by including woody biofuel feedstock collection and processing alternatives.

There are many sources for woody biofuel feedstock, often with substantial regional differences, that need to be considered including:

- forest residuals from sustainable production of traditional wood products,
- pre-commercial thinning,
- forest thinnings to reduce fire risks,
- thinnings or other regeneration efforts to restore historic forest functions and habitat,
- high yield short rotation woody crops (SRWC),
- deconstruction and other end of useful life alternatives for waste.

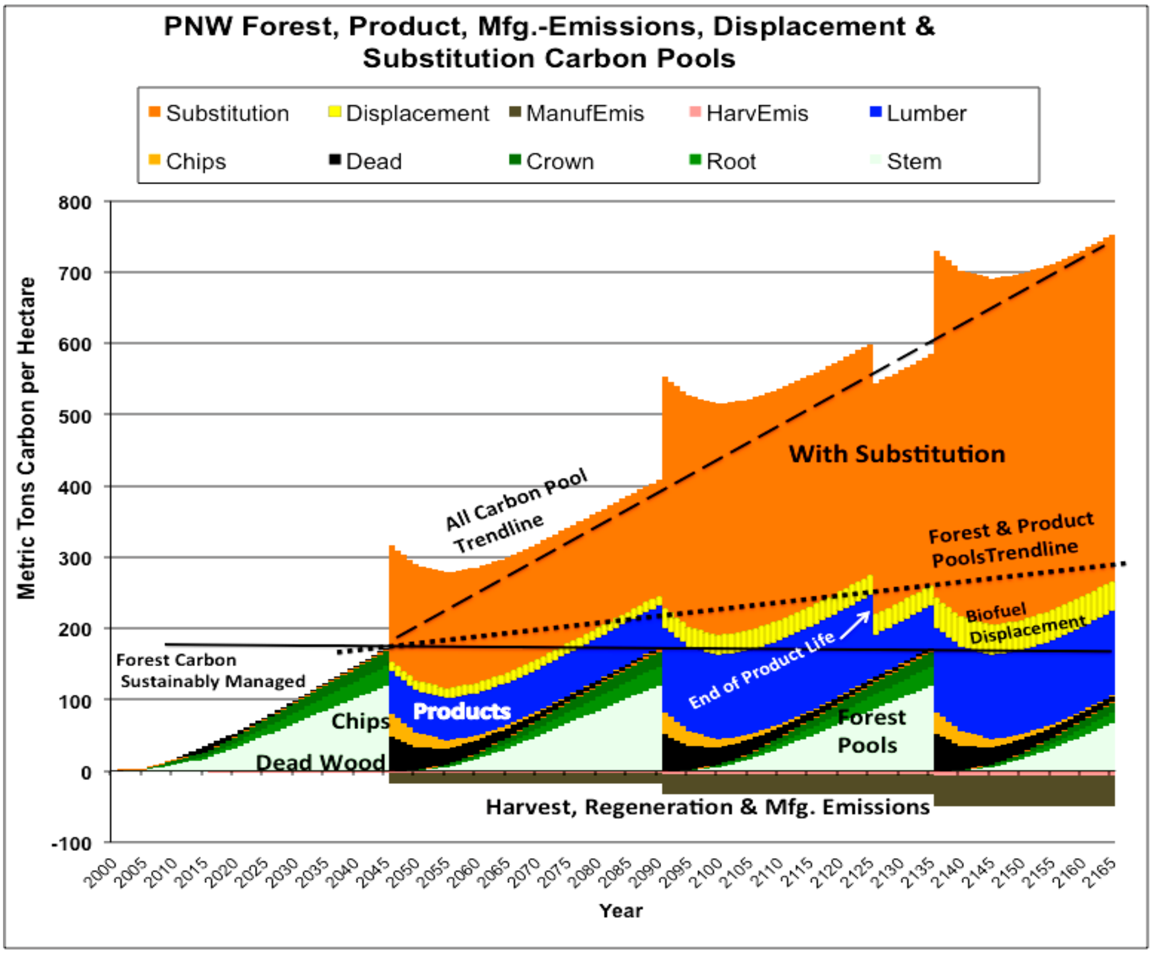
Each of these feedstocks is unique and their LCI/LCA implications are treated separately to fully understand their impacts for biofuel production.

2. Sustainable Timber Production Impact on Carbon Mitigation

The Consortium for Research on Renewable Industrial Materials (CORRIM), a non-profit consortium of mostly university research institutions [3], has measured all the inputs and outputs for every stage of wood processing and use across most structural and high volume non-structural wood products in each of the major US wood producing regions (Pacific Northwest—PNW, Southeast—SE, Northeast Northcentral—NE/NC and Inland West—INW) [4,5]. This work has identified a wide range of carbon mitigation impacts. Since these products come from sustainably managed forests, land use change such as deforestation is not a significant issue, nor is the maintenance of other forest values except those mandated by state laws that become a part of sustainable management forest treatments.

Perez-Garcia *et al.* [6] characterized carbon impacts in the forest, in the production of products, and in their use as substitutes for non-wood building products. These findings were extended to include broader considerations for substitution shown in Figure 1 [7]. Using the PNW example scenario, Figure 1 starts at bare ground with forest regeneration (yr 2000); the forest carbon pools include the carbon in the managed forest stand (stems, branches, roots, foliage, litter) as they grow across the rotation, while the dead forest residuals increase after harvest followed by decay. The accumulation of biomass outside of the forest during sustainable harvest cycles (45, 90, 135 years) includes short and long-lived wood products, and their processing emissions (a negative carbon store) including the planting phase for each subsequent crop. Solid wood products are shown with an 80-year half-life assumption consistent with the Perez-Garcia analysis but conservatively the end of life wood products are burned at disposal without energy recapture or landfill storage. Short-lived products are shown as decomposing rapidly. Mill residuals used to reduce fossil processing energy needs provide a partial offset to manufacturing emissions. Finally, substitution for non-wood products (such as concrete framing in residential construction) displaces the need for fossil intensive products. The end result is that total carbon accumulation across all pools increases at 4.6 tonnes of carbon per hectare per year (4.6 tC/h/y) for typical PNW forests. Other forests with lower productivity have lesser increases but similar sustainable carbon mitigation trends. Regardless of the actual gain, this sustainable carbon mitigation from using wood products and biofuels has the potential to exceed the growth rate in forest carbon because of the high leverage when wood substitutes for fossil intensive products and their emissions. The impact of substitution more than offsets the decay of dead wood in the forest not collected after harvesting. Lippke *et al.* [7] also show a substantial variation in the impact of substitution across different product uses. A more recent study by Sathre and O'Connor [8] analyzed available substitution studies and derived from a meta-analysis an average displacement from substitution of 2.1 C (or CO_2) displaced per 1 C (or CO_2) used in the wood, providing some bounds on the uncertainty of substitution impacts.

Figure 1. Carbon pools from a sustainably managed forest stand and its wood products, including biofuel displacement from mill residuals and product substitution. Reproduced with permission to publish from Wood Fiber Science [7].



A similar comparison was made for the INW region where total carbon grew at 2.5 tC/h/y, a rate consistent with the lower site productivity of that region [9]. Sustainable management supports sustainable carbon mitigation across all carbon pools. The carbon mitigation is not capped by the carrying capacity of the land or offset by the substantial amount of slash and dead wood that is left in the forest after harvest when we account for the carbon stored in products and used in place of fossil fuel derived carbon emissions. The collection of residual materials (currently left in the forest to decay) for biofuel production was not included in these life cycle studies of currently merchantable products. Collecting more of the post harvest forest residuals as an energy feedstock could substantially increase the biofuel displacement of fossil fuels and their emissions.

3. Impact of Using Forest Residuals for Biofuel

Oneil and Lippke [10] collected data on almost 2000 slash piles in NE Washington representative of the INW region, sampled the remaining area for dispersed slash volume, and compared measured slash volume versus actual volume recovered at a cogeneration plant to derive a total estimate of available slash per unit area and per unit volume harvested. Final tallies concluded that the merchantable timber removed approximately half of the above ground biomass. Some of the remaining material was too difficult to collect and some would be required for ecosystem function. The remaining volume considered potentially collectable for biofuel feedstock was equivalent to about 45% of the merchantable volume currently being removed or about 23% of the total above ground volume. Currently, mill residuals used for energy at the mill are approximately 6% of the above ground inventory. Therefore, for the INW, the potentially available biofuel feedstock is approximately 4-times more than the current carbon offset produced from mill residuals. The recovery of forest residuals varies greatly by region and site. It can be nearly 80% from whole tree thinnings in flat terrain in the SE [11]. Even when the recovery rate of forest residuals is quite low it can provide a substantial contribution to renewable energy, carbon mitigation, and energy independence.

In order to recover this potentially collectable feedstock for biofuel use, higher fossil fuel prices, incentives, increased carbon values, or cost reducing collection technology changes will be needed. Increased feedstock recovery may not necessarily increase the return to the landowner but would contribute more jobs and profits from the increased biofuel-processing infrastructure.

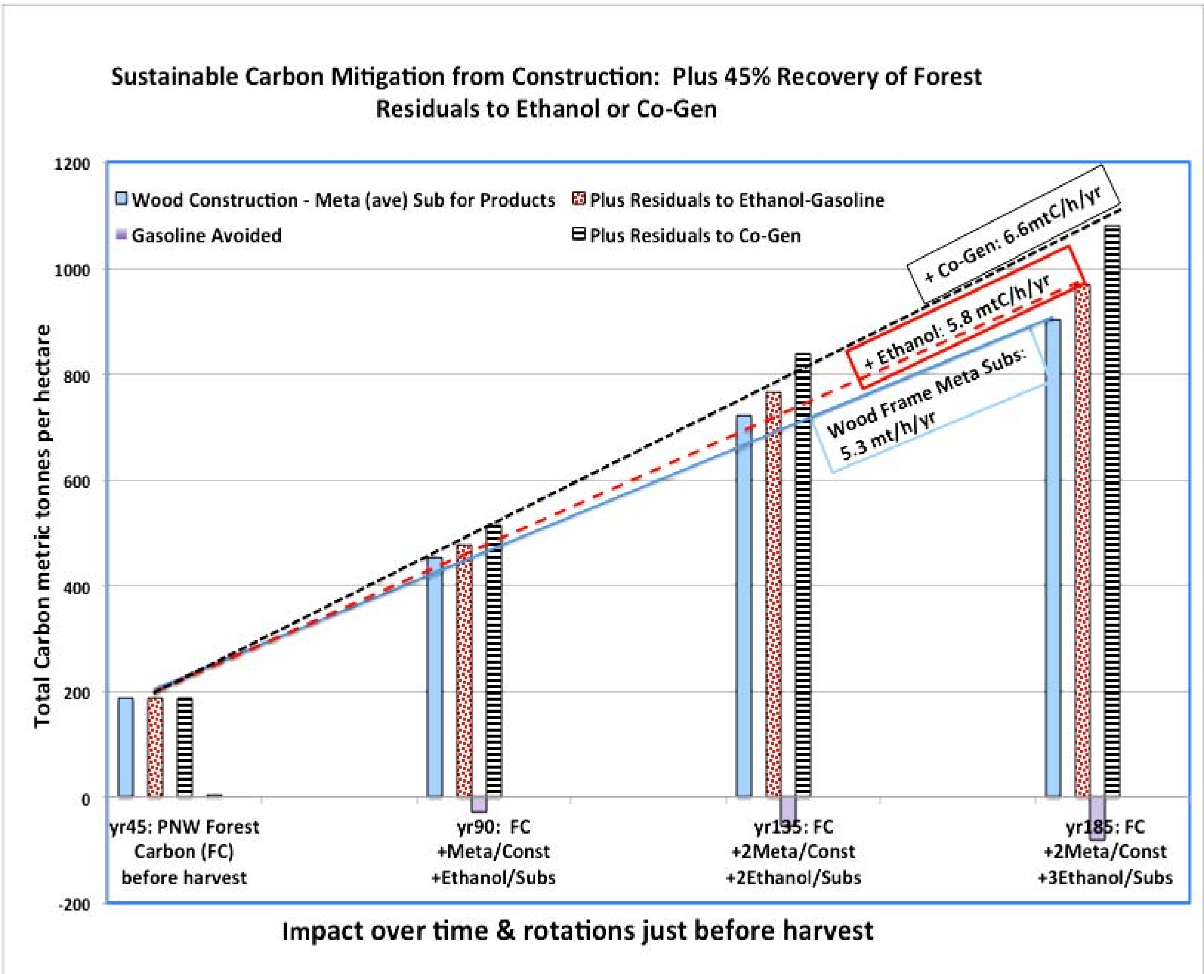
The complexity of Figure 1 can be simplified by looking at snapshots in time. Note that while the dead wood pools and short lived product pools in Figure 1 do add to carbon stores early in each rotation, they become negligible by the end of each rotation with no accumulation from one rotation to the next. Hence they do not contribute to increasing carbon storage over time or sustainable mitigation of carbon emissions. From the perspective of sustainable carbon mitigation we can measure sustainable trend impacts in carbon pools by measurements taken at the end of each rotation absent these short-lived carbon pools.

4. Impact of Using Forest Residuals to Displace Coal or Gasoline

Using the end of rotation values only, in Figure 2 we illustrate the impact of a 45% biomass recovery of forest residuals from the PNW forest featured in Figure 1 as an addition to the product carbon stores and substitution impacts. Two alternative scenarios to the standard harvest serving wood frame structural products (the lowest trend line) are evaluated: (1) biomass used as biofuel is processed in a large cogeneration energy facility with equivalent efficiency to that of coal ('Plus residuals to Co-Gen'); and (2) biomass is gasified to produce ethanol ('Plus residuals to Ethanol-Gasoline'). In both cases we include the emission impacts from the fossil energy displaced by the pulp chips consumed for energy production, an impact outside the wood products mill and not included in Figure 1. Comparing year 90 'Plus residuals to Co-Gen' to year 90 'Average Wood Frame Substitution' in Figure 2 shows a 25% increase in carbon stores and offsets across all carbon pools for the 'Plus residuals to Co-Gen' option when we recover 45% of forest residuals. This relatively small gain from recovery of almost half of the residuals occurs because the efficiency of direct energy displacement is less than half the impact of structural wood product substitution. In the Co-Gen case the substitution for domestic coal does not have a direct impact on energy independence even though it has a substantive impact on carbon mitigation.

Using biomass to produce ethanol as a direct substitute for gasoline requires more processing energy for refining the fuel than the cogeneration example but has the additional benefit of contributing directly to energy independence objectives. Ongoing research that analyzes the life cycle impacts of the collection of biofuel feedstock and processing to produce ethanol shows that carbon efficiency to displace ethanol was nearly the same for thermochemical gasification methods [12], or biochemical fermentation methods [13], with each producing a C:C displacement ratio of 0.33 to 0.37 compared to 1.0 for large scale cogeneration and 2.1 for the average found in product substitution studies.

Figure 2. Sustainable carbon mitigation trend from a Pacific Northwest (PNW) forest: (**1**) wood frame meta (average) substitution, (**2**) addition of ethanol from forest residuals, and (**3**) addition of co-gen from forest residuals.



It should be noted that the emissions from harvesting residuals was only about 3% of the emissions generated in the ThermoChem process, reflective of the general observation that harvesting residuals has low emissions relative to the conversion of wood to biofuel at the conversion plant.

The impact of producing ethanol from forest residuals on total carbon mitigation may appear to be small (a 10% increase for the 'Plus ethanol' trend in Figure 2) largely because of the high substitution leverage when structural wood products substitute for fossil intensive steel and concrete materials. In addition, biofuels impact energy independence much more directly than other wood product uses and may be valued more highly than carbon mitigation. A study done for the Washington State Legislature [14] reviewed several studies producing value estimates for the cumulative costs of US imported oil dependence to be as high as $8 trillion [15]. A broader analysis attempting to capture the total economic impacts of imported oil including military and political costs estimated that if hidden costs of imported oil were summed they would equal $3.50 per gallon added to the price paid at the pump [16]. Updates to this original study have resulted in even higher cost estimates. For perspective, $3.50 per gallon would be equivalent to a carbon emissions (CO_2) tax of $400 per US ton, 15- to 20-times higher than the values of carbon trades by the European Climate Exchange (ECX) [17].

Since reducing energy dependence has many economic impacts beyond just measuring a reduction in imports, there may not be a consensus metric for energy independence comparable to measuring total life cycle carbon pools as an easily measured metric for carbon mitigation. To the degree that ethanol substitutes for gasoline, it also creates domestic jobs and economic activity equivalent to the cost of the petroleum import, while reducing capital outflows as a key source for domestic investments. All of the jobs associated with collection of the biofuel feedstock are additional domestic jobs along with the jobs associated with building the required infrastructure. Those additional jobs for processing wood to ethanol may not all be new jobs if the ethanol production is not needed for an increasing demand and instead reduces the production of fossil transportation fuels and their domestic jobs in refining gasoline. Net domestic employment would still be substantially positive even without growth in transportation fuel needs.

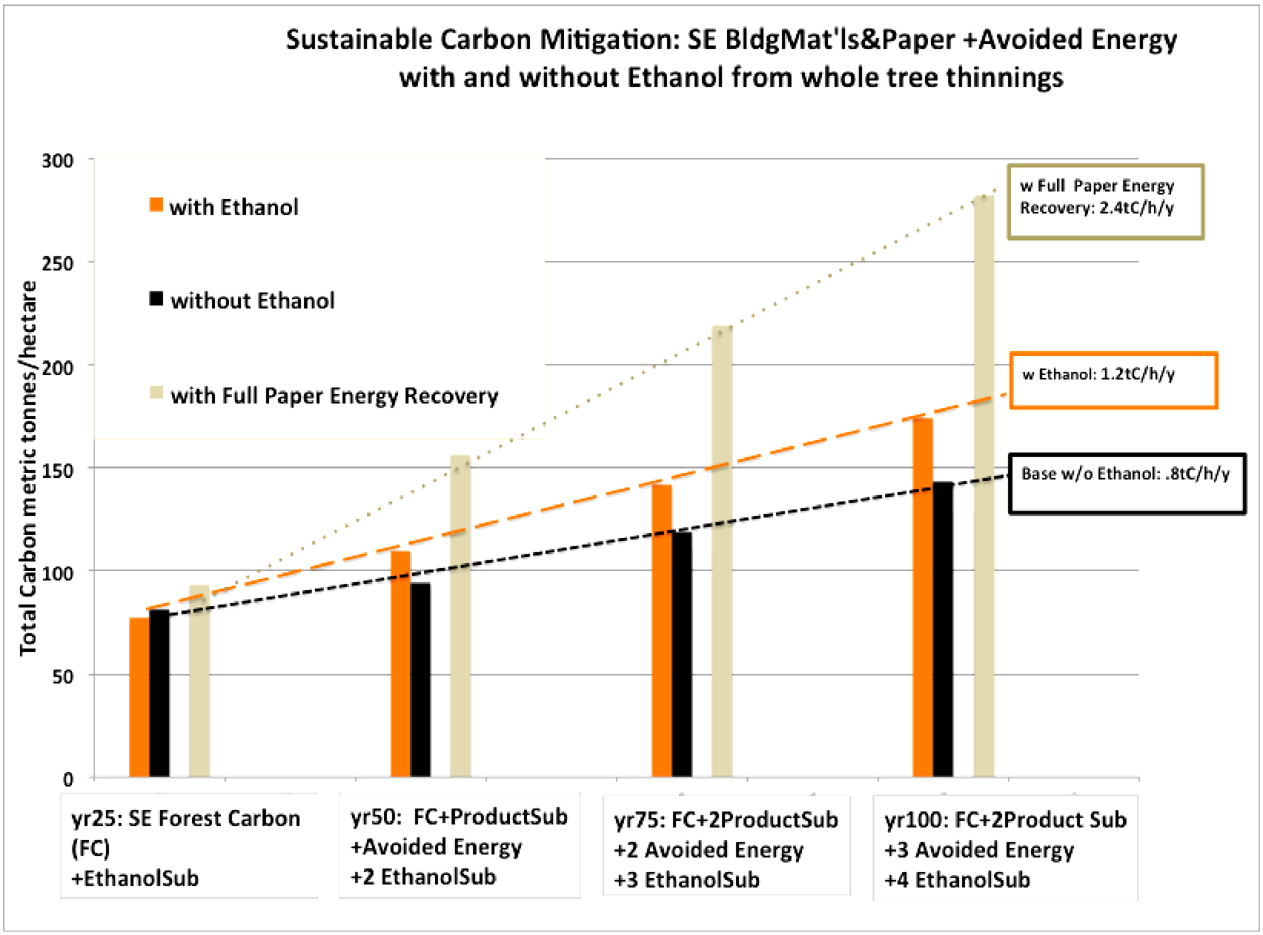
5. The Impact of Whole Tree Chipping

Collecting post-harvest forest residuals is only one of the many potential feedstocks for biofuels. The efficiency of collecting whole tree chips for biofuel feedstock is considerably higher than the collection of forest residuals after harvesting. We illustrate this impact for a SE forest where pre-commercial thinning on mid and higher site lands helps to raise the final value of the merchandised logs (Figure 3). Unlike the PNW, in the SE a large share of the merchandised logs flows directly to chips for pulp and paper. Lacking studies on the substitution impacts for not producing pulp and paper the otherwise short life cycle on pulp and paper products does not contribute to the high product substitution leverage noted for the PNW. We do include the avoided energy from the portion of chips in making pulp that avoids the need for fossil energy but believe this substantially understates the true value of chips relative to substitute products.

For the SE sustainable production of logs for building materials and avoided energy for the production of pulp and paper, our LCI data produces a 0.8 tC/h/y sustained carbon mitigation trend. The incremental contribution of ethanol substitution for gasoline from whole tree thinnings that would otherwise be left to decompose raises the contribution to 1.2 tC/h/y, a 50% increase. While the sustained trend in carbon mitigation is much lower than for the PNW, the increase in contribution from generating ethanol to displace gasoline has a higher leverage impact than collecting forest residuals in the PNW.

As a more direct comparison of the impact on carbon mitigation we include a scenario where all the wood volume going to pulp and paper or ethanol is processed with the efficiency of a large-scale cogeneration plant. This provides a reasonable proxy for evaluating the value from the biomass in chips for pulp and paper as not less than their energy value. The sustainable trend carbon mitigation of 2.4 tC/h/y is 2-times the base scenario including the ethanol production from whole tree thinnings, although still substantially lower than the PNW example, which includes a much higher volume of carbon leveraged through product substitution.

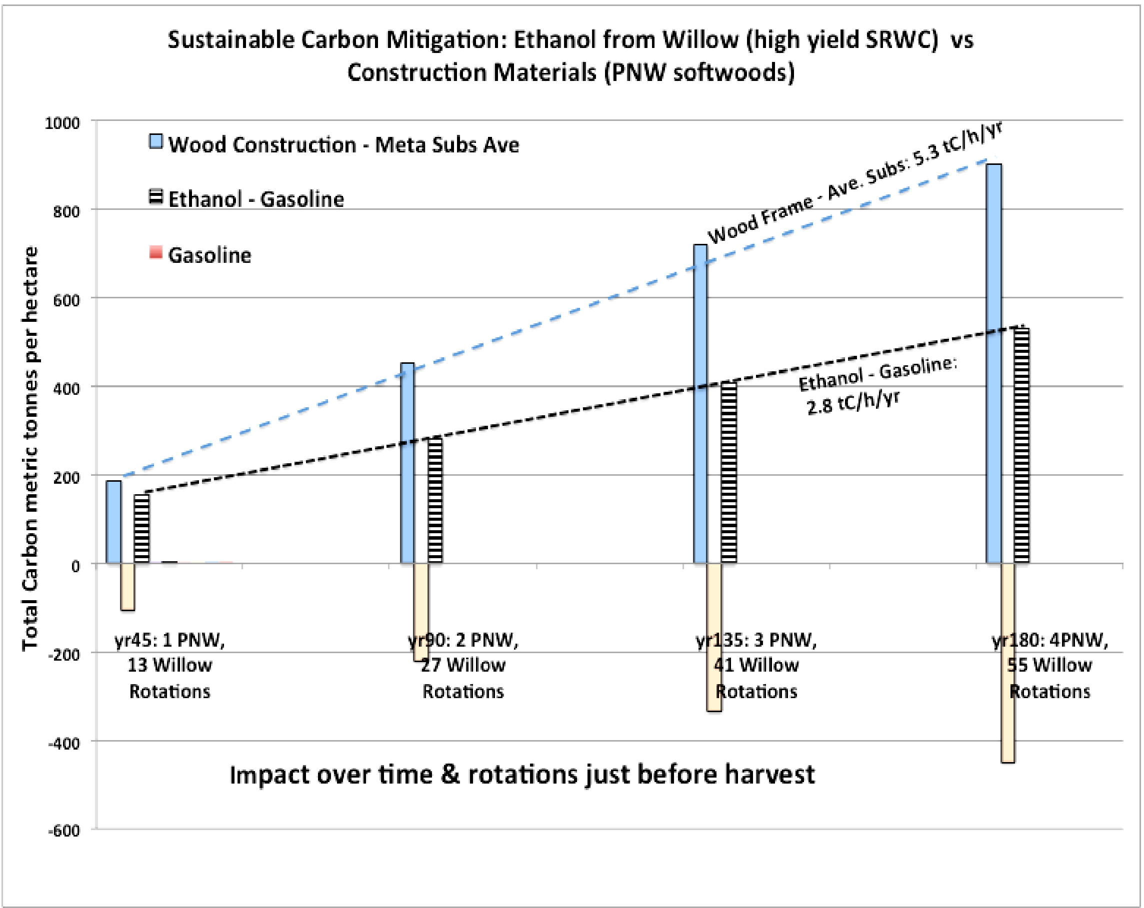
Figure 3. Sustainable carbon mitigation trend from a SE Forest: (**1**) Base production of construction and paper products, (**2**) with ethanol production from pre-commercial thinnings, and (**3**) with full energy recovery from the chips.



6. Impact of Short Rotation Woody Crops

Devoting the land solely to biofuel production provides opportunities to increase the yield over that possible when producing structural materials. Willow is but one of several woody crops that can be grown with high yields on short rotations. In spite of the low carbon conversion efficiency to ethanol, willow's high growth rate results in a significant sustainable carbon mitigation trend as shown in Figure 4, as well as contributing to energy independence [13]. The willow sample plots in the NE region grew at 7.5 tC/h/y compared to 4.2 tC/h/y, for the highest structural wood analyzed from the PNW region. While willow processing to ethanol produces a lower carbon mitigation trend than the PNW carbon mitigation trend, the 2.8 tC/h/y for willow-sourced ethanol displacing gasoline exceeds even the full energy recovery alternative for the SE region. We show the emissions from the combustion of gasoline separately to provide perspective on the impact of using short rotation woody crops to displace the equivalent energy that would otherwise be provided by gasoline.

Figure 4. Total carbon mitigation potential from high yield short rotation crop of willow producing ethanol by biochemical-fermentation *vs.* PNW wood construction materials (Meta-average substitution).



7. Performance Efficiency Metrics

The US Environmental Protection Agency (EPA) grandfathered lower threshold requirements for existing agricultural feedstocks supporting corn-ethanol production that produces as little as a 20% decrease in emissions from gasoline to meet federal standards. For cellulosic ethanol they required a 60% decrease. Even though thermochemical (gasification) and biochemical (fermentation) ethanol produce nearly the same carbon displacement efficiency ratio, since the fermentation process produces excess energy offsetting the need for fossil energy it is approximately carbon neutral [13]. As a consequence, ethanol from fermentation scores substantially better than ethanol from gasification on the EPA displacement of gasoline emissions scale, as summarized in Table 1. From a pure fiber efficiency comparison the two processes are only marginally different with each tCO_2 in the wood used displacing about 0.33 to 0.37 tCO_2 of gasoline emissions. Fermentation processes use substantially more water than gasification. The fermentation process is relatively efficient for moisture prone feedstock such as willow, but may be less efficient where natural drying in the collection process may be practical.

Table 1. Processing efficiency measures.

Efficiency measures	Ethanol from whole tree thinning SE by gasification	Ethanol from SRWC by fermentation	Co-gen from forest residuals	Wood product meta-substitution
% CO_2 reduction *vs* gasoline	68%	110%	-	-
% CO_2 reduction *vs* coal	-	-	96%	-
CO_2 avoided/CO_2 in wood	0.33	0.37	1.0	2.1

8. The Impact of Incentives

Using wood as a biofuel falls short of the carbon mitigation potential provided by the use of quality wood to substitute for more fossil intensive building materials. However, not all wood is suitable for these products. Also, the harvest of wood suitable for these products always generates a lower grade wood source that can be exploited positively for biofuels. For wood-quality that cannot be effectively used in producing such high valued products, using the fiber as a biofuel is still effective in directly displacing fossil fuels. The 60 to over 100% reduction in the emissions from combusting gasoline with equivalent energy value to ethanol understates the simultaneous and even more valuable benefits for energy independence goals.

Since the cost of biofuel feedstock collection generally falls short of economic breakeven efforts, policy incentives are being advocated as low cost methods to increase the use of renewable energy contributing to carbon mitigation. Congress initially provided a $0.51 tax credit for producing corn-ethanol, which helped to raise the production of corn ethanol substantially in recent years. The effectiveness of the tax credit has been much in doubt as life cycle studies developed after the increase in production have shown the carbon efficiency in producing corn ethanol is low. EPA analyzed 14 energy alternatives noting that corn ethanol reduced the emissions of gasoline only about 22% [18]. Stiles *et al.* [19] reported that it may be as low as 12%. Using the EPA estimate it takes almost 5-times the volume of corn-ethanol to eliminate the carbon emissions from one gallon of gasoline. Considering the value of CO_2 reduction relative to $13–30/$tCO_2$ that has been available in the European Climate Exchange (ECX, a non-voluntary exchange for carbon emission credits [17]) the carbon incentive for ethanol was about $295/$tCO_2$. Congress's incentive has been more than 10-times larger than the ECX value of carbon over many years. This high cost incentive no doubt contributed to the requirements set by Congress in the 2007 Energy Independence and Security Act [1] that alternative fuels be subjected to a life cycle analysis of their emission reductions relative to gasoline and that they must exceed specified threshold levels of improvement in order to meet federal standards, a very important step in increasing the transparency of carbon mitigation impacts.

Efforts to incentivize the use of woody biomass as a biofuel feedstock will likely divert some feedstock away from the production of products that have a higher leverage in reducing carbon mitigation than the biofuel. The incentive to produce more ethanol bids away feedstock from users that may have reduced emissions more than that possible from ethanol such as composite panel manufacturers. To avoid the risk of counterproductive impacts on carbon mitigation, incentives need to be directed to the most highly leveraged carbon mitigation opportunities not the lowest, such that any diversion of feedstock use raises the carbon mitigation impact rather than lowers it. Attempts to incentivize only the collection of biomass that was not previously collected could focus the incentive on an increase in the supply of biofuel feedstock rather than a diversion of feedstock from existing uses. However, the definition of what is collectable changes with economic/market conditions and will not remain the same, a very ineffective criteria for a policy baseline that will likely have negative carbon mitigation impacts as prices change.

Even the renewable energy standards for electric utilities that require a minimum threshold level of biomass in their feedstock may be counterproductive in some regions in that the utility must pay whatever it takes to procure the necessary renewable biomass volume, which inherently can be bid away from existing product users of the feedstock before paying for the cost to collect bio-material that is left as waste.

Some regions such as the PNW export considerable amounts of surplus electrical energy to Southern California while at the same time importing energy for transportation making renewable electrical energy standards ineffective. Renewable energy standards can promote fragmentation of biofuel feedstock increasing the cost of biofuels while increasing the surplus in regional electrical energy. But without renewable portfolio standards there would be little woody feedstock going into power production.

In order to avoid counterproductive policy the value of carbon must be reflected in material costs proportional to the carbon mitigation potential. Using the carbon tax on fossil fuels as an example, it would be passed forward along each processing stage so that the cost of final products would reflect cost increases proportional to the product's contribution to carbon emissions. While objectionable from the perspective of the tax lowering income, any income affect could be offset by tax reductions of a like magnitude. More difficult may be attempting to avoid becoming uncompetitive internationally as import costs decline relative to the impact of the domestic tax increase. However, there are substantially different tax-impacts across developed countries already, as some form of emission taxes have been adopted in many countries more than a decade ago.

9. Conclusions

Effectively using wood to displace fossil emissions involves displacing the most fossil intensive products and fuels. Substituting wood for non-wood building materials can displace far more carbon emissions than using the wood for biofuel. This fact creates a hierarchy of wood uses that can provide the greatest carbon mitigation for each quality spectrum of material. From a carbon efficiency perspective, the opportunity for biofuels lies in using wood that is not suitable for products that have higher leverage carbon displacement opportunities. There are large potential sources of biofuel feedstock in forest residuals, thinnings, waste recovery and short rotation fast growing species. While each material source relies on different collection methods, the emissions from the collection activities are typically small relative to the carbon displacement potential of the biofuel. Regional differences can be large and must be assessed for optimal carbon mitigation potential against existing uses that may provide higher leverage.

Using biomass for feedstock to produce transportation fuels such as ethanol requires more energy inputs than heat and power uses of biofuels, resulting in less carbon displacement efficiency per unit of wood fiber. The carbon efficiency is however only one part of the equation. Transportation fuels depend heavily on imported oil and therefore have value in terms of their additional contributions to the domestic economy, including energy independence and rural economic development. These additional benefits from developing biofuels add complexity to the policy making process. Until there is a higher value for carbon the benefits of energy independence may more than offset the benefits from carbon mitigation derived by displacing fossil emissions from heat and power uses. Socio-economic research is needed to better determine the relative values of carbon mitigation and energy independence noting that there will be regional differences. We can estimate the production cost of ethanol by processing methods and regional differences with and without incentives/subsidies. We can also estimate the relative costs of producing sustainable carbon mitigation from a mix of biomass products. Lower cost carbon mitigation may not be more valuable. We need to better understand the economic impacts of prices and how indirect impacts such as land use change and global geopolitical risks should be considered.

Each biofuel processing and feedstock collection alternative produces different carbon mitigation impacts. Custom fitting the feedstock to the processing option within each region is needed to maximize carbon mitigation potential. There are opportunities to improve carbon mitigation substantially. It will require more effective use of currently merchantable wood and overcoming the cost barriers to substantial investment in renewable biofuel production from waste wood. Incentives are another option. Without incentives the low cost floors for producing fossil fuels will limit investments in using renewable fuel options. However, avoiding counterproductive incentives is complex and is best addressed by requiring life cycle assessment measurements to determine total carbon impacts on a regional basis.

Acknowledgements

This report integrates findings across many previous CORRIM reports with recent biofuel life cycle research funded by the USFS Forest Products Laboratory and CORRIM's member institutions. Any opinions, findings, conclusions or recommendations as expressed in this article are however those of the authors and do not necessarily reflect the views of the contributing entities.

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