Greenhouse gas and air pollutant emissions of alternatives for woody biomass residues

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Preface

This report and the accompanying Woody Biomass Emissions Calculator (WBEC) were commissioned to provide regional air managers and decision makers in the Pacific Northwest and Alaska with tools for evaluating air emissions implications of alternatives for managing the woody biomass residues from forest practices. In addition to producing merchantable timber, forest practices generate considerable volumes of woody biomass residues, including branches, tops of trees, and small diameter trees. Forest practices can include harvest followed by reforestation; thinning for forest fuel reduction or timber management; or clearing for an alternate land use. In all such cases, woody biomass residues are generated and are commonly collected in "slash piles" to be burned or left to decompose. On average, one third of a ton of woody biomass residues are generated for every ton of merchantable timber harvested in the region.[1] In Washington State, approximately 2.4 million bone dry tons (bdt) of logging residues are generated annually.[2] If accessible and used to generate power, this material could represent a significant energy resource.

This report considers alternative fates for woody biomass residues and their implications on air emissions associated with both global climate change (carbon dioxide, methane, and nitrous oxide) and local air pollution (fine particulates and carbon monoxide). Results presented in this report can help decision makers understand potential implications of alternatives, such as whether greenhouse gas (GHG) and air pollutant emissions are reduced by using woody biomass residues for off-site uses instead of burning it on-site. While there has been ongoing and extensive research to assess the emissions implications of alternative forest management activities, little research has considered options for managing the woody biomass residues generated by these activities. This report is intended to help fill this gap.

Sustainably managed forests can offer the opportunity to produce valuable forest products while providing ecosystem services, economic benefits, cultural value and helping to maintain the global carbon balance. Unlike the "fossil carbon" found in oil, gas and coal, where combustion releases carbon otherwise sequestered for the long-term, "forest carbon" is part of the "current carbon cycle", where regrowth can naturally recapture carbon released from forest practices. Decision makers are faced with significant challenges in developing sustainable forest management policies that address the potential of sequestering carbon in forests and generating bioenergy from wood, while considering the interlocking policy concerns of energy security, climate change and natural resource management.. By focusing on alternatives for using woody biomass residues, this report touches upon a little-studied segment of the energy-climate-forest policy nexus.[3]

In the Pacific Northwest (PNW) and Alaska, several state policies help to promote sustainable forest management. Soon after harvest, reforestation of forest lands is required in Washington, Oregon, Idaho

[1] Reference 230 (References are cited in this report using a 3-digit code and are listed in the reference section.)
[2] Reference 226
[3] Reference 222

and Alaska, unless the land is converted to another use.[4] However, projected climate impacts may weaken the carbon storage capacity and potentially increase emissions from forests in the PNW, as drought and warmer temperatures would likely contribute to plant growth decline, insect outbreak and forest fire risk.[5] Removing or leaving woody biomass residues on the ground following harvest can have varying impacts depending on the local climate conditions, nutrient-level and forest type. In nutrient-poor forest sites, leaving woody biomass residues behind may improve productivity of reforested stands by enhancing nutrient and water retention.[6] On the other hand, in forest stands at risk of forest fire, especially in eastern Washington, Oregon and Idaho, the removal of woody biomass residues together with thinning can reduce forest fire severity by reducing forest fuel availability.[7] These important issues demand further research and attention to develop effective forest land use management practices. This study, evaluating alternatives for woody biomass residues, represents one piece of the complex forest management puzzle that has previously received little attention. We hope that this research, together with the work of others, can help inform forest management in the Pacific Northwest.

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[4] Washington (RCW 76.09.070), Oregon (ORS 527. 745), Idaho (Idaho Administrative Code, Department of Lands, 20. 02. 06) and Alaska (Alaska Admin. Code 11 § 95. 375)

[5] References 221,224

[6] References 227-229

[7] Reference 225

How to Use this Report

The analysis presented in this report starts *after* the point where timber is harvested and woody biomass residues are generated; it begins at the point where the residue is collected in the forest and ends with its ultimate use or disposal. Based on these starting and ending points, this report represents a "post--harvest-to-grave" analysis of fates for woody biomass residue utilization. By design, our analysis does not encompass the woody biomass life cycle "upstream" of the point where the woody biomass residues are collected, and therefore does not include the emissions and/ or carbon sequestration from forest growth, forest practices or forest regrowth. It is important that this report and the accompanying analysis tool not be used out of the context or beyond the explicit limits of the study boundary; that is, it should only be used for comparing alternative fates for existing streams of woody biomass residues. This analysis has no implication or bearing on forest management choices that affect forest growth or forest harvest.

Acknowledgments

This report was requested by the regional air directors from the U.S. EPA Region 10 to analyze the life cycle air emissions of options for utilization of woody biomass residues generated from forest practices in the PNW and Alaska. This research was funded by the U.S. EPA Region 10 and managed by the Olympic Region Clean Air Agency (ORCAA). This analysis was prepared by the Seattle, WA based staff of the Stockholm Environment Institute (SEI) in collaboration with a Technical Advisory Committee made up of staff members from the U.S. EPA Region 10, Washington State Department of Ecology, Washington State Department of Natural Resources, Olympic Region Clean Air Agency, Washington State University and representatives from Grays Harbor Paper LLC.

Contents

Executive Summary

In the Pacific Northwest[8] (PNW) and Alaska, woody biomass residues from forest practices are most commonly burned on-site or left to decay. These disposal approaches are a source of air pollution and greenhouse gas (GHG) emissions. Air quality and climate change concerns have increased interest in examining alternatives for managing the woody biomass residues created through forest practices in the Pacific Northwest. Despite interest in alternatives to these practices, no comprehensive assessment of the air quality and climate change implications of the range of options or alternatives yet exists. This report and the accompanying Woody Biomass Emission Calculator (WBEC) spreadsheet tool can help decision makers understand potential air implications of alternatives, such as whether using woody biomass residues off-site can reduce GHG and criteria pollutant emissions compared to the standard practices.

The analysis starts *after* the point in the woody biomass life cycle where timber is harvested and woody biomass residues are generated. As shown in Figure 1, it begins at the point where this residue material is collected in the forest, and ends with its ultimate use or disposal. This report provides what might be termed, in life-cycle analysis parlance, a "post-harvest to grave" analysis. It accounts for emissions associated with the gathering, processing, transport, use and disposal of the woody biomass residue. It also accounts for air emissions associated with the manufacture of equipment used to harvest, process and transport the woody biomass (e.g. loaders, grinders and transport vehicles).[9] Emissions and/or carbon sequestration associated with forest management practices (e.g. harvesting, planting, and growth) are assumed to be identical for a given source of residues being compared and are by design not included in this analysis. In summary, this study quantifies and compares "post-harvest to grave" air emissions from alternatives for woody biomass residues and is not intended to account for air emissions over the entire woody biomass life cycle nor evaluate the sustainability of wood bioenergy or the carbon sequestration implications of different forest land management practices.

[8] This report includes the following U.S. States: Washington, Oregon, Idaho and Alaska.
[9] Emissions from the manufacture of equipment are referred to as capital manufacturing emissions in this report.

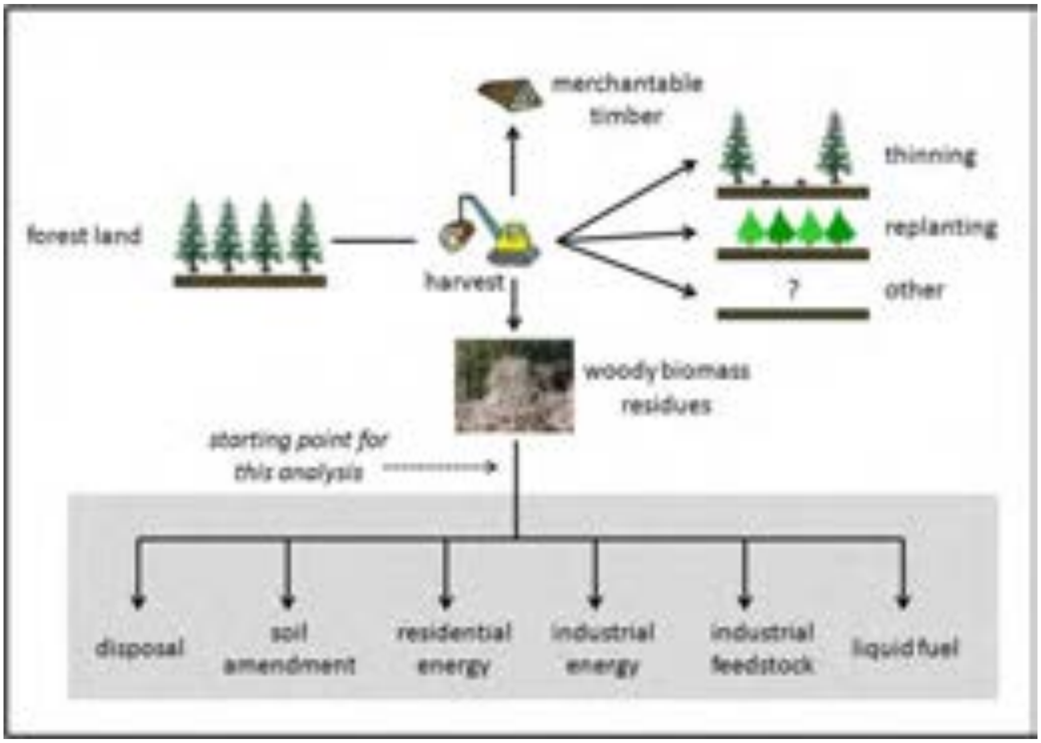

Figure 1. Schematic of post-harvest to grave analysis boundary of this report. The analysis starts *after* the point where timber is harvested and woody biomass residues are generated; it begins at the point where this residue material is collected in the forest and ends with its ultimate use or disposal. This analysis focuses on evaluating the GHG and criteria air pollutant emissions of the different alternatives for using woody biomass residues, as indicated by the shaded box. Emissions or carbon sequestration associated with forest management practices (e.g. harvesting, planting, and growth) are assumed to be identical for a given source of residues being compared and are by design not included in this analysis.

In the Pacific Northwest, the most common practice is to dispose of woody biomass residues either by burning in slash-piles or leaving residues to decompose on-site. However, this analysis explores several alternatives to these common practices that use the residues to generate new products and/or energy. There are several different alternative fates for woody biomass residues. This report compares the GHG and air pollutant emissions for 15 different fates across six categories: 1. disposal, 2. soil amendment, 3. residential energy, 4. industrial energy, 5. industrial feedstock and 6. liquid fuel. A description of each fate is provided in Table 1.

Table 1. Description of Woody Biomass Residue Fates. The table includes a definition of each product material and description of how woody biomass residues could be used to generate each product.

Woody Biomass Residue Fate	Description
1. disposal	
decomposition	Decay of scattered woody biomass residues at the forest harvest site.
combustion	Burning of “slash piles” of woody biomass residues at the forest harvest site.
2. soil amendment	
mulch	Chipping woody biomass residues for use as a protective covering for plants to improve soil moisture retention and reduce weed growth.
compost	Chipped woody biomass residues can serve as a bulking agent to be mixed with a nitrogen rich material (e.g. food waste or chicken manure) to generate compost.
biochar	Pyrolysis of biomass to make charcoal and generate electricity. Charcoal can be applied to agricultural fields as a soil amendment and be a form of biosequestration.
3. residential energy	
fireplace	Burning of fuel wood in an open hearth fireplace.
EPA-certified stove	Burning of fuel wood in a wood stove that meets U.S. EPA emissions certification standards.
pellet stove	Burning of wood pellets in a pellet stove.
4. industrial energy	
displace fossil fuel boiler	Burning of hog fuel in an industrial boiler to replace the use of fossil fuel. Hog fuel is coarsely chipped woody biomass that is used as fuel.
displace hog fuel boiler	Burning of hog fuel in an industrial boiler to replace the use of hog fuel from a different source. Hog fuel is coarsely chipped woody biomass that is used as fuel.
IGC	Integrated gasification and combustion is the gasification of a fuel to power a gas-fired engine/generator to generate heat and electricity. .
cogenerator	Production of both electricity and heat for the same industrial process.
5. industrial feedstock	
pulp feedstock	Wood pulp is fibrous material prepared from wood or recovered waste paper used in manufacturing paper or cellulose products.
6. liquid fuel	
cellulosic ethanol	Production of ethanol (and electricity) through a process of hydrolysis and fermentation.
ethanol by gasification	Production of ethanol through a process of gasification and synthesis.

Our methodology for this analysis was to estimate the net emissions for five air pollutants and compare them across 15 different alternative fates for woody biomass residues using a life cycle approach. The analysis covers three greenhouse gases (GHGs): carbon dioxide (CO_2), nitrous oxide (N_2O) and methane

(CH_4); and, two criteria pollutants: carbon monoxide (CO) and fine particulate matter ($PM_{2.5}$).[10] Carbon dioxide, methane and nitrous oxide are GHGs that contribute to climate change. Carbon monoxide and fine particulates are considered criteria air pollutants and a regulated under the Clean Air Act.

A life cycle inventory approach was used to estimate the post-harvest to grave GHG and air pollutant emissions for each of the 15 fates examined. Results in this report are based on an assumption that products created from biomass residues displace an equivalent amount of an existing product – in other words, that overall market demand for those products is fixed. For this post- harvest to grave analysis, to estimate the *net emissions* impacts of each fate in two over-arching steps. First, we calculate the *systems emissions. System emissions* are emissions associated with gathering, transporting, processing, and using or disposing of woody biomass residues. We then calculate the *displaced emissions*, which are emissions that would otherwise have occurred from the manufacture and use of products (e.g. oil for heating) that are displaced by the use of woody biomass residues. Displaced emissions, for existing products assumed to be supplied from waste streams, include emissions associated with alternate uses of products (e.g. fire wood) that are diverted by the use of woody biomass residues. Displaced emissions are normalized by energy and material yields, for example energy yield from 1 bdt of wood residues displaces the amount of heating fuel that provides the equivalent energy yield. The existing products that are avoided and displaced vary by fate and were selected based on common practices in the PNW. Lastly, *net emissions* are calculated as *system emissions* minus *displaced emissions*. This report is accompanied by the Woody Biomass Emissions Calculator (WBEC) tool, a spreadsheet based model, which can be used to estimate emissions of each woody biomass fate under different project specific conditions. As stated above, results presented in this report assume that overall market demand for products is “fixed.” However, the WBEC tool allows users to turn off this “fixed market” assumption to view results that reflect an expanding or “elastic” market for woody biomass residues.[11] We drew data and emission factor sources from current published literature, site visits, state agency reporting and facility managers (equipment/mill operation data).

Results from this analysis are presented in the figures that follow. Net GHG, CO and $PM_{2.5}$emissions for each fate and displaced product option are included in Figures 3 -5. The contribution of process steps (pre-processing, processing, distribution and use/disposal) to the GHG system emissions of each fate is presented in Figure 2.

GHG emissions from pre-processing and distribution of woody biomass residues, including gathering, chipping and transport, make up less than 4% of the overall system GHG emissions for each fate, as shown in Figure 2,. Contribution of air pollutants evaluated (CO and $PM_{2.5}$) to overall system emissions follow a similar trend for fates where woody biomass is burned or used as fuel. For fates where no combustion of woody biomass occurs (e.g. compost and mulch), combustion of fossil fuels in the pre-

[10] This analysis does not include evaluation of climate impacts of black carbon and aerosol fine particulate matter.
[11] The market is assumed to be either fixed or completely elastic. The reality is likely in-between and could be approximated by researching or developing economic *elasticities* for each product. Development of such elasticities was beyond the scope of this analysis.

processing and distribution steps are the only sources of CO and $PM_{2.5}$, thereby making up the largest contribution to these emissions.

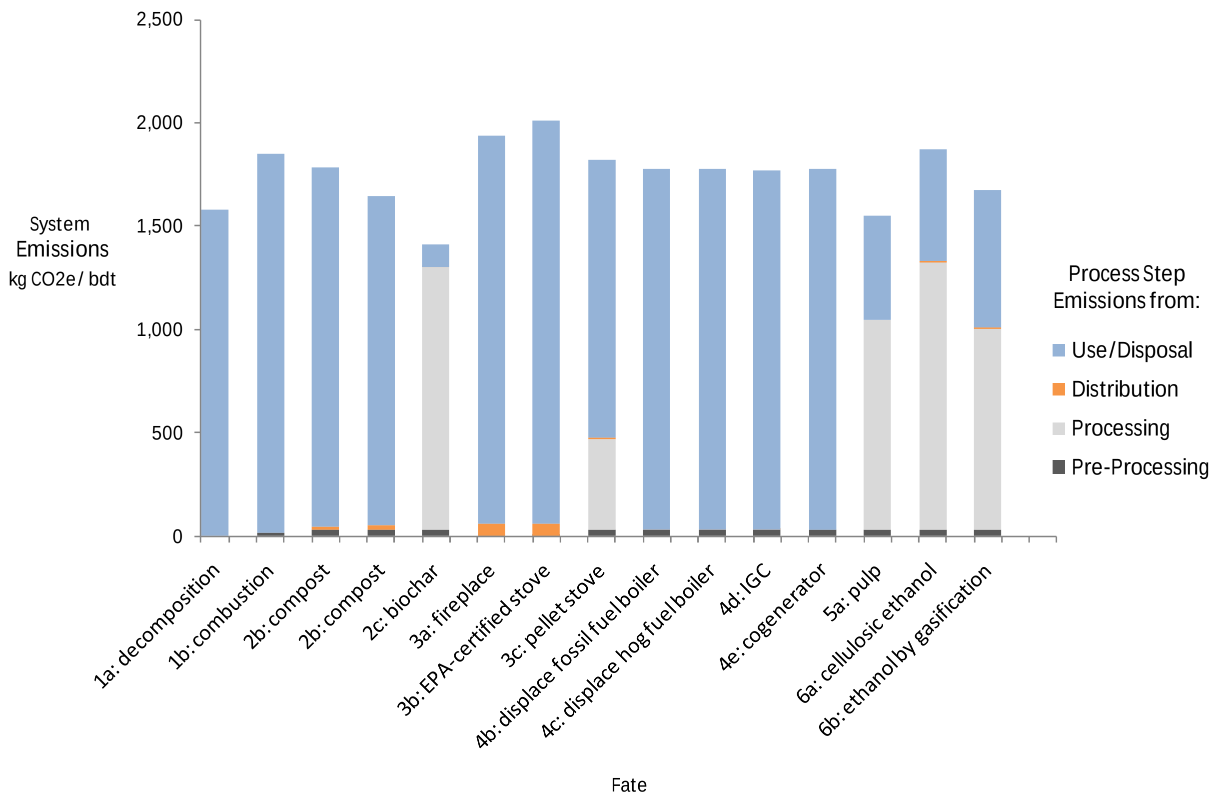

Figure 2. Contribution of GHG Process Step Emissions to GHG System Emissions for Woody Biomass Residue Fates. Chart presents the contribution of the system process steps (pre-processing, processing, distribution and use/disposal) to the overall system emissions. Process steps for each fate have been grouped into four common categories: pre-processing (black bar), processing (gray bar), distribution (orange bar) and use/disposal (blue bar).

Net GHG emissions results for each of the 15 fates considered, shown in Figure 3. For each fate, the net GHG emissions for each possible displaced existing product are plotted individually in Figure 3 using circle plots shown in green. For example, use of woody biomass in an EPA-certified stove (fate 3b) may displace electric heat, natural gas or fuel oil in a furnace, or other wood (which may then be diverted to other alternate uses), and each of these possible displaced products are plotted as a different green circle. However very similar values may overlap and may not be clearly distinguishable in the figure. For example, there are 6 different net GHG emissions values for the EPA-certified stove fate, however only 5 circle plots are clearly distinguished in Figure 3. This is because the net GHG emissions values for the alternate use of fuel wood in an EPA-certified stove or for on-site combustion are very similar and overlap in the figure.

Several fates studied result in net GHG emissions well (20% or more) below the two common practice activities, on-site combustion and on-site decomposition. These include biochar (2c), fossil fuel boiler (4b), IGC (4d), cogenerator (4e), pulp (5a) and ethanol (6a and 6b). All of these fates involve displacing fossil fuel use with biomass residue use. Cases where the use of an EPA-certified stove or pellet stove avoids the use of fossil fuels also result in net GHG emissions well below the two common practice activities. The reduction in net GHG emissions for fates that displace fossil fuel is dependent on the amount of energy generated from the woody biomass fate and the emissions intensity of the fossil fuel displaced. The more energy generated from woody biomass and the higher the emissions intensity of the fossil fuel displaced, the greater the net GHG emission reduction relative to common practice. Use of woody biomass in an industrial boiler for heat production generates more energy per bdt of woody biomass residue fuel and would displace more fossil energy resulting in net GHG emissions lower than any other fate considered. Cases where woody biomass residues displace an existing wood source do not significantly reduce net GHG emissions relative to the common practices. For these fates, unlike the case of displacing fossil fuel, there is limited GHG emissions benefit of diverting an existing wood source to another use. Even for cases where the end use is decay, as in mulch and compost, the net GHG emissions are slightly greater than the common practice of on-site decomposition because there are emissions from pre-processing and distribution. For cases where the end use is combustion, as in hog fuel boiler or residential energy, the net GHG emissions are very similar to the common practice of on-site combustion and vary depending on the alternate use emissions of existing wood sources.

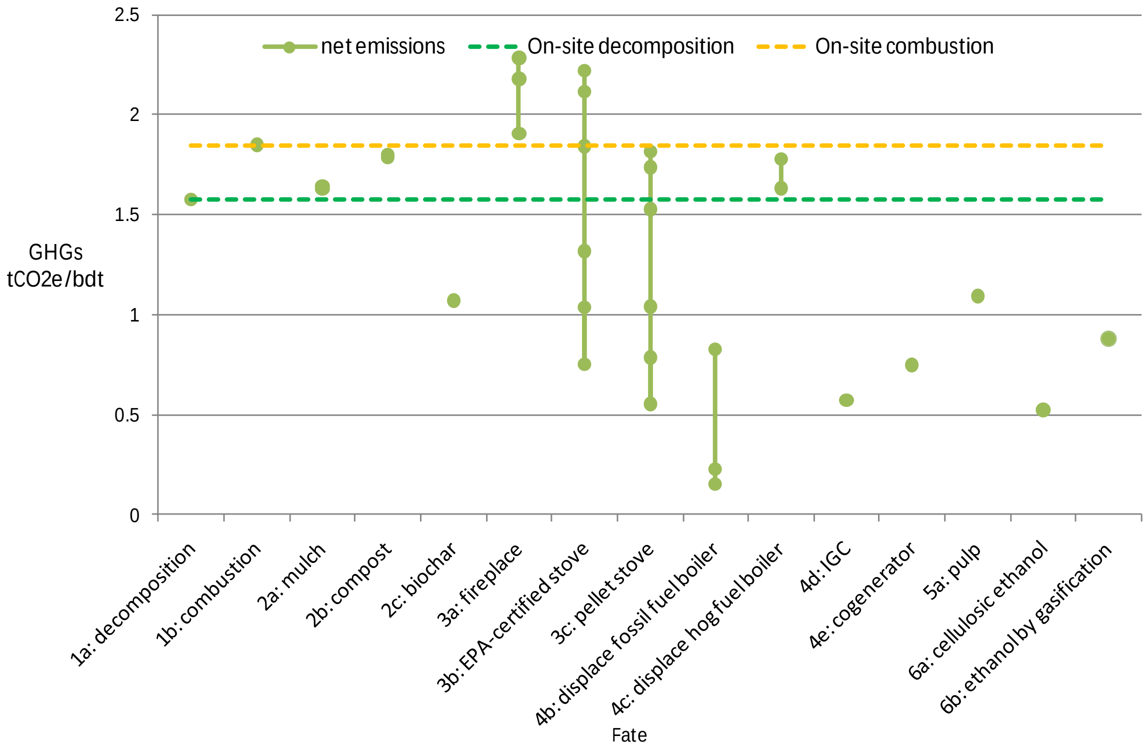

Figure 3. Net Greenhouse Gas Emissions for Post-harvest to Grave Life cycle Emissions of Woody Biomass Residue Fates. GHG emissions including CO_2, CH_4, and N_2O emissions for the 15 woody biomass residue fates included in this analysis. Common practices for woody biomass residues, on-site decomposition (green-dashed line) and on-site combustion (orange dashed line) are plotted for reference. Circle plots (green) show net emissions for each fate and displaced existing product option. Fates where there are no or only one displaced existing product option show only one net GHG emissions value. For fates where there are several net GHG emissions values for each displaced existing product, each individual value is plotted, however very similar values overlap and are not clearly distinguishable in the figure. Results assume a transport-then-chip woody biomass preprocessing approach, 35 mile transportation (to processing site) distance, 100 mile distribution (to market) distance, 100% recovery rate and fixed market demand. Negative values for net emissions reflect cases where the displaced emissions are larger than system emissions.

Air pollutant emissions from burning biomass at industrial facilities, with emissions controls, result in CO and $PM_{2.5}$ emissions that are much lower than emissions from uncontrolled burning on-site. For these fates, including biochar (2c), displace fossil fuel boiler (4b), displace hog fuel boiler (4c), IGC (4d), cogenerator (4e), and pulp (5a), use of residues results in a large reduction in CO (93% or more) and $PM_{2.5}$ (85% or more) emissions relative to on-site combustion.

Biomass combustion is a larger source of CO and $PM_{2.5}$ emissions than fossil fuel combustion. As a result the displacement of fossil fuel consumption provides a limited reduction in CO and $PM_{2.5}$ emissions. With the exception of residual oil and gasoline, there is little variation in net CO and $PM_{2.5}$ emission by fossil fuel type. Of the fossil fuels considered, gasoline is the largest source of CO emissions. CO emissions from ethanol are lower than from gasoline use. Fates that generate ethanol (6a, 6b) result in negative net CO emissions values. Of the fossil fuel types considered, residual oil is the largest $PM_{2.5}$

emissions source. The net $PM_{2.5}$ emissions for the displace fossil fuel boiler and IGC fates are lowest when use of residual oil is displaced with hog fuel use.

For residential energy use fates the CO and $PM_{2.5}$ emissions varies by stove type. Emissions from fireplaces and EPA-certified stoves emit 4 times more CO and 6 times more $PM_{2.5}$ per bdt than pellet stoves. CO and $PM_{2.5}$ emissions are higher per bdt from fireplaces and EPA-certified wood stoves than from on-site combustion.

Net CO and $PM_{2.5}$ emissions for the residential energy fates range depending on the displaced existing product. The net CO and $PM_{2.5}$ emissions are lowest if the existing fuel wood source is diverted to on-site decomposition and no burning occurs. The mid-range net CO and $PM_{2.5}$ emissions value is the case where existing fuel wood is diverted to on-site combustion. The highest net CO and $PM_{2.5}$ emissions values occur if fossil fuel is displaced or existing fuel wood is used in an EPA-certified stove. Similar to industrial energy fates, CO and $PM_{2.5}$ emissions from fossil fuel use for residential energy are much smaller than wood energy use. As a result displacement of fossil fuel provides a limited reduction in net CO and $PM_{2.5}$ emissions for the residential energy fates. Overall the largest reduction in net CO and $PM_{2.5}$ emissions, relative to the common practices, occurs when pellet stove use replaces existing use of an EPA-certified stove and existing fuel wood is left to decay.

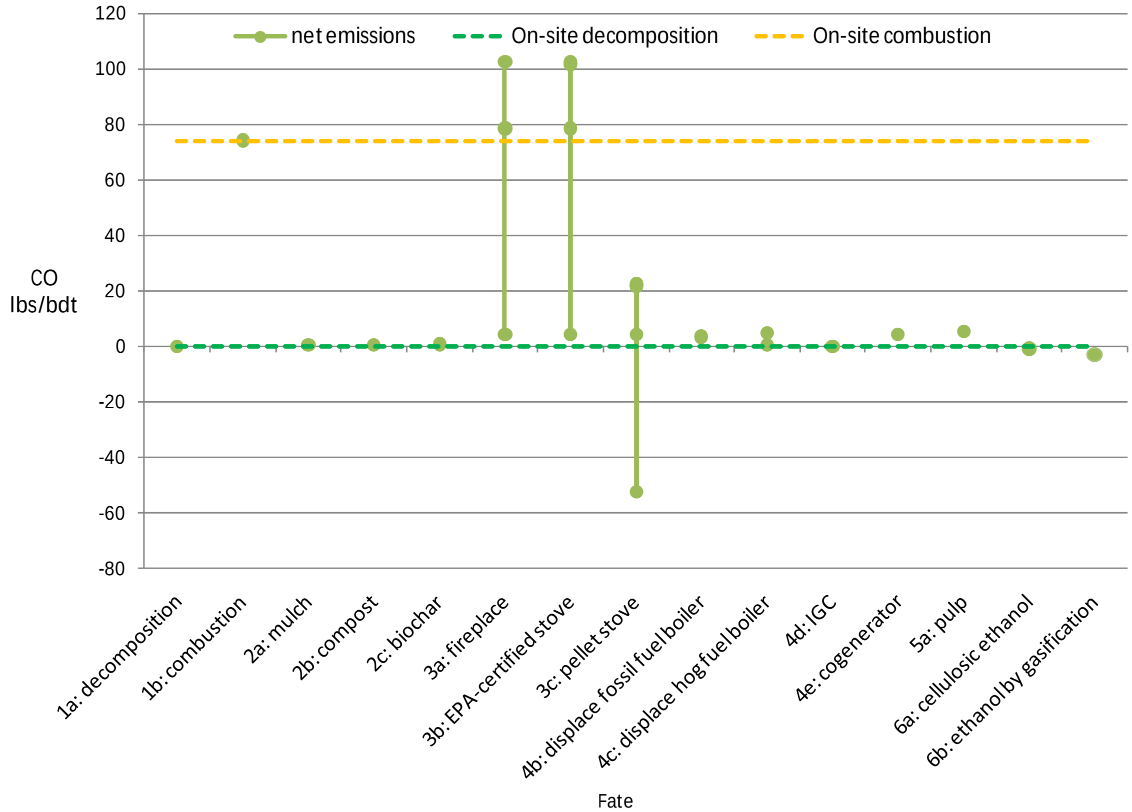

Figure 4. Net Carbon Monoxide Emissions of Post-harvest to Grave Life cycle for Woody Biomass Residue Fates. Figure shows net CO emissions for the 15 woody biomass residue fates included in this analysis. Common practices for woody biomass residues, on-site decomposition (green-dashed line) and on-site combustion (orange dashed line) are plotted for reference. Circle plots (green) show net emissions for each fate and displaced existing product option. Fates where there are no or only one displaced existing product option show only one net emissions value. For fates where there are several net emissions values for each displaced existing product, each individual value is plotted, however very similar values overlap and are not clearly distinguishable in the figure. Results assume a transport-then-chip woody biomass preprocessing approach, 35 mile transportation (to processing site) distance, 100 mile distribution (to market) distance, 100% recovery rate and fixed market demand. Negative values for net emissions reflect cases where the displaced emissions are larger than system emissions.

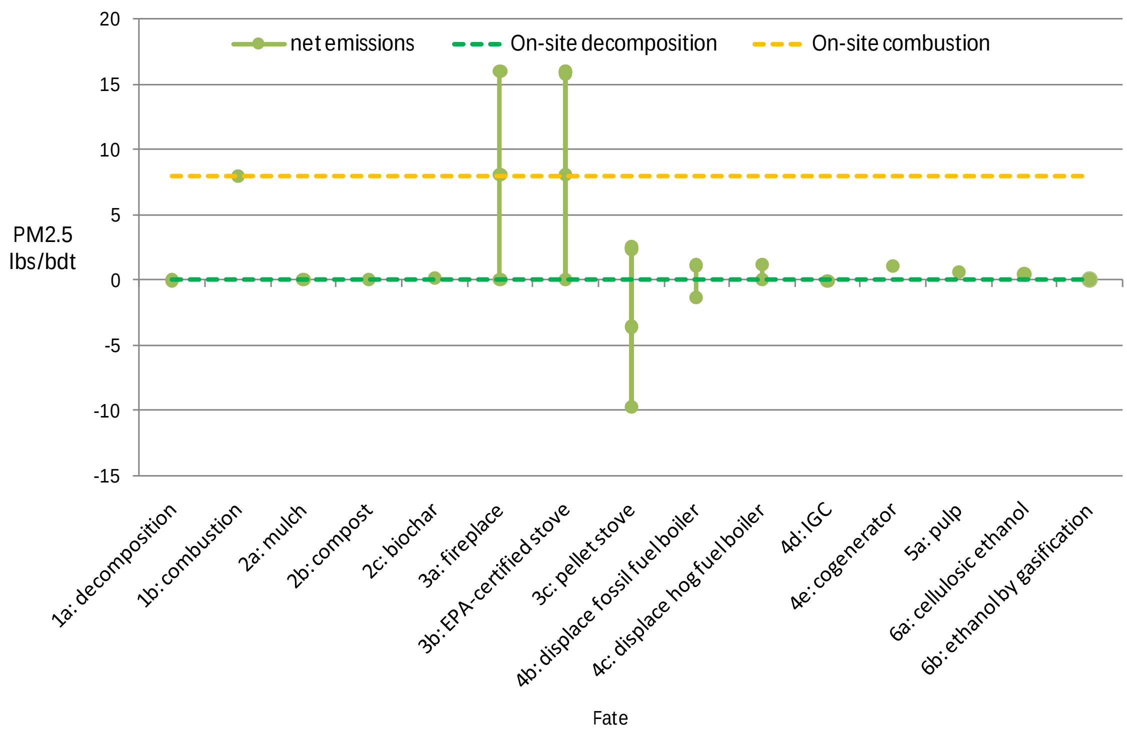

Figure 5. Net Fine Particulate Matter Emissions from Post-harvest to Grave Life cycle of Woody Biomass Residues. Figure shows net $PM_{2.5}$ emissions for the 15 woody biomass residue fates included in this analysis. Common practices for woody biomass residues, on-site decomposition (green-dashed line) and on-site combustion (orange dashed line) are plotted for reference. Circle plots (green) show net emissions for each fate and displaced existing product option. Fates where there are no or only one displaced existing product option show only one net emissions value. For fates where there are several net emissions values for each displaced existing product, each individual value is plotted, however very similar values overlap and are not clearly distinguishable in the figure. For example, there are 6 different net $PM_{2.5}$ emissions values for the fate 3b. EPA-certified stove depending on the displaced existing product, however only 3 circle plots are clearly distinguished in the figure. This is because the net $PM_{2.5}$ emissions values for some displaced products are very similar and overlap in the figure. Results assume a transport-then-chip woody biomass preprocessing approach, 35 mile transportation (to processing site) distance, 100 mile distribution (to market) distance, 100% recovery rate and fixed market demand. Negative values for net emissions reflect cases where the displaced emissions are larger than system emissions.

This analysis serves to support decision making of air managers in the Pacific Northwest region when comparing options for the use and disposal of woody biomass residues. Results demonstrate that there are many alternative uses for woody biomass residues that present a reduction in GHG, CO and $PM_{2.5}$ emissions relative to the common practice of on-site combustion. The primary conclusions of this analysis are bulleted below.

GHG emissions:

- GHG emissions from pre-processing of residues, including the gathering, chipping and transporting residues from the harvest site to a processing facility make up less than 4% of system emissions.

- Use of woody biomass residues to displace the use of fossil fuels provides the greatest reduction in net GHG emissions relative to the common practices of on-site combustion and on-site decomposition.
- The net GHG emissions for woody biomass residues that displace fossil fuels vary depending on the how efficiently residues are used as an energy source and the fossil fuel type displaced. Reductions in net GHG emissions are greatest for the fates with a higher energy output per bdt (e.g., industrial boilers) and lowest for the less efficient processes like generating ethanol via gasification.
- Use of woody biomass residues to displace existing wood and organic products results in a minimal change in net GHG emissions from the common practices of on-site combustion and on-site decomposition.

CO and $PM_{2.5}$ emissions:

- Use of woody biomass residues for a fireplace or EPA-certified stove results in an increase in CO and $PM_{2.5}$ emissions relative to the common practices of on-site combustion and on-site decomposition. The only exception is when existing fuel wood is diverted to on-site decomposition and no combustion of the displaced fuel wood occurs. Compared to on-site combustion, emissions from fireplace and wood stove use are much more likely to occur near populated areas.
- Use of woody biomass residues for residential energy in pellet stoves results in a decrease in CO and $PM_{2.5}$ relative to the common practices.
- Use of woody biomass residues for soil amendment, industrial energy, industrial feedstock and liquid fuel all result in large net CO and net $PM_{2.5}$ reductions relative to the common practice of on-site combustion.
- Use of woody biomass residues for liquid fuel to displace gasoline provides the largest net CO emissions benefit from fossil fuel displacement.
- Use of woody biomass residues for industrial energy to displace residual oil provides the largest net $PM_{2.5}$ emissions benefit from fossil fuel displacement.

Introduction

Air quality and climate change concerns have increased interest in examining alternatives for managing the woody biomass residues created by forest practices in the Pacific Northwest[12] (PNW) and Alaska. Most commonly, these residues are burned on-site or left to decay. Wood smoke generated from the burning of slash piles, as well as from residential energy and wildfire sources, is a primary air quality concern in the PNW. Reducing the threat of climate change has been a driver for the development of climate reduction goals and action plans in several states in the region. Forest activities can contribute to climate change mitigation if they serve to enhance carbon sequestration, generate bioenergy and reduce forest fire.

Despite interest in alternatives to the existing woody biomass practices of burning or on-site decay, no comprehensive assessment of the air quality and climate change implications of the range of options for the PNW yet exists. This report considers alternative fates for woody biomass residues and their implications for emissions of selected air pollutants associated with global climate change (carbon dioxide, methane, and nitrous oxide) and local air pollution (fine particulates and carbon monoxide). Results presented in this report and in the accompanying Woody Biomass Emissions Calculator (WBEC) can serve as a decision support tool for decision makers to better understand potential implications of alternatives, such as whether greenhouse gas (GHG) and criteria pollutant emissions can be reduced by using woody biomass residues for some off-site use instead of burning it on-site or leaving it to decay.

Many different types of forest practices in the PNW generate woody biomass residues. For example, forest lands may be thinned for forest fuel reduction or pre-commercial thinning, harvested and replanted, or converted into an alternate land use. In all cases, in addition to generating merchantable timber, woody biomass residues are also created. For every ton of merchantable timber harvested in this region, on average one-third of a ton of woody biomass residues are generated. [13] In Washington State, approximately 2.4 million bone-dry tons (bdt) of logging residues and forest thinnings are generated annually.[14] This material could represent a significant energy resource. However, the air-quality and greenhouse gas implications of these alternatives are not well understood. While there has been ongoing and extensive research to assess the emissions implications of alternative forest management activities, little research has considered options for managing the woody biomass residues generated by these activities. This report helps to fill this gap.

The analysis starts *after* the point where timber is harvested and woody biomass residues are generated; it begins at the point where this residue material is collected in the forest and ends with its ultimate use or disposal, as shown in Figure 6. This report provides what might be termed, in life cycle analysis parlance, a "post-harvest to grave" analysis. The analysis includes emissions associated with the processing, use and disposal of the woody biomass residue. Emissions and/or carbon sequestration

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[12] This report includes the following U.S. States: Washington, Oregon, Idaho and Alaska.
[13] Reference 230 (References are cited in this report using a 3-digit code and are listed in the reference section.)
[14] Reference 226 (References are cited in this report using a 3-digit code and are listed in the reference section.)

associated with forest management practices (e.g. harvesting, planting, and growth) are assumed to be identical for a given source of residues being compared and are by design not included in this analysis. In summary, this study provides a "post-harvest to grave" comparison of emissions from alternatives for woody biomass residues that already exist, but is not intended to characterize emissions from the entire forest management life cycle because it by design does not account for carbon sequestration or emissions from forest land management practices. Therefore, these results should not be used alone to assess overall emissions or sustainability of wood bioenergy or to evaluate the carbon sequestration implications of different forest land management practices.

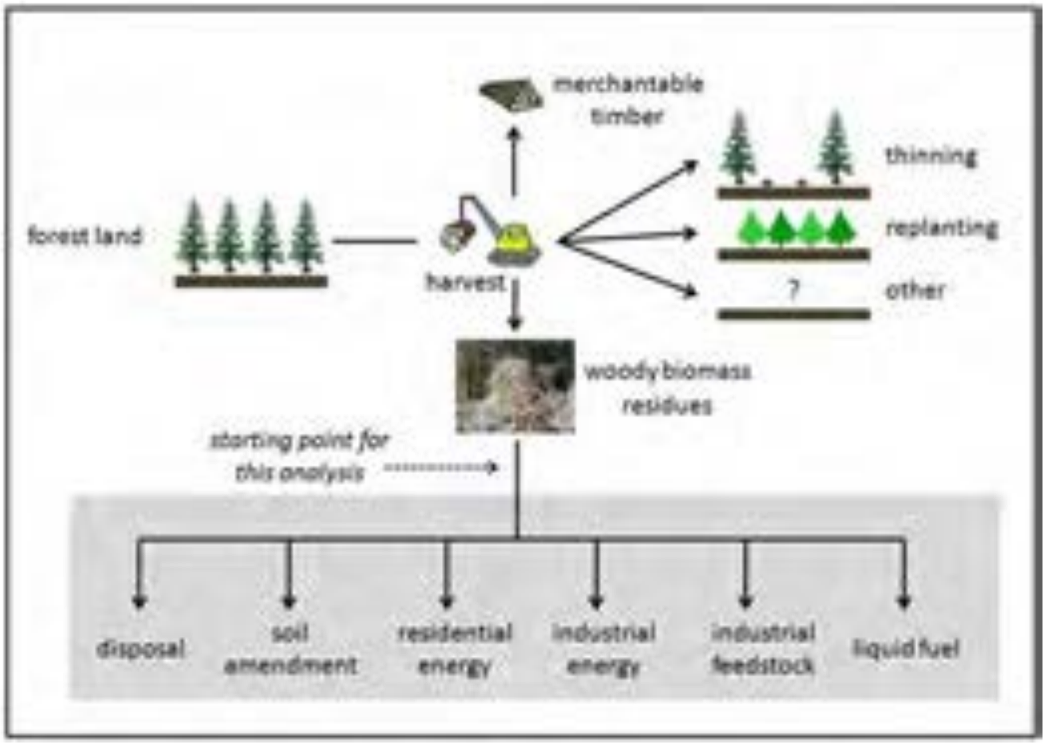

Figure 6. Schematic of post-harvest to grave analysis boundary of this report. The analysis starts *after* the point where timber is harvested and woody biomass residues are generated; it begins at the point where this residue material is collected in the forest and ends with its ultimate use or disposal. This analysis focuses on evaluating the GHG and criteria air pollutant emissions of the different alternatives for using woody biomass residues, as indicated by the shaded box. Emissions and/or carbon sequestration associated with forest management practices (e.g. harvesting, planting, and growth) are assumed to be identical for a given source of residues being compared and are by design not included in this analysis.

Overview of Biomass Fates and Emissions Considered

There are several different alternative fates for woody biomass residues. This report compares the GHG and air pollutant emissions for 15 different fates for woody biomass residues across six categories: 1. disposal, 2. soil amendment, 3. residential energy, 4. industrial energy, 5. industrial feedstock and 6. liquid fuel. A description of each fate is provided in

Table 2.In the Pacific Northwest, woody biomass residues are most commonly either burned on-site or left to decompose. However, this analysis explores several alternatives to disposal that use the residues to generate new products and energy sources. Residues can be used as a soil amendment. Chipped residues are currently used for mulch in gardens and farming. Woody biomass is also used as a "bulking material" to make compost by mixing it with food waste and other organic feedstock. A climate mitigation strategy currently being explored is conversion of residues into biochar, which is a charcoal material that can be applied to agriculture fields to amend the soil. Biochar that can remain stored over a long-term can serve as a means of biosequestration. In addition, through the process of making biochar electricity can be generated. Residues can be used for residential, industrial and transportation energy to displace fossil fuel or existing wood sources. Another common practice in the PNW is using wood residues as a source of heat in residential fireplaces and wood stoves. Chipped residues can also be used as a raw material for pellet production and used in residential pellet stoves. Hog fuel (chipped residues) is currently used as a fuel source for industrial boilers and cogeneration. Integrated gasification and combustion (IGC) is an emerging high efficiency technology for generating electricity and heat that is a potentially feasible use of residues in this region. Generating ethanol, either via fermentation or gasification, may be an option for generating liquid fuel from residues though it is not yet demonstrated on a commercial scale. Residues could be used as a raw material input and energy source for pulp and paper production, if chipped residues meet quality and uniformity standards. Alternative fates for woody biomass residues were selected based on an assessment of the existing and emerging technologies with potential application in the PNW. In other regions a different set of fates may be more appropriate for consideration.

Table 2. Description of Woody Biomass Residue Fates. The table includes a definition of each product material and description of how woody biomass residues could be used to generate each product.

Woody Biomass Residue Fate	Description
1. disposal	
decomposition	Decay of scattered woody biomass residues at the forest harvest site.
combustion	Burning of "slash piles" of woody biomass residues at the forest harvest site.
2. soil amendment	
mulch	Chipping woody biomass residues for use as a protective covering for plants to improve soil moisture retention and reduce weed growth.
compost	Chipped woody biomass residues can serve as a bulking agent to be mixed with a nitrogen rich material (e.g. food waste or chicken manure) to generate compost.
biochar	Pyrolysis of biomass to make charcoal and generate electricity. Charcoal can be applied to agricultural fields as a soil amendment and be a form of biosequestration.
3. residential energy	
fireplace	Burning of fuel wood in an open hearth fireplace.
EPA-certified stove	Burning of fuel wood in a wood stove that meets U.S. EPA emissions certification standards.
pellet stove	Burning of wood pellets in a pellet stove.
4. industrial energy	
displace fossil fuel boiler	Burning of hog fuel in an industrial boiler to replace the use of fossil fuel. Hog fuel is coarsely chipped woody biomass that is used as fuel.
displace hog fuel boiler	Burning of hog fuel in an industrial boiler to replace the use of hog fuel from a different source. Hog fuel is coarsely chipped woody biomass that is used as fuel.
IGC	Integrated gasification and combustion is the gasification of a fuel to drive steam and turbine engines generating heat and electricity.
cogenerator	Production of both electricity and heat through the same industrial process.
5. industrial feedstock	
pulp feedstock	Wood pulp is fibrous material prepared from wood or recovered waste paper used in manufacturing paper or cellulose products.
6. liquid fuel	
cellulosic ethanol	Production of ethanol (and electricity) through a process of hydrolysis and fermentation.
ethanol by gasification	Production of ethanol through a process of gasification and synthesis.

Our life cycle analysis approach covers three greenhouse gases (GHGs): carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4); and two criteria pollutants: carbon monoxide (CO) and fine particulate matter ($PM_{2.5}$). Carbon dioxide is emitted to the atmosphere from the burning of fossil fuels, as well as the combustion and decomposition of biomass. Nitrous oxide is emitted during industrial and agricultural activities, as well as from the burning of fossil fuels. Methane is emitted during the production of natural gas, coal and oil, fossil fuel combustion, livestock operations, and the decay of organic material under anaerobic conditions. All GHGs are reported in terms of carbon dioxide equivalents (CO_2e), and CH_4 and N_2O emissions are weighted by their global warming potential (GWP).[15] Both CO and $PM_{2.5}$ are considered criteria air pollutants and are regulated by the U.S. EPA under the Clean Air Act. Carbon monoxide is formed when carbon in fossil fuels and biomass is not burned completely; it is a concern for human health by decreasing the oxygen-carrying capacity of the blood. Recently the U.S. EPA tightened the 24-hour standard for $PM_{2.5}$. Fine particulate matter are particles that measure 2.5 micrometers in diameter or less that are generated upon combustion and are comprised of elemental carbon, organic carbon and metals, as well as components formed in the atmosphere after combustion. The small size of $PM_{2.5}$ allows the particles to travel deep into lungs and is linked to respiratory disease, asthma, heart attacks and premature death. $PM_{2.5}$ generated from residential wood smoke and land-clearing burning are a primary air quality concern in this region. This analysis focuses on implications of $PM_{2.5}$ emissions from options for woody biomass and does not include consideration of the climate effects of black carbon or aerosol $PM_{2.5}$ emissions.

Methodology

A life cycle inventory approach was used to estimate the post-harvest to grave GHG and air pollutant emissions for each of the 15 fates examined. As defined by ISO 14040, a life cycle inventory is the "compilation and quantification of inputs and outputs for a given product system throughout its life cycle" (214).[16] Results in this report are based on an assumption that products created from biomass residues displace an equivalent amount of an existing product – in other words, that overall market demand for those products is fixed. For this post- harvest to grave analysis, to estimate the *net emissions* impacts of each fate in two over-arching steps. First, we calculate the *systems emissions. System emissions* are emissions associated with gathering, transporting, processing, and using or disposing of woody biomass residues. We then calculate the *displaced emissions*, which are emissions that would otherwise have occurred from the manufacture and use of products (e.g. oil for heating) that are displaced by the use of woody biomass residues. Displaced emissions, for existing products assumed to be supplied from waste streams, include emissions associated with alternate uses of products (e.g. fire wood) that are diverted by the use of woody biomass residues. Displaced emissions are normalized by energy and material yields, for example energy yield from 1 bdt of wood residues displaces the amount of heating fuel that provides the equivalent energy yield. The existing products that are avoided and displaced vary by fate and were selected based on common practices in the PNW. Lastly, *net emissions* are calculated as *system emissions* minus *displaced emissions*.

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[15] In this report we follow the standard GHG inventory approach of using the1996 IPCC Guidelines and assign a GWP of 21 for CH_4 and 310 for N_2O.

[16] References are cited in this report using a three-digit code and are listed in the reference section.

Woody Biomass Emissions Calculator

This report is accompanied by the Woody Biomass Emissions Calculator (WBEC) tool, a spreadsheet based model, which can be used to estimate emissions of each woody biomass fate under different project specific conditions. As stated above, results presented in this report assume that overall market demand for products is "fixed." However, the WBEC tool allows users to turn off this "fixed market" assumption to view results that reflect an expanding or "elastic" market for woody biomass residues.[17] In this report and in the WBEC tool, for comparison across fates net emissions for each fate are normalized as emissions per bone dry ton of woody biomass residue available on-site. Using the WBEC tool, users are able to scale emissions results to project conditions based on project size (acres) and woody biomass residue loads (mass per acre), thereby providing results in terms of total emissions (e.g., metric tons of CO_2e) rather than normalized units (e.g., metric tons of CO_2e per bone dry ton). Users can also tailor results by selecting the processing approaches used, existing products displaced, recovery rate and units of reported results.

The WBEC tool will be managed and administered by the Olympic Region Clean Air Agency.[18]

Fates Considered and Analyzed

There are a wide range of options for the use and disposal of woody biomass in the PNW and Alaska, including both existing practices currently in operation and emerging practices not yet commercially viable. Table 3 presents the full set of 21 fates considered as potential options for the use and disposal of woody biomass residues. From this list, a subset of 15 fates was included in this analysis based on the likelihood of their application in the PNW. The full set of 21 fates considered is included here as a reference for potential future additional work or applications to different regions. Common practices for disposal of woody biomass residues included are: on-site decomposition and on-site combustion. Existing practices and technologies included are: mulching, composting, fireplace, EPA-certified stove, pellet stove, displacement of natural gas, residual oil, diesel or hog fuel in an industrial boiler, electricity generation by cogenerator and pulp/paper production (Table 3). Emerging technologies for use included are: biochar, integrated gasification and combustion, ethanol by fermentation + hydrolysis and ethanol by gasification (Table 3). Each of these fates is described in more detail in the *Appendix* beginning on page 47.

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[17] The market is assumed to be either fixed or completely elastic. The reality is likely in-between and could be approximated by researching or developing economic *elasticities* for each product. Development of such elasticities was beyond the scope of this analysis.

[18] Olympic Region Clean Air Agency (ORCAA): http://www.orcaa.org/

Table 3. Woody Biomass Residue Fates Considered. Fates for woody biomass residues included in this analysis are listed in the table below. Fates considered, but excluded from this analysis are included in italics, as well as the reason for exclusion. The full list of fates considered is included here for reference for potential future work in the PNW or expansion to different regions.

Potential fate to consider		considered here	reason if excluding
1.	Disposal		
a)	on-site decomposition	√	
b)	on-site combustion	√	
c)	*off-site landfilling*	---	*low economic potential*
2.	Soil amendment		
a)	chipping for mulch	√	
b)	composting	√	
c)	biochar (with energy generation)	√	
3.	Residential energy		
a)	combustion in fireplace	√	
b)	combustion in EPA-certified stove	√	
c)	pelletization & combustion in pellet stove	√	
4.	Industrial energy		
a)	*displacement of coal or coal blend in boiler*	---	*low prevalence in PNW*
b)	displacement of natural gas, diesel or residual oil in boiler	√	
c)	displacement of hog fuel in boiler	√	
d)	integrated gasification + combustion	√	
e)	new exported electricity by cogenerator	√	
f)	*hog fuel for pulp or paper industry*	---	*covered by 4b,4c or 4e*
5.	Industrial feedstock		
a)	pulp or paper	√	
b)	*manufactured wood products*	---	*system complexity*
6.	Liquid fuel		
a)	ethanol by hydrolysis + fermentation ("cellulosic")	√	
b)	ethanol by gasification + synthesis	√	
c)	*methanol by gasification + synthesis*	---	*low likelihood in PNW*
d)	*Fischer-Tropsch fuel by gasification + synthesis*	---	*low likelihood in PNW*

Project Boundary

The ISO-14040 standard defines a product system as a collection of unit processes connected by flows of intermediate products and the system boundary serves to define the unit processes to be included in the system to be modeled (215). Figure 7 is the life cycle system boundary diagram developed for this post-harvest to grave analysis and serves as a key for the diagrams included in this report for each of the 15 woody biomass options considered. The boundary diagram in Figure 7 is divided into two sections: all *system emissions* from processing, use and disposal of the woody biomass residues are included above the heavy horizontal line; all *displaced emissions* including the *avoided use*, *avoided manufacture* and *alternate use* of displaced products are included below the horizontal line. The *net emissions* for each fate are the *system emissions* minus the *displaced emissions*. Definition of emissions related terms used in this analysis are included in

Table 4. For this post-harvest to grave analysis, forest management and harvest activities are excluded from all woody biomass residue fates. In this report, total net emissions estimates for each fate are reported. The emissions inventory includes all sources of CO_2 emissions, including those from the decay and combustion of woody biomass residues. Results in this report do not differentiate between CO_2 emissions from biomass versus fossil fuel sources. Results in this report and WBEC tool are meant to be compared across fates relative to a reference or common practice for existing sources of woody biomass residues. This is a key consideration when comparing results from this report to other work.

Table 4. Definition of emissions-related terms. Table provides a definition of the emissions-related terms used in this analysis. These terms are also used in Figure 9.

Term	Related Term (if applicable)	Definition in this Analysis
net emissions		Net emissions are system emissions minus displaced emissions.
system emissions		System emissions are the sum of the emissions from pre-processing, processing, distribution, use and disposal of the new product generated from woody biomass residues.
displaced emissions		Displaced emissions are the emissions associated with either the avoided use and avoided manufacture for existing products avoided by the new product or the avoided use and alternate use for existing products diverted by the new product.
	avoided use emissions	Avoided use emissions are the use emissions from the existing product that are avoided by the use of the new woody biomass residue product use.
	avoided manufacture emissions	Avoided manufacture emissions are the emissions from the manufacture of the existing product that are avoided by the manufacture of the new woody biomass residue product.
	alternate use emissions	Alternate use emissions are the emissions from the use of the existing product for an alternate use due to the displacement by the new woody biomass residue product.
capital manufacturing emissions		Capital manufacturing emissions are emissions caused by constructing a new facility or piece of equipment.

Capital manufacturing emissions are the emissions caused by constructing new facilities or equipment. Our analysis considers capital manufacturing emissions for mobile equipment to be within the project boundary, but capital manufacturing emissions with stationary facilities (e.g., factories) to be excluded. (Emissions from facility *operation* are included separately as part of the system and displaced emissions, as appropriate). Capital manufacturing emissions associated with the manufacture of new mobile equipment is included since projects are likely to require the purchase of mobile equipment such as feller-bunchers, skidders, chippers, and trucks, or at least increase wear and reduce value of existing equipment through increased use and operation. . This analysis includes manufacturing emissions for all mobile equipment, even equipment (e.g., chainsaws) that may not strictly be considered capital goods (i.e., for the accounting or tax purposes of individual companies). Capital emissions associated with construction of any new stationary facilities is considered outside the scope of the analysis, as we consider that these emissions would not be a consequence of any changes in use of woody biomass residues, but be largely driven by other factors such as financial incentives for renewable energy.

Figure 7 presents a diagram of the emissions sources within and outside of this project's boundary, including delineation of the *system* and *displaced* emissions (and their components), as discussed above. The use of a double border around a process step indicates that capital manufacturing emissions of mobile equipment are included in the quantification of that process step. Variations of this general diagram are presented later in this report for each particular fate considered.

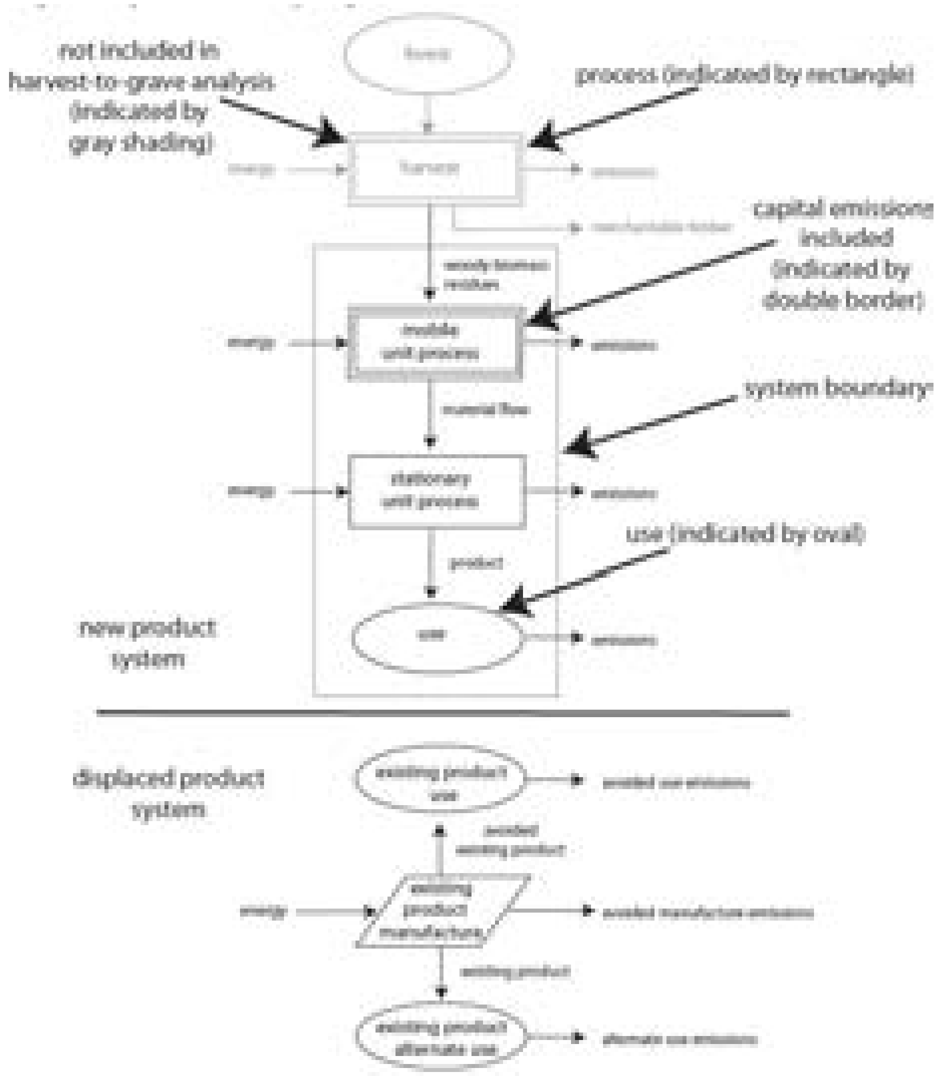

Figure 7. Project Boundary Diagram Key for this Analysis. Individual unit processes in the system emissions diagram ("new product system") are designated with a rectangle. In that portion of the diagram, the woody biomass residue material flows from top to bottom through each of the process steps (starting at *forest* and flowing through *use*). Each product system ends with the final use of the woody biomass residue and is designated with an oval. The displaced emissions ("displaced product system") for the avoided use, avoided manufacture and alternate use of existing products are represented in simplified process diagrams. For each displaced product, the entire manufacturing process is represented by a parallelogram; existing product material can flow either upward in the diagram, to the original use that is being displaced by the new woody biomass fate or downward to an alternate use after the new woody biomass fate has displaced the product. In cases where more than one

displaced product option is possible, the analysis includes the emissions associated with each displaced product separately. Process steps excluded from the analysis (e.g., *forest* and *harvest*) are shaded in gray.

Using the conventions documented in Figure 7, Figure 8 shows the post-harvest to grave life cycle boundary diagram for pellet production and combustion in a pellet stove, one of the 15 fates considered in this analysis. The system emissions include emissions from gathering, processing, transport, pellet production, distribution and final combustion in a pellet stove. As indicated by the double border, capital manufacturing emissions of mobile equipment are included in the gathering, processing, transport and distribution steps. The use of pellets (i.e., combustion in a pellet stove) is indicated by the oval in Figure 8. For pellet production and combustion there are two displaced existing products options that may be considered: displacement of fuel wood use in a wood stove or displacement of fossil fuel[19] use in a furnace.

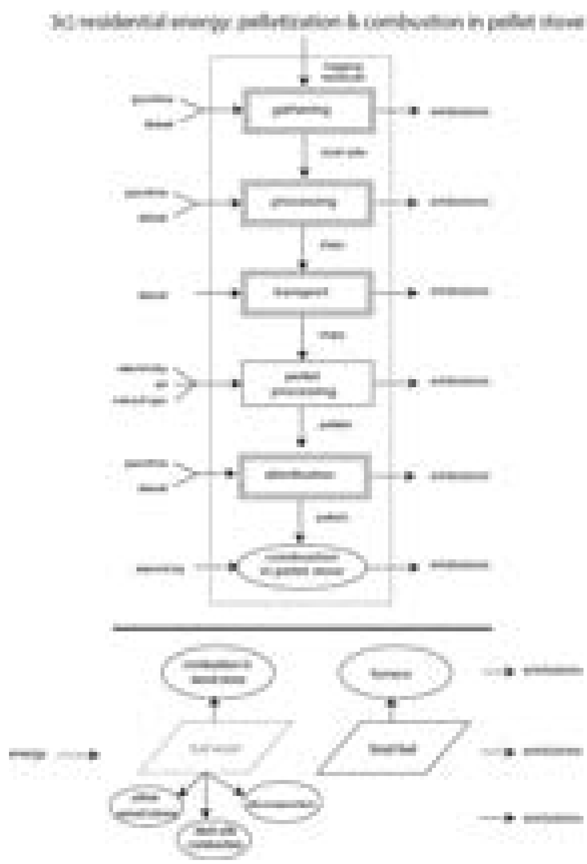

Figure 8. Life cycle boundary diagram of pellet production and combustion in pellet stove. This figure is an example of the post-harvest to grave life cycle boundary diagrams for each of the 15 fates considered.

[19] Note there are 3 different fossil fuel uses considered as displaced residential energy use: natural gas, electric heat and diesel.

Quantification of Post-Harvest to Grave Emissions Using a Life Cycle Approach

For each of the 15 fates considered, net post-harvest to grave emissions are the system emissions (for the new product generated) minus the displaced emissions (for the existing product that is displaced). As described previously, displaced emissions can include the avoided manufacturing of the displaced product or they can instead include the diversion of a product to alternate uses, depending on the nature of the product being displaced. Figure 9 provides a diagram of the quantification approach for calculations of the post-harvest to grave life cycle emissions for each of these two different scenarios.[20]. In the left-hand panel, the new fate causes a reduction in both the use and the manufacture of the existing product. For example, in the case where woody biomass residues displace fossil fuel in a boiler, under the assumption that the overall demand for energy is fixed, the reduction in demand for fossil fuel due to this project will translate into a proportional decrease in the use and manufacture of fossil fuel. In the right-hand panel, in the case where the existing product is a by- or waste-product of another system, then the existing product is diverted to an alternate use. For example, this analysis assumes that fuel wood is generated as a by-product of timber harvesting, in which case the same quantity of fuel wood is still being generated and must go to an alternate use – namely, either a different wood stove or else be left on-site to be burned or decompose. Hence there is no change in the emissions from manufacture, but there are new emissions associated with the alternate use that are included. In select cases where analysts are confident that new production will generate new demand, the fixed market assumption may not be appropriate. To accommodate this case, the WBEC tool allows users to indicate whether or not to maintain the fixed market assumption for a given option. However, all results presented in this report assume that the market is fixed.

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[20] As is the default for all analyses presented in this report, both of these scenarios assume a fixed product market, meaning that the economy's total demand for a given product does not change when more of the product from one project is introduced to the market. Under this assumption, production of a new woody biomass product stream displaces an equivalent amount of an existing product so that the total volume of the product on the market stays the same

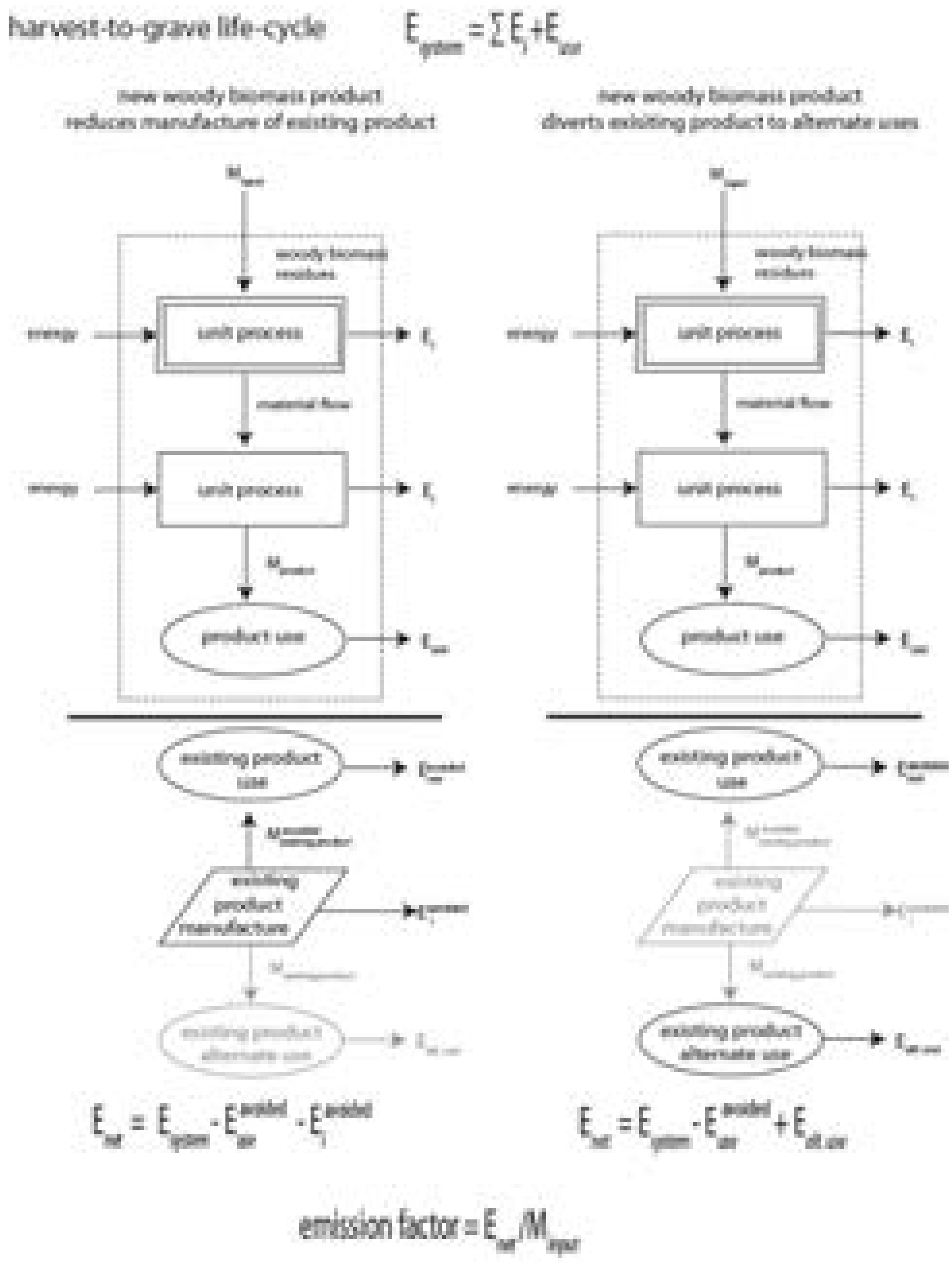

Figure 9. Diagram of quantification approach of post-harvest to grave life cycle emissions for two different product displacement scenarios. In the left-hand panel, the new fate causes a reduction in manufacture of the existing product. In the right-hand panel, the new fate does not affect the quantity of existing product.

Data Resources

The emission factors and data resources used in this analysis relied upon current published literature, reports, site visits, air emissions data reported by state agencies and equipment/mill operation data from facility managers. When appropriate and when available, data values specific to the PNW and Alaska are used. All references used in this analysis are listed in the *References* section at the end of this report and referenced in the WBEC tool, using a designated three-digit code for each reference. When sufficiently large datasets were available, the midrange value or nominal value is the mean, and the low and high values represent a 95% confidence interval. In instances where data was sparse, the midrange value is the value reported by the highest quality source, and the low and high values are the extremes available in the dataset. In some cases, especially in the case of emerging technologies where data is unavailable, emissions factors for similar processes are substituted. This analysis was designed to be representative of forest types in the PNW and Alaska. Carbon content and heating value of woody biomass residues are based values for Douglas-fir (*Pseudotsuga menziesii).*[21] Decomposition rates, for the on-site decomposition fate and residues per acre, for the on-site combustion fate, are based on an average of data for forest types found in the PNW.

Decisions regarding which products were assumed to be displaced by woody biomass (e.g., the displaced home heating fuels displaced by an EPA-certified stove in fate 3b) were made in consultation with the Technical Advisory Committee and were intended to reflect existing products most common in the PNW. It is likely that in other regions or certain situations, different existing products may be displaced that are not included in this analysis.

Results and Conclusions

This section presents summary figures and conclusions comparing emissions across fates. For detailed results of emissions for each woody biomass residue fate, please see the *Appendix*. For each fate, the *Appendix* includes the post-harvest to grave life cycle boundary diagram and description, a summary of emission factor data and information used, net emissions estimates including emissions for each process step, and a description of emissions factor data assumptions and considerations.

Figure 10 shows the contribution of each process step to the system GHG emissions. For the majority of fates, GHG emissions from the end *use* (e.g., combustion) of the woody biomass make up the largest percentage of the overall system emissions. For fates where woody biomass residues are a raw material input converted into a new product, as is the case for biochar, pulp and ethanol*, processing* emissions make up a larger portion of systems emissions than *use*. It is noteworthy that despite the use of several pieces of heavy duty equipment, GHG emissions from pre-processing and distribution of woody biomass residues makes up less than 4% of the system GHG emissions in every fate. Even as these steps are not a primary driver of net GHG emissions for each fate, the technical feasibility and economics of

[21] Carbon content and heating value of residues can be adjusted for different species compositions on the advanced user tab of the WBEC tool.

pre-processing and distribution steps may be critical to determining the viability of woody biomass recovery.

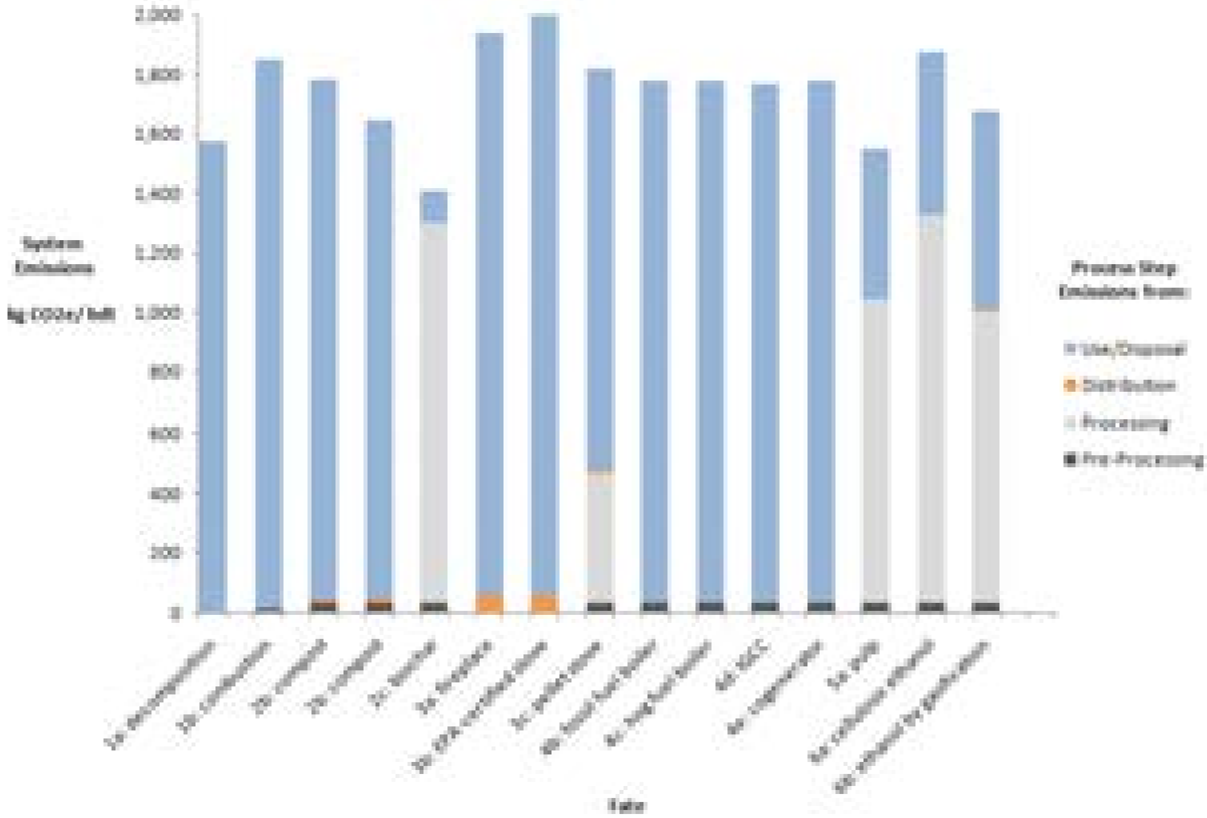

Figure 10. Contribution of GHG Process Step Emissions to GHG System Emissions for Woody Biomass Residue Fates. Chart presents the contribution of the system process steps (pre-processing, processing, distribution and use/disposal) to the overall system emissions. Process steps for each fate have been grouped into four common categories: pre-processing (black bar), processing (gray bar), distribution (orange bar) and use/disposal (blue bar).

The contribution of emissions from process steps to the overall system CO emissions, as shown in Figure 11, follows similar trends as observed for GHG emissions. The exception is for fates where there are no CO emissions from the product end use via combustion, such as on-site decomposition, mulch and composting. For the mulch and composting fates, since *pre-processing* and *distribution* are the only sources of CO emissions, these steps make up the largest percentage of system emissions. There are no CO emissions for on-site decomposition. For the biochar and pulp fates, processing makes up the largest contribution of system emissions.

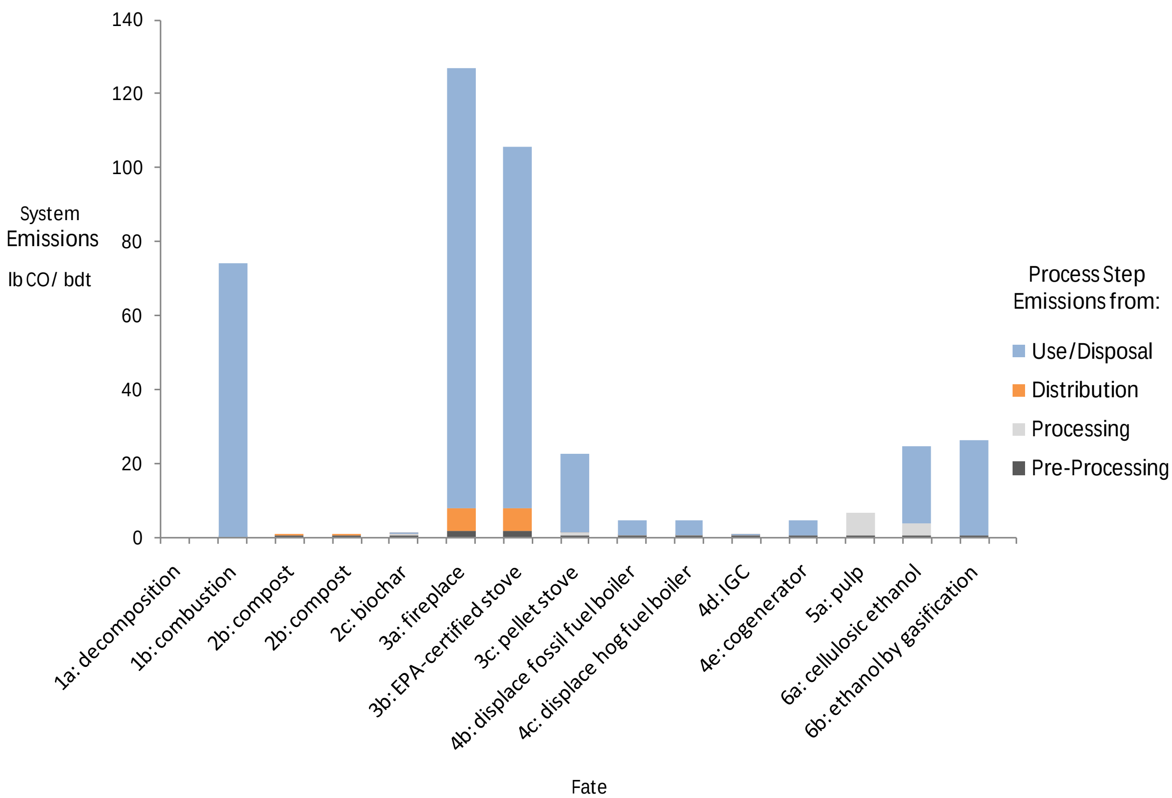

Figure 11. Contribution of CO Process Step Emissions to CO System Emissions for Woody Biomass Residue Fates. Chart presents the contribution of the system process steps (pre-processing, processing, distribution and use/disposal) to the overall system emissions. Process steps for each fate have been grouped into four common categories: pre-processing (black bar), processing (gray bar), distribution (orange bar) and use/disposal (blue bar).

The contribution of process step emissions to system $PM_{2.5}$ emissions, as shown in Figure 12, follows similar patterns to CO emissions. For system emissions, the largest sources of $PM_{2.5}$ emissions are combustion of woody biomass residues. *Use* emissions make up the largest contribution of system $PM_{2.5}$ emissions for fates where woody biomass residues are burned including, on-site combustion, fireplace, EPA-certified stove, pellet stove, fossil fuel boiler, hog fuel boiler, IGC and cogenerator. For the biochar, pulp and ethanol fates, $PM_{2.5}$ emissions from the *processing* steps make up the largest contribution of system emissions since this is the step in these fates when there is combustion of woody biomass residues.

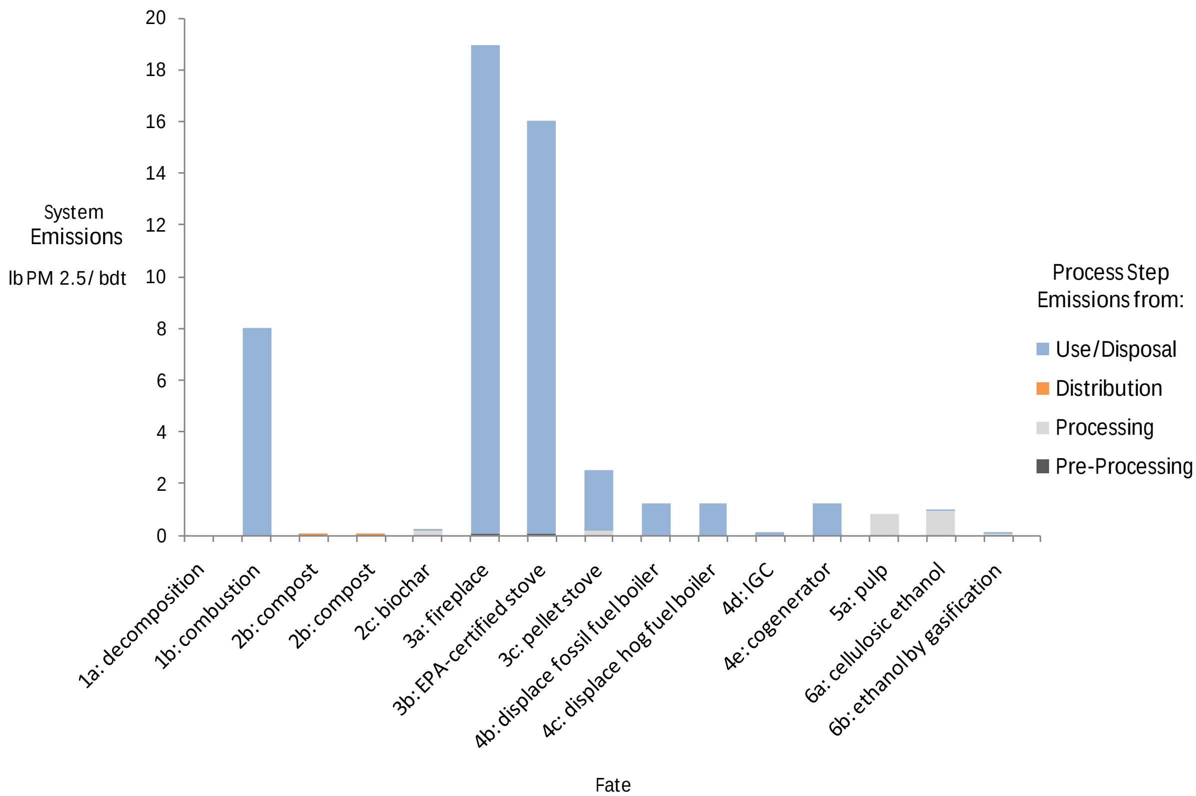

Figure 12. Contribution of $PM_{2.5}$ Process Step Emissions to $PM_{2.5}$ System Emissions for Woody Biomass Residue Fates. Chart presents the contribution of the system process steps (pre-processing, processing, distribution and use/disposal) to the overall system emissions. Process steps for each fate have been grouped into four common categories: pre-processing (black bar), processing (gray bar), distribution (orange bar) and use/disposal (blue bar). .

Net GHG emissions for the post-harvest to grave emissions of each fate are presented in Figure 13. . For each fate, the net GHG emissions for each possible displaced existing product are plotted individually in Figure 3 using circle plots shown in green. For example, use of woody biomass in an EPA-certified stove (fate 3b) may displace electric heat, natural gas or fuel oil in a furnace, or other wood (which may then be diverted to other alternate uses), and each of these possible displaced products are plotted as a different green circle. However very similar values may overlap and may not be clearly distinguishable in the figure. For example, there are 6 different net GHG emissions values for the EPA-certified stove fate however only 5 circle plots are clearly distinguished in Figure 3. This is because the net GHG emissions values for the alternate use of fuel wood in an EPA-certified stove or for on-site combustion are very similar and overlap in the figure.

Several fates studied result in net GHG emissions well (20% or more) below the two common practice activities, on-site combustion and on-site decomposition. These include biochar (2c), fossil fuel boiler (4b), IGC (4d), cogenerator (4e), pulp (5a) and ethanol (6a and 6b). All of these fates involve displacing fossil fuel use with biomass residue use. Cases where the use of an EPA-certified stove or pellet stove avoids the use of fossil fuels also result in net GHG emissions well below the two common practice activities. The reduction in net GHG emissions for fates that displace fossil fuel is dependent on the amount of energy generated from the woody biomass fate and the emissions intensity of the fossil fuel displaced. The more energy generated from woody biomass and the higher the emissions intensity of the fossil fuel displaced, the greater the net GHG emission reduction relative to common practice. Use of woody biomass in an industrial boiler for heat production generates more energy per bdt of woody biomass residue fuel and would displace more fossil energy resulting in net GHG emissions lower than any other fate considered. Cases where woody biomass residues displace an existing wood source do not significantly reduce net GHG emissions relative to the common practices. For these fates, unlike the case of displacing fossil fuel, there is limited GHG emissions benefit of diverting an existing wood source to another use. Even for cases where the end use is decay, as in mulch and compost, the net GHG emissions are slightly greater than the common practice of on-site decomposition because there are emissions from pre-processing and distribution. For cases where the end use is combustion, as in hog fuel boiler or residential energy, the net GHG emissions are very similar to the common practice of on-site combustion and vary depending on the alternate use emissions of existing wood sources.

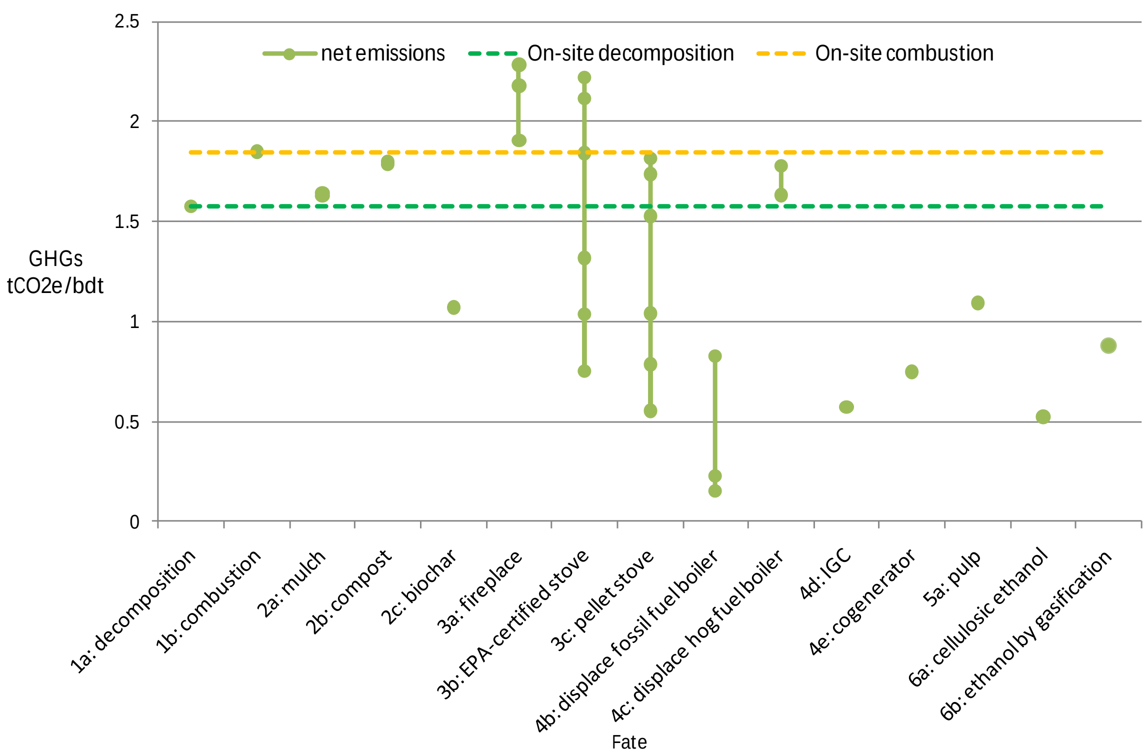

Figure 13. Net Greenhouse Gas Emissions for Post-harvest to Grave Life cycle Emissions of Woody Biomass Residue Fates. GHG emissions including CO_2, CH_4, and N_2O emissions for the 15 woody biomass residue fates included in this analysis. Common practices for woody biomass residues, on-site decomposition (green-dashed line) and on-site combustion (orange dashed line) are plotted for reference. Circle plots (green) show net emissions for each fate and displaced existing product option. Fates where there are no or only one displaced existing product option show only one net GHG emissions value. For fates where there are several net GHG emissions values for each displaced existing product, each individual value is plotted, however very similar values overlap and are not clearly distinguishable in the figure. Results assume a transport-then-chip

woody biomass preprocessing approach, 35 mile transportation (to processing site) distance, 100 mile distribution (to market) distance, 100% recovery rate and fixed market demand. Negative values for net emissions reflect cases where the displaced emissions are larger than system emissions.

Carbon monoxide (CO) is a product of the incomplete combustion of fossil fuel and biomass. CO emissions from combustion can be controlled through the use of emission control technologies. CO emissions decrease as a function of the combustion efficiency and control technology used. With the exception of combustion in a fireplace and EPA-certified stove, all other fates result in a significant reduction in net CO emissions relative to the common practice of on-site combustion, as shown in Figure 14. Fates where no material is burned, including on-site decomposition, mulch and compost, unsurprisingly have no CO emissions. Net CO emissions are only negative, and lower than the common practice of on-site decomposition, when displaced emissions are larger than system emissions.

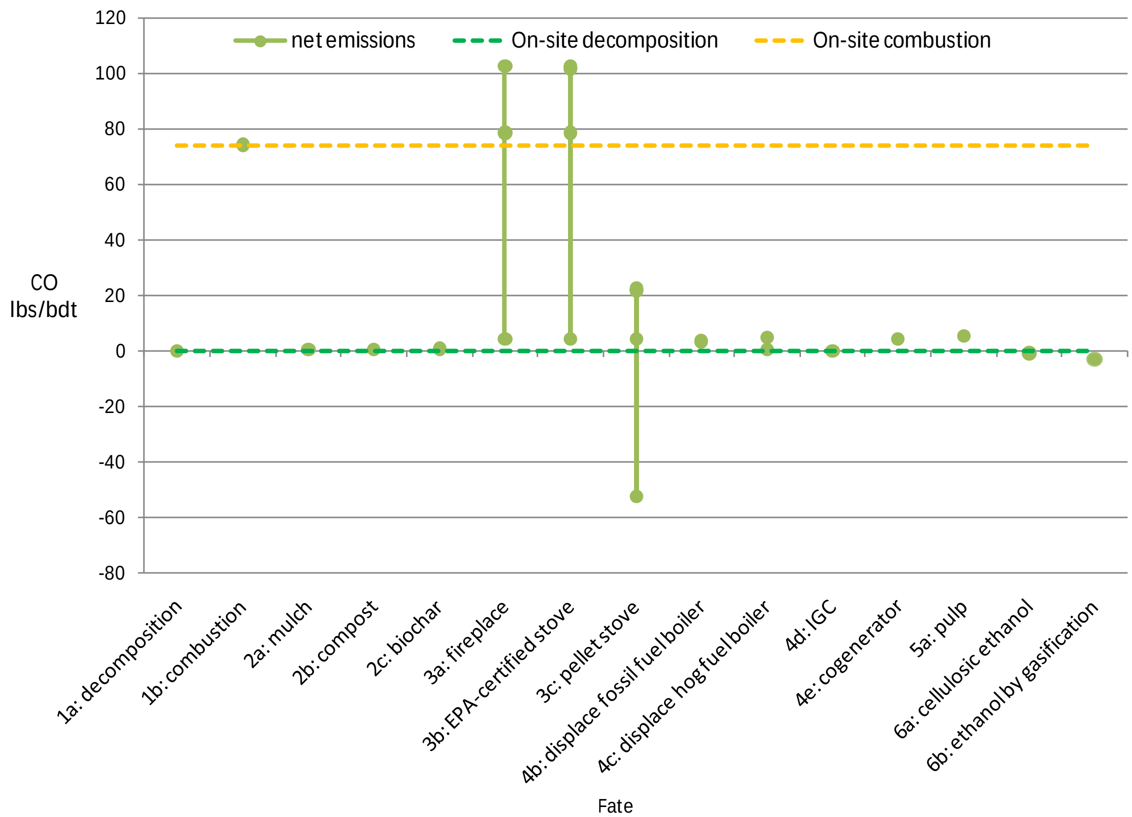

Figure 14. Net Carbon Monoxide Emissions of Post-harvest to Grave Life cycle for Woody Biomass Residue Fates. Figure shows net CO emissions for the 15 woody biomass residue fates included in this analysis. Common practices for woody biomass residues, on-site decomposition (green-dashed line) and on-site combustion (orange dashed line) are plotted for reference. Circle plots (green) show net emissions for each fate and displaced existing product option. Fates where there are no or only one displaced existing product option show only one net emissions value. For fates where there are several net emissions values for each displaced existing product, each individual value is plotted, however very similar values overlap and are not clearly distinguishable in the figure. Results assume a transport-then-chip woody biomass preprocessing approach, 35 mile transportation (to processing site) distance, 100 mile distribution (to market) distance, 100% recovery rate and fixed market demand. Negative values for net emissions reflect cases where the displaced emissions are larger than system emissions.

Fine particulate matter emissions, including soot and smoke, are primarily generated from the combustion of woody biomass residues and fossil fuels. With the exception of fireplace and EPA-certified wood stove use, all other fates for woody biomass residues present a significant reduction in net $PM_{2.5}$ emissions relative to the common practice of on-site combustion, as shown in Figure 15. Fates where no material is burned, including on-site decomposition, mulch and compost, unsurprisingly have no $PM_{2.5}$ emissions. Only fates where net emissions are negative result in lower $PM_{2.5}$ emissions than the common practice of on-site decomposition.

Air pollutant emissions from burning biomass at industrial facilities, with emissions controls, result in CO and $PM_{2.5}$ emissions that are much lower than emissions from uncontrolled burning on-site. For these fates, including biochar (2c), displace fossil fuel boiler (4b), displace hog fuel boiler (4c), IGC (4d), cogenerator (4e), and pulp (5a), use of residues results in a large reduction in CO (93% or more) and $PM_{2.5}$ (85% or more) emissions relative to on-site combustion.

Biomass combustion is a larger source of CO and $PM_{2.5}$ emissions than fossil fuel combustion. As a result the displacement of fossil fuel consumption provides a limited reduction in CO and $PM_{2.5}$ emissions. With the exception of residual oil and gasoline, there is little variation in net CO and $PM_{2.5}$ emission by fossil fuel type. Of the fossil fuels considered, gasoline is the largest source of CO emissions. CO emissions from ethanol are lower than from gasoline use. Fates that generate ethanol (6a, 6b) result in negative net CO emissions values. Of the fossil fuel types considered, residual oil is the largest $PM_{2.5}$ emissions source. The net $PM_{2.5}$ emissions for the displace fossil fuel boiler and IGC fates are lowest when use of residual oil is displaced with hog fuel use.

For residential energy use fates the CO and $PM_{2.5}$ emissions varies by stove type. Emissions from fireplaces and EPA-certified stoves emit 4 times more CO and 6 times more $PM_{2.5}$ per bdt than pellet stoves. CO and $PM_{2.5}$ emissions are higher per bdt from fireplaces and EPA-certified wood stoves than from on-site combustion.

Net CO and $PM_{2.5}$ emissions for the residential energy fates range depending on the displaced existing product. The net CO and $PM_{2.5}$ emissions are lowest if the existing fuel wood source is diverted to on-site decomposition and no burning occurs. The mid-range net CO and $PM_{2.5}$ emissions value is the case where existing fuel wood is diverted to on-site combustion. The highest net CO and $PM_{2.5}$ emissions values occur if fossil fuel is displaced or existing fuel wood is used in an EPA-certified stove. Similar to industrial energy fates, CO and $PM_{2.5}$ emissions from fossil fuel use for residential energy are much smaller than wood energy use. As a result displacement of fossil fuel provides a limited reduction in net CO and $PM_{2.5}$ emissions for the residential energy fates. Overall the largest reduction in net CO and $PM_{2.5}$ emissions, relative to the common practices, occurs when pellet stove use replaces existing use of an EPA-certified stove and existing fuel wood is left to decay.

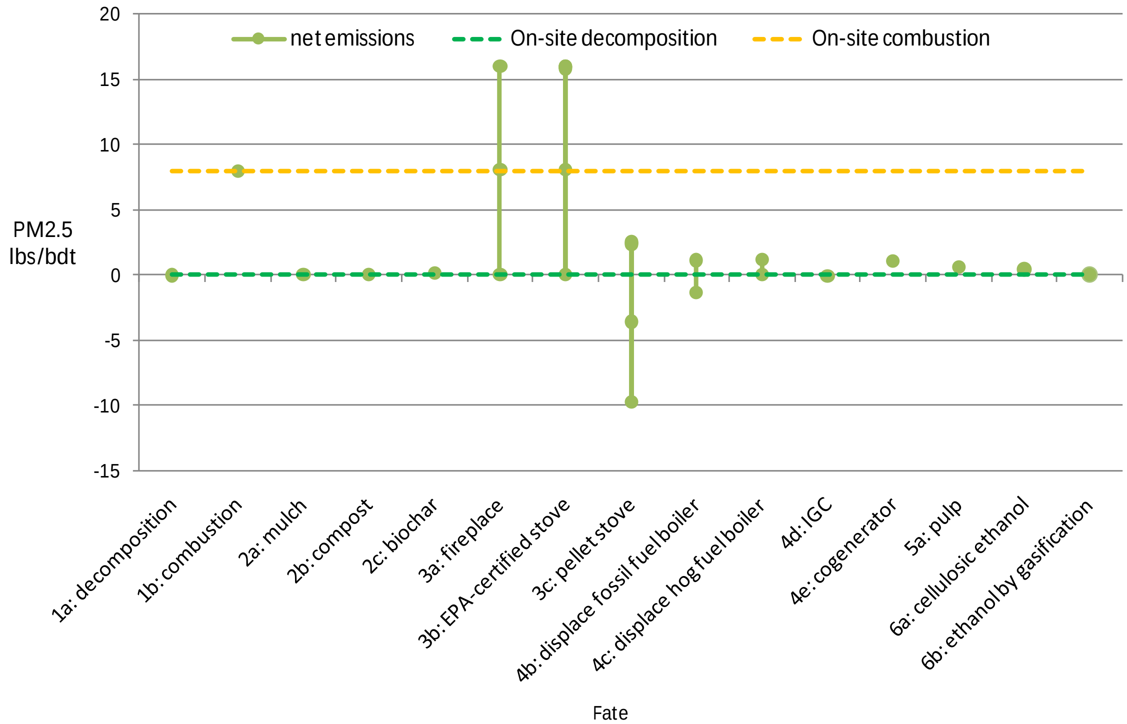

Figure 15. Net Fine Particulate Matter Emissions from Post-harvest to Grave Life cycle of Woody Biomass Residues. Figure shows net $PM_{2.5}$ emissions for the 15 woody biomass residue fates included in this analysis. Common practices for woody biomass residues, on-site decomposition (green-dashed line) and on-site combustion (orange dashed line) are plotted for reference. Circle plots (green) show net emissions for each fate and displaced existing product option. Fates where there are no or only one displaced existing product option show only one net emissions value. For fates where there are several net emissions values for each displaced existing product, each individual value is plotted, however very similar values overlap and are not clearly distinguishable in the figure. Results assume a transport-then-chip woody biomass preprocessing approach, 35 mile transportation (to processing site) distance, 100 mile distribution (to market) distance, 100% recovery rate and fixed market demand. Negative values for net emissions reflect cases where the displaced emissions are larger than system emissions.

A summary of the net emissions of GHG, CO and $PM_{2.5}$ emissions for each woody biomass residue fate and displaced existing product combination is presented in Table 5. The primary conclusions of this analysis are bulleted below.

GHG emissions:

- GHG emissions from pre-processing of residues, including the gathering, chipping and transporting residues from the harvest site to a processing facility make up less than 4% of system emissions.
- Use of woody biomass residues to displace the use of fossil fuels provides the greatest reduction in net GHG emissions relative to the common practices of on-site combustion and on-site decomposition.

- The net GHG emissions for woody biomass residues that displace fossil fuels varyi depending on the how efficiently residues are used as an energy source and the fossil fuel type displaced. Reductions in net GHG emissions are greatest for the fates with a higher energy output per bdt (e.g., industrial boilers) and lowest for the less efficient processes like generating ethanol via gasification.
- Use of woody biomass residues to displace existing wood and organic products results in a minimal change in net GHG emissions from the common practices of on-site combustion and on-site decomposition.

CO and $PM_{2.5}$ emissions:

- Use of woody biomass residues for a fireplace or EPA-certified stove results in an increase in CO and $PM_{2.5}$ emissions relative to the common practices of on-site combustion and on-site decomposition. The only exception is when existing fuel wood is diverted to on-site decomposition and no combustion of the displaced fuel wood occurs. Compared to on-site combustion, emissions from fireplace and wood stove use are much more likely to occur near populated areas.
- Use of woody biomass residues for residential energy in pellet stoves results in a decrease in CO and $PM_{2.5}$ relative to the common practices.
- Use of woody biomass residues for soil amendment, industrial energy, industrial feedstock and liquid fuel all result in large net CO and net $PM_{2.5}$ reductions relative to the common practice of on-site combustion.
- Use of woody biomass residues for liquid fuel to displace gasoline provides the largest net CO emissions benefit from fossil fuel displacement.
- Use of woody biomass residues for industrial energy to displace residual oil provides the largest net $PM_{2.5}$ emissions benefit from fossil fuel displacement.

Table 5. Relative Comparison of Net Post-harvest to Grave Life cycle Emissions of Woody Biomass Residue Fates. Post-harvest to grave emissions for each fate and displaced product combination. Emissions ranking for GHG (blue), CO (yellow) and $PM_{2.5}$ (green) emissions are shown. Negative net emission values are shown in red.

Fate	GHGs	CO	PM2.5
1a: on-site decomposition			
1b: on-site combustion			
2a: mulch			
alternate use of wood mulch: wood bulking agent			
alternate use of other organic mulch: other organic bu			
2b: composting			
alternate use of wood bulking agent: wood mulch			
alternate use of other organic bulking agent: other or			
2c: biochar			
avoided fuel: electricity			
3a: fireplace			
alternate use of fuel wood: EPA-certified stove			
alternate use of fuel wood: on-site combustion			
alternate use of fuel wood: on-site decomposition			
3b: EPA-certified stove			
alternate use of fuel wood: EPA-certified stove			
alternate use of fuel wood: on-site combustion			
alternate use of fuel wood: on-site decomposition			
avoided: natural gas (in furnace)			
avoided: oil (in furnace)			
avoided: electricity			
3c: pellet stove			
alternate use of fuel wood: EPA-certified stove			
alternate use of fuel wood: on-site combustion			
alternate use of fuel wood: on-site decomposition			
avoided: natural gas (in furnace)			
avoided: oil (in furnace)			
avoided: electricity			
4b: fossil fuel boiler			
avoided: natural gas			
avoided: diesel			
avoided: residual oil			
4c: hog fuel boiler			
alternate use of hog fuel: alternate boiler			
alternate use of hog fuel: wood mulch			
4d: IGC			
avoided: natural gas and electricity			
avoided: diesel and electricity			
avoided: residual oil and electricity			
4e: cogenerator			
avoided: electricity			
5a: pulp feedstock			
avoided: pulp + electricity			
6a: cellulosic ethanol			
avoided: gasoline + electricity			
6b. ethanol by gasification			
avoided: gasoline			

This analysis serves to support decision making by air managers in the Pacific Northwest region when comparing options for the use and disposal of woody biomass residues. As shown, there are many alternative uses for woody biomass residues that present a reduction in GHG, CO and $PM_{2.5}$ emissions relative to the common practice of on-site combustion. Our analysis of the emissions implications of alternatives for biomass residues has been based on characterization of system processes and displaced products as accurately as current knowledge and this project's resources allow. Understanding of how displaced wood products would ripple through the supply chain for waste wood products was a source of uncertainty in our analysis. This analysis assumes that all existing wood products are by-products of existing forest practices and if displaced by a new source of woody biomass residues would have to be diverted to an alternate use. Unlike the uncertainty around emissions from the displacement of wood products, emissions implications of the avoided use and avoided manufacture of displaced fossil fuels are based on well-published and readily available data sources. Most fates examined are existing and proven technologies with well published emissions factor data. For the subset of fates that represent emerging and not yet full commercialized technologies, emissions factors for some emissions sources are not yet well understood. In cases where specific emissions factors were not available, appropriate proxies, documented in the *Appendix* and WBEC tool, were selected and used. Further investigation of existing wood fuel supply chains, as well as expansion of this analysis to include additional fates, emissions types, and climate feedbacks of $PM_{2.5}$ presents several opportunities for further research.

Appendix: Detailed Results of Woody Biomass Residue Fates

This appendix provides a detailed discussion of the net emissions for each of the 15 fates included in this analysis. For each fate the following information is presented: the post-harvest to grave life cycle boundary diagram and description, summary of emission factor data and information used, net emissions estimates including emissions for each process step and description of emissions factor data assumptions and considerations. Estimates of net emissions reported here for each fate assume a fixed/static market. The WBEC tool allows users to select which preprocessing approach was used at the project under consideration. Some of the logging residue material recovered from the harvest site is not likely to be of sufficient quality to be used as input material for some of the product systems considered, this is especially true of products requiring high quality uniform chips, e.g. pulp production. The WBEC tool allows users to adjust the recovery rate for each fate in terms of the percent of woody biomass residues that can be recovered from on-site, as well as the percent of residues that meet the quality threshold for a given new product. If the recovery rate is not 100%, then any remaining material not recovered is assumed to either decompose or be burned on-site. The results reported here assume a default recovery rate of 100%. The user of the WBEC tool can select whether uncovered material is decomposed or burned. The WBEC tool calculates net emissions for each fate based on the user selection of one displaced existing product options. Tables in the following sections of this report, present the net emissions for each displaced existing product option separately.

Woody Biomass Preprocessing

Several of the woody biomass fates considered require woody biomass debris to be collected, chipped and transported to a facility for further processing or use. These woody biomass preprocessing steps are required for 10 fates, including all of the options in the soil amendment, industrial energy, industrial feedstock and liquid fuel category areas listed in Table 6 and Table 7. Two primary approaches for logging residue preprocessing were identified by the Technical Advisory Committee based on current practices in the PNW. Each of these approaches is presented here. Users of the WBEC tool have the option of choosing which of the two approaches is most applicable to the project conditions.

Life cycle description

Emissions associated with woody biomass preprocessing include gathering/pre-processing, transport and chipping off-site for the “transport-then-chip” option in Figure 17 and gathering, processing (chipping) and transport for the “chip-then-transport” option presented in Figure 16.

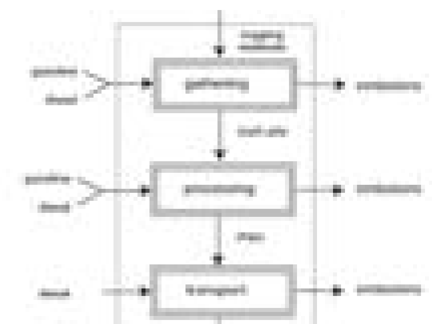

Figure 16. Chip-then-transport life cycle boundary diagram.[22] Diagram shown includes only the woody biomass preprocessing steps.

[22] In the life cycle boundary diagrams in the final report “logging residuals” will be replaced with “woody biomass residues”.

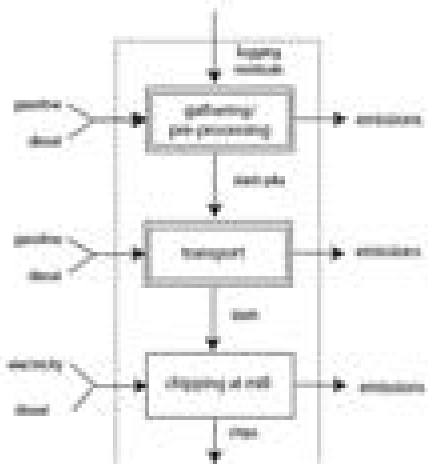

Figure 17. Transport-then-chip option life cycle boundary diagram. Diagram shown includes only the woody biomass preprocessing steps.

Emission factor data and information

Each of the woody biomass preprocessing approaches considered was based on current operations in the PNW. The transport-then-chip option was modeled based on the practices of Grays Harbor Paper in Hoquiam, WA. Under this approach, logging residuals are gathered by log loaders, transported in tractor trailers and ground at the mill site using 2 log loaders and 1 log stacker for sorting, a tub grinder for chipping and a grinder and stump splitter for large woody debris. The chip-then-transport option was modeled based on practices used by Herman Bros. Logging and Construction, Ltd. in Port Angeles, WA. Under this approach, a log loader is used to load woody biomass residues into an on-site chipper and ground material is transported in tractor trailers.

Data on equipment used and operating capacity for these woody biomass preprocessing approaches was based on information provided directly by contacts at Grays Harbor Paper and Hermann Bros. via personal communication, email, written documentation and site visits (Gray Harbor Paper: 106, 113, 123, 134, 146; Herman Bros.: 126, 127, 128). Emissions factors for non-road machinery were based on values reported in the U.S. EPA NONROAD model (131,132) and based on MOBILE 6 for on-road equipment emissions (139, 190, 191, 202) and fuel efficiency (129). Emissions associated with the manufacturing emissions for all mobile equipment, including non- and on-road equipment are based on the equipment retail value (158, 162, 165, 166, 173, and 174), retail value manufacturing emissions (149) and lifetime operating hours.

Life cycle emissions data

For each of the woody biomass preprocessing approaches considered, emissions estimates for each process step are presented in Table 6 and Table 7.

Table 5. Transport-then-chip option process steps emissions estimates. Values that are approximately zero (<0.005 or >-0.005) are indicated by ~0.

	CO_2	N_2O	CH_4	CO	$PM_{2.5}$
	(t CO_2e/bdt)			(lb/bdt)	
gather & size in field	0.01	~0	~0	0.05	0.01
transport	0.01	~0	~0	0.05	~0
chip at plant	0.03	~0	~0	0.23	0.03
transport-then-chip subtotal	0.05	~0	~0	0.32	0.04

Table 6. Chip-then-transport option process steps emissions estimates. Values that are approximately zero (<0.005 or >-0.005) are indicated by ~0.

	CO_2	N_2O	CH_4	CO	$PM_{2.5}$
	(t CO_2e/bdt)			(lb/bdt)	
gather & chip in field	0.03	~0	~0	0.25	0.03
transport	0.01	~0	~0	0.05	~0
chip-then-transport subtotal	0.03	~0	~0	0.29	0.03

Emission factor data assumptions and considerations

Data collected and emission factors used closely model the current operations of Grays Harbor Paper and Hermann Bros. for logging residue collection, grinding and transport. These two approaches are assumed to be representative of practices expected in the Pacific Northwest region in the near term. Innovations in gathering equipment and processes, if utilization of residues increases, will require updating of the approaches modeled in the WBEC tool.

1. Disposal

Two options for the disposal of woody biomass are considered: on-site decomposition and on-site combustion.

1a. On-site decomposition

Life cycle description

Life cycle emissions from the disposal of woody biomass through on-site decomposition include only the emissions associated with the decay of logging residuals, as shown in Figure 18. No new products are generated under disposal options; as a result there are no existing products that have been displaced.

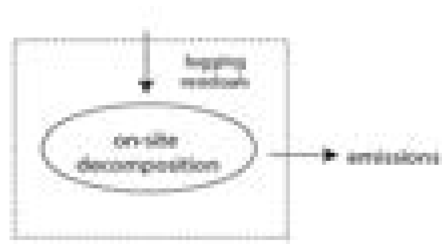

Figure 18. On-site decomposition life cycle boundary diagram.

Emission factor data and information

Emissions from decay are based on decomposition[23] of logging residuals. Decay rates are based on an average of wood types across the PNW (118) and carbon content of residues (230,232,235).

Life cycle emissions data

Life cycle emissions for the disposal option of on-site decomposition are presented in Table 7.

Table 7. On-site decomposition life cycle emissions estimates. System, displaced and net emissions are presented. Data presented assume the chip-then-transport woody biomass preprocessing approach, 50 mile transport distance, 100 mile distribution distance and a fixed market demand.

	CO_2	N_2O	CH_4	CO	$PM_{2.5}$
	(t CO_2e/bdt)			(lb/bdt)	
System					
decomposition	1.58	--	--	--	--
system emissions	1.58	--	--	--	--
Displaced					
net emissions	1.58	--	--	--	--

[23] To determine the complete emissions associated with on-site decomposition decay over a period of 100-yr is considered.

Emission factor data assumptions and considerations

The on-site decomposition option considered here assumes that logging residuals are left scattered on-site to decompose following harvest or land-clearing. Very large slash piles of logging residuals stored for several years have been shown to generate methane emissions (196), where size and moisture levels were sufficient to create anaerobic conditions where methane was generated from decomposition. In this fate, since woody biomass residues are assumed to remain scattered, these conditions are would not generate the anaerobic conditions necessary for methane generation. No methane or nitrous oxide emissions are expected from the decomposition of scattered woody biomass residues considered by this fate.

1b. On-site combustion

Life cycle description

Life cycle emissions associated with the disposal of woody biomass through on-site decomposition include emissions from gathering logging residuals into slash piles and combustion of slash piles, as shown in Figure 19. There are no new products generated under the disposal options and therefore no avoided use emissions from displaced products.

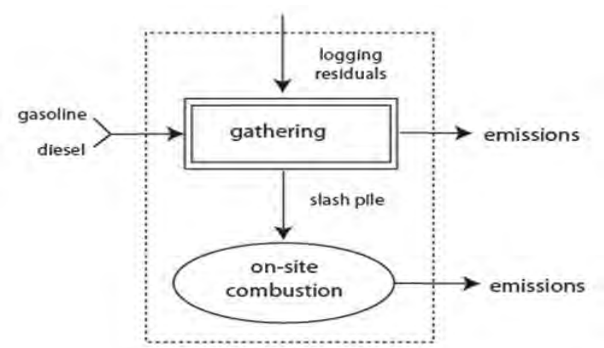

Figure 19. On-site combustion life cycle boundary diagram.

Emission factor data and information

Data from gathering is based on an average of logging residual volume across PNW forest types (118), bulldozer operational capacity (134, 135) and emissions (131) to gather logging residuals into slash piles. Combustion emissions for slash pile logging residuals are based on values reported on AP-42 (115).

Life cycle emissions data

Life cycle emissions data for the on-site combustion option are presented in Table 8.

Table 8. On-site combustion life cycle emissions estimates. System, displaced and net emissions are presented. Data presented assume the chip-then-transport woody biomass preprocessing approach, 50 mile transport distance, 100 mile distribution distance and a fixed market demand. Values that are approximately zero (<0.005 or >-0.005) are indicated by ~0.

	CO_2	N_2O	CH_4	CO	$PM_{2.5}$
	(t CO_2e/bdt)			(lb/bdt)	
System					
gathering	0.01	~0	~0	0.14	0.01
combustion	1.74	0.06	0.03	74.01	8.00
system emissions	1.75	0.06	0.03	74.15	8.02
displaced	--	--	--	--	--
net emissions	1.75	0.06	0.03	74.15	8.02

Emission factor data assumptions and considerations

Based on discussion with practitioners of this common practice, this analysis assumes that slash piles are ignited by hand on-site. Complete combustion of residues is assumed.

2. Soil Amendment

Three options for using woody biomass as a soil amendment are considered in this analysis: chipping for mulch, composting and biochar (with energy generation).

2a. Chipping for mulch

Life cycle description

Production of mulch from woody biomass includes emissions associated with woody biomass preprocessing, distribution and decay from mulch use. The net emissions of mulch production include the mulch production and use emissions minus the avoided use emissions from displacing either wood mulch or non-wood organic mulch plus the alternate use emissions from the displaced existing products as a compost bulking agent, as shown in Figure 20.

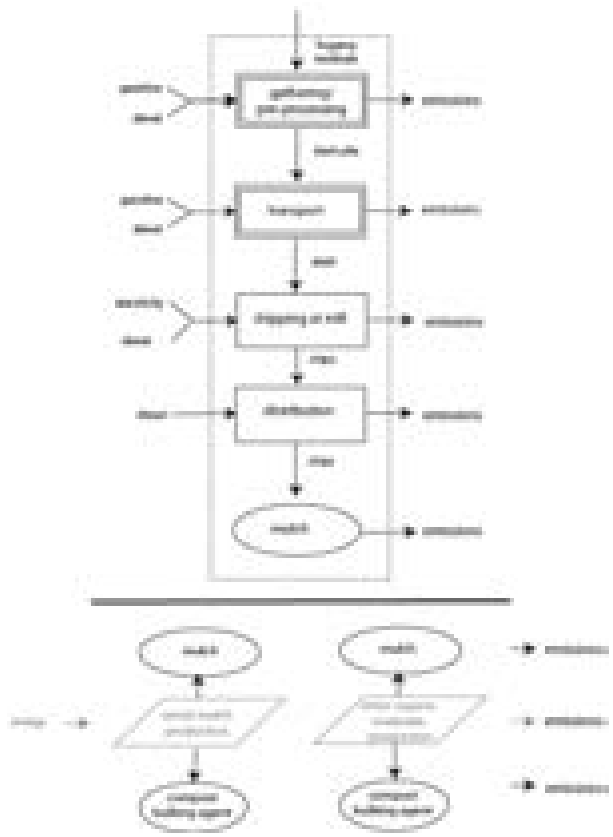

Figure 20. Chipping for mulch life cycle boundary diagram. Diagram shows transport-then-chip woody biomass preprocessing approach.

Emission factor data and information

Emissions associated with woody biomass preprocessing are discussed in the above section. Distribution emissions are based on capital manufacturing emissions (149, 165), lifetime operating hours and operating emissions (139, 190, 191, 202) for heavy duty trucks. Decay emissions for mulch are based on the carbon content of residues (230, 232, 235) and decay rates over 100 yrs. (164). Decay emissions for the alternate use as a compost bulking agent are identical to those discussed in the *section 2b. composting*.

Life cycle emissions data

Life cycle emissions for the chipping for mulch option are presented in Table 9.

Table 9. Chipping for mulch life cycle emissions estimates. System, displaced and net emissions are presented. Data presented assume the chip-then-transport woody biomass preprocessing approach, 50 mile transport distance, 100 mile distribution distance and a fixed market demand. Values that are approximately zero (<0.005 or >-0.005) are indicated by ~0.

	CO_2	N_2O	CH_4	CO	$PM_{2.5}$
	(t CO_2e/bdt)			(lb/bdt)	
System					
woody biomass preprocessing	0.03	~0	~0	0.29	0.03
distribution (100 mi)	0.01	~0	~0	0.15	0.01
use	1.74	--	--	--	--
system emissions	1.78	~0	~0	0.44	0.04
displaced: wood mulch					
alternate use: wood bulking agent	-0.14	--	--	--	--
net emissions	1.64	~0	~0	0.44	0.04
displaced: other organic material					
alternate use: other organic bulking agent	-0.15	--	--	--	--
net emissions	1.63	~0	~0	0.44	0.04

If transport-then-chip preprocessing approach were used, the woody biomass preprocessing emissions would be: CO_2 - 0.04 t CO_2e/bdt, N_2O - 0.00 t CO_2e/bdt, CH_4 - 0.00 t CO_2e/bdt, CO 0.29 lb/bdt and $PM_{2.5}$ 0.03 lb/bdt.

Emission factor data assumptions and considerations

Emissions estimates assume that there are no emissions associated with further processing or storage of mulch once the logging residuals are ground/chipped. Wood based mulch with a low nutrient content and moisture levels less than 55% are not expected to generate methane and nitrous oxide emissions (124).

2b. Composting

Life cycle description

Production of compost involves the combination of a bulking agent and nitrogen source. This analysis considers the emissions associated with the use of woody biomass as a composting bulking agent. When the static market assumption is ON[24] no new demand for compost is generated, so there is no change in the use of existing nitrogen sources and, therefore, emissions from new nitrogen sources are not

[24] The static market assumption, as discussed further in the introduction, assumes that new product production directly displaces an equivalent amount of an existing product.

considered. Production of compost bulking agent, causes emissions due to woody biomass preprocessing and decay of bulking agent that is displaced. This analysis considers emissions from producing and using the bulking agent minus the avoided use emissions from either existing wood bulking agent or other organic bulking agent and plus emissions from the alternate use of either wood or other organic bulking agent as mulch. When the static market assumption is OFF, [25] it is assumed that new demand for compost is generated proportional to the quantity of new bulking agent available to support it. A proportional quantity of nitrogen source is also modeled to satisfy the expanded compost demand. The nitrogen source is diverted from existing, alternate uses represented by the ovals above the upward-pointing arrows. Under this case, the life cycle emissions for composting are the bulking agent production emissions, use of either manure or food waste based compost minus the avoided use emissions from field spread and landfill of manure and food waste, respectively. The life cycle boundary under both the static market and expanding market is shown in Figure 21.

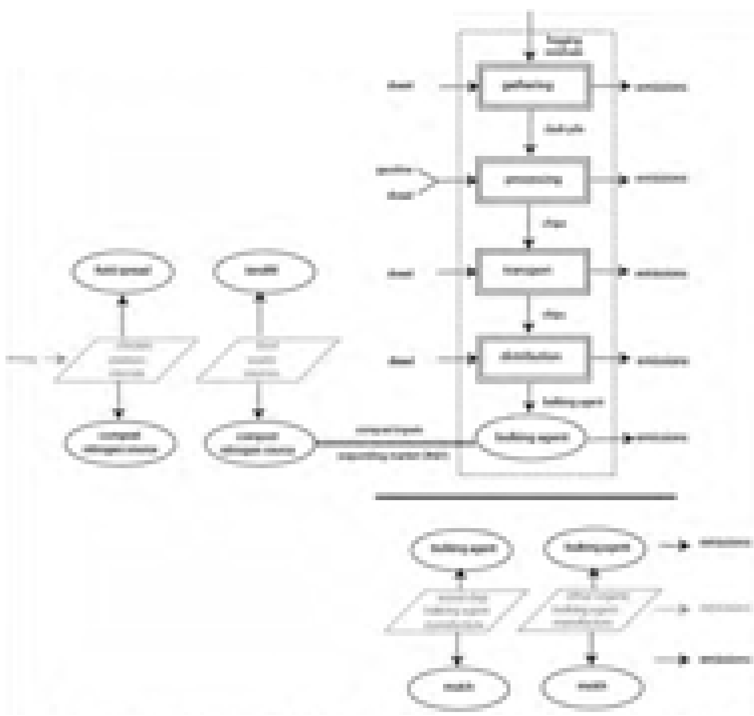

Figure 21. Composting life cycle boundary diagram.

Emission factor data and information

Emissions associated with woody biomass preprocessing are discussed in the above section. Distribution emissions are based on capital manufacturing emissions (149, 165) and operating emissions (139, 190,

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[25] When the static market assumption is turned off, this assumes that new production of wood bulking agent under this use option increase the overall market demand and use of compost.

191, and 202) for heavy duty trucks. Decay emissions for wood bulking agent and avoided use of wood bulking agent are based on decay rate of 92% of carbon fraction (125) and carbon content of wood (230,232,235). Avoided use emissions of non-wood bulking agent are based on decay emissions for pine straw (101, 164, and 177). Alternate use emissions for wood and non-wood mulch are identical to those discussed under *2a. chipping for mulch*. Composting emissions for food waste are based on emissions from material handling (133), nitrogen content of food waste (178), 11.5% mass loss during composting (125) and GHG emissions from composting (124, 125, 133). No data for composting with manure were found and food waste composting emissions were used as a proxy. When the static market assumption is turned off and nitrogenous compost inputs are increased, the emissions factors for composting with chicken manure and food waste are based on references 164 and 101. Avoided use emissions for field spread of manure are based on manure methane production (151), average annual temperatures in the PNW (198-201), carbon content of manure (101) and decay rate of carbon fraction of 92% (125).

Life cycle emissions data

Life cycle emissions data for the composting option, when the market is assumed to be fixed are presented in Table 10.

Table 10. Composting life cycle emissions estimates. System, displaced and net emissions are presented. Data presented assume the chip-then-transport woody biomass preprocessing approach, 50 mile transport distance, 100 mile distribution distance and a fixed market demand. Values that are approximately zero (<0.005 or >-0.005) are indicated by ~0.

	CO_2	N_2O	CH_4	CO	$PM_{2.5}$
	($t\ CO_2e/bdt$)			(lb/bdt)	
system					
woody biomass preprocessing	0.03	~0	~0	0.29	0.03
distribution (100 mi)	0.02	~0	~0	0.22	0.01
use	1.60	--	--	--	--
system emissions	1.65	~0	~0	0.51	0.04
displaced: wood bulking agent					
alternate use: wood mulch	0.14	--	--	--	--
net emissions	1.79	~0	~0	0.51	0.04
displaced: other organic bulking agent					
alternate use: other organic mulch	0.15	--	--	--	--
net emissions	1.80	~0	~0	0.51	0.04

If transport-then-chip preprocessing approach were used, the woody biomass preprocessing emissions would be: CO_2 - 0.04 t CO_2e/bdt, N_2O - 0.00 t CO_2e/bdt, CH_4 - 0.00 t CO_2e/bdt, CO 0.29 lb/bdt and $PM_{2.5}$ 0.03 lb/bdt.

Emission factor data assumptions and considerations

When the static market assumption is turned off, the ratio of compost production to bulking agent input is assumed to range from 1.5-2.5. Wood based bulking agent with a low nutrient content and moisture levels less than 55% are not expected to generate methane and nitrous oxide emissions (124). Compost production is kept sufficiently aerated so that methane emissions are not generated (125). Users of the WBEC tool may choose to turn off the static market assumption, based on the assumption that increased production of compost bulking agent from woody biomass logging residues actually expands the market and production of compost increasing the use of nitrogen sources of either food waste or chicken manure. Although this scenario is a possibility, recent published studies suggest that organic waste nitrogen sources and not bulking agent is the supply barrier for compost processors (210). In Washington State, Pacific Topsoils reported it ran out of yard waste organics to mix with woody biomass from logging debris and was forced to sell woody biomass as hog fuel (210). This suggests that the expectation that increasing woody biomass from logging residuals will expand use of nitrogen sources may not be a valid assumption until food and yard waste supply expands significantly through increased collection. Additionally, a 2006 study of organic waste management in Kitsap County in Washington found that "chipped land clearing debris also can be used as a landscape product or composted with a high nitrogen source, but this type of composting is relatively uncommon" (211). This further suggests that increasing woody biomass from logging residuals is unlikely to be a major driver for expanding compost production. If users of the WBEC tool turn off the static market assumption for this option they should be confident that this is a valid assumption for their project conditions.

2c. Biochar

Life cycle description

The use of woody biomass for the production of biochar includes emissions from woody biomass preprocessing, pyrolysis (biochar production), distribution, soil application and decay of biochar used as a soil amendment. Biochar production generates electricity and heat, though there are no emissions associated with the use of either of these products of biochar production. The net emissions for biochar are the production emissions minus the avoided use emissions for displaced soil amendment, electricity and heat and the avoided manufacture emissions of displaced soil amendment, electrical grid and fossil heat production, as a shown in Figure 22.

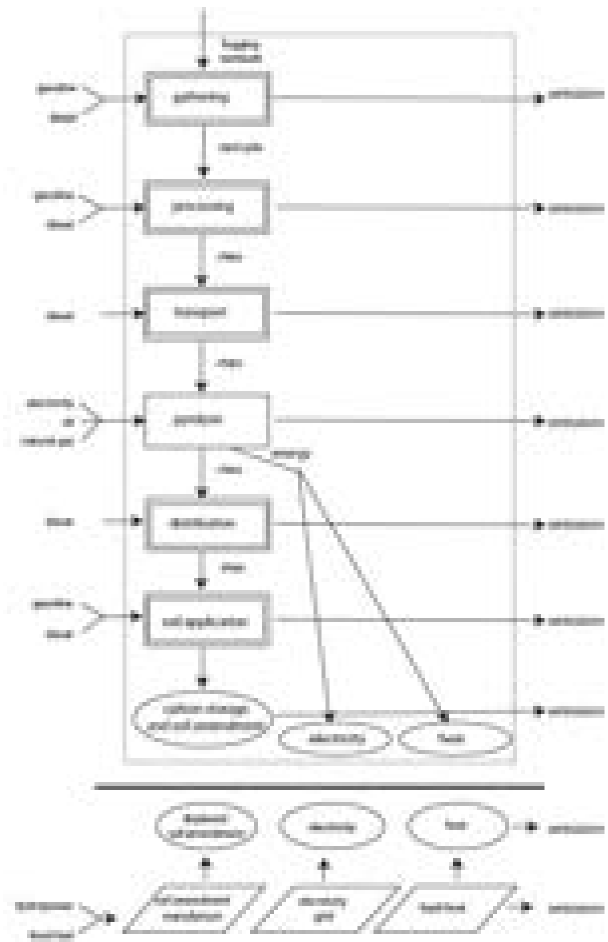

Figure 22. Biochar (with energy generation) life cycle boundary diagram.

Emission factor data and information

Emissions associated with woody biomass preprocessing are discussed in the above section. Pyrolysis emissions are based on a conversion efficiency of woody biomass to biochar (236), carbon content of wood (230,232,235), carbon content of biochar (185) and syngas combustion (237). Distribution emissions are based on capital manufacturing emissions (149, 165) and operating emissions (139, 190, 191, and 202) for heavy duty trucks. Application emissions are based on tractor capital manufacturing (149, 189), fuel requirements for biochar application (187) and emissions from diesel use (186, 131). Biochar carbon storage and soil amendment emissions are based on the carbon content of biochar (185) and a value of 20% for the fraction of carbon that decays (185). Electricity generation yield value from syngas of 40% (238) is used and a syngas yield of 11,835 MJ/bdt (237). No avoided use emissions are associated with the use of displaced soil amendment, electricity or heat. Avoided manufacture emissions for electricity generation are based on the marginal electric emissions for the PNW as reported by the Northwest Power and Conservation Council (140) and a combined-cycle natural gas turbine (147). No avoided manufacture emissions are included for heat or soil amendment production.

Life cycle emissions data

Life cycle emissions data for the option to use woody biomass to produce biochar are presented in Table 11.

Table 11. Biochar (with energy generation) life cycle emissions estimates. System, displaced and net emissions are presented. Data presented assume the chip-then-transport woody biomass preprocessing approach, 50 mile transport distance, 100 mile distribution distance and a fixed market demand. Values that are approximately zero (<0.005 or >-0.005) are indicated by ~0.

	CO_2	N_2O	CH_4	CO	$PM_{2.5}$
	(t CO_2e/bdt)			(lb/bdt)	
System					
woody biomass preprocessing	0.03	~0	~0	0.29	0.03
distribution (100 mi)	~0	~0	~0	0.04	~0
pyrolysis	1.27	~0	~0	0.44	0.14
soil application	~0	~0	~0	~0	~0
carbon storage and soil amendment	0.10	--	--	--	--
system emissions	1.41	~0	~0	0.77	0.17
displaced: soil amendment and electricity					
avoided: soil amendment and electricity	-0.33	~0	~0	-0.11	-0.05
net emissions	1.07	~0	~0	0.66	0.12

If transport-then-chip preprocessing approach were used, the woody biomass preprocessing emissions would be: CO_2 - 0.04 t CO_2e/bdt, N_2O - 0.00 t CO_2e/bdt, CH_4 - 0.00 t CO_2e/bdt, CO 0.29 lb/bdt and $PM_{2.5}$ 0.03 lb/bdt.

Emission factor data assumptions and considerations

Biochar production from woody biomass is an emerging technology and not fully commercialized in the PNW or elsewhere. As a result, emissions associated with the production and use of biochar is inherently more uncertain. Production of biochar from chips was assumed to range from 20-40%. Heat is a by-product of biochar production, use of heat output requires having an on-site or nearby heat demand. For this analysis, we assumed that heat produced did not displace existing heat demand and no avoided use or avoided heat manufacture emissions were included.

Adding biochar to soil is widely reported as enhancing nutrient cycling, plant growth, or crop yields (203). However, benefits do not occur in all cases. Biochar is a general term, and the chemical composition, biological reactivity, and yield of biochar depends on the feedstock and charring process (204). In the last few years, knowledge has advanced and it is known that pyrolization at low temperatures (below 300 degrees C) can leave aromatic compounds in the char that can negatively affect plant growth. Also, it is know than pyrolization at high temperatures (above 500 degrees C) decreases the bioactivity of the char, and reduces the yield of char per unit input (204). Applying biochar to soil has greater opportunity to increase crop production in poor soils, where plants achieve far below their biological potential. Benefits appear to plateau at high char application rates (205).

Some authors have asserted that applying biochar to agriculture soil would result in GHG emission reductions from reduction in nitrogen fertilizer use (206), however the there has not been overall consensus in the published literature. Crop yield increases have been reported after application of biochar (203, 208). Over time it is possible that, with biochar applications to soil, a higher proportion of applied nitrogen fertilizer will be utilized by crops, and leaching (209, as cited in 208) and gaseous losses could be reduced (207, as cited in 208). Increased crop yields and nitrogen utilization with biochar do not necessarily mean that farmers will reduce the amounts of nitrogen they apply to their fields. It is also possible that fertilizer application rates will remain constant or rise as farmers seek to increase total crop yields. Potentially, immediately after application of biochar, demand for nitrogen could increase as nitrogen is absorbed by the biochar. Further research on the impact of biochar application on nitrogen fertilizer use in current on-farm practices is needed. Since the impact is uncertain, we do not attribute avoided use of soil amendment or avoided manufacture of fertilizer to the life cycle of biochar production from woody biomass in this analysis.

3. Residential Energy

Three options for use of woody biomass as a residential energy source are considered: combustion in a fireplace, combustion in an EPA-certified stove, and pelletization and combustion in a pellet stove.

3a. Combustion in fireplace

Life cycle description

Use of woody biomass for residential energy in a fireplace includes emissions associated with the gathering, chopping, transport and combustion. The net emissions for this fate include fuel wood production and fireplace combustion minus the avoided use of existing fuel wood in a fireplace plus the alternate use of existing fuel wood as either fuel for an EPA-certified wood stove, slash pile combustion, or decomposition, as shown in Figure 23.

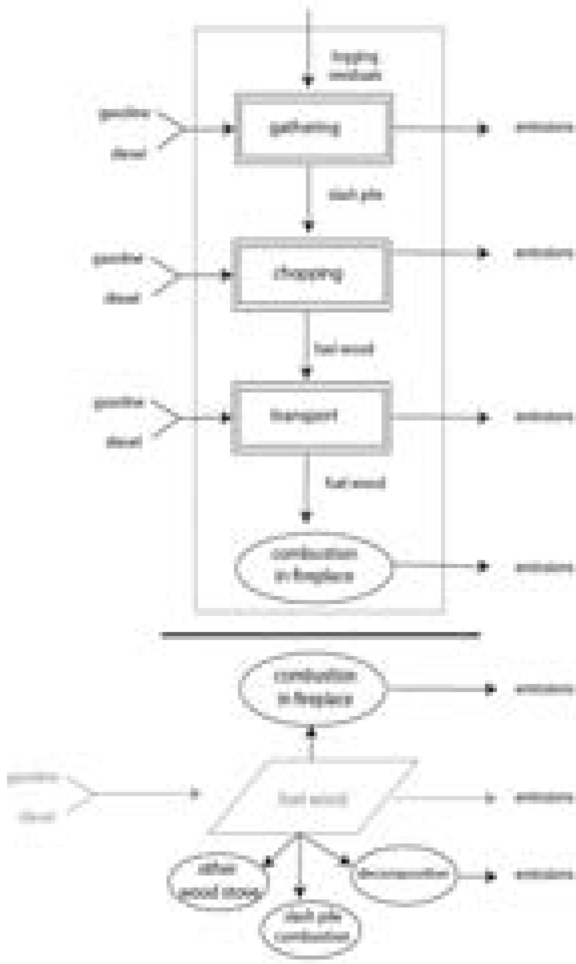

Figure 23. Combustion in fireplace life cycle boundary diagram.

Emission factor data and information
No emissions are associated with the gathering of woody biomass (130). Chopping emissions are based on chain saw use at a rate of 1 cord/hr (130), chain saw emissions (131), log splitter rate of 1 cord/hr (130), gasoline powered log splitter emissions (131), electric splitter emissions (140, 145, 147), and manufacturing emissions of chain saw, gasoline splitter and electric splitter equipment (149, 169, 170, 171). Transport emissions are based on fuel wood load per truck load of 0.25 – 1.0 cord (130), fuel efficiency of two axle, four wheel truck of 18 mpg (129), light-duty truck emissions for all fuel types (136, 190, 1919) and capital manufacturing of light-duty trucks (149, 167). Combustion emissions for fuel wood in a fireplace and avoided use for combustion in fireplace for CO_2 are based on the carbon content of wood (230,232,235), for N_2O the values are from AP-42 (116) and for other gases from updated emissions factors for woodstoves from EPA work group provided by WA Dept. of Ecology staff (119). Slash pile combustion emissions are the same as described under option *1b. on-site combustion* and decomposition emissions are the same as described under option *1a on-site decomposition*.

Life cycle emissions data
Life cycle emissions data for the option of using woody biomass as fuel wood for a fireplace is presented in Table 12.

Table 12. Combustion in fireplace life cycle emissions estimates. System, displaced and net emissions are presented. Data presented assume the chip-then-transport woody biomass preprocessing approach, 50 mile transport distance, 100 mile distribution distance and a fixed market demand. Values that are approximately zero (<0.005 or >-0.005) are indicated by ~0.

	CO_2	N_2O	CH_4	CO	$PM_{2.5}$
	(t CO_2e/bdt)			(lb/bdt)	
System					
gathering	--	--	--	--	--
chopping	~0	~0	~0	1.55	0.05
transport (50 mi)	0.05	0.07	0.21	2.80	~0
combustion	1.74	0.03	0.11	119.22	18.88
system emissions	1.79	0.10	0.32	123.57	18.93
displaced: fuel wood					
alternate use: EPA-certified stove	--	-0.02	0.10	-21.12	-2.88
net emissions	1.79	0.07	0.42	102.44	16.05
alternate use: on-site combustion	0.01	0.03	-0.08	-45.07	-10.87
net emissions	1.81	0.13	0.24	78.50	8.07
alternate use: on-site decomposition	-0.16	-0.03	-0.11	-119.22	-18.88
net emissions	1.63	0.07	0.21	4.34	0.05

If transport-then-chip preprocessing approach were used, the woody biomass preprocessing emissions would be: CO_2 - 0.04 t CO_2e/bdt, N_2O - 0.00 t CO_2e/bdt, CH_4 - 0.00 t CO_2e/bdt, CO 0.29 lb/bdt and $PM_{2.5}$ 0.03 lb/bdt.

Emission factor data assumptions and considerations
Gathering of fuel wood is assumed to be carried out by hand (130), where individuals or groups select and collect woody biomass that is of sufficient quality for fuel wood. The selected woody biomass is then chopped into logs and transported to the site of use in light-duty pick-up trucks. Moisture content of fuel wood is assumed to be 20%. CO_2 emissions for fireplace use assume complete combustion of

carbon in wood, no data on carbon content of ash residue was identified. Fireplace use is assumed not to serve as a primary heat source, so this option is not considered to displace fossil-fuel-generated heat.

3b. Combustion in EPA-certified stove

Life cycle description

The system emissions for the use of woody biomass for residential energy in an EPA-certified stove includes emissions associated with the gathering, chopping, transport and combustion of fuel wood. The net emissions for this fate include the system emissions minus the avoided use and plus the alternate use of existing fuel wood or minus the avoided use and manufacture of natural gas, diesel or electric heat, as shown in Figure 24.

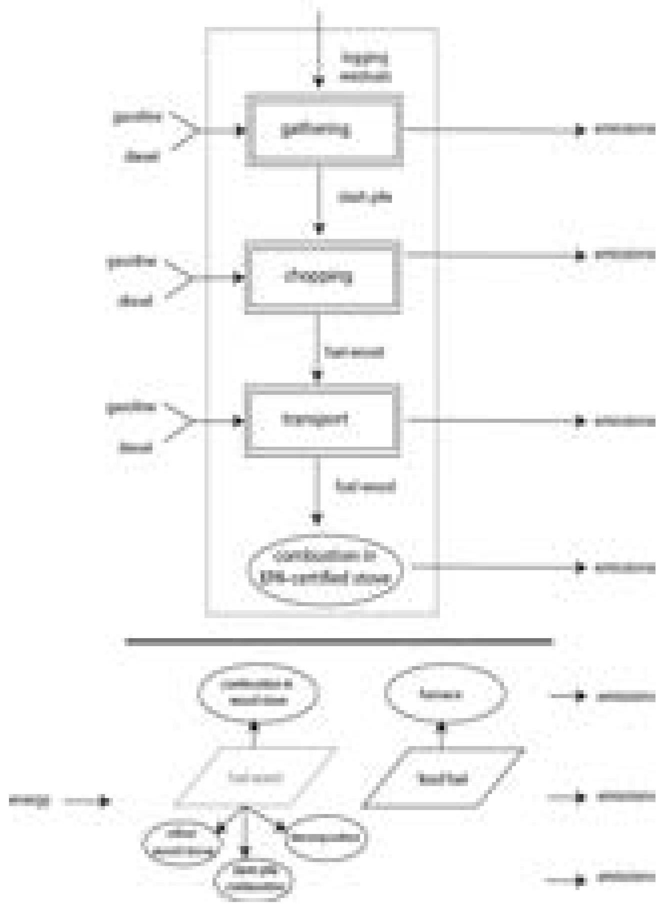

Figure 24. Combustion in EPA-certified stove life cycle boundary diagram.

Emission factor data and information

All data and information used for gathering, chopping, transport, other stove combustion, slash pile combustion and decomposition are as described under section *3a. combustion in a fireplace*. Emissions for combustion in an EPA-certified stove for CO_2 are based on the carbon content of wood (230,232,235) and for other gases the average of emissions for EPA-certified stove types (119, 217). Residential furnace efficiency is based on reference 104 and heating efficiency of EPA-certified stove based on references 101 and 102. Emissions factors for natural gas combustion are based on reference 142 and manufacture emissions are based on reference 148. For diesel (heating oil) in a furnace, emission factors for combustion are based on reference 141 and manufacture emissions are based on reference 180. The marginal electric emissions for the PNW are based on emissions data as reported by the Northwest Power and Conservation Council (140) and emissions for a combined-cycle NG turbine (147).

Life cycle emissions data

Life cycle emissions data for the option of using woody biomass for fuel wood production in an EPA-certified stove are presented in Table 13.

Table 13. Combustion in EPA-certified stove life cycle emissions estimates. System, displaced and net emissions are presented. Data presented assume the chip-then-transport woody biomass preprocessing approach, 50 mile transport distance, 100 mile distribution distance and a fixed market demand. Values that are approximately zero (<0.005 or >-0.005) are indicated by ~0.

	CO_2	N_2O	CH_4	CO	$PM_{2.5}$
	(t CO_2e/bdt)			(lb/bdt)	
System					
gathering	--	--	--	--	--
chopping	~0	~0	~0	1.55	0.05
distribution (50 mi)	0.05	--	0.21	2.80	~0
combustion	1.74	0.01	0.21	98.10	16.00
system emissions	1.79	0.01	0.42	102.44	16.05
displaced: fuel wood					
alternate use: EPA-certified stove	--	--	--	--	--
net emissions	1.79	0.01	0.42	102.44	16.05
alternate use: on-site combustion	0.01	0.06	-0.17	-23.95	-7.99
net emissions	1.81	0.06	0.24	78.50	8.07
alternate use: on-site decomposition	-0.16	-0.01	-0.21	-98.10	-16.00
net emissions	1.63	~0	0.21	4.34	0.05
displaced: fossil fuel heat					
avoided: natural gas (in furnace)	-0.89	-0.01	-0.01	-0.74	-0.10
net emissions	0.91	~0	0.41	101.71	15.95
avoided: fuel oil (in furnace)	-1.45	-0.01	-0.01	-0.94	-0.07
net emissions	0.34	~0	0.40	101.50	15.99
avoided: electric heat	-1.17	-0.01	~0	-0.39	-0.18
net emissions	0.62	~0	0.41	102.06	15.87

If transport-then-chip preprocessing approach were used, the woody biomass preprocessing emissions would be: CO_2 - 0.04 t CO_2e/bdt, N_2O - 0.00 t CO_2e/bdt, CH_4 - 0.00 t CO_2e/bdt, CO 0.29 lb/bdt and $PM_{2.5}$ 0.03 lb/bdt.

Emission factor data assumptions and considerations

Gathering of fuel wood is assumed to be carried out by hand (130), where individuals or groups select and collect woody biomass that is of sufficient quality for fuel wood. The selected woody biomass is then chopped into logs and transported to the site of use in light-duty pick-up trucks. Moisture content of fuel wood is assumed to be 20%. CO_2 emissions for wood stove use assume complete combustion of carbon in wood, no data on carbon content of ash residue was identified.

3c. Pelletization & Combustion in Pellet Stove

Life cycle description

The system emissions for the production of pellets and combustion in a pellet stove includes emissions associated with woody biomass preprocessing, pellet processing, packaging, distribution and combustion in pellet stove. The net emissions are the system emissions minus the avoided use emissions of minus displaced emissions from fuel wood or fossil fuel heat usage, as shown in Figure 25.

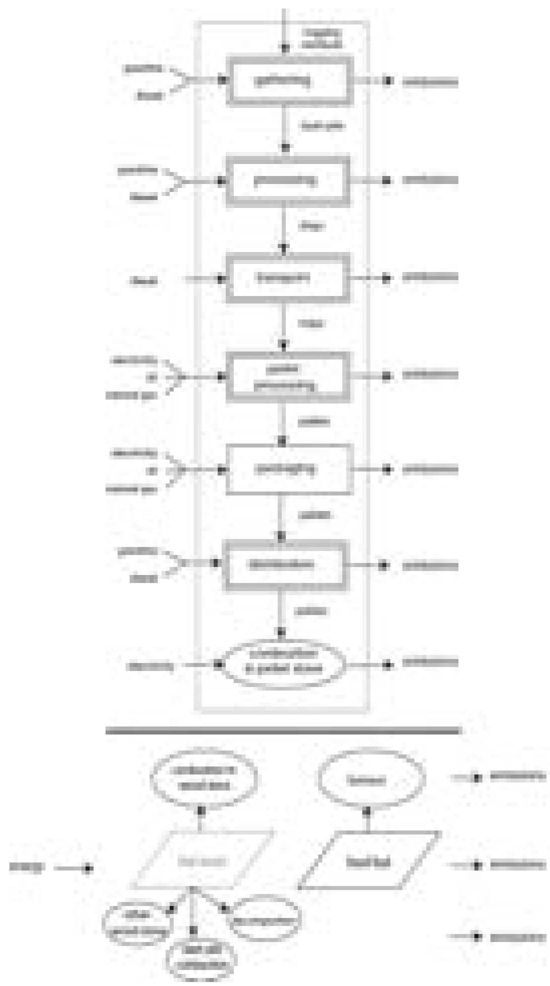

Figure 25. Pelletization & combustion in pellet stove life cycle boundary diagram.

Emission factor data and information

Emissions associated with woody biomass preprocessing are discussed in the above section. Pellet processing emissions are based the carbon content of wood (230,232,235), emissions reported from a pellet production facility in Washington State (154) and published life cycle emissions estimates from pellet production facilities in Canada (138, 139). Production efficiency of pellets from residues is 85% (138). Pellet stove combustion emissions are based on the carbon content of wood (230,232,235) and an average of emissions from current pellet stoves (117,119). N_2O emissions from wood stoves (217) are used as a proxy for pellet stove emissions. Distribution is based on heavy duty truckload of 16 bdt/truckload (an average of values from 113 and 127) and capital manufacturing emissions (149, 165) and operating emissions (139, 190, 191, and 202) for heavy duty trucks. Residential furnace efficiency is based on reference 104. Heating efficiency of pellet stove is based on references 138 and 239; and of EPA-certified stove based on references 101 and 102. Emissions factors for natural gas combustion are based on reference 142 and manufacture is based on reference 148. For diesel (heating oil) in a furnace emission factors for combustion are based on 141 and manufacture is based on 180. The marginal electric emissions for the PNW is based on emissions data as reported by the Northwest Power and Conservation Council (140) and emissions for a combined-cycle NG turbine (147).

Life cycle emissions data

Life cycle emissions data for the use of woody biomass to generate pellets and to use in a pellet stove is presented in Table 14.

Table 14. Pelletization & combustion in pellet stove life cycle emissions estimates. System, displaced and net emissions are presented. Data presented assume the chip-then-transport woody biomass preprocessing approach, 50 mile transport distance, 100 mile distribution distance and a fixed market demand. Values that are approximately zero (<0.005 or >-0.005) are indicated by ~0.

	CO_2	N_2O	CH_4	CO	$PM_{2.5}$
	(t CO_2e/bdt)			(lb/bdt)	
system					
woody biomass preprocessing	0.03	~0	~0	0.29	0.03
pelletization and packaging	0.43	~0	~0	0.83	0.16
distribution (100 mi)	0.01	~0	~0	0.11	0.01
combustion	1.33	0.01	~0	21.16	2.34
system emissions	1.80	0.01	~0	22.39	2.54
displaced: fuel wood					
alternate use: EPA-certified stove	--	--	--	--	--
net emissions	1.80	0.01	~0	22.39	2.54
alternate use: on-site combustion	0.01	0.04	-0.13	-18.32	-6.11
net emissions	1.81	0.05	-0.13	4.07	-3.57
alternate use: on-site decomposition	-0.12	-0.01	-0.16	-75.05	-12.24
net emissions	1.68	~0	-0.15	-52.66	-9.70
displaced: fossil fuel heat					
avoided: natural gas (in furnace)	-0.76	~0	-0.01	-0.63	-0.09
net emissions	1.04	0.01	-0.01	21.75	2.45
avoided: fuel oil (in furnace)	-1.25	~0	-0.01	-0.81	-0.06
net emissions	0.55	0.01	-0.01	21.58	2.48
avoided: electric heat	-1.02	-0.01	~0	-0.34	-0.16
net emissions	0.78	~0	~0	22.05	2.38

If transport-then-chip preprocessing approach were used, the woody biomass preprocessing emissions would be: CO_2 - 0.04 t CO_2e/bdt, N_2O - 0.00 t CO_2e/bdt, CH_4 - 0.00 t CO_2e/bdt, CO 0.29 lb/bdt and $PM_{2.5}$ 0.03 lb/bdt.

Emission factor data assumptions and considerations

This analysis assumes that pellets produced are not packaged and instead are distributed in bulk. Distribution is assumed to be via heavy duty trucks. It is assumed that 10% of residues gathered do not meet the quality requirements for pellet production and are diverted to combustion in an industrial hog fuel boiler.

4. Industrial Energy

Four options for the use of woody biomass as an industrial energy source are considered in this analysis: displacement of natural gas, diesel or residual oil in boiler; displacement of hog fuel in boiler; integrated gasification and combustion, and new exported electricity by cogeneration for the grid.

4b. Displacement of natural gas, diesel or residual oil in boiler

Life cycle description

The use of woody biomass as an industrial energy source for boilers includes the emissions associated with woody biomass preprocessing, combustion of hog fuel in boiler and ash transport to landfill. The net emissions for use of woody biomass in an industrial boiler include emissions from hog fuel production, combustion, ash disposal minus the avoided use emissions of the displaced fossil fuel energy source either natural gas, diesel or residual oil and the avoided manufacture emissions of the displaced fuel source, as shown in Figure 26.

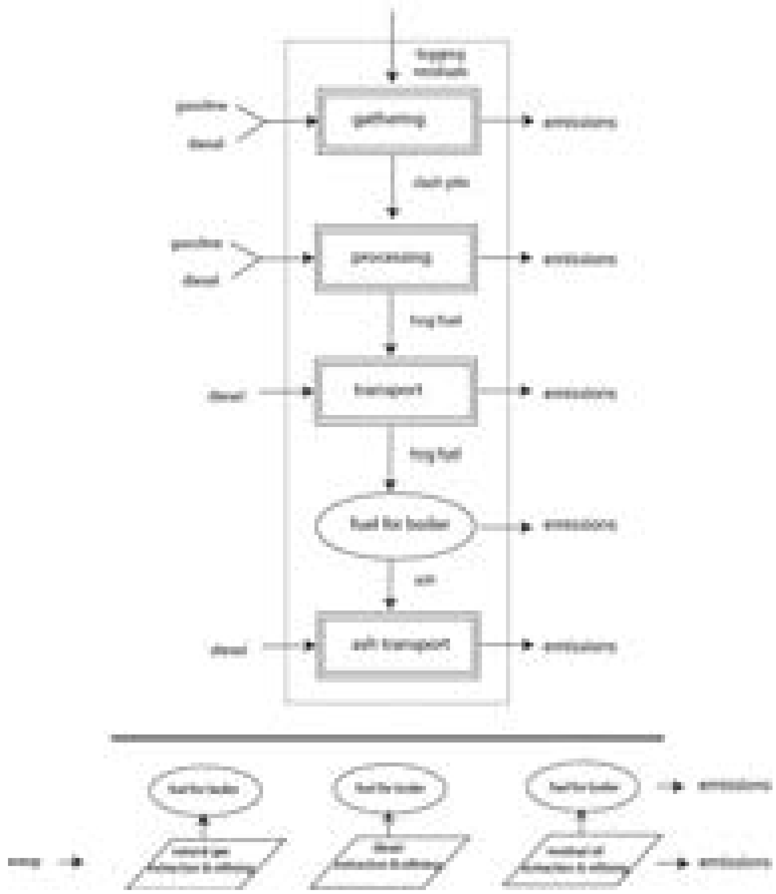

Figure 26. Displacement of natural gas, diesel or residual oil in boiler life cycle boundary diagram.

Emission factor data and information

Emissions associated with woody biomass preprocessing are discussed in the woody biomass preprocessing section above. Combustion of hog fuel in boiler are based on emissions from AP-42 (150) and emissions reported from hog fuel boiler facilities in Washington State provided by ORCAA (162). Ash transport emissions are equivalent to emissions associated with distribution and are based on heavy duty truckload of 16 bdt/truckload (an average of values from 113 and 127) and capital manufacturing emissions (149, 165) and operating emissions (139, 190, 191, 202) for heavy duty trucks. Ash transport distance of 50 miles is used. Ash content of less than 1% per bdt is used (231). Data for avoided use and manufacture emissions include emissions factors for combustion of natural gas (142), diesel (141) and residual oil (141), as well as the manufacture and production of natural gas (148), diesel (180) and residual oil (141).

Life cycle emissions data

Life cycle emissions data for the option of displacing fossil fuel in boiler with hog fuel is presented in Table 15.

Table 15. Displacement of natural gas, diesel or residual oil in boiler life cycle emissions estimates. System, displaced and net emissions are presented. Data presented assume the chip-then-transport woody biomass preprocessing approach, 50 mile transport distance, 100 mile distribution distance and a fixed market demand. Values that are approximately zero (<0.005 or >-0.005) are indicated by ~0.

	CO_2	N_2O	CH_4	CO	$PM_{2.5}$
	(t CO_2e/bdt)			(lb/bdt)	
System					
woody biomass preprocessing	0.03	~0	~0	0.29	0.03
combustion	1.74	~0	~0	4.36	1.19
ash transport	~0	~0	~0	~0	~0
system emissions	1.77	~0	~0	4.65	1.22
displaced: fossil fuel					
avoided: natural gas	-0.94	-0.01	-0.01	-1.52	-0.10
net emissions	0.83	~0	-0.01	3.13	1.12
avoided: diesel	-1.53	-0.01	-0.01	-0.99	-0.07
net emissions	0.24	~0	-0.01	3.66	1.15
avoided: residual oil	-1.61	-0.01	-0.01	-0.92	-2.54
net emissions	0.16	~0	-0.01	3.74	-1.31

If transport-then-chip preprocessing approach were used, the woody biomass preprocessing emissions would be: CO_2 - 0.04 t CO_2e/bdt, N_2O - 0.00 t CO_2e/bdt, CH_4 - 0.00 t CO_2e/bdt, CO 0.29 lb/bdt and $PM_{2.5}$ 0.03 lb/bdt.

Emission factor data assumptions and considerations

CO_2 emissions assume complete combustion of carbon in hog fuel. Ash transport distance of 50 mi is used.

4c. Displacement of hog fuel in boiler

Life cycle description

The use of woody biomass as an industrial energy source for the displacement of hog fuel in boilers includes the emissions associated with woody biomass preprocessing, combustion of hog fuel in boiler and ash transport to landfill. The net emissions for use of woody biomass in an industrial boiler include hog fuel production, combustion, ash disposal minus the avoided use emissions of the displaced hog fuel and associated ash transport plus emissions from the alternate use of the displaced hog fuel as either mulch or in an alternate boiler, as shown in Figure 27.

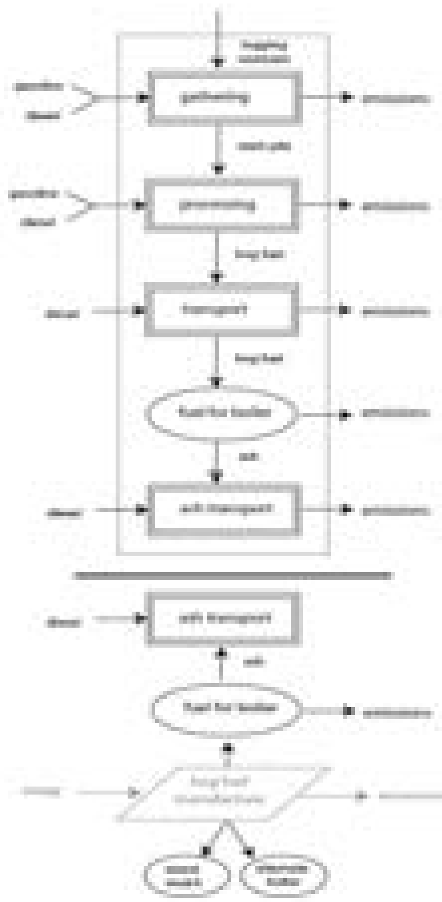

Figure 27. Displacement of hog fuel in boiler life cycle boundary diagram.

Emission factor data and information

Emissions associated with woody biomass preprocessing are discussed in the woody biomass preprocessing section above. Combustion of hog fuel in boiler are based on emissions from AP-42 (150) and emissions reported from hog fuel boiler facilities in Washington State provided by ORCAA (162). Ash transport emissions are equivalent to emissions associated with distribution and are based on heavy duty truckload of 16 bdt/truckload (an average of values from 113 and 127) and capital manufacturing emissions (149, 165) and operating emissions (139, 190, 191, 202) for heavy duty trucks. Ash transport distance of 50 miles is used. Ash generation of 1% per bdt is used (231). Data for alternate use as mulch are based on emissions discussed in *section 2a. chipping for mulch*. Data for avoided use and alternate use of hog fuel in boiler are the same as data used for the combustion of hog fuel in boiler and ash transport.

Life cycle emissions data

Life cycle emissions for the option of using woody biomass as hog fuel to displace existing hog fuel in boilers is presented in Table 16.

Table 16. Displacement of hog fuel in boiler life cycle emissions estimates. System, displaced and net emissions are presented. Data presented assume the chip-then-transport woody biomass preprocessing approach, 50 mile transport distance, 100 mile distribution distance and a fixed market demand. Values that are approximately zero (<0.005 or >-0.005) are indicated by ~0.

	CO_2	N_2O	CH_4	CO	$PM_{2.5}$
	(t CO_2e/bdt)			(lb/bdt)	
system					
woody biomass preprocessing	0.03	~0	~0	0.29	0.03
combustion	1.74	~0	~0	4.36	1.19
ash transport	~0	~0	~0	~0	~0
system emissions	1.77	~0	~0	4.65	1.22
displaced: hog fuel					
alternate use: alternate boiler	--	--	--	--	--
net emissions	1.77	~0	~0	4.65	1.22
alternate use: wood mulch	-0.14	~0	~0	-4.36	-1.19
net emissions	1.63	~0	~0	0.29	0.03

If transport-then-chip preprocessing approach were used, the woody biomass preprocessing emissions would be: CO_2 - 0.04 t CO_2e/bdt, N_2O - 0.00 t CO_2e/bdt, CH_4 - 0.00 t CO_2e/bdt, CO 0.29 lb/bdt and $PM_{2.5}$ 0.03 lb/bdt.

Emission factor data assumptions and considerations

CO_2 emissions assume complete combustion of carbon in hog fuel. Ash transport distance of 50 mi is used.

4d. Integrated gasification and combustion

Life cycle description

The use of woody biomass for generation of heat and electricity through an integrated gasification and combustion system includes emissions associated with woody biomass preprocessing, gasifier/combustor and ash transport. The net emissions are based on the woody biomass use in the integrated gasifier and combustion minus the avoided use and avoided manufacturing emissions of heat and electricity, as shown in Figure 28.

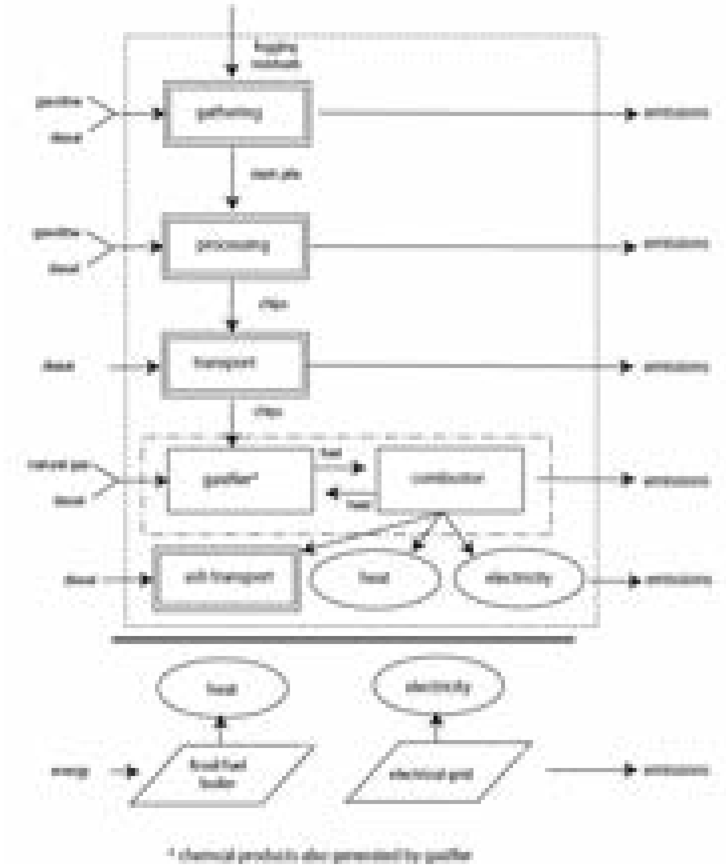

Figure 28. Integrated gasification and combustion life cycle boundary diagram.

Emission factor data and information

Emissions from woody biomass preprocessing are discussed in the woody biomass preprocessing section above. Emissions from the gasifier/combustor are based on syngas combustion (based on combustion emissions for natural gas (142)). Ash transport emissions are equivalent to emissions associated with distribution and are based on heavy duty truckload of 16 bdt/truckload (an average of values from 113 and 127) and capital manufacturing emissions (149, 165) and operating emissions (139, 190, 191, 202) for heavy duty trucks. The ash residue generation rate ranges from 1-10% (188). Electricity generation yield is based on projected electrical conversion efficiencies of biomass gasifiers ranging from 60-80% (236) and the HHV of wood (234). Gasifier and combustor emissions are from references 237 and 238. $PM_{2.5}$ emissions from a natural gas boiler as used as a conservative proxy for the IGC system. Avoided manufacture emissions for electricity generation are based on the marginal electric emissions for the PNW as reported by the Northwest Power and Conservation Council (140) and a combined-cycle NG turbine (147). For heat avoided use and manufacture emissions include emissions factors for combustion of natural gas (142), diesel (141) and residual oil (141), as well as the manufacture and production of natural gas (148), diesel (180) and residual oil (141).

Life cycle emissions data

Life cycle emissions data for the option of using woody biomass in an integrated gasification and combustion system is presented in Table 17.

Table 17. Integrated gasification and combustion life cycle emissions estimates. System, displaced and net emissions are presented. Data presented assume the chip-then-transport woody biomass preprocessing approach, 50 mile transport distance, 100 mile distribution distance and a fixed market demand. Values that are approximately zero (<0.005 or >-0.005) are indicated by ~0.

	CO_2	N_2O	CH_4	CO	$PM_{2.5}$
	($t\ CO_2e/bdt$)			(lb/bdt)	
system					
woody biomass preprocessing	0.03	~0	~0	0.29	0.03
gasification + combustion	1.74	--	--	--	0.07
ash transport	~0	~0	~0	~0	~0
heat	--	--	--	--	--
electricity	--	--	--	--	--
system emissions	1.77	~0	~0	0.29	0.10
displaced: fossil fuel					
avoided: natural gas + electricity	-1.19	-0.01	~0	-0.39	-0.19
net emissions	0.58	-0.01	~0	-0.10	-0.08
avoided: diesel + electricity	-1.19	-0.01	~0	-0.39	-0.19
net emissions	0.58	-0.01	~0	-0.10	-0.08
avoided: residual oil + electricity	-1.19	-0.01	~0	-0.39	-0.19
net emissions	0.58	-0.01	~0	-0.10	-0.08

If transport-then-chip preprocessing approach were used, the woody biomass preprocessing emissions would be: CO_2 - 0.04 t CO_2e/bdt, N_2O - 0.00 t CO_2e/bdt, CH_4 - 0.00 t CO_2e/bdt, CO 0.29 lb/bdt and $PM_{2.5}$ 0.03 lb/bdt.

Emission factor data assumptions and considerations

Integrated gasification and combustion of woody biomass remains an emerging technology and is not widely commercialized, as a result data availability is inherently limited and more uncertain. Natural gas combustion emissions were assumed to be a reasonable proxy for $PM_{2.5}$ emissions. Heat is a by-product of the IGC system, use of heat output requires having an on-site or nearby heat demand. For this analysis, we conservatively assumed that heat produced did not displace existing heat demand and no avoided use or avoided heat manufacture emissions were included. It is assumed that ash is transported a distance of 50 miles to landfill site.

4e. New exported electricity by cogenerator

Life cycle description

The use of woody biomass as an industrial boiler energy source for electricity generation for export includes the emissions associated with woody biomass preprocessing, combustion of hog fuel in boiler and ash transport to landfill. The net emissions for use of woody biomass in an industrial boiler include hog fuel production, combustion, ash disposal minus the avoided use emissions of the displaced electricity use and generation emissions, as shown in Figure 29.

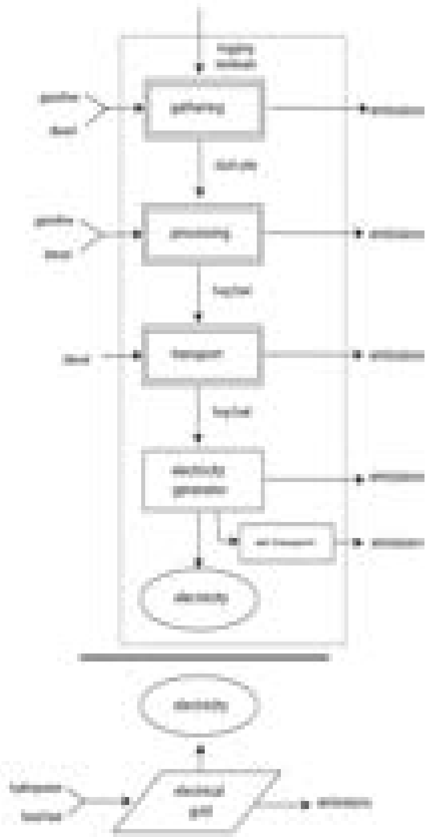

Figure 29. New exported electricity by cogenerator life cycle boundary diagram.

Emission factor data and information

Emissions associated with woody biomass preprocessing are discussed in the woody biomass preprocessing section above. Combustion of hog fuel in a boiler are based on emissions from AP-42 (150) and emissions reported from hog fuel boiler facilities in Washington State provided by ORCAA (162). Ash transport emissions are equivalent to emissions associated with distribution and are based on heavy duty truckload of 16 bdt/truckload (an average of values from 113 and 127) and capital manufacturing emissions (149, 165) and operating emissions (139, 190, 191, 202) for heavy duty trucks. Data on the effective electric efficiency of the cogenerator range from 51 – 69% (233). Data for avoided use and manufacture emissions for electricity are based on the marginal electric emissions for the PNW as reported by the Northwest Power and Conservation Council (140) and a combined-cycle NG turbine (147).

Life cycle emissions data

Life cycle emissions data for the option of using woody biomass for the production of new exported electricity are presented in Table 18Table 18.

Table 18. New exported electricity by cogenerator life cycle emissions estimates. System, displaced and net emissions are presented. Data presented assume the chip-then-transport woody biomass preprocessing approach, 50 mile transport distance,

100 mile distribution distance and a fixed market demand. Values that are approximately zero (<0.005 or >-0.005) are indicated by ~0.

	CO_2	N_2O	CH_4	CO	$PM_{2.5}$
	(t CO_2e/bdt)			(lb/bdt)	
system					
woody biomass preprocessing	0.03	~0	~0	0.29	0.03
combustion	1.74	~0	~0	4.36	1.19
ash transport	~0	~0	~0	~0	~0
system emissions	1.77	~0	~0	4.65	1.22
displaced: electricity					
avoided: electricity	-1.02	-0.01	~0	-0.33	-0.16
net emissions	0.75	~0	~0	4.32	1.06

If transport-then-chip preprocessing approach were used, the woody biomass preprocessing emissions would be: CO_2 - 0.04 t CO_2e/bdt, N_2O - 0.00 t CO_2e/bdt, CH_4 - 0.00 t CO_2e/bdt, CO 0.29 lb/bdt and $PM_{2.5}$ 0.03 lb/bdt.

Emission factor data assumptions and considerations

Analysis assumes ash is transported 50 miles to landfill disposal site. Ash generation of 1% per bdt is used (231). CO_2 emissions assume complete combustion of carbon in hog fuel. Heat is a by-product of the cogenerator, use of heat output requires having an on-site or nearby heat demand. For this analysis, we conservatively assumed that there is no net useful heat production and no avoided use or avoided heat manufacture emissions were included.

5. Industrial Feedstock

Use of woody biomass for pulp or paper production is the only industrial feedstock option considered in this analysis.

5a. Pulp or paper

Life cycle description

Use of woody biomass as a feedstock for pulp production includes emissions associated with woody biomass preprocessing, recovery boiler and pulp use and decay. The net emissions include pulp production and use minus the avoided use emissions of pulp and the avoided manufacture emissions of electricity and pulp, as shown in Figure 30.

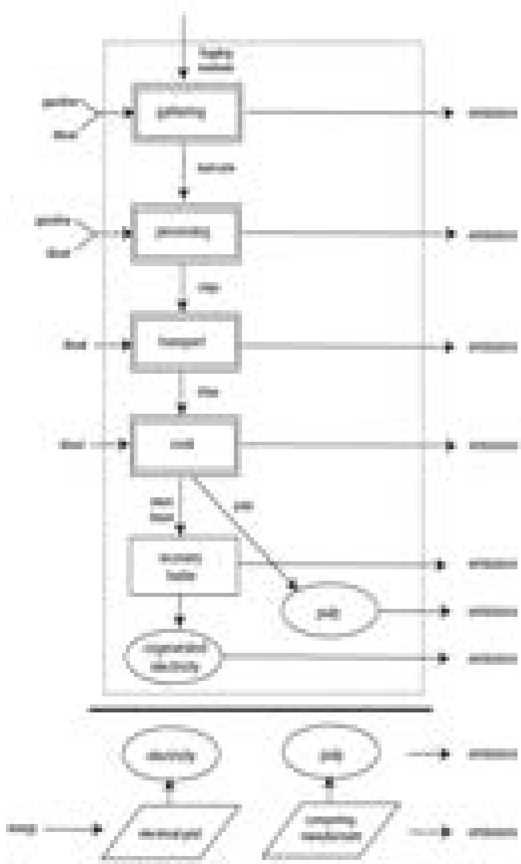

Figure 30. Pulp or paper life cycle boundary diagram.

Emission factor data and information

Emissions for woody biomass preprocessing are discussed in the woody biomass preprocessing section above. Emissions for the cooker/digester are based on bulldozer operating (143, 131, and 135) and capital manufacturing emissions (149, 158) for loading chips. Recovery boiler emissions are based on the carbon content of chips (230,232,235), recovery boiler emissions reported in AP-42 (144) and the proportion of chips added into the recovery boiler (143). Pulp production, use and avoided use emissions from CO_2 are based the proportion of chips in the recovery boiler (143), the proportion of carbon in wood chips (230,232,235) and the proportion of paper remaining in landfills of 8% over the long-term (118). Pulp emissions and avoided use pulp emissions for CH_4 are based on the proportion of paper remaining in landfills (118) and the average maximum proportion of land filled paper wastes that become methane (193). Data on the volume of cogenerated electricity are based on a value of 500 kWh/bdt and range of purchased electricity from 10-15.8 mmBtu/bdt (184). Lime kiln emissions are based on daily lime kiln energy use (195) and emissions from natural gas (142) and residual oil (141) for powering the lime kiln. Avoided manufacture of pulp emissions are identical to system emissions estimated for this option, as discussed here. Avoided generated electrical emissions are based on the marginal electric emissions for the PNW as reported by the Northwest Power and Conservation Council (140) and a combined-cycle NG turbine (147).

Life cycle emissions data

Life cycle emissions associated with the use of woody biomass for pulp or paper production are presented in Table 19.

Table 19. Pulp or paper life cycle emissions estimates. System, displaced and net emissions are presented. Data presented assume the chip-then-transport woody biomass preprocessing approach, 50 mile transport distance, 100 mile distribution distance and a fixed market demand. Values that are approximately zero (<0.005 or >-0.005) are indicated by ~0.

	CO_2	N_2O	CH_4	CO	$PM_{2.5}$
	(t CO_2e/bdt)			(lb/bdt)	
system					
woody biomass preprocessing	0.03	~0	~0	0.29	0.03
cook	0.17	~0	~0	0.45	0.12
recovery boiler/lime kiln	0.84	--	--	6.02	0.66
pulp	0.40	--	0.10	--	--
electricity	--	--	--	--	--
system emissions	1.45	~0	0.10	6.76	0.81
displaced: pulp + electricity					
avoided: pulp + electricity	-0.46	~0	~0	-1.50	-0.20
net emissions	0.99	~0	0.10	5.26	0.61

If transport-then-chip preprocessing approach were used, the woody biomass preprocessing emissions would be: CO_2 - 0.04 t CO_2e/bdt, N_2O - 0.00 t CO_2e/bdt, CH_4 - 0.00 t CO_2e/bdt, CO 0.29 lb/bdt and $PM_{2.5}$ 0.03 lb/bdt.

Emission factor data assumptions and considerations

Pulp production requires high quality wood chips preferably of uniform size and species with no bark. Pulp chips are generally sourced from saw mill residues, which produce chips of sufficient quality. Producing wood chips for pulp from logging residue woody biomass is not currently common practice. This analysis assumes that 10% of residues gathered do not meet the quality requirements for pulp production and this material is diverted to combustion in an industrial hog fuel boiler

6. Liquid Fuel

Two options for the use of woody biomass logging residues for ethanol production are considered via hydrolysis and fermentation and via gasification and synthesis.

6a. Ethanol by hydrolysis and fermentation

Life cycle description

The use of woody biomass logging residuals for ethanol production by hydrolysis and fermentation include emissions from woody biomass preprocessing, combustor/hydrolysis, fermentation + distillation, distribution and ethanol combustion. The net emissions are based on the ethanol production and use emissions minus the avoided use of gasoline (there are no electricity use emissions) and the avoided manufacturing of electricity and gasoline extraction +refining, as shown in Figure 31.

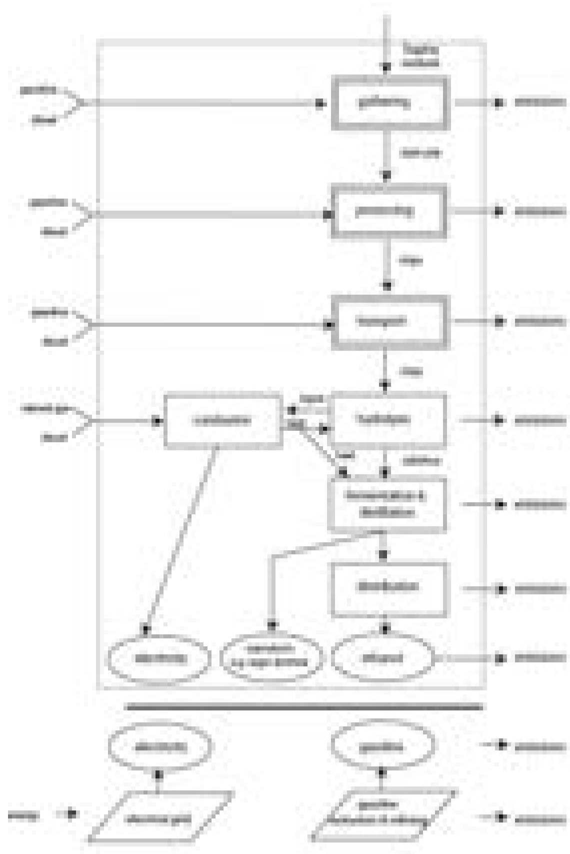

Figure 31. Ethanol by hydrolysis and fermentation life cycle boundary diagram.

Emission factor data and information

Proportion of lignin in residues ranges from 27-42% (163). Lignin combustion emissions are based on emissions for hog fuel combustion in an industrial boiler as discussed under section 4b, 4c, and 4e for hog fuel in an industrial boiler above. Process N_2O and CH_4 emissions for ethanol production from hydrolysis, fermentation and distillation are based on reference 240. Distribution is based on heavy duty truckload of 16 bdt/truckload (an average of values from 113 and 127) and capital manufacturing emissions (149, 165) and operating emissions (139, 190, 191, and 202) for heavy duty trucks. Ethanol yield is based on production from switchgrass ranges from 330-470 L/bdt (240). Electricity yield ranges from 322-545 kWh/bdt and is based on use of lignin, coproduct material and residues that do not meet ethanol product quality requirements in a cogernator. Ethanol combustion is based on published emissions factors from a life cycle emission model for transportation fuels (181). Avoided use emissions for gasoline are based on emissions factor for gasoline use as a transportation fuel (129,181). Avoided manufacture emissions associated with electricity generation are based on the marginal electric emissions for the PNW as reported by the Northwest Power and Conservation Council (140) and a combined-cycle NG turbine (147) and for gasoline extraction + refining (180).

Life cycle emissions data

Life cycle emissions from the use of woody biomass for the production of ethanol via hydrolysis and fermentation are presented in Table 20.

Table 20. Ethanol by hydrolysis and fermentation life cycle emissions estimates. System, displaced and net emissions are presented. Data presented assume the chip-then-transport woody biomass preprocessing approach, 50 mile transport distance, 100 mile distribution distance and a fixed market demand. Values that are approximately zero (<0.005 or >-0.005) are indicated by ~0.

	CO_2	N_2O	CH_4	CO	$PM_{2.5}$
	($t\ CO_2e/bdt$)			(lb/bdt)	
system					
woody biomass preprocessing	0.03	~0	~0	0.29	0.03
combustor	0.72	~0	~0	1.80	0.49
hydrolysis, fermentation + distillation	--	--	--	--	--
distribution	~0	--	--	--	--
ethanol	0.45	0.09	~0	20.94	0.05
electricity	--	--	--	--	--
co-products	--	--	--	--	--
system emissions	1.20	0.09	~0	23.03	0.58
displaced: gasoline + electricity					
avoided: gasoline + electricity	-0.70	-0.07	-0.01	-23.93	-0.12
net emissions	0.50	0.03	~0	-0.90	0.46

If transport-then-chip preprocessing approach were used, the woody biomass preprocessing emissions would be: CO_2 - 0.04 t CO_2e/bdt, N_2O - 0.00 t CO_2e/bdt, CH_4 - 0.00 t CO_2e/bdt, CO 0.29 lb/bdt and $PM_{2.5}$ 0.03 lb/bdt.

Emission factor data assumptions and considerations

Ethanol generation by hydrolysis and fermentation from woody biomass logging residues is an emerging technology and data availability is inherently more limited and uncertain. Ethanol yield data used is an average of projected yields in 2010 and 2020. Sugar alcohols are likely to be a co-product of this ethanol production approach, in this analysis it was assumed that co-products were used as fuel in a cogenerator similar to fate 4e.   It is assumed that 10% of residues gathered do not meet the quality requirements for ethanol production and are diverted to combustion in a cogenerator.

6b. Ethanol by gasification and synthesis

Life cycle description

The use of woody biomass logging residuals for ethanol production by gasification and synthesis include emissions from woody biomass preprocessing, gasifier/combustor, ethanol synthesis, distribution and ethanol combustion. The net emissions are based on the ethanol production and use emissions minus the avoided use of gasoline and the avoided manufacturing of gasoline extraction +refining, as shown in Figure 32.

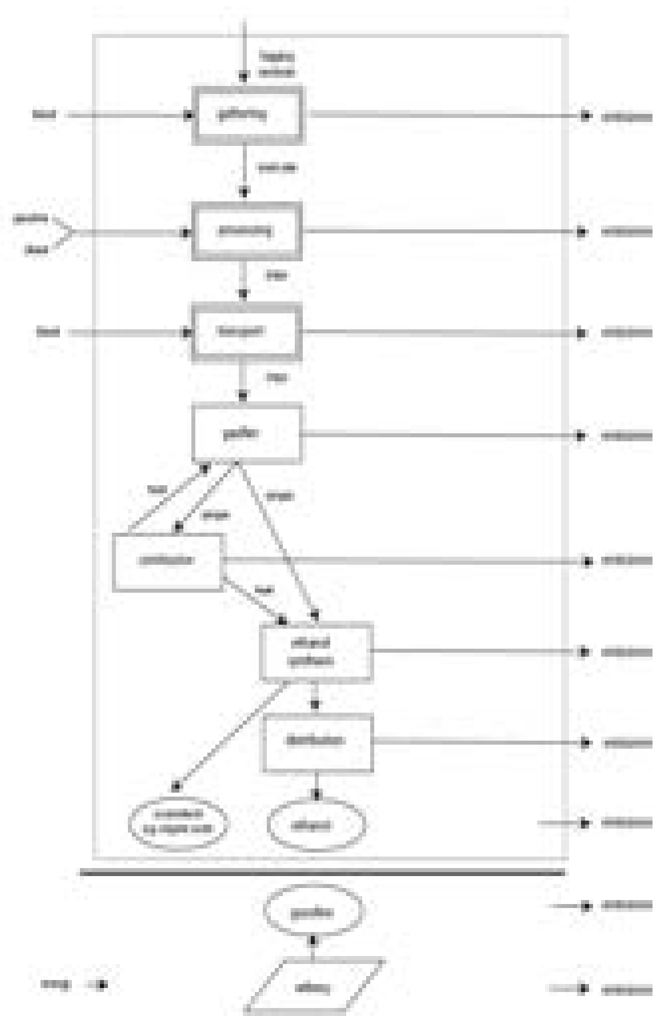

Figure 32. Ethanol by gasification and synthesis life cycle boundary diagram.

Emission factor data and information

Gasifier/combustor emissions are based on emissions for hog fuel integrated gasification and combustion as discussed under section *4d. integrated gasification and combustion*. Distribution is based on heavy duty truckload of 16 bdt/truckload (an average of values from 113 and 127) and capital manufacturing emissions (149, 165) and operating emissions (139, 190, 191, and 202) for heavy duty trucks. Ethanol yield is based on reference 241 of 44%. Ethanol combustion is based on published emissions factors from a life cycle emission model for transportation fuels (181). Avoided use emissions are based on an emissions factor for gasoline use as transportation fuel (129,181). Avoided manufacture emissions for gasoline are based on emissions from gasoline extraction + refining (180).

Life cycle emissions data

Life cycle emissions from the use of woody biomass for ethanol production by gasification and synthesis are presented in Table 21.

Table 21. Ethanol by gasification and synthesis life cycle emissions estimates. System, displaced and net emissions are presented. Data presented assume the chip-then-transport woody biomass preprocessing approach, 50 mile transport distance, 100 mile distribution distance and a fixed market demand. Values that are approximately zero (<0.005 or >-0.005) are indicated by ~0.

	CO_2	N_2O	CH_4	CO	$PM_{2.5}$
	(t CO_2e/bdt)			(lb/bdt)	
system					
woody biomass preprocessing	0.03	~0	~0	0.29	0.03
gasifier/combustor	0.97	--	--	--	0.04
ethanol synthesis	--	--	--	--	--
distribution	~0	--	--	--	--
ethanol	0.55	0.11	~0	25.75	0.07
co-products	--	--	--	--	--
system emissions	1.56	0.11	~0	26.04	0.14
displaced: gasoline					
avoided: gasoline	-0.72	-0.08	~0	-29.20	-0.11
net emissions	0.84	0.03	~0	-3.15	0.03

If transport-then-chip preprocessing approach were used, the woody biomass preprocessing emissions would be: CO_2 - 0.04 t CO_2e/bdt, N_2O - 0.00 t CO_2e/bdt, CH_4 - 0.00 t CO_2e/bdt, CO 0.29 lb/bdt and $PM_{2.5}$ 0.03 lb/bdt.

Emission factor data assumptions and considerations

Ethanol generation by gasification and synthesis from woody biomass logging residues is an emerging technology and data availability is inherently more limited and uncertain. Emissions from the integrated gasification and combustion of hog fuel are used as a proxy for gasifier/combustor emissions for this option. No emissions data were found for the ethanol synthesis process steps. Organic acids are likely to be a co-product of this ethanol production approach. This analysis assumes that all co-products are combusted as part of gasification process. It is assumed that 10% of residues gathered do not meet the quality requirements for ethanol production and are diverted to combustion in an industrial hog fuel boiler.

List of Acronyms and Units of Measure

bdt	bone dry ton
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
t CO_2e	metric tons carbon dioxide equivalent
GHG	greenhouse gas
GWP	global warming potential
IGC	integrated gasification and combustion
ISO	International Organization for Standardization
kg	kilogram
lbs	pounds
$PM_{2.5}$	fine particulate matter
PNW	Pacific Northwest
N_2O	nitrous oxide
ORCAA	Olympic Region Clean Air Agency
WBEC	Woody Biomass Emissions Calculator
U.S. EPA	United States Environmental Protection Agency

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call no.	file type	cite or <filename as received>	received	notes: source (person or <URL>)
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102	.htm	40 CFR 60.536(i)(3)		In "subpart AAA" at http://www.tceq.state.tx.us/permitting/air/rules/federal/60/60hmpg.html
103	.pdf	U.S. EPA, letter dated February 26, 2009.		Documents that 90% AFUE furnaces command 30% of 2008 market.
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110	.xls	<OperatorsLogSheetTable.xls>	12/21/09	Mark Goodin, ORCAA; sent from John Pelligrini at Grays Harbor
111	.xls	<TimeSheetTable.xls>	12/21/09	Mark Goodin, ORCAA; sent from John Pelligrini at Grays Harbor
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113	.xls	<HogFuelTable.xls>	12/21/09	Mark Goodin, ORCAA; sent from John Pelligrini at Grays Harbor
114	.docx	FW: Ash Data: Nippon	12/22/09	Mark Goodin, ORCAA; sent from Paul Perlxitz
115	.pdf	AP 42, Fifth Edition, Volume I: Chapter 13 Miscellaneous Sources		Chapter 13.1 Wildfires and Prescribed Burning http://www.epa.gov/ttn/chief/ap42/ch13/final/c13s01.pdf
116	.pdf	AP 42, Fifth Edition, Volume I: Chapter 1 External Combustion Sources		Chapter 1.9: Residential Fireplaces http://www.epa.gov/ttn/chief/ap42/ch01/final/c01s09.pdf
117	.pdf	AP 42, Fifth Edition, Volume I: Chapter 1 External Combustion Sources		Chapter 1.10: Residential Wood Stoves http://www.epa.gov/ttn/chief/ap42/ch01/final/c01s10.pdf
118	.pdf	EIA. 2006. Technical Guidelines for Voluntary Reporting for Greenhouse Gas Program, Chapter 1, Emission Inventories, Part 1 Appendix: Forestry. March 2006		http://www.eia.doe.gov/oiaf/1605/Forestryappendix[1].pdf
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127	--	<Woody Biomass Project>	2/18/2010	Fax sent by Bill Hermann in response to email from Carrie Lee
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143	--	<Simpson-FiberFlowsheet>	02/09/10	Fiber Flowsheet from Simpson Tacoma Kraft Co. provided by Greg Narum during site visit
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156	.html	http://www.mylittlesalesman.com/frontend/content/listingdetail.aspx?pos=20&adv=03127e12-5b93-4244-94cd-d73c7e8077d1&item=455267&ind=1&status=all	03/18/10	Price listing for 2007 Peterson Pacific 5710 Grinder - used as minimum price estimates
157	.html	http://www.kbb.com/kbb/PerfectCarFinder/Default.aspx	03/18/10	Kelly Blue Book - Price range for new light duty trucks
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