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Forest treatment residues for thermal energy compared with disposal by onsite burning: Emissions and energy return

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ABSTRACT

Mill residues from forest industries are the source for most of the current wood-based energy in the US, approximately 2.1% of the nation's energy use in 2007. Forest residues from silvicultural treatments, which include limbs, tops, and small non-commercial trees removed for various forest management objectives, represent an additional source of woody biomass for energy. We spatially analyzed collecting, grinding, and hauling forest residue biomass on a 515,900 ha area in western Montana, US, to compare the total emissions of burning forest residues in a boiler for thermal energy with the alternatives of onsite disposal by pile-burning and using either natural gas or #2 distillate oil to produce the equivalent amount of useable energy. When compared to the pile-burn/fossil fuel alternatives, carbon dioxide emissions from the bioenergy alternative were approximately 60%, methane emissions were approximately 3%, and particulate emissions less than 10 μm were 11% and 41%, respectively, for emission control and no-control boilers. Emissions from diesel consumption for collecting, grinding, and hauling biomass represented less than 5% of the total bioenergy emissions at an average haul distance of 136 km. Across the study area, an average 21 units of bioenergy were produced for each unit of diesel energy used to collect, grind, and haul biomass. Fossil fuel energy saved by the bioenergy alternative relative to the pile-burn/fossil fuel alternatives averaged 14.7–15.2 GJ t^{-1} of biomass.

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1. Introduction

Wood provided 2.3 EJ of energy in the US in 2007, or approximately 2.1% of the nation's energy use [1]. Mill residues from forest industries are the source for most of this current wood-based energy in the US [2] and Zerbe [3] estimates that up to 10% of the US energy requirement could eventually be produced from wood. Forest residues from silvicultural treatments, which include limbs, tops, and small non-commercial trees removed for various forest management objectives, represent a potential source for producing significant additional quantities of woody biomass for energy production [4–8]. For example, in the western US alone there are approximately 3.7 Mha of accessible forestland that could benefit from mechanical fuel treatments to reduce hazardous fuels and effects of severe wildfires [7]. The majority of

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residues from forest treatments, including mechanical fuel treatments, historically have been disposed of by burning onsite, releasing a significant quantity of energy that potentially could be used to offset fossil fuel consumption.

Increasing the use of woody biomass for energy production is one of the ways that forest management may contribute to carbon management objectives [9]. Based on USDA Forest Service inventories, forest ecosystem carbon stocks in the US have increased since 1953 providing an important offset to fossil fuel emissions, but in recent years the rate of increase has slowed because of increasing harvest in some areas and declining growth with maturing forests in other areas [10]. Various forestry activities may enable the sequestration of additional carbon by either increasing the sequestration rate or reducing emissions, although more information is needed about best management practices for carbon [11].

Studies have addressed various aspects of utilizing forest residue biomass for energy production and the associated carbon emissions and sequestration. For example, several studies have looked at the financial aspects of utilizing forest residues from silvicultural treatments and the potential quantities of biomass available over time [5,12,13]. Skog [14] estimates carbon sequestered in harvested wood products. Markewitz [15] highlights a framework for carbon accounting during silvicultural activities within the forest, and additionally notes that overall, little effort has been applied to carbon accounting during forestry operations. The Consortium for Research on Renewable Industrial Materials produced estimates of fuel consumption per cubic meter harvested for stump-to-truck and stump-to-mill [16], and a much earlier estimate was produced by Watson et al. [17].

There is inadequate information about the trade-offs and benefits of using forest residues to produce thermal energy as compared to standard slash burning practices. In order to compare the trade-offs all fossil fuels used in collecting, grinding, and hauling must be considered, as well as the amount of fossil fuel energy offset through use of this biofuel. Forest residues are often dispersed over extensive landscapes, sometimes requiring long haul distances to deliver the residues for energy utilization. How much fossil fuel is required to harvest, grind, and haul this woody biomass from various landscape locations, and how does it compare with the bioenergy produced? What are the net emissions of key greenhouse gases and particulate matter of utilizing forest residues for energy production from various landscape locations? How do these emissions compare with the common practice of burning these forest residues onsite? Answers to questions such as these are needed to inform policy as well as potential investments in infrastructure.

We conducted a spatial analysis on a 515,900 ha area in western Montana to compare the total emissions from utilizing forest residues for thermal energy production with the alternative of disposing of these residues by onsite burning and using fossil fuels for the energy that the biomass would have produced. Specifically, this paper compares the carbon dioxide, methane, and particulate matter emissions as well as fossil fuel consumption among biomass disposal alternatives that dispose of the forest residues and produce the equivalent thermal energy in a boiler (Fig. 1):

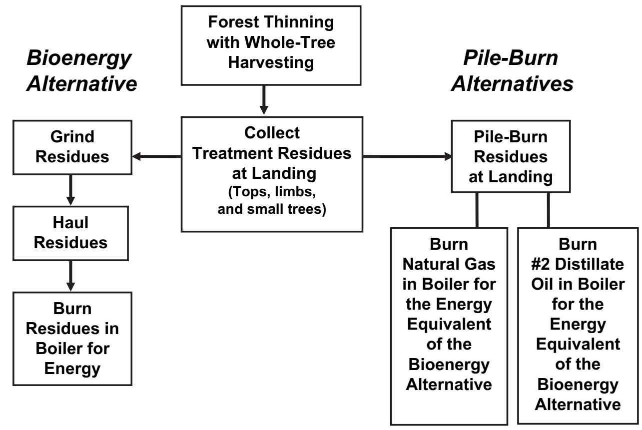

Fig. 1 – Emissions from collecting, grinding, and hauling forest residues in the bioenergy alternative were compared with pile-burn alternatives that include use of fossil fuels to collect residues for onsite burning and provide thermal energy in a boiler to produce the equivalent usable energy as the bioenergy alternative.

- *Bioenergy alternative*: Collecting, grinding, and hauling forest residues to a facility to be burned in a boiler to produce thermal energy.
- *Pile-burn alternatives*: Collecting and disposing of the forest residues by burning onsite and using either natural gas or #2 distillate oil to produce the equivalent energy of the forest biomass.

2. Study area

The study area included the Bitterroot National Forest and adjacent forested lands in the Bitterroot Valley of western Montana, comprising a total of 515,900 ha (Fig. 2). The low to mid elevations in this area historically experienced frequent low severity wildfires that removed shade-tolerant trees from the forest understory. Fire suppression over many years and other factors have resulted in a build-up of shade-tolerant trees which create ladder fuels that increase the risk of severe wildfire as well as reduce the vigor of the larger trees making them more susceptible to insects and disease. We were specifically interested in examining alternatives for disposing of forest residues produced by mechanical fuel treatments where they are needed on the landscape to reduce the threat of severe wildfire and improve forest health. Disposal of these forest residues is important to accomplish the treatment objectives of reducing fuel loading to reduce the risk of wildfire. Reducing forest fuels and improving forest health are predominate reasons for forest vegetation treatments in the area, especially on the National Forest.

We analyzed transporting the treatment residues to a wood residue boiler located 27.4 km from the study area boundary. Forest residues provide a possible additional source of biomass for such plants that traditionally used residues from sawmills and other primary wood product manufactures, which have declined in numbers in many areas of the US in recent years

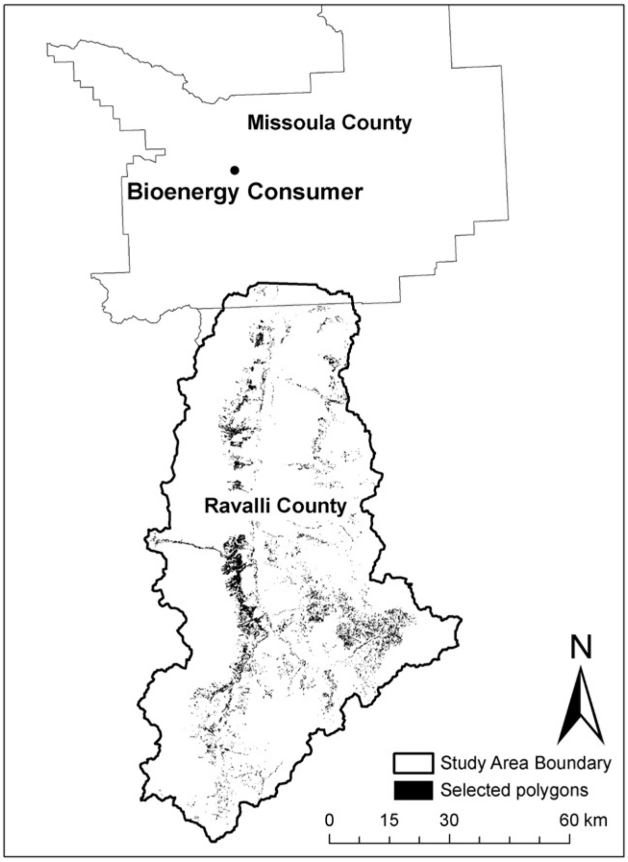

Fig. 2 – Study area showing treatment polygons and mill location for consuming bioenergy.

due to greater forest management emphasis on non-commodity use and amenity values. Transportation to the mill is from forest roads and secondary roads that feed into a main highway.

3. Methods

3.1. *Modeling forest vegetation treatments*

A wide variety of silvicultural treatments are available to land managers to achieve differing fuel treatment and/or forest health restoration objectives. In this analysis we focused on a mechanical treatment designed to reduce ladder and crown fuels to mitigate the potential for wildfire effects and restore forests to sustainable and historical conditions [18]. In these stands prescribed burning is not feasible without first conducting mechanical treatments. This mechanical treatment, called comprehensive restoration, removes all trees below 17.8 cm diameter at breast height plus some larger diameter trees with a target residual stand having a basal area in the range 9.2–13.8 $m^2\ ha^{-1}$ comprised of fire resistant tree species such as ponderosa pine (*Pinus ponderosa*) and western larch (*Larix occidentalis*). This treatment provides an open stand of trees that reduces the potential for crown fire and promotes health of the residual trees by removing competition for moisture and nutrients.

We assume whole-tree harvesting is used to cut and skid trees to a landing accessible by road. In this system, which is commonly used in the western US, whole trees, including the main stem, limbs, and tops are delivered to a landing. We assume the tree boles suitable for higher valued commercial products are removed and the portion that remains is what is available for bioenergy and consists of the tops and limbs of the commercial trees, and all of the smaller, non-commercial trees that were skidded to the landing to accommodate treatment objectives. This green biomass typically has a moisture content around 50% and is allowed to air dry to 30% moisture content prior to grinding and hauling offsite [19].

The approach to modeling forest vegetation treatments is based on the method described in Loeffler et al. [5]. The Northern Idaho/Inland Empire variant of the Forest Vegetation Simulator (FVS, www.fs.fed.us/fmsc/fvs) was used to model the outcome of applying the comprehensive treatment prescription to Forest Inventory and Analysis (FIA, http://www.fs.fed.us/rm/ogden) plot data. To ensure adequate data, we supplemented the FIA plots from the study area with plots from similar sampled forests outside the study boundary. Analyzing these plots provided estimates of per hectare merchantable timber volumes and non-merchantable biomass volumes that are in the tops, and branch wood of merchantable trees and in non-merchantable trees that are skidded to meet prescription objectives. Stokes [20] reported that about 90% of biomass residues are recoverable with whole-tree harvesting, while the default for the Fuel Reduction Cost Simulator [21] is 80% recovery of residues for whole-tree harvesting. Baral and Guha [22] assumed 20% of biomass is lost during harvesting and hauling. We assume 80% recovery for the base case and present sensitivity analysis results for both 60% and 100% recovery.

Weights for all merchantable logs that would be removed were computed through a combination of the FVS Database Extension, tree component ratio equations from published biomass estimators [23], and dry volume weights obtained from the Fire and Fuels Extension of FVS [24]. Quadratic mean diameter (QMD) and trees cut per FIA plot were tallied for both the merchantable and non-merchantable categories. The Fire and Fuels Extension of FVS was also utilized to estimate the weight of the total biomass removed. Subtracting the removed merchantable log weight from the weight of the total biomass removed yielded the weight of the non-merchantable biomass. Summary statistics of cut materials are displayed in Table 1.

3.2. *Modeling spatial distribution of forestlands and treatment*

The locations on the study area landscape where the comprehensive treatment is applicable were identified using a GIS-based forest vegetation classification system, R1-VMP, produced by the Northern Region of the USDA Forest Service [25]. R1-VMP categorizes forested polygons based on dominant and co-dominant tree species, stand size class, and stand density as measured by percent canopy cover. R1-VMP polygons selected as candidates for treatment contained species associated with low-elevation, frequent low-intensity fire

Table 1 – Summary statistics from modeling application of the comprehensive restoration treatment on 0.405 ha (1 acre) plots ($n = 458$).

	Biomass removed (dry t)	QMD[a] of trees removed ≥17.8 cm (cm)	QMD of trees removed <17.8 cm (cm)	Number of trees removed ≥17.8 cm	Number of trees removed <17.8 cm	Volume removed from trees ≥17.8 cm (m^3)	Volume removed from trees <17.8 cm (m^3)
Mean	10.51	26.75	9.75	95.97	294.98	38.83	11.28
Median	9.37	26.16	10.18	82.46	187.25	30.91	8.17
Standard deviation	6.61	5.58	4.57	64.03	328.35	32.92	11.93
Minimum	0.49	17.78	0.00	1.85	0.00	0.68	0.00
Maximum	43.14	61.98	17.53	363.95	1 962.14	185.65	80.49

a Quadratic mean diameter.

regimes (*Pinus ponderosa* and mixtures of *Pinus ponderosa*, *Larix occidentalis*, and *Pseudotsuga menziessi* and miscellaneous shade-tolerant species) that fell into fire regime condition classes 2 and 3. These fire regime condition classes have the greatest deviation from natural fire regimes and are most in need of treatment [26,27]. Candidate polygons were further restricted to average slopes less than 35%, are within 457 m from the polygon centers to existing roads, and are Forest Service non-reserved or non-industrial privately owned land. This resulted in 15,800 polygons comprising 30,920 ha (Fig. 2).

The spatial R1-VMP forest vegetation classification does not contain forest inventory data, nor did any other spatial vegetation classification system at the time of this study. Therefore, the FIA plots were classified into the R1-VMP vegetation categories based upon dominant species, tree size class, and stand canopy cover. The results from analyzing the plots were averaged within the R1-VMP categories such that each R1-VMP category contained the average tree attributes calculated from the FIA plots in the corresponding category.

3.3. *Modeling biomass haul*

A GIS roads coverage obtained from the Bitterroot National Forest (www.fs.fed.us/r1/bitterroot) provided the road network for modeling haul of biomass from the candidate treatment polygons to the bioenergy facility northwest of the study area. This GIS coverage contains road segments separated by nodes, which were placed at every road intersection and in the vicinity of candidate treatment polygons. The location where biomass volume from each polygon enters the road system was approximated by choosing the nearest down-slope node.

Many of the treatment polygons are on roads inaccessible by large chip vans, which are generally considered the most cost-effective way of trucking biomass on paved surfaces. Therefore we assumed the biomass is hauled from the polygons to the bioenergy facility by hook-lift trucks hauling roll-on/off containers resembling extremely large trash bins [19]. These trucks are suitable for low-standard mountain roads and have essentially the same access capabilities as a logging truck. These hook-lift trucks haul one roll-on/off container and pull a pup trailer with a second container, providing a total payload of approximately 22.7 t [28]. This compares with 24.5–27.2 t payloads for a chip van. We assume that the biomass is ground and conveyed by the grinder's outfeed into these roll-on/off containers at the landings. The hook-lift trucks then pick up the loaded containers, one on the truck, one on the pup trailer, and haul them to the biomass utilization facility. Empty containers are returned to the landing on the return trip.

3.4. *Fossil fuel consumption*

Fossil fuels are consumed in the bioenergy alternative to collect, grind, and haul the forest treatment residue to a biomass utilization facility (Fig. 1). The pile-burn alternatives use fossil fuels to collect the forest residue and provide the same amount of useable thermal energy in a boiler that the bioenergy alternative provides. Incidental consumption of fossil fuels in these alternatives, such as the fuel used to transport workers to the field, was not included in this analysis.

Diesel consumption for collecting biomass in whole-tree harvesting (cutting, skidding, and processing) was estimated at 2.85 L m^{-3} of harvested timber (15). We assumed the diesel consumption attributable to biomass collection was proportional to the biomass percentage of the total weight of material delivered to the landing, which based on FVS analysis averaged 25% of total weight.

Diesel consumption for grinding biomass was estimated using the Forest Residue Trucking Simulator (FoRTS, http://www.srs.fs.usda.gov/forestops/biomass) at 1.7 L t^{-1} of biomass which had been allowed to dry in piles to an average 30% moisture content. In addition, we used FoRTS to estimate the diesel consumed during a 20 min idle time for each hook-lift truck and pup trailer to be loaded at 0.8 L. This factor is the difference between estimated fuel consumption using 'standing time' model inputs of 0 and 20 min. The diesel consumption for trucks hauling biomass was estimated at 0.6 L km^{-1} [28]. This consumption was applied to the loaded haul distance as well as the return trips with empty containers.

The quantities of #2 distillate oil and natural gas required to produce the same useable thermal energy in a boiler were computed using published heat values and efficiency rates [29]. The energy contents used in this calculation were 14.005 GJ t^{-1} for wood, 0.039 GJ L^{-1} for #2 distillate oil, and 0.038 GJ m^{-3} for natural gas. The efficiency rates used were 74% for wood, 83% for #2 distillate oil, and 80% for natural gas.

A fossil energy ratio factor was incorporated into our estimates of fossil energy used in the alternatives. The fossil energy ratio is the useable fuel energy divided by the total fossil energy inputs required to collect, refine, and deliver the fossil fuel to market [30]. The direct consumption of diesel, #2 distillate oil, and natural gas was divided by the fossil energy ratio of 0.8337 [30] to include the fossil fuel energy required to deliver the fossil fuels to the final market as well as the direct usage of fossil fuels in the alternatives analyzed.

3.5. *Spatial modeling of the biomass utilization system*

The spatial R1-VMP polygons and road network data, vegetation treatment data, and fossil fuel consumption data were incorporated into MAGIS, a spatial decision support system for scheduling vegetation treatments and road-related activities (www.fs.fed.us/rm/econ/magis). MAGIS was used to simulate the application of the comprehensive restoration treatment on the relevant polygons on the landscape, load the biomass residue onto the road network, and route the loaded trucks over the shortest path to the mill facility where the biomass would be used for energy production. In this process MAGIS calculated the hectares receiving treatment, tonnes of biomass that is produced by the treatments and either hauled for energy production or burned onsite, the truck-kilometers required to haul the biomass for energy production, and the diesel consumption involved in collecting, grinding, and hauling the biomass. The emission factors discussed below were applied to the model results. The scheduling capability in MAGIS was used to analyze applying the comprehensive treatment to incremental portions of the study area having increasing average haul distances.

3.6. *Emission factors*

In this analysis we focus on two greenhouse gases, carbon dioxide and methane, as well as particulate matter emissions less than 10 μm in size (PM10). PM10 is one of several measurements of air quality used by the US Environment Protection Agency (www.epa.gov/air/criteria.html). For the bioenergy alternative, we focus on emissions from internal combustion diesel engines used to collect, grind and haul biomass, and stack emissions produced by burning biomass in a boiler for thermal energy. For the pile-burn alternatives we focus on emissions from internal combustion diesel engines used to collect the treatment residues for burning, from pile-burning the biomass in the forest, and the stack emissions from using either #2 distillate oil or natural gas to produce the equivalent usable energy in a boiler.

The emission factors used in the study are summarized in Table 2. Carbon dioxide, methane, and PM10 emissions for internal combustion diesel engines were estimated using the US Environmental Protection Agency AP-42 report [31] and data from the US Energy Information Administration [32]. Stack emissions from burning biomass in a boiler both with and without a wet scrubber were estimated using the AP-42 report and data from the USDA Forest Service Forest Products Lab [29]. AP-42 factors were also used for the stack emissions from burning either #2 distillate oil or natural gas in a boiler and emission factors for pile-burning the biomass in the forest came from published fuel management data [26].

Table 2 – Carbon dioxide, methane, and PM10 emissions by source and associated reference.

Source	Carbon dioxide	Methane[a]	PM10	Reference
Internal combustion diesel engine	2.731 $kg\,L^{-1}$	–	0.005 $kg\,L^{-1}$	US EPA [26] US EIA [27]
#2 Distillate oil – stack	2.672 $kg\,L^{-1}$	–	0.0002 $kg\,L^{-1}$	US EPA [26]
Natural gas – stack	1953.158 $kg\,km^{-3}$	0.032 $kg\,km^{-3}$	0.130 $kg\,km^{-3}$	US EPA [26] US FPL [28]
Biomass – pile-burn	1460.085 $kg\,t^{-1}$	5.089 $kg\,t^{-1}$	5.535 $kg\,t^{-1}$	Hardy et al. (2001) [23]
Biomass – stack (no PM10 control)	1048.083 $kg\,t^{-1}$	0.113 $kg\,t^{-1}$	1.559 $kg\,t^{-1}$	US EPA [26] US FPL [28]
Biomass – stack (wet scrubber)	1048.083 $kg\,t^{-1}$	0.113 $kg\,t^{-1}$	0.350 $kg\,t^{-1}$	US EPA [26] US FPL [28]

a US EPA [26] does not report the insignificant methane emissions from internal combustion diesel engines or use of #2 distillate oil in a boiler.

4. Results

4.1. *Comparing emissions among alternatives*

Total carbon dioxide emissions from both biomass disposal alternatives are displayed in Fig. 3. The pile-burn alternatives consist of emissions from three components, 1) biomass collection, 2) onsite pile-burning and, 3) use of fossil fuels in a boiler to produce the amount of useable energy estimated in the bioenergy alternative. The bioenergy alternative includes diesel emissions from collecting, grinding, and hauling biomass as well as the biomass boiler stack emissions.

These results show that the bioenergy alternative produces substantially less total carbon dioxide emissions than do the pile-burn alternatives. Carbon dioxide emissions from the bioenergy alternative are only 55% of the pile-burn alternative using distillate oil and 62% of the pile-burn alternative using natural gas. The amount of carbon dioxide emissions from burning diesel fuel to collect, grind, and haul the biomass to the boiler facility represents only a very small percentage of the total carbon dioxide emissions in the bioenergy alternative.

The reduction in methane emissions (Fig. 4) is much greater than the reductions calculated for carbon dioxide, with the methane emissions from the bioenergy alternative representing only about 3% of the pile-burn alternatives. The methane in the pile-burn alternatives is produced by onsite pile-burning, while the methane produced in the bioenergy alternative is produced by the biomass boiler. Methane is not produced in appreciable amounts by burning fossil fuels in a boiler or in diesel engines.

For the PM10 comparison we computed stack emissions for biomass boilers both with and without wet scrubber particulate matter emission control (Fig. 5). Although most large biomass

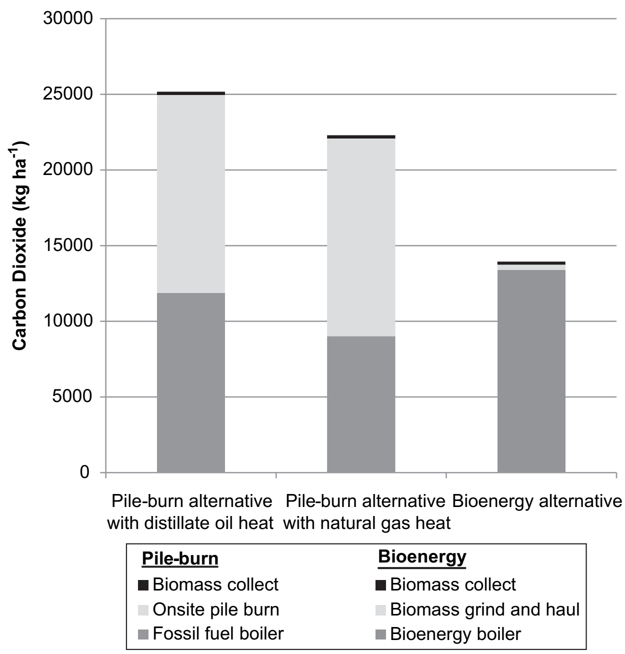

Fig. 3 – Carbon dioxide emissions ha^{-1} treated compared across the forest residue disposal alternatives.

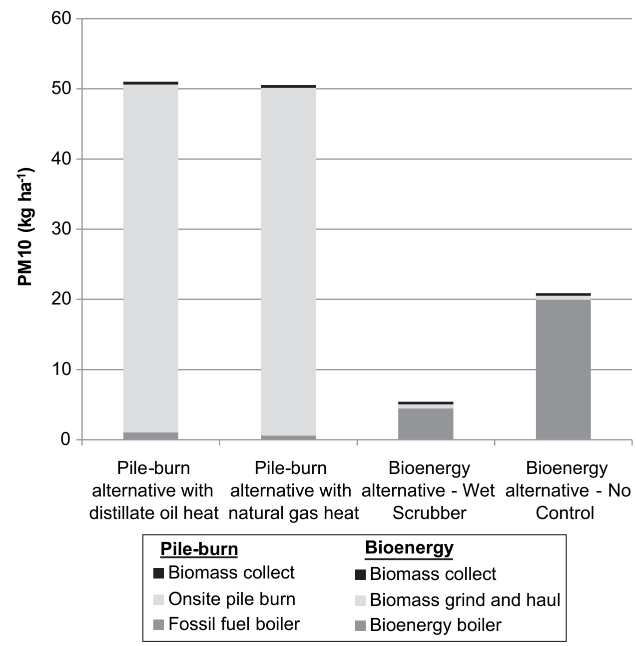

Fig. 5 – PM10 emissions ha^{-1} treated compared across the forest residue disposal alternatives.

boilers would be expected to have particulate matter emission controls, we were also interested in comparing emissions from small boilers without these controls. PM10 emissions from the bioenergy alternative with wet scrubber emission control were 11% of the pile-burn alternatives and without the emission control were 41% of the pile-burn alternatives. For the pile-burn alternatives PM10 emissions are almost entirely produced by the pile-burning, very little is produced by burning either distillate oil or natural gas in a boiler.

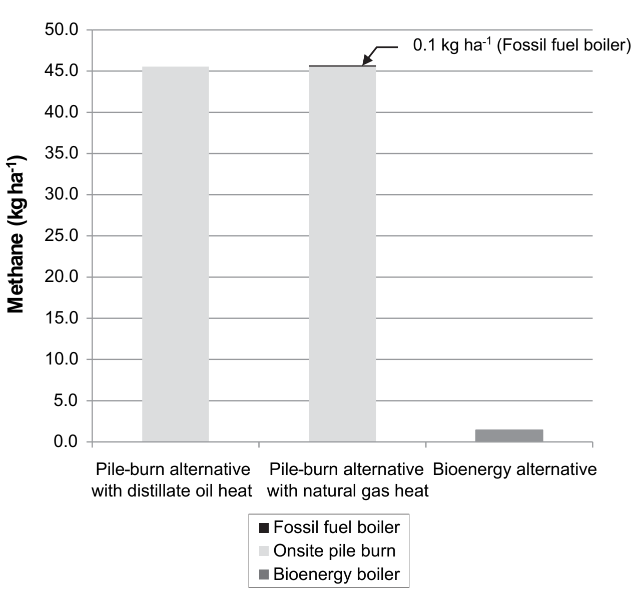

Fig. 4 – Methane emissions ha^{-1} treated compared across the forest residue disposal alternatives.

4.2. *Effect of haul distance on total bioenergy emissions*

Next we looked at the effect of biomass haul distance on the amount of emissions originating from diesel fuel consumption as a percentage of the total emissions in the bioenergy alternative. For this analysis the MAGIS model was used to schedule treatments for 10% increments in available biomass volume from the comprehensive restoration treatment. The first increment represents the area providing 10% of the total biomass volume available with the least haul cost, the second represents the area providing 20% of the volume with the least haul cost, and so on through the tenth increment which included all the treatable area. The average haul distance for the ten increments ranged from 75 to 136 km.

Carbon dioxide emissions from the entire biomass delivery process of collecting, grinding, and hauling biomass comprised only 3.2% of the total carbon dioxide emissions for the bioenergy alternative at the 75 km average haul distance, increasing to 3.9% at the 136 km distance (Fig. 6). This increase was entirely due to the increasing haul distance, as emissions from collecting and grinding were a constant percentage of the total over this range. Although the carbon dioxide emissions from diesel are increasing with increasing average haul distances, it still represents a small percentage of total emissions even at the relatively long average distance of 136 km.

Similar results were obtained for PM10 from diesel emissions as a percentage of total PM10 emissions in the bioenergy alternative in which no particulate matter emission control is used. PM10 emissions from diesel consumption from harvesting, grinding, and hauling increased from 3.7% at the 75 km distance to 4.6% at the 136 km distance. When wet scrubber particulate matter emission control is used, PM10 emissions from diesel consumption range from 14.8% to 17.7% of total emission PM10 emissions for the bioenergy alternative.

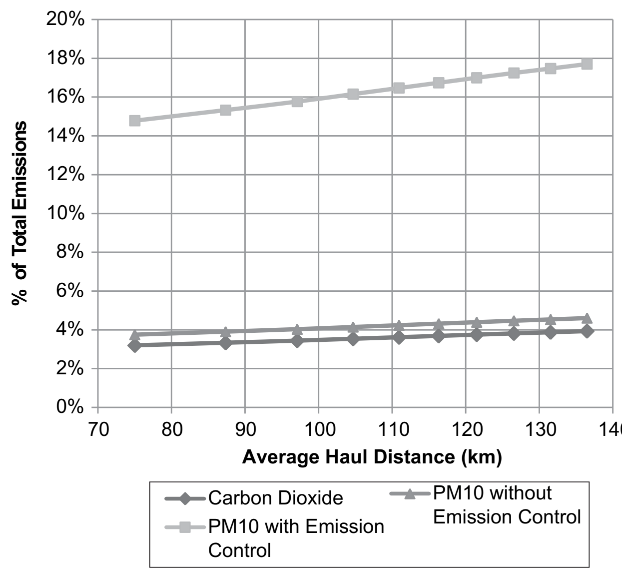

Fig. 6 – Carbon dioxide and PM10 emissions (with and without web scrubber control) from harvesting, grinding, and hauling as a percentage of the total bioenergy emissions, respectively, across increasing average haul distances.

4.3. *Effect of haul distance on bioenergy return*

Fig. 7 shows the units of bioenergy obtained for each unit of diesel energy expended to collect, grind, and haul the biomass over increasing average haul distances. As in the boiler emission calculations, the fossil energy ratio of 0.8337 was applied to our estimate of the amount of diesel consumed by these activities to account for the total amount of energy required for a liter of fuel. At the 75 km average haul distance, 26 units of energy are obtained for each unit of diesel fuel energy required to deliver the ground biomass to the energy facility. This ratio drops to 21 units of energy per unit of diesel fuel energy consumed at the 136 km average haul distance, a 19% decrease.

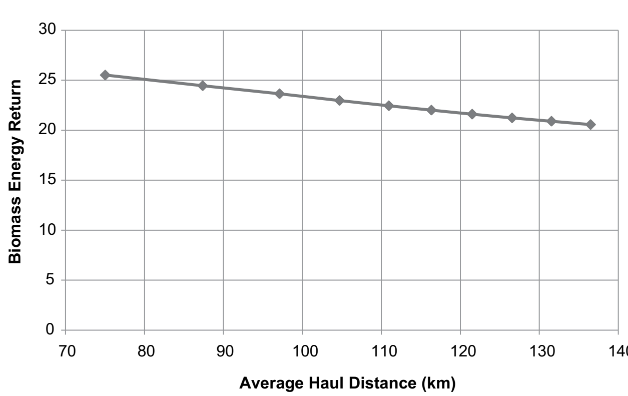

Fig. 7 – Biomass energy return per unit of fossil fuel energy used to collect, grind, and haul biomass across increasing average haul distances.

4.4. *Fossil energy use among alternatives*

Fig. 8 compares average fossil fuel energy consumed to collect, grind, and haul 1 t of biomass in the bioenergy alternative with the fossil fuel energy consumed in the pile-burn alternatives to collect biomass in piles for burning at the landing and provide the equivalent amount of thermal energy in a fossil fuel boiler. The difference in fossil fuel energy between the pile-burn alternative using distillate oil and the bioenergy alternative averages 14.7 GJ t^{-1} of biomass available from the study area, assuming 83% efficiency for the distillate oil boiler. The difference for the pile-burn alternative using natural gas averages 15.2 GJ t^{-1} of biomass, assuming 80% efficiency for the natural gas boiler. The energy used to collect biomass is a minor component in all alternatives. The reason for the large difference in fossil fuel consumption between the pile-burn alternatives and the bioenergy alternative is that the quantity of #2 distillate oil or natural gas required to provide the equivalent usable thermal energy is many times greater than the diesel energy required to grind and haul the biomass in the bioenergy alternative.

4.5. *Sensitivity analysis*

The sensitivity of results to residue recovery rates around the base case of 80% recovery was analyzed using recovery rates of 60% and 100%. The change in carbon dioxide emissions across recovery rates is displayed in Fig. 9. Total carbon dioxide emissions change proportionally across the residue recovery rates for each residue disposal alternative. Thus, as the recovery rate increases, the absolute difference in carbon dioxide emissions increases between the pile-burn alternatives and the bioenergy alternative.

Changes in methane and PM10 across recovery rates are displayed in Figs. 10 and 11, respectively. The values for the pile-burn alternative with distillate oil heat are almost identical to the displayed pile-burn alternative with natural gas heat. The changes in methane and PM10 are also proportional to the recovery rate and the absolute difference in emissions

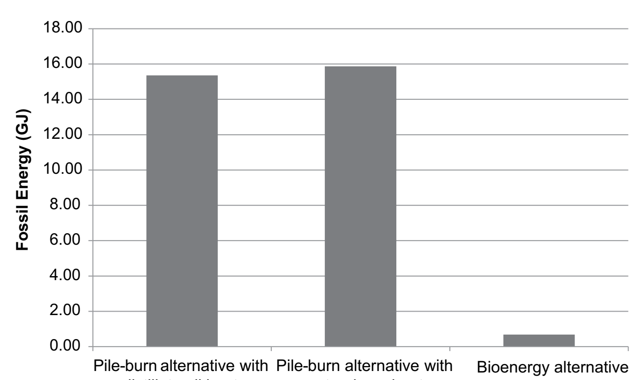

Fig. 8 – Fossil fuel energy consumed to collect, grind, and haul 1 t of biomass in the bioenergy alternative compared to the fossil fuel energy consumed in the pile-burn alternatives to collect biomass for burning and provide the equivalent thermal energy in a boiler.

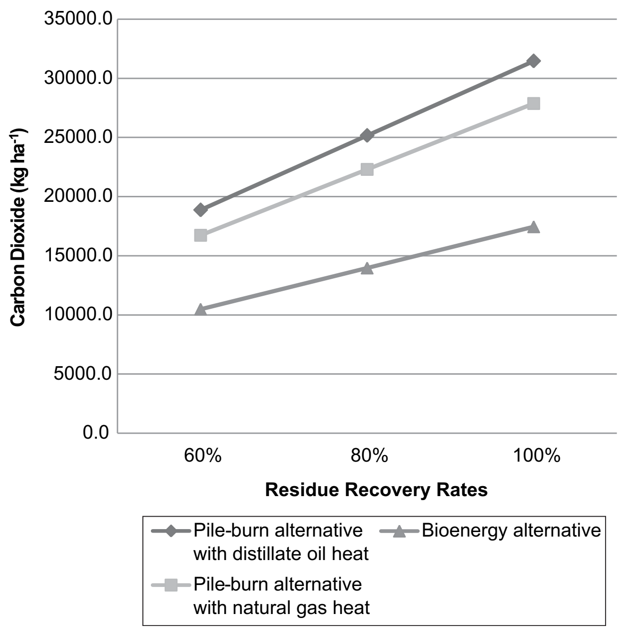

Fig. 9 – Carbon dioxide emissions ha^{-1} treated across three residue recovery rates for the forest residue disposal alternatives.

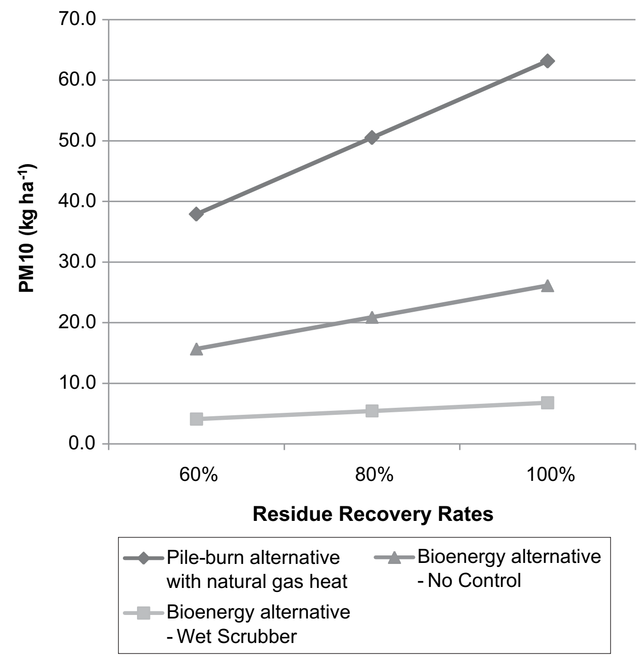

Fig. 11 – PM10 emissions ha^{-1} treated across three residue recovery rates for two forest residue disposal alternatives.

between the pile-burn alternatives and the bioenergy alternative increase with the residue recovery rate.

We also computed the biomass energy return ratio for the bioenergy alternative and found that the ratio was not affected by the residue recovery rate. Likewise the fossil fuel consumption to dispose of one dry tonne of biomass via each alternative was unaffected by the residue recovery rate. The fossil fuel consumption for each residue disposal alternative is a linear function of the quantity of residues that are skidded to the landing for disposal.

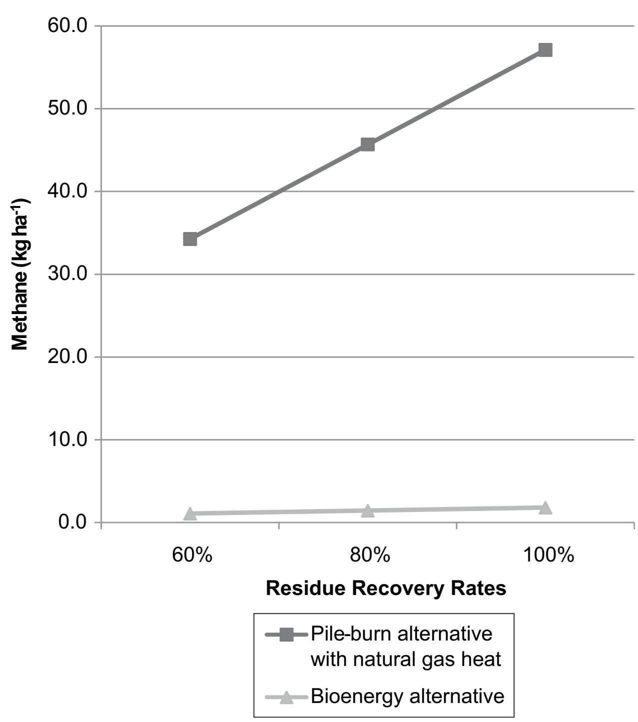

Fig. 10 – Methane emissions ha^{-1} treated across three residue recovery rates for two forest residue disposal alternatives.

5. Discussion and conclusions

These results show that when a bioenergy alternative to onsite pile-burning is available, far fewer carbon dioxide, methane, and particulate matter emissions are generated, and useable energy produced offsets the use of fossil fuels for thermal energy production. At the haul distances we analyzed, the fossil fuel energy required for the bioenergy alternative is small compared to the energy produced in the bioenergy alternative. Fossil fuel energy saved by the bioenergy alternative compared to the pile-burn alternatives using fossil fuel for thermal energy averaged 14.7–15.2 GJ t^{-1} of biomass used.

The analysis presented in this paper is based on collecting biomass residues in the whole-tree harvesting process, grinding biomass residue, and hauling loaded roll-on/off containers to the location where the biomass is burned for thermal energy. We expect that other ground-based harvesting systems or biomass comminution systems would produce somewhat different emission trade-offs and energy consumption ratios. However, the changes in magnitude of these results that would be required to make bioenergy the less attractive method of residue disposal from an emissions standpoint are very unlikely.

In this paper we analyzed disposal alternatives for piled forest residues which are generally burned onsite. There are, however, many ways to conduct treatments and handle residues, some of which could be designed to leave a greater portion of the residues dispersed over a treatment area for nutrient cycling, wildlife habitat, or other forest management objectives. Although our sensitivity analysis showed reducing recovery rates have no effect on the fossil fuel energy required per tonne for collecting biomass, other methods for intentionally leaving biomass onsite could have an effect. However, the fossil energy consumed per tonne for grinding and hauling would not be expected to change significantly by leaving more biomass onsite.

Our results indicate that utilizing woody residues for thermal energy can contribute to solving energy needs while at the same time reducing greenhouse gas and particulate matter emissions compared to alternative methods of residue disposal. The reduction in particulate matter emissions may also provide an advantage in areas where open burning is restricted by air quality standards. Finally, with the emergence of carbon trading markets, assessments such as those carried out in this paper may help to quantify the appropriate carbon offset credits that should become available to biomass utilization facilities. These credits may help to offset the high material collection costs, enhancing the economic feasibility of future bioenergy development.

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