Emissions, Energy Return and Economics From Utilizing Forest Residues for Thermal Energy Compared to Onsite Pile Burning

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Abstract—The emissions from delivering and burning forest treatment residue biomass in a boiler for thermal energy were compared with onsite disposal by pile-burning and using fossil fuels for the equivalent energy. Using biomass for thermal energy reduced carbon dioxide emissions on average by 39 percent and particulate matter emissions by 89 percent for boilers with emission control. Over 21 units of bioenergy were produced for each unit of diesel energy used to collect, grind, and haul biomass. At prices in place at the time of the study, utilizing biomass was economically viable on 49 percent of the study area.

Keywords: biomass energy, bioenergy, carbon emissions, greenhouse gases, logging residues

Introduction

In the western U.S. approximately 16.8 million acres of accessible forestland could benefit from mechanical fuel treatments that reduce hazardous fuels (Rummer and others 2003). Such treatments have the potential to produce significant quantities of forest residue biomass, which includes the tops and limbs from merchantable trees and smaller trees removed by prescription (Barbour and others 2004; Loeffler and others 2006; Perlack and others 2005, Rummer and others 2003). The common practice of disposing of these residues via onsite open burning has drawbacks, however, including negative effects on air quality, potential for escaped fires, and seasonal limits on burning. Open burning also releases atmospheric carbon dioxide and methane, two internationally recognized greenhouse gases and prominent compounds of interest in the global warming literature (IPCC 2007a; US Environmental Protection Agency 2009a). Furthermore, no energy is captured by open burning.

An alternative to onsite, open burning of forest residues is to utilize them instead as feedstock for energy production. Most of the wood-based energy in the US has historically been generated from industrial mill residues (Malmsheimer and others 2008), but there is increasing interest in generating energy directly from forest treatment residue biomass. Additionally, new research is investigating different methods for expanding the use of forest residues as a feedstock for various approaches to energy production. There are a number of potential advantages to utilizing forest residues for energy including: reducing smoke from onsite burning, providing a source of energy for offsetting fossil fuel consumption, promoting new industries in rural economies, and improving the balance sheet for forest fuel reduction and forest restoration treatments by opportunities to add product value.

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Many questions remain regarding the contributions that expanding the use of forest residues for energy can make toward offsetting fossil fuel consumption or for meeting objectives for carbon and particulate matter emissions and sequestration (Tilman and others 2009). Forest residues are often dispersed over forested landscapes, sometimes requiring long haul distances for energy utilization to occur. We contend that the spatial configuration of forest residues will influence their energetic and economic contribution to management or policy goals. In this analysis we consider the following questions: How much fossil fuel is required to harvest, grind, and haul these forest residues from various landscape locations, and how does it compare with the amount of bioenergy that can be produced? What are the net emissions of key greenhouse gases and particulate matter produced by utilizing forest residues from various landscape locations? How do these emissions compare with the common practice of burning these forest residues onsite? Under what conditions is it economically viable to utilize these forest residues?

To address these questions, we considered the case of collecting, grinding, and hauling forest residue biomass from potential treatment units (74,352 acres) spread across a forested 1.3 million-acre landscape in western Montana. We computed the consumption of diesel fuel needed to utilize these forest residues and compared it with the thermal energy that they would produce in a boiler. In addition, the total greenhouse gas and particulate matter emissions from delivering and burning forest residues in a boiler for thermal energy were compared with onsite disposal by pile-burning and then using fossil fuels to produce the equivalent amount of useable energy (fig. 1). We also compared the fossil fuel requirements to use this forest biomass in a boiler for thermal energy with the fossil fuels needed to provide the equivalent heat in a boiler. Finally, we analyzed where biomass utilization is economically viable within the study area for various diesel and delivered biomass prices.

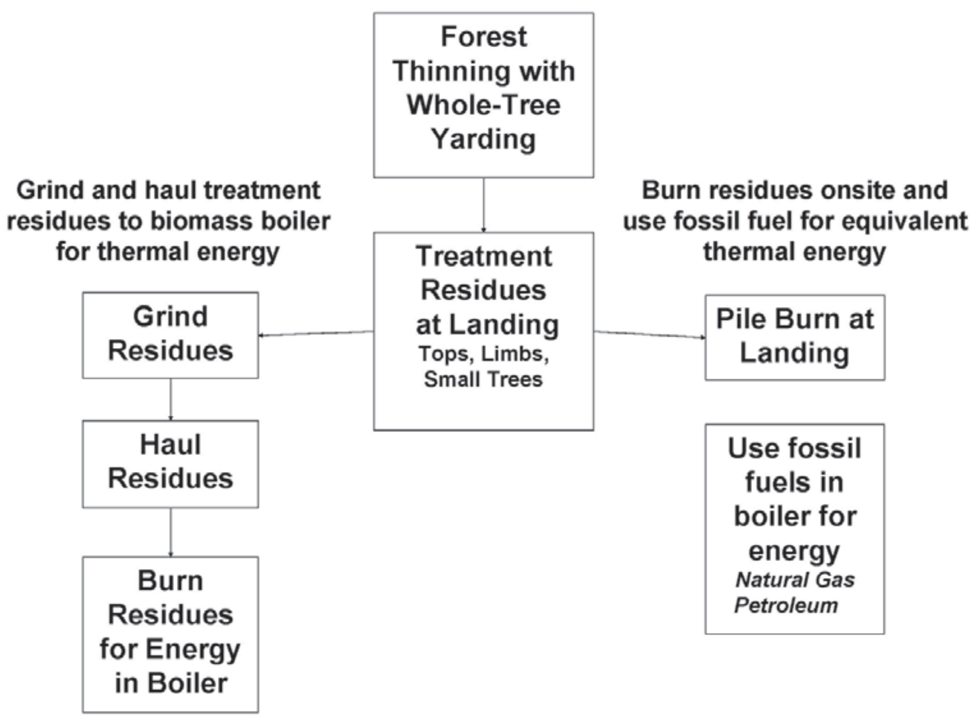

Figure 1—Comparison of burning forest residues in a boiler for thermal energy with onsite disposal by pile-burning and then using fossil fuels to produce the equivalent amount of useable energy.

Methods

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 1.3 million acres (fig. 2). Past fire suppression, together with other factors, has contributed to increased densities of shade-tolerant trees over much of the study area. This forest cohort creates "ladder fuels," which can increase the risk of crown fire and can reduce the growth and vigor of larger trees via competitive stress. Thinning and other density reduction treatments offer ways to accomplish forest and fuels management objectives of reducing fire severity, promoting tree growth, and fostering natural regeneration. We examined two options for disposal of forest residues produced by mechanical fuel treatments, onsite burning and removal for producing energy. Disposal of these forest residues is important to accomplish the treatment objectives of reducing forest fuels to in turn reduce the risk of wildfire.

A GIS-based forest vegetation classification system, R1-VMP (Brewer and others 2004), was used to identify the locations for mechanical fuel treatments within the mapped study area. R1-VMP categorizes polygons based on dominant and co-dominant tree species, stand size class, and stand density as measured by percent canopy cover. The R1-VMP polygons selected as candidates for treatment

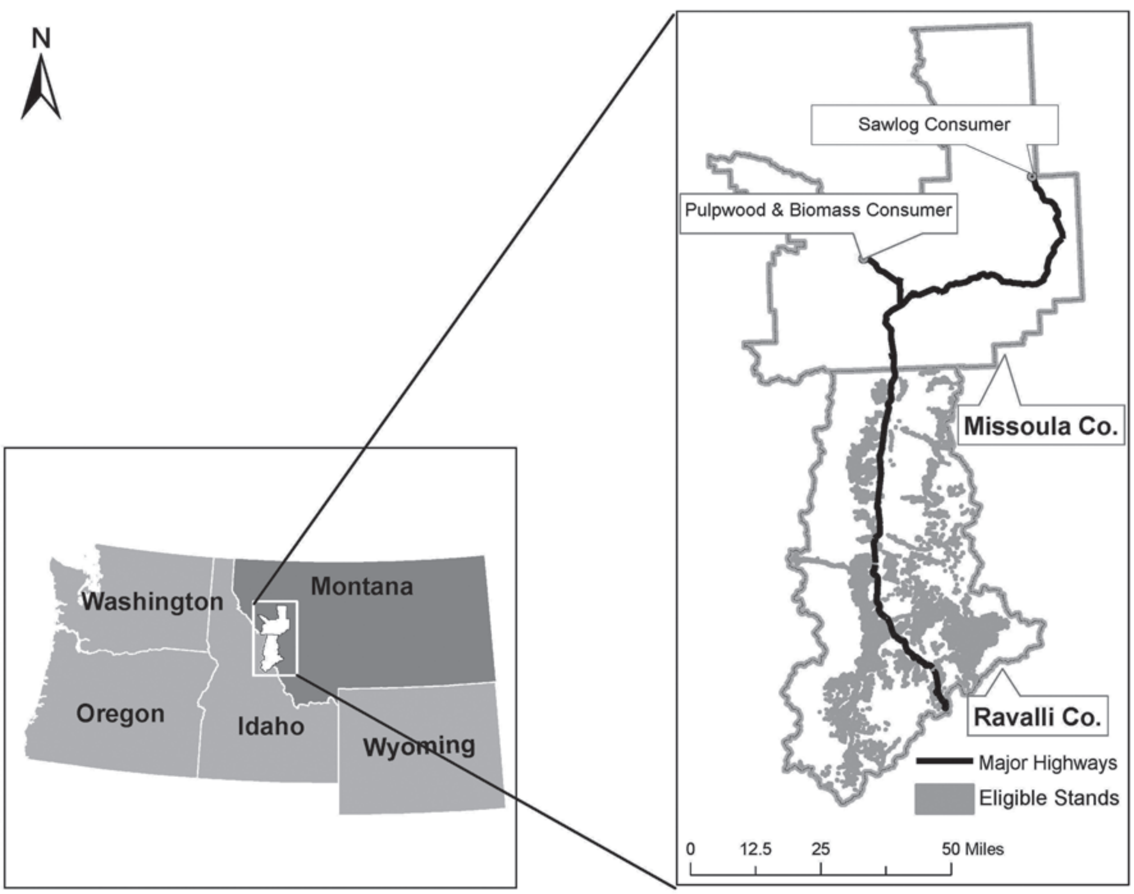

Figure 2—Study area showing treatment polygons and mill locations for consuming sawlogs, pulpwood, and forest treatment residue biomass.

contained species that are associated with low-elevation, frequent low-intensity fire regimes (ponderosa pine [*Pinus ponderosa* C. Lawson] and mixtures of *Pinus ponderosa,* western larch [*Larix occidentalis* Nutt.], and Douglas-fir [*Pseudotsuga menziessi* (Mirb.) Franco] and miscellaneous shade-tolerant species) and fell into fire regime condition classes 2 and 3. Land categorized as condition classes 2 and 3 contain fuel loading that places these forests at the greatest risk of environmental damage from uncharacteristic wildfire (Hardy and others 2001, Schmidt and others 2002). Candidate polygons were further restricted to those with average slopes less than 35 percent, that lie within 1500 feet from polygon center to existing roads, and are classified as Forest Service non-reserved or non-industrial privately owned land. This resulted in 15,800 polygons (average size is five acres) comprising 74,352 acres.

The treatment residues were assumed to go to a wood residue boiler 17 road miles north of the study area boundary that produces electricity and heat for a commercial manufacturing plant. Pulpwood was assumed to go to the same facility and sawlogs to a mill 67 road miles north of the study area boundary. Transportation to these mills is over forest roads and secondary roads that feed into a main highway that exits the north end of the study area.

Modeling Silvicultural Treatments

A variety of silvicultural treatments are available to land managers to achieve differing fuel treatment and/or forest health restoration objectives. For this analysis we focused on a mechanical treatment called "comprehensive restoration" that was designed to reduce ladder and crown fuels, thereby mitigating severe wildfire effects and restoring forests to historical conditions (Fiedler and others 1999). This mechanical treatment removes all trees below seven inches diameter at breast height plus some larger diameter trees with a target residual stand basal area in the range of 40-60 ft^2 per acre comprised of fire resistant tree species such as ponderosa pine and western larch. This treatment is designed to produce 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 assumed that whole tree harvesting is used to cut and skid trees to a landing accessible by road. Further, we assumed the tree boles that are suitable for sawlogs and pulpwood are removed and the portion that remains is the residue available for bioenergy. This residue consists of the tops and limbs of the commercial trees, and all of the smaller, noncommercial trees that are skidded to the landing to meet treatment objectives. This green biomass typically has a moisture content around 50 percent and is allowed to air dry to 30 percent moisture content prior to grinding and hauling offsite (Han and others 2008).

Volumes of logs and treatment residues produced by this treatment were estimated using the method described in Loeffler and others (2006). 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 within the study area with similar inventory plots from outside the study boundary. Analyzing all plots provided estimates of merchantable timber volumes and non-merchantable biomass volumes that would be removed per acre, assuming that all cut trees are whole tree skidded to the landing (table 1). 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 used 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

Table 1—Summary statistics from modeling application of the comprehensive restoration treatment on 1-acre plots (n=458).

	Treatment residue biomass	**QMD[a] of merchantable[b] trees removed**	**Number of merchantable trees removed**	**Volume of merchantable trees removed**
	(dry tons)	*(inches)*	*(number)*	*(cubic feet)*
Mean	11.6	10.5	96.0	1,371.1
Median	10.3	10.3	82.5	1,091.7
Standard Deviation	7.3	2.2	64.0	1,162.7
Minimum	.5	7.0	1.9	24.1
Maximum	47.6	24.4	364.0	6,556.3

[a] Quadratic mean diameter.

[b] Merchantable trees are greater than four inches diameter at breast height.

weight of the non-merchantable biomass. Based on the default residue recovery fraction in the Fuel Reduction Cost Simulator (FRCS; Fight and others 2006), we assumed 80 percent of the non-merchantable biomass was skidded to a landing; the remaining 20 percent represented breakage that stays in the treatment unit.

The volumes estimated from analyzing the FIA plots were assigned to the R1-VMP vegetation categories based on 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.

Treatment costs (excluding administrative and planning) were modeled for each application of the comprehensive treatment using the FRCS. Required FRCS input variables include trees per acre removed, QMD, average tree volume, green wood weight, and residue weight to bole weight fractions. These were calculated from the FVS-generated cut tree lists (table 1), regression equations from Jenkins and others (2003) and dry wood weights from Reinhardt and Crookston (2003) adjusted to 50 percent wood fiber moisture content. We classified the treatment polygons into three slope categories and assumed an average skidding distance of 1,000 feet. Average skidding distance is approximately 2/3 of the maximum skid distance assuming logs are skidded to a centralized landing for a triangular treatment unit (Matthews 1942). The model was calibrated to reflect western Montana wage rates – $14.72 per hour (ACINET 2008). The model's default labor benefit rate of 35 percent was retained and move-in costs were included.

Mill-delivered prices at the time of the analysis were used to value the products produced by the comprehensive treatment: $28 per ton at 30 percent moisture content for ground biomass, $40 per ton for pulpwood, and $425 per MBF for sawlogs.

Modeling Transportation

A GIS roads coverage obtained from the Bitterroot National Forest (www.fs.fed.us/r1/bitterroot) provided the road network for modeling haul of treatment residue biomass, pulpwood, and sawlogs from the candidate treatment polygons to the respective processing facilities. 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 next to 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 was hauled from the polygons to the bioenergy facility by hook-lift trucks hauling roll-on/off containers resembling extremely large trash bins (Han and others 2008). 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 25 tons (Thomas, personal communication). This compares with 27 to 30 ton payloads for a chip van. We assumed that the biomass is ground into these roll-off containers at the landings. The hook-lift trucks then pick up the loaded containers and haul them to the biomass utilization facility. Empty containers are returned to the landing on the return trip.

Haul costs were estimated on a per mile basis for each of two types of roads, paved and non-paved, using the Forest Residue Trucking Model (FoRTS; http://www.srs.fs.usda.gov/forestops/). Costs were calibrated to reflect local wages and conditions and various diesel fuel prices. Standard log trucks were assumed for haul of pulpwood and sawlogs. Log trucks were assumed to haul 30 tons of pulpwood and five MBF of sawlogs. The average haul distance from all the potential treatment polygons to the biomass utilization facility was 85 miles (fig. 2).

Fossil Fuel Consumption Associated with Utilization of Forest Biomass

Diesel fuel is used in cutting, skidding, and processing the whole trees at the landing into merchantable logs, for grinding the biomass into the roll-on/off containers, and for hauling the ground biomass to the energy utilization site. Diesel consumption for cutting, skidding, and processing was estimated at 0.022 gallon per cubic foot of harvested timber (CORRIM 2004). We assumed the diesel attributable to biomass removal was proportional to the biomass percentage of the total weight of material delivered to the landing, which based on FVS analysis averaged 25 percent of total weight.

Diesel consumption for grinding into the roll-on/off containers was estimated using the FoRTS model at 0.42 gallon per ton of biomass, which had been allowed to dry in piles to an average 30 percent moisture content. In addition, we used FoRTS to estimate the diesel consumed during a 20 minute idle time for each hook-lift truck and pup trailer to be loaded at 0.21 gallon. The diesel consumption for trucks hauling biomass was estimated at four miles per gallon (Thomas, personal communication). This consumption rate was applied to the loaded haul distance as well as the return trips with empty containers.

Spatial Modeling of Components

MAGIS, a spatial decision support system for scheduling vegetation treatments and road-related activities (www.fs.fed.us/rm/econ/magis) was used to simulate the treatments on the study area. The spatial R1-VMP polygons and road network data, vegetation treatment data, costs, delivered product prices, and fossil fuel consumption data served as inputs in the MAGIS model. MAGIS was then applied to simulate the application of the comprehensive restoration treatment on the relevant polygons on the landscape, load the biomass residue, pulpwood, and sawlogs onto the road network, and route the loaded trucks over the shortest path to their respective mill facility locations. In this process MAGIS calculated the acres receiving treatment, tons of biomass produced by the treatments and either hauled for energy production or burned onsite, the truck-miles 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.

Emission Factors

This paper focuses on two greenhouse gases, carbon dioxide and methane, as well as particulate matter emissions less than 10 microns in size (PM10). PM10 is one of several measurements of air quality used by the US Environment Protection Agency (2009b). For the alternative of utilizing forest residues in a boiler, we include emissions from internal combustion diesel engines, and stack emissions produced by burning biomass in a boiler for generating electricity and/or thermal energy. For the alternative of onsite disposal of forest residues by pile-burning and using fossil fuels to produce the equivalent amount of useable energy we include the emissions from pile-burning as well as the stack emissions from using either #2 distillate oil or natural gas to produce the equivalent usable energy in a boiler. The pile-burn emission calculations assume 95 percent of the residues in the piles are burned based on the assumption that unburned material at the edge of the piles is manually thrown into the fire (Hardy 1998; Fox, personal communication; Parks, personal communication)

Carbon dioxide, methane, and PM10 emissions for internal combustion diesel engines were estimated using the US Environmental Protection Agency AP-42 report (US Environmental Protection Agency 1995) and data from the US Energy Information Administration (US Energy Information Administration 2008). 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 (USDA Forest Service Forest Products Laboratory 2004). 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 (Hardy and others 2001). We assume boiler efficiency ratings of 83 percent, 80 percent, and 74 percent respectively, for distillate oil, natural gas, and biomass at 30 percent moisture content (USDA Forest Service Forest Products Laboratory 2004) to calculate the amounts of distillate oil and natural gas required in the pile-burn alternatives to produce the equivalent heating value of bioenergy.

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 (National Renewable Energy Laboratory 1998). The direct consumption of diesel, #2 distillate oil, and natural gas was divided by the fossil energy ratio of 0.8337 (National Renewable Energy Laboratory 1998) 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.

Results

Emissions

Figure 3 compares the total carbon dioxide emissions from using forest treatment residues for thermal energy (the bioenergy alternative) with disposal of treatment residues by on-site pile burning and using fossil fuels in a boiler to produce the equivalent amount of usable thermal energy. Carbon dioxide emissions from the bioenergy alternative are only 57 percent of the pile-burn alternative

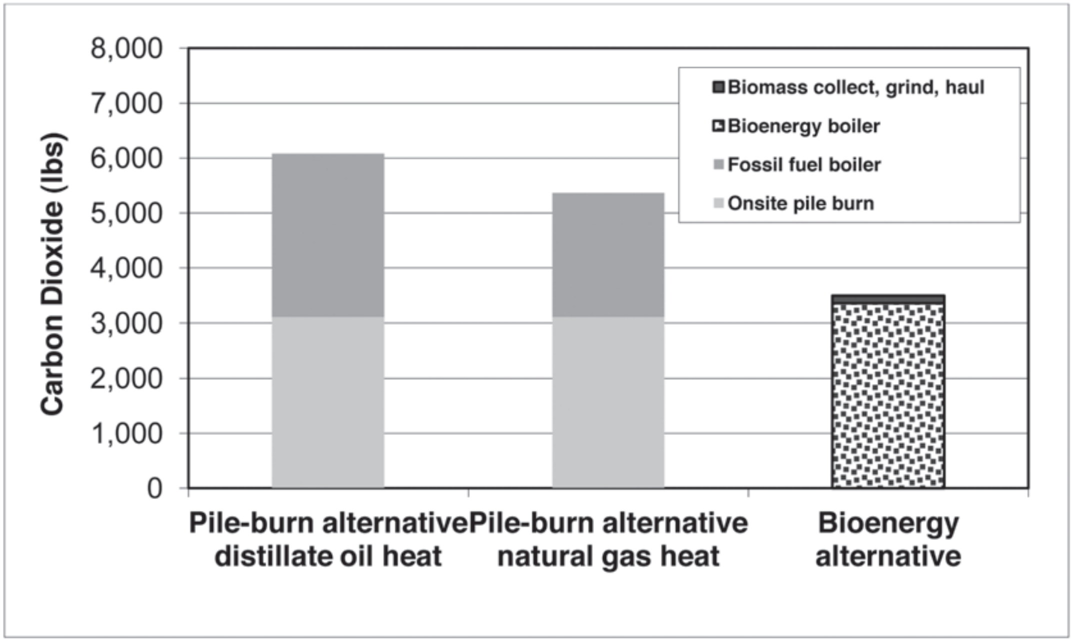

Figure 3—Carbon dioxide emissions per dry ton of forest treatment residues utilized in the bioenergy alternative compared with disposal by on-site pile burning and using either distillate oil or natural gas to provide the equivalent thermal heat in a boiler.

using distillate oil and 65 percent of the pile-burn alternative using natural gas. Notice that the carbon dioxide emissions from the consumption of 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 associated with using fossil fuels in boilers to provide the equivalent heat in the pile-burn alternatives.

The reductions in methane emissions (fig. 4) are much greater than the reductions calculated for carbon dioxide, with the methane emissions from the bioenergy alternative representing only about 3 percent of the pile-burn alternatives. Methane is not produced in appreciable amounts by burning fossil fuels in a boiler or in diesel engines. The methane production, while small compared to carbon dioxide, is important because the global warming potential of methane is about 21 times that of carbon dioxide (IPCC 2007b, US Environmental Protection Agency 2009c).

For the PM10 comparison, stack emissions were computed for biomass boilers both with and without wet scrubber particulate matter emission control (fig. 5). Although large biomass 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 percent of the pile-burn alternatives, and without the emission control were 44 percent of the pile-burn alternatives. For the pile-burn alternatives, PM10 emissions are almost entirely produced by pile-burning, very little is produced by burning either distillate oil or natural gas in a boiler.

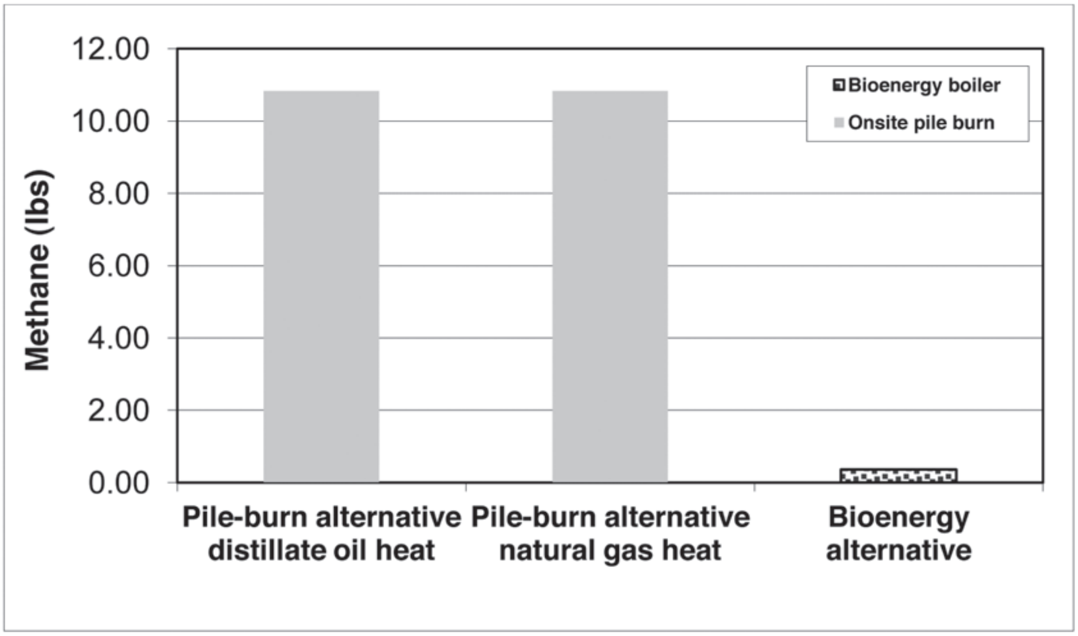

Figure 4—Methane emissions per dry ton of forest treatment residues utilized in the bioenergy alternative compared with disposal by on-site pile burning and using either distillate oil or natural gas to provide the equivalent thermal heat in a boiler.

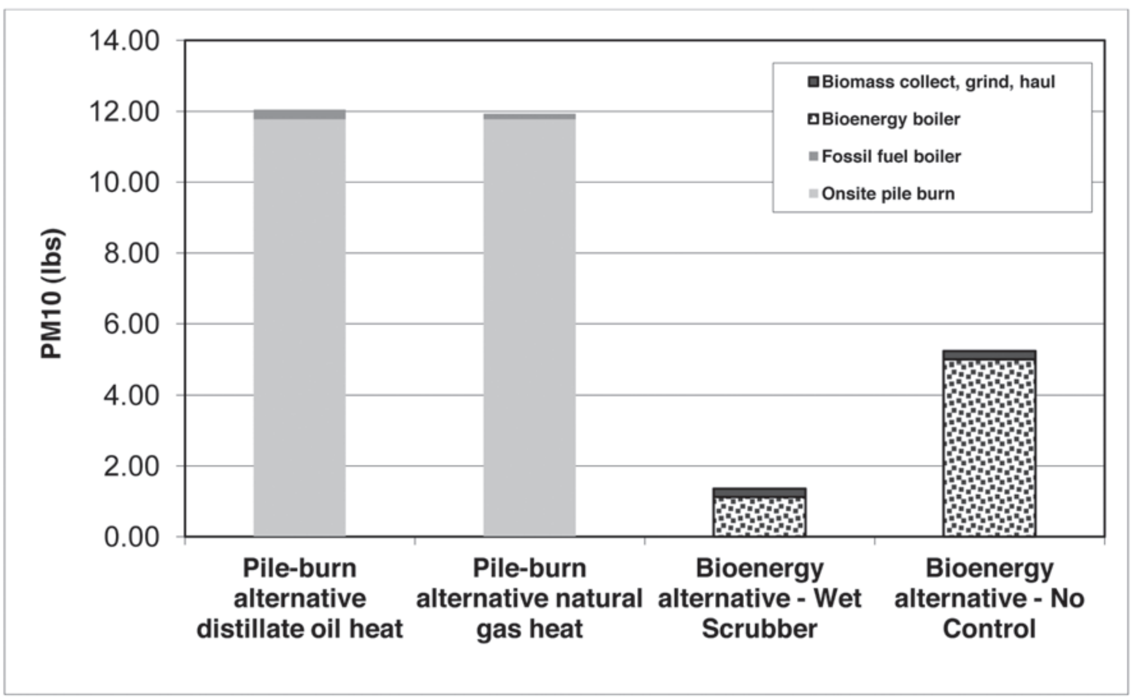

Figure 5—PM10 emissions per dry ton of forest treatment residues utilized in the bioenergy alternatives compared with disposal by on-site pile burning and using either distillate oil or natural gas to provide the equivalent thermal heat in a boiler.

Biomass Energy Returns

The scheduling capability in MAGIS was used to analyze energy returns from delivering forest residues in ten percent increments of total potential residues available on the study area. The first ten percent cost the least to haul to the bio-energy consumer; the second ten percent costs the next least, and so on. Figure 6 shows the average haul distances for each of the ten increments and the units of biomass energy obtained for each unit of diesel energy expended to collect, grind, and haul the biomass over these ten percent increments. 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 gallon of fuel. At the 47-mile 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 decreases to 21 units of energy per unit of diesel fuel energy consumed at the 85-mile average haul distance.

These bioenergy returns compare well with other bioenergy alternatives. For example, in a survey of literature of energy return Hammerschlag (2006) reported ratios for corn ethanol energy produced per unit of nonrenewable energy expended ranging from 0.84 to 1.65. For cellulosic ethanol Hammerschlag reported ratios of 6.61 for a mixed feedstock, 4.55 for poplar, 4.40 for corn stover, and 0.69 for switchgrass. Wu and others (2008) estimated year 2030 production cellulosic ethanol energy returns per unit of nonrenewable energy expended at 6.25 for wood residue and 11.11 for corn stover.

The fossil fuel energy consumed to collect, grind, and haul one dry ton of biomass in the bioenergy alternative is on average four percent of the fossil fuel energy required to provide the equivalent usable thermal energy in a boiler. In other words, the fossil fuel energy required in a boiler to provide the equivalent heat in the pile burn alternatives is many times greater than the fossil energy consumed in the bioenergy option.

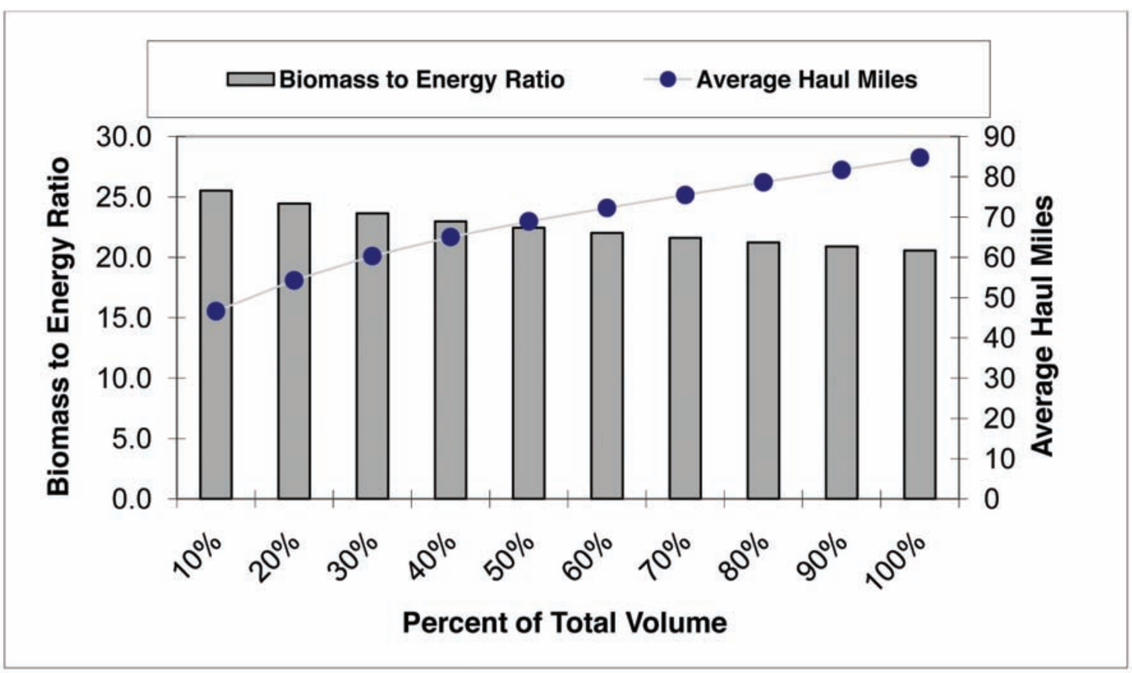

Figure 6—Biomass energy obtained for each unit of diesel fuel used to collect, grind, and haul forest treatment residue biomass across increasing average haul distances.

Economics of Biomass Utilization

Figure 7 identifies the candidate treatment units within the study area where utilization of biomass for thermal energy production is economically feasible. For these units, the delivered value of removed treatment residue biomass is greater than or equal to the cost of handing, grinding, and hauling biomass to that mill location. We assumed whole tree harvesting, so the biomass costs apply to piled treatment residues either at a landing or at road-side.

When diesel price is $4 per gallon and the delivered biomass price is $28 per ton at 30 percent moisture content, 36,447 acres (49 percent of the 74,352 total acres in polygons analyzed for potential treatment) are economically viable (left-most map in fig. 7). If the diesel price were to increase 50 percent to six dollars per gallon (center map in fig. 7), the number of economically viable acres drops to 23,445 (31 percent of the potential acres). The polygons that drop out at this higher diesel price are those with the longer hauling distances and/or more unpaved road hauling distance. If both the diesel and delivered biomass price were to increase 50 percent from the base case (right-most map in fig. 7), then the economically viable acres increases to 37,915 acres (51 percent of the potential acres). This suggests that changes in the delivered price of biomass are slightly more important in economic feasibility than changes in the price of diesel fuel.

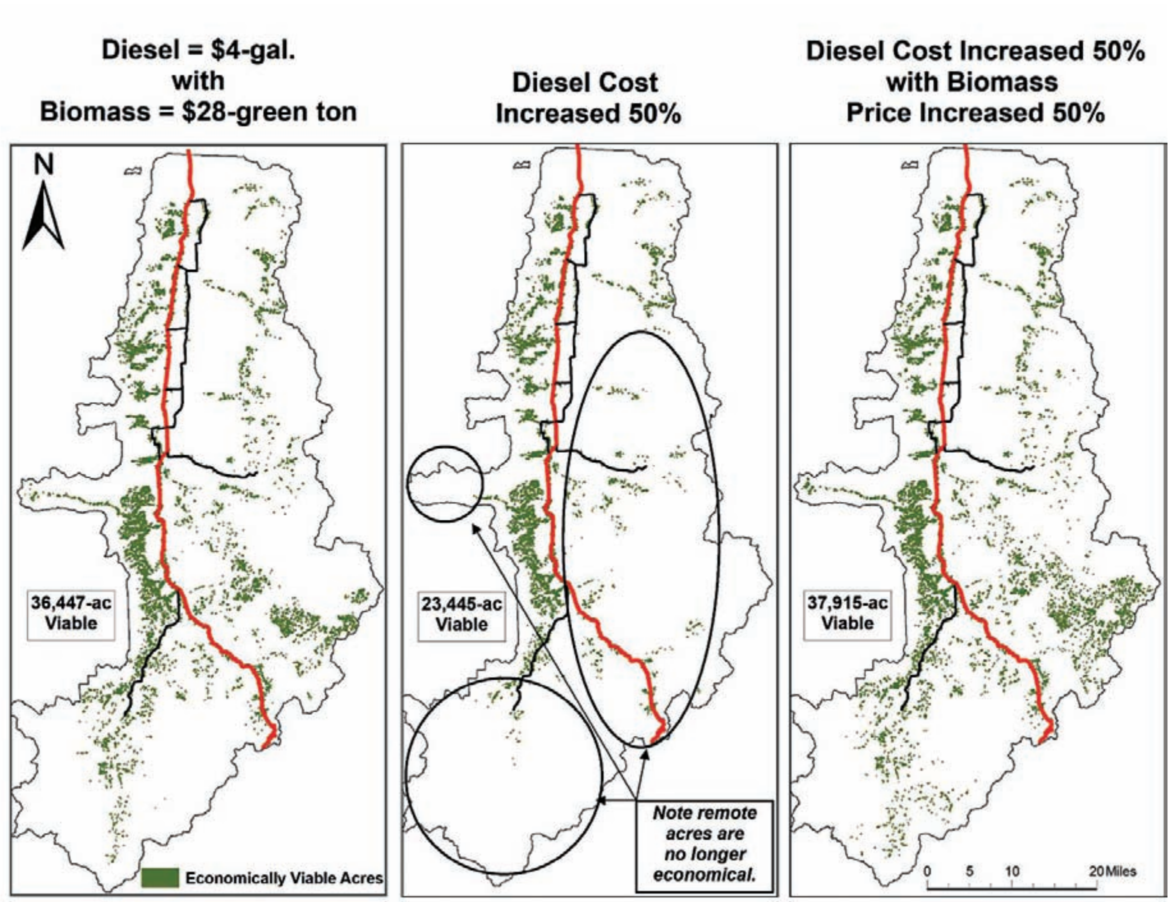

Figure 7—Where biomass utilization is economically viable within the study area across various diesel and delivered biomass prices.

Conclusions

These results suggest that when a bioenergy alternative to onsite pile-burning is available, far fewer carbon dioxide, methane, and particulate matter emissions would be generated and useable energy is produced that could offset the use of fossil fuels for thermal energy production. In addition, the fossil fuel energy required for the bioenergy alternative is small compared to the energy produced in the bioenergy alternative. Based on the economics of biomass utilization results, these relationships hold for haul distances that are many times longer than what are financially feasible.

The analysis we present in this paper is based on whole tree harvesting, grinding the skidded biomass residue into containers, and trucking these containers to the location where the biomass is burned for heat energy. We expect that other wood utilization standard and ground-based harvesting or biomass handling methods would produce different emission trade-offs and energy consumption ratios.

Our results indicate that utilizing woody residues for thermal heat can contribute to generating energy while also 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.

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