BIOMASS AND BIOENERGY 48 (2013) 171–180

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The financial feasibility of delivering forest treatment residues to bioenergy facilities over a range of diesel fuel and delivered biomass prices

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ARTICLE INFO

Article history:
Received 8 December 2011
Received in revised form
27 September 2012
Accepted 28 November 2012
Available online

Keywords:
Woody biomass
Bioenergy
Logging residues
Biomass supply
Biomass price
Biomass cost

ABSTRACT

Forest 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 to meet management objectives. We spatially analyzed the sensitivity of financially feasible biomass volumes for delivery to a bioenergy facility across 16 combinations of delivered biomass and diesel prices for a 515,900 ha area in western Montana. At the lowest delivered biomass price analyzed, $31.52 per oven dried tonne (ODT), 28% of the potential volume was financially feasible at the lowest diesel price, $0.053 L^{-1}, dropping off to 6% of the volume at the highest diesel price analyzed, $1.32 L^{-1}. With a 50% increase in delivered biomass price to $47.28 ODT^{-1}, feasibility increased to 88% at the $0.53 L^{-1} diesel price, dropping to 36% of the volume at the $1.32 L^{-1} diesel price. Another 50% increase in delivered biomass price to $63.05 ODT^{-1} resulted in the feasible volume converging on the total potential volume at the lower diesel prices, and at the highest delivered price, $78.81 ODT^{-1}, nearly all potentially available biomass is financially feasible even at the highest diesel fuel price analyzed. Haul was almost entirely restricted to paved roads closest to the bioenergy facility at the lowest delivered biomass price. As delivered price increased, feasible volume expanded further into areas accessed by unpaved roads as well as paved roads further from the bioenergy facility. Results show that financial feasibility is much more sensitive to changes in delivered biomass prices than diesel prices.

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1. Introduction

Industrial mill residues have historically generated most of the wood-based energy in the US [1]. Now, however, forest treatment residues are getting more attention as an energy source. Instead of disposing of them by on-site, in-woods burning, there is growing interest in expanding the use of forest treatment residues as feedstocks for energy production

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0961-9534/$ – see front matter Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.biombioe.2012.11.023

[2–4]. There are several potential benefits to using forest treatment residues as feedstocks for energy production, including reducing greenhouse gas and particulate emissions, diversifying energy sources away from fossil fuels, expanding rural employment and economic development, and improving the balance sheet for forest fuel reduction and forest restoration treatments by providing opportunities to add product value [5–7].

Forest treatments have the potential to produce significant quantities of forest residue biomass, which includes the tops and limbs from merchantable trees and the entirety of smaller trees removed to meet management objectives [2,8–10]. Furthermore, a wood-based energy industry would not necessarily compete directly with the forest products industry. Buchholz et al. [4] found that from 4.2 to 6.3 million tonnes per year of forest biomass could be available for energy production over an eight-state region in the Northeastern US without diverting biomass currently used in the pulp and paper industry. Conner et al. [11] reported that new facilities that use wood to produce energy in South Carolina could capitalize on the 8.0 million tonnes per year of unutilized biomass and operate without overly impacting existing forest industries or increasing harvest levels above 2006 estimates. Perez-Verdin et al. [12] reported about 3.6 million dry tonnes of woody biomass are available for production of up to 1.2 billion liters of ethanol each year in Mississippi.

Although utilization of large volumes of forest treatment residues may be technically feasible, an important challenge to utilizing this woody biomass is the cost of recovery and delivery relative to its value as a raw material for producing energy, liquid fuels and bio-based products [13]. Recovery and delivery costs are often higher than the value of the delivered product because of poor access to, and distribution of, biomass supply areas relative to feasible locations for utilization facilities [14]. In the western US, haul distances are often long and forest roads can limit the type and size of truck that can be used, particularly in mountainous environments [15,16]. In addition, green woody biomass is bulky with high water content, which provides weight, but no energy value [17]. Moreover, utilization of forest treatment residues is inhibited by the lack of biomass markets in many geographic locations, particularly in the western US.

Numerous studies have estimated the costs of collecting, comminuting, and hauling biomass produced by forest fuel and restoration treatments in various geographic locations [18–22]. FIA Biosum [23,24] uses estimates of the costs for delivering biomass from various forest locations to assess the feasibility of alternative facility locations. BioSAT (http://www.biosat.net) is a model used to identify the top facility locations for utilizing forest biomass in 13 southern U.S. states. Skog et al. [25] developed biomass supply curves by county for the western states to estimate the volumes of biomass that forest residues could provide for energy production. The Coordinated Resource Offering Protocol (CROP; http://www.crop-usa.com) is a series of models to identify biomass offerings from public agencies to stabilize uncertainty associated with regional biomass supply. These studies generally focus on available biomass volume and assume constant energy prices.

Recent years have seen much volatility in fossil fuel prices [26]. In cases where wood-based energy can be substituted for fossil fuels, higher fossil fuel prices can result in more demand for wood energy and higher prices for wood-based feedstocks [27]. However, higher fossil fuel costs also result in higher diesel fuel prices. Because collecting, grinding, and hauling forest biomass all use diesel fuel, higher diesel prices mean higher costs for delivering forest residue biomass to bioenergy facilities. To examine the effects of increases both in delivered biomass price and in diesel fuel price on the volume of residue biomass that is financially feasible to deliver, we examined the case of a forested landscape in western Montana.

2. Study area

Our study area includes the Bitterroot National Forest and adjacent private forestlands in the Bitterroot Valley of western Montana, comprising a total of 515,900 ha (Fig. 1). In this area, low- to mid-elevation sites historically experienced frequent low-severity wildfires that removed shade-tolerant trees from the forest understory. Over many years, past management practices and fire suppression have contributed to increased stocking of shade-tolerant conifers. Increased inter-tree competition can make the larger, overstory trees more susceptible to insects and disease and increase mortality of the subdominant trees [28]. In turn, the higher levels of dead and down wood contribute to "laddered" fuel that can increase fire severity. Reducing forest fuels and improving forest health are predominate reasons for silvicultural treatments in the area, especially on the National Forest. Disposal

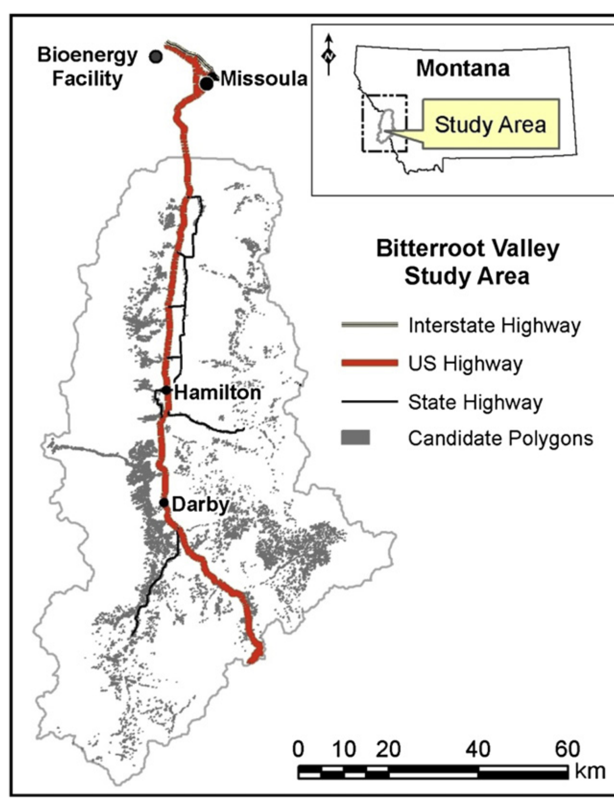

Fig. 1 – Study area.

of these forest residues is important to accomplishing the treatment objectives of reducing forest fuels to reduce the risk of wildfire and improve forest health.

We were specifically interested in understanding how various biomass and diesel prices affect the financial feasibility of collecting, grinding, and delivering forest residue biomass produced by mechanical fuel treatments where they are applied on the landscape to reduce the threat of severe wildfire and improve forest health. We analyzed transporting the treatment residues to a bioenergy facility located 27.4 km north of study area boundary. Transportation of residue biomass originating from forest treatments in the study area to this facility is by forest roads and secondary roads that feed into a main highway.

3. Methods

3.1. *Spatial distribution of treatment residues*

The potential residue biomass we analyzed in this study is produced by mechanical forest fuel reduction and forest health restoration treatments. Locations for these treatments were identified using a GIS-based forest vegetation classification system, R1-VMP, produced by the Northern Region of the USDA Forest Service [29]. R1-VMP categorizes 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 regimes (*Pinus ponderosa* and mixtures of *P. 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 [30,31]. Candidate polygons were further restricted to those on non-reserved lands managed by the US Forest Service, or private, non-industrial forestlands. In addition, candidate polygons had average slopes less than 35% and were within 457 m from polygon center to existing open system roads suitable for hauling treatment residues. This resulted in a data set of 11,662 polygons comprising 24,904 ha (Fig. 1).

3.2. *Treatment residue volumes and prices*

A variety of silvicultural treatments can produce differing amounts of residues, depending on their intensity. In this analysis we focused on a mechanical treatment called comprehensive restoration that is designed to reduce ladder and crown fuels to mitigate the potential for wildfire effects and restore forests to sustainable and historical conditions [32]. This treatment removes all trees below 17.8 cm diameter at breast height plus some larger diameter trees with a target residual stand having basal area in the range 9.2–13.8 $m^2\ ha^{-1}$ (40–60 $ft^2\ acre^{-1}$) comprised of fire resistant tree species such as ponderosa pine (*P. ponderosa*) and western larch (*L. occidentalis*). It creates a relatively open stand of trees with reduced potential for crown fire and promotes health of the residual trees by reducing the competition for moisture and nutrients.

We assumed that whole-tree harvesting is used to cut and skid trees to road-accessible landings. Whole tree harvesting, which is commonly used in the western U.S., delivers whole trees, including the main stem, limbs, and tops to a landing. We assumed the tree boles suitable for higher valued commercial products are removed at the landing and the residue biomass that remains is available for bioenergy. This residue consists of the tops and limbs of the commercial trees, and all of the smaller, noncommercial trees that were removed and skidded to the landing to meet treatment objectives. Some of the tops and limbs that are present on the trees prior to harvest are broken in the whole tree harvesting process and stay on site. We assumed that 80% of the treatment residues are recovered at the landing [33,34]. When first harvested, the moisture content of green trees can range from about 30% to more than 200% [35]. We assumed that following removal of the commercial component the piled treatment residues are allowed to air dry to an average moisture content of 30% [36], and then are ground and hauled to the bioenergy facility.

Our approach for estimating the volume of treatment residues followed the method described in Loeffler et al. [9]. The Northern Idaho/Inland Empire variant of the Forest Vegetation Simulator (FVS, www.fs.fed.us/fmsc/fvs) was applied to Forest Inventory and Analysis (FIA, http://www.fs.fed.us/rm/ogden) plot data to estimate the residue biomass volumes produced by the comprehensive restoration treatment. To ensure adequate data, we supplemented the FIA plots from the study area (Ravalli County) with FIA plots from similar western Montana forests in Missoula, Mineral, and Lake Counties. Plots taken in forest conditions unsuitable for our silvicultural treatment due to low stocking were excluded from further analysis. This included plots having less than 10% canopy cover, and plots where application of the treatment would remove fewer than twenty trees per acre.

Weights for all merchantable logs from the trees that would be removed via treatment were computed through a combination of the FVS Database Extension, tree component ratio equations from published biomass estimators [37], and dry volume weights obtained from the Fire and Fuels Extension of FVS [38]. 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 oven dried tonnes (ODT) of the total biomass removed. Subtracting the removed merchantable log weight from the weight of the total biomass removed yielded the total weight of the non-merchantable residue biomass. Summary statistics for cut materials estimated by using these methods are displayed in Table 1.

The volumes estimated from analyzing the FIA plots were assigned to the R1-VMP polygons using the k-nearest neighbor imputation method [39]. In this process, FIA plots are imputed (assigned) to polygons based on the similarity of zonal statistics computed from spectral images of the study area and FIA plot locations. These zonal statistics were based on Landsat spectral imagery (http://landsat.gsfc.nasa.gov/) processed by the US Forest Service Northern Region. Zonal statistics for twenty-two topographic variables identified as significant predictor variables when imputing forest inventory data [40] were assigned to the FIA plots and to the R1-VMP

Table 1 – Summary statistics from modeling application of the comprehensive restoration treatment on 0.405 ha (1 acre) plots ($n = 315$).

	QMD[a] of merchantable[b] trees removed (cm)	QMD of non-merchantable[c] trees removed (cm)	Number of merchantable trees removed (count)	Number of non-merchantable trees removed (count)	Merchantable volume of trees removed (m^3)	Treatment residue biomass (ODT)
Mean	23.3	4.1	179	125	51.0	7.2
Median	21.9	5.8	164	60	45.5	6.9
Standard deviation	7.0	3.6	125	196	35.3	4.0
Minimum	12.3	0	20	0	2.2	0.9
Maximum	59.4	9.9	738	1900	195.8	20.0

a Quadratic mean diameter.
b Merchantable trees are greater than 10.2 cm diameter at breast height.
c Non-merchantable trees are greater than 2.54 cm and less than 10.2 cm diameter at breast height.

polygons selected as candidates for treatment. The nearest neighbor imputation process assigned the most similar FIA plot to each polygon based on zonal statistics computed for these 22 topographic variables.

We analyzed the financial feasibility of collecting, grinding, and delivering piled treatment residues to the bioenergy facility at four different ODT delivered biomass prices that spanned a range from low to very high prices. Those ODT prices were $31.52, $47.28 (50% increase), $63.05 (100% increase), and $78.81 (150% increase).

3.3. *Treatment residue collecting, grinding, and transportation costs*

A GIS roads coverage obtained from the Bitterroot National Forest (www.fs.fed.us/r1/bitterroot) provided a network of open forest system roads for modeling routes for hauling treatment residue biomass from the candidate treatment polygons to the bioenergy facility. 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 candidate polygon enters the road system was approximated by choosing the nearest node that does not involve skidding logs across an unacceptable physical feature, such as a gully or stream channel.

Many of the treatment polygons are adjacent to roads that are 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 [36]. 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 tonnes [41]. This compares with 24.5–27.2 tonne 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.

Costs were estimated for each component using four off-road, untaxed, diesel fuel prices: $0.53 L^{-1}, $0.79 L^{-1} (50% increase), $1.06 L^{-1} (100% increase), and $1.32 L^{-1} (150% increase) (Table 2). These off-road prices were used in estimating costs for the grinding operation. The federal and Montana State tax that applies to diesel fuel used by vehicles driven on roads, $0.12 L^{-1}, was added to the off-road diesel prices to estimate costs for the on-road biomass hauling portion of the analysis.

The Forest Residue Trucking Simulator (FoRTS; http://www.srs.fs.usda.gov/forestops/biomass.htm) was used to estimate biomass loading, grinding, and haul costs for the four diesel prices, based on local wages and conditions (Table 2).

Table 2 – Estimated costs by diesel fuel price.

Cost item	Price for off-road diesel fuel			
	$0.53 L^{-1}	$0.79 L^{-1}	$1.06 L^{-1}	$1.32 L^{-1}
Move-in & grinding cost ($ ODT^{-1})	$6.71	$7.41	$8.10	$8.73
Unpaved haul cost per truck[a] ($ km^{-1})	$5.41	$6.18	$6.96	$7.71
Paved haul cost per truck[a] ($ km^{-1})	$1.35	$1.54	$1.74	$1.93
Trucking costs associated with loading and unloading ($ per load)	$48.48	$51.24	$54.06	$56.76

a Haul costs are expressed on a round trip basis.

Biomass loading and grinding costs were based on the machine rate calculations for a tracked, self-loading horizontal grinder with an 80% utilization rate. The biomass system move-in costs ODT^{-1} were based on the average size of mechanical fuel reduction and forest restoration treatment projects on the Bitterroot National Forest from 2002 to 2008, 148 ha [42], the average residue volume ha^{-1}, and the cost of an average 263 km round trip for a lowboy equipment hauling trailer. Road maintenance costs associated with the projects were assumed to be paid by the contractors that remove the commercial product. Round trip haul costs for trucks were estimated for two types of roads, paved and unpaved. The FoRTS model predicts hourly haul costs which were converted to cost km^{-1} by assuming an average speed on paved roads of 64 km h^{-1} and 16 km h^{-1} on unpaved roads. An additional cost for trucking was included to account for the wait time for loading and unloading biomass. We assumed that the loading and unloading processes summed to an average of 1 h of idling time per load.

3.4. *Spatial modeling of biomass delivery*

A spatial modeling system called MAGIS (www.fs.fed.us/rm/econ/magis) was used to analyze the financial feasibility of utilizing residues from the polygons identified as candidates for fuel reduction/forest health restoration treatments. MAGIS is a system for scheduling vegetation treatments on polygons and routing biomass haul over a road network through the least-cost path from the polygons to the biomass processing facility. The spatial R1-VMP polygons and road network data, volumes of treatment residues, costs related to collecting, grinding, and hauling biomass, and delivered biomass prices were input into the MAGIS model. The optimization capability in MAGIS was used to assess the financial feasibility for each candidate polygon. This was accomplished by maximizing net revenue across the study area. In this process MAGIS compares the sum of the residue collecting, grinding, and hauling costs for utilizing biomass on individual polygons with the revenue that the delivered biomass would generate, and selects biomass utilization for every polygon that results in positive net revenue. Polygons for which biomass utilization results in negative net revenue are not selected. Separate analyses were performed for each combination of four diesel fuel prices and four delivered biomass prices, 16 cases in all.

The results of each MAGIS solution includes the number of hectares on which treatment residue utilization is financially feasible, the volume of financially feasible treatment residue biomass, and the costs, total revenues, and net revenues associated with utilizing that volume of biomass. The results also provide the quantity of biomass hauled over each road segment from which the average paved and unpaved haul distances are computed. Finally, because MAGIS is a spatial model, maps can be produced showing the polygons for which utilization of treatment residues is financially feasible.

4. Results

Fig. 2 presents the financially feasible volumes of forest treatment residue biomass for the four diesel fuel prices analyzed across the four delivered biomass prices. The total volume of biomass available across all polygons that were candidates for biomass utilization in the study was 385,100 ODT. The financially feasible volumes for each diesel price converge on that volume at the highest delivered biomass price analyzed ($78.81 ODT^{-1}).

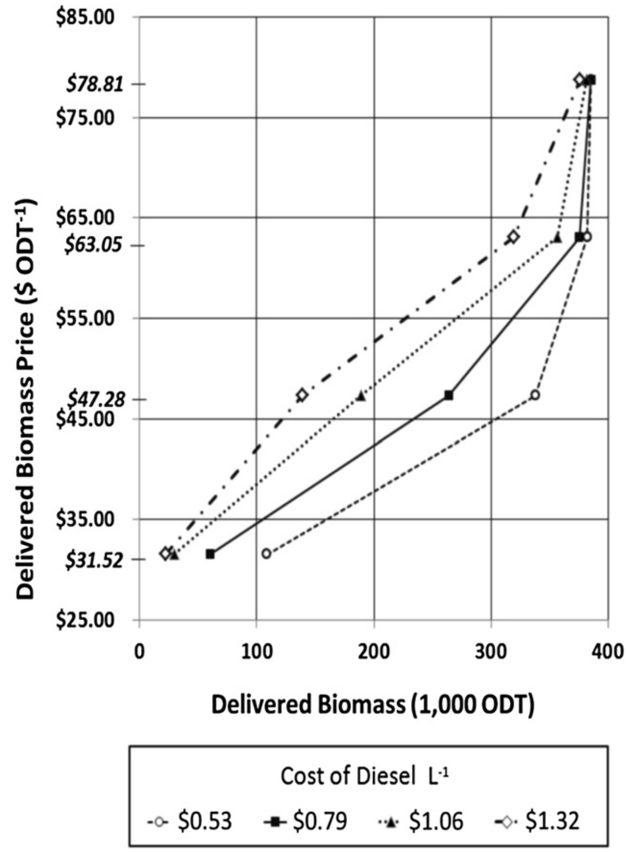

Fig. 2 – Financially feasible volumes of forest treatment residue biomass for four diesel fuel prices across four delivered biomass prices.

At the lowest delivered biomass price analyzed ($31.52 ODT^{-1}), relatively little of the potential biomass volume was financially feasible to process and deliver. When diesel price was $1.32 L^{-1} only 22,500 ODT (6% of the potential volume) were financially feasible, rising to 108,700 ODT (28% of the potential volume) at the $0.53 L^{-1} diesel price.

A 50% increase in the delivered biomass price to $47.28 ODT^{-1} resulted in substantial increases in feasible volumes across all diesel prices analyzed. At the $0.53 L^{-1} diesel price 337,800 ODT (88% of the potential volume) were financially feasible (up from 28% of the potential volume at the lower biomass price). Successive 50% increases in diesel price from $0.53 L^{-1} to $0.79 L^{-1} to $1.06 L^{-1} resulted in 74,000 ODT reductions in the feasible volume (approximately 19% of the potential volume for each reduction). Another 50% increase in diesel price to $1.32 L^{-1} reduced the feasible volume another 50,000 ODT to 139,150 ODT (36% of the potential volume).

A 100% increase in the base biomass price to $63.05 ODT^{-1} resulted in additional large increases in the financially feasible volumes for all but the lowest diesel price, where only a modest increase in feasible volume occurred. At the lowest diesel price (\$0.53 L^{-1}) the feasible volume increased to 382,000 DBT (99% of the potential volume). A 50% increase in diesel price (\$0.79 L^{-1}) only reduced the feasible volume to 375,000 ODT (97% of the potential volume). Another 50% increase in diesel price (\$0.79 L^{-1}) reduced the feasible volume to 356,800 ODT (93% of the potential volume). The highest diesel price resulted in a feasible volume of 319,200 ODT (83% of the potential volume).

At the highest delivered biomass price tested, \$78.81 ODT^{-1}, nearly all the potentially available residue biomass was financially feasible at each of the diesel fuel prices analyzed. At the two lower diesel prices all the potential volume was financially feasible (385,100 ODT). The feasible volume only dropped to 381,300 ODT (99% of the potential volume) at the \$1.06 L^{-1} diesel price, and to 375,600 ODT (98% of the potential volume) at the \$1.32 L^{-1} diesel price.

Fig. 3 displays the relationships among varying diesel and biomass prices, haul distances, financially feasible residue biomass volumes, and net revenues associated with collecting, grinding, and hauling biomass. The top four charts in Fig. 3 compare the financially feasible volumes of forest treatment residue biomass with the net revenues associated with those volumes and combinations of prices. The lower four charts in Fig. 3 display the average paved and total haul distances for the corresponding biomass volumes and combinations of prices in the charts immediately above. Unpaved haul distance is the difference between paved haul and total haul. All haul distances are reported as 1-way, loaded haul distances, although the round trip distance was used in the haul cost calculations.

At the delivered biomass price of \$31.52 ODT^{-1} very little of the biomass was estimated to be financially feasible to deliver at all but the lowest diesel price, net revenues were low, and haul distances short compared to the higher delivered prices that we analyzed. At the lowest diesel price (\$0.53 L^{-1}) 108,700 ODT were feasible yielding net revenue of \$535,000. At this combination of prices, average total haul distance was 87 km with only 3 km over unpaved roads. Feasible biomass volume, net revenue, and haul distance all decreased as the price of diesel fuel increased. At the highest diesel fuel price only 22,500 ODT were feasible, average haul distance dropped to 61 km (all on paved roads) and net revenue fell to \$89,000.

Increasing the delivered biomass price to \$47.28 ODT^{-1} substantially changed the potential supply. At the lowest diesel price, the financially feasible volume was 337,800 ODT yielding net revenue of \$4,030,000, and the average total haul distance was 125 km, with 8 km occurring on unpaved roads.

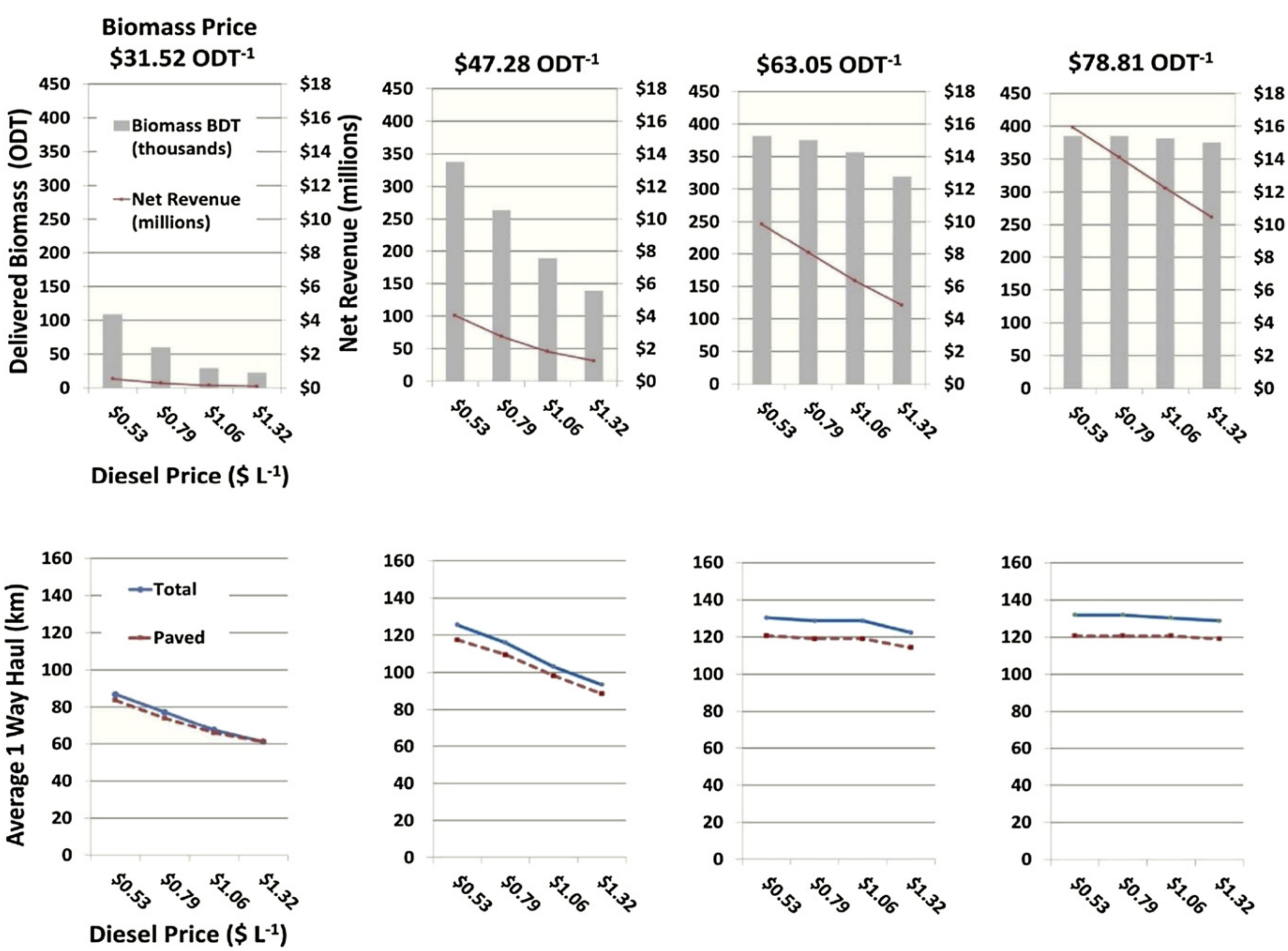

Fig. 3 – Financially feasible biomass volumes, net revenues, and haul distances compared across four diesel fuel prices for each of four delivered biomass prices.

Table 3 – Percent of the total potential volume of biomass that is financially feasible to deliver at each combination of delivered biomass price and diesel price.

Diesel price	Biomass price			
	$31.52 ODT^{-1} (base level)	$47.28 ODT^{-1} (50% increase)	$63.05 ODT^{-1} (100% increase)	$78.81 ODT^{-1} (150% increase)
$1.32 L^{-1} (150% increase)	6%	36%	83%	98%
$1.06 L^{-1} (100% increase)	8%	49%	93%	99%
$0.79 L^{-1} (50% increase)	16%	68%	97%	100%
$0.53 L^{-1} (base level)	28%	88%	99%	100%

The quantity of financially feasible biomass was quite sensitive to diesel fuel prices at this delivered biomass price. A 50% increase in diesel price to $0.79 L^{-1} resulted in a 74,100 ODT reduction in feasible volume to 263,700 ODT, with a total average haul distance of 116 km with 6 km on unpaved roads, and net revenue of $2,757,000. Similar incremental decreases in volume, haul distance, and net revenue occurred with each successive 50% increase in diesel fuel price. At the highest diesel price, the estimated feasible volume dropped to 139,150 ODT, total average haul distance to 93 km with 5 km on unpaved roads, and net revenue to $1,252,000.

The next increment in delivered biomass price to $63.05 ODT^{-1} resulted in nearly all the potential biomass volume becoming financially feasible at all but the highest diesel price, with corresponding large increases in the net revenues. Increases also incurred in haul distances at the higher diesel prices. At the lowest diesel price, net revenue was $9,854,000, and dropped approximately $1,700,000 over each increment in diesel price to $4,851,000 at the $1.32 diesel price. Average haul distance, however, remained relatively constant over the range in diesel prices, because similar biomass volumes were transported from similar forest treatment locations. At the $0.53 diesel price average haul distance is130 km with 10 km on unpaved roads, dropping only to 122 km with 8 km on unpaved roads at the $1.32 diesel price.

At the highest delivered biomass price analyzed all the potential biomass was feasible at the two lower diesel fuel prices and the feasible volume decreased by only 1% for each additional increment in diesel fuel price. Net revenue at each diesel price nearly doubled compared to the next lower biomass price. This increase in net revenues was caused almost entirely by the direct effect of the higher biomass price, as neither the biomass volumes nor average haul distances differ substantially from the next lower biomass price.

Table 3 is a convenient format for showing how the financially feasible volume changed with percentage changes in biomass and diesel fuel prices. Looking at the diagonal from the lower left to the upper right we see the percentage of total biomass volume that was financially feasible increased with equal percentage changes in biomass and diesel prices.

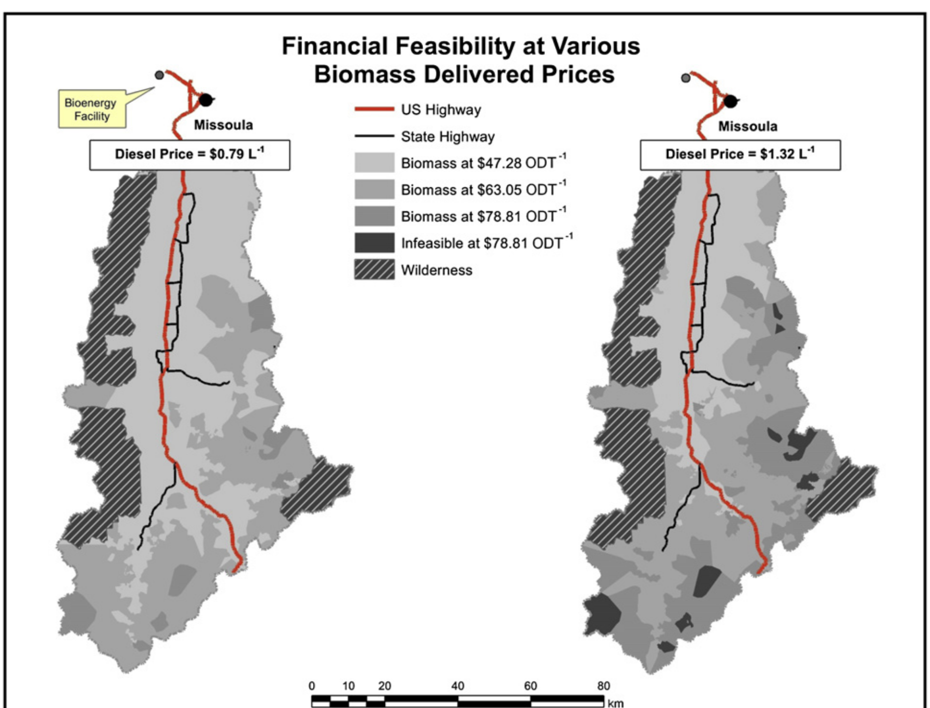

Fig. 4 – Locations where utilizing treatment residue biomass is financially feasible at various delivered biomass prices compared for two diesel prices.

Clearly, the increase in revenue that was associated with the higher biomass price outweighed the increase in delivered cost associated with an equal percentage increase in diesel prices. Combinations off the diagonal show that, in fact, delivered biomass prices were much more important than diesel fuel prices in determining the percentage of total biomass that was financially feasible to deliver. For example, at the base prices for biomass and diesel fuel, 28% of the potential biomass volume was financially feasible. With a 100% increase in diesel fuel price from the base price and a 50% increase in biomass price, the feasible volume increased from 28% to 49%. Feasible volume still increased from the 28% base level to 36% of the potential volume when diesel fuel price increased 150% from the base price and biomass price increased 50%.

The Thiessen polygons displayed in Fig. 4 approximate the locations in our study area where biomass utilization was financially feasible at various biomass prices when diesel fuel price was \$0.79 L^{-1} (map on left) and when it was \$1.32 L^{-1} (map on right). These Thiessen polygons, which were created in GIS, identify the area closest in proximity to the centroid of each candidate treatment unit polygon. At the higher diesel price, when the delivered biomass price was \$47.28 ODT^{-1} financial feasibility was limited to the treatment locations in northern and central portions of the study area (closer to the bioenergy facility) and adjacent to or near paved roads where hauling cost is less than on unpaved roads. Feasibility at the lower diesel price extended much further south (further from the biomass facility) and further into the locations accessed only by unpaved roads in the northern portion of the study area. The same patterns are observed for the higher delivered biomass prices. At the higher diesel price, there are a few areas where biomass utilization was infeasible even with the highest delivered price.

5. Discussion and conclusions

The price of diesel fuel in the US has been fluctuating with a general upward trend in recent years and all expectations are for the upward trend to continue in the future. The price of delivered biomass can also be variable over time and biomass prices also vary by geographic locations where markets for biomass can differ widely. Our results show that the financial feasibility of delivering forest treatment residue biomass is greatly affected by the level of these prices, from essentially no biomass to all potential biomass being financially feasible to deliver to a bioenergy facility. Although both prices are important, results show that financial feasibility is much more sensitive to percentage changes in the delivered price of biomass (positive effect on feasible volume) than the price of diesel fuel (negative effect on feasible volume). This occurs even though the average haul distances in our study area are relatively long compared to typical biomass utilization haul distances in the western US.

The trends in financially feasible volumes associated with relative changes in delivered biomass prices and diesel fuel displayed in our results would be expected to hold in other locations in the western US and possibly other geographic locations. However, precise changes in financially feasible volumes of biomass in other locations can be expected to vary based on a number of factors. An important factor is the proximity of the potentially available forest treatment residues to a bioenergy facility. Longer average haul distances caused by residues located in more distant locations would be expected to make the financially feasible volume more sensitive to diesel fuel prices than the results we present, and the converse for shorter haul distances. Similarly, the characteristics of the access roads would be expected to affect sensitivity of feasible volume to diesel fuel prices. Increases in diesel fuel price are less important if the majority of the haul is over high-speed roads where hauling is more efficient, but will have a somewhat larger effect than what we reported if a significant portion of the haul is over low-speed roads or roads that limit the type of equipment for hauling biomass. Also, truck capacity affects the financial feasibility of hauling biomass. We assumed an average payload of 22.7 tonnes (of 30% moisture residues) to allow for hauling over forest roads that are inaccessible to large chip vans. Larger capacity trucks would be expected to decrease haul cost per tonne and vice versa for smaller capacity trucks.

The analysis we present in this paper is based on utilizing forest treatment residues that are accessible in piles at roadside or at a landing at no charge for the material. This provides a no-cost residue disposal option for landowners. If landowners are willing to pay a fee to remove the residues, that has the same financial effect as an equivalent increase in the delivered biomass price – an upward effect on financial feasibility of delivering treatment residues to a bioenergy facility. Conversely, if landowners require a payment for residue removal, that has the same financial effect as an equivalent decrease in the delivered biomass price – a downward effect on financial feasibility of delivering treatment residues to a bioenergy facility.

The residue biomass volumes that we estimated were based on the comprehensive restoration treatment described earlier. The costs of collecting, grinding, and hauling treatment residues piled at roadside from other forest treatments would be expected to be the same, provided there is a sufficient volume in a project area to warrant incurring the move-in costs. In this paper move-in costs were based on the average volume of residue (18 ODT ha^{-1}) produced by the average size of mechanical fuel reduction and forest restoration treatment projects on the Bitterroot National Forest from 2002 to 2008, 148 ha. Substantially smaller residue volumes in a project area will increase the move-in cost ODT^{-1}, which reduces the financial feasibility of utilization.

One of the most cost-effective situations for utilizing forest biomass occurs when mechanical forest treatments, which are undertaken for a variety of reasons, produce piled treatment residues accessible at roadside or at landings, the case analyzed in this paper. This occurs when whole tree harvesting, a common practice in the western US, is used to remove cut trees from the treated area. There are, however, other situations that have the potential to provide forest biomass for bioenergy production, but these involve more biomass utilization costs. One such case is when the forest treatment leaves residues dispersed throughout the area treated, adding costs for collecting and transporting the biomass to locations accessible by road to the utilization process. Another is when trees are harvested specifically for bioenergy production, adding the harvesting cost to the cost of biomass utilization. The financial feasibility of delivering biomass from cases such as these can vary widely from the results presented in this paper.

The effect of varying delivered biomass prices and diesel fuel prices on the financially feasible volumes of biomass for delivery to bioenergy facilities is of interest to potential investors in bioenergy facilities, forest managers, and policy makers. The trends in feasible volumes predicted for the study area in this paper would be expected to apply to other geographic locations in the western US. In addition, the methods and data used for these analyses are in the public domain and could be applied to analyze other possible biomass utilization scenarios in other geographic locations. Hopefully these results and methods will help understanding of how feasible biomass volumes change with future changes in delivered biomass prices and diesel fuel costs.

Role of the funding source

Financial support for this research came from the USDA Forest Service National Fire Plan Research and Development Program. This study sponsor did not contribute in the study design; the collection, analysis, and interpretation of data; in the writing of the report; or in the decision to submit the paper for publication.

Acknowledgments

We thank Kurt Krueger of the Rocky Mountain Research Station for his help in applying the MAGIS model in this study. We also thank the Bitterroot National Forest for providing data and GIS coverages used in this study.

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