WASTE TO WISDOM: INTEGRATING FEEDSTOCK SUPPLY, FIRE RISK AND LIFE CYCLE ASSESSMENT INTO A WOOD TO ENERGY FRAMEWORK

Final Report on
Waste to Wisdom: SubtaskTask 4.2.5, 4.7.6 and 4.8

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EXECUTIVE SUMMARY

This report is part of a larger project called Waste to Wisdom that was directed by Dr. Han-Sup Han at Humboldt State University. From prior research on using wood residues as feedstocks for energy generation, it was known that the logistics and economics of feedstock recovery were a substantial barrier to establishing a bio-based energy sector in the Pacific Coast States, namely Washington, Oregon, and California. Though these three states contains some of the most productive forests in North America, much of the forest land is located on steep mountainous terrain that presents particularly daunting challenges for forest management and for the recovery of woody biomass for energy uses.

The overall Waste to Wisdom project was designed to assess the viability of developing mobile biomass conversion technologies, optimize biomass operations logistics, and integrate these field-based R&D activities with techno-economic and life cycle assessment analyses. The ultimate goal of this study was to establish regional systems that could be used to improve rural economic opportunities, generate environmental benefits associated with reduced smoke from wildfires, and produce bio-based products with a lower greenhouse gas footprint than comparable fossil energy products. In this report we examine several elements of the project, which when taken together, characterize why, despite years of effort, there has been little movement in establishing a biomass to energy industry in the region.

The report is organized so that each chapter builds on information from the prior chapter. We start by characterizing the land base and forests using a high resolution spatially explicit database (Task 4.8). The landowner database synthesizes data on ownership pattern, forest cover and type, water, roads, reserved forests, processing locations, geographic and topographic detail and links it to a forest inventory layer to provide 'wall to wall' forest inventory across the entire region. Assumptions on harvest activity, markets, and residue recovery are overlain on the database to derive estimates of potentially available biomass at the parcel level that reflect historical harvest levels by owner type and forest type. The potentially available biomass is aggregated for each parcel across the three state region. Using road network analysis, the biomass is 'hauled' to all potential locations with time and distance calculated based on road quality. Aggregating across the entire region provides an estimate of ten million bone dry metric tons (10 MM BDT) per year of potentially available biomass (Table 1).

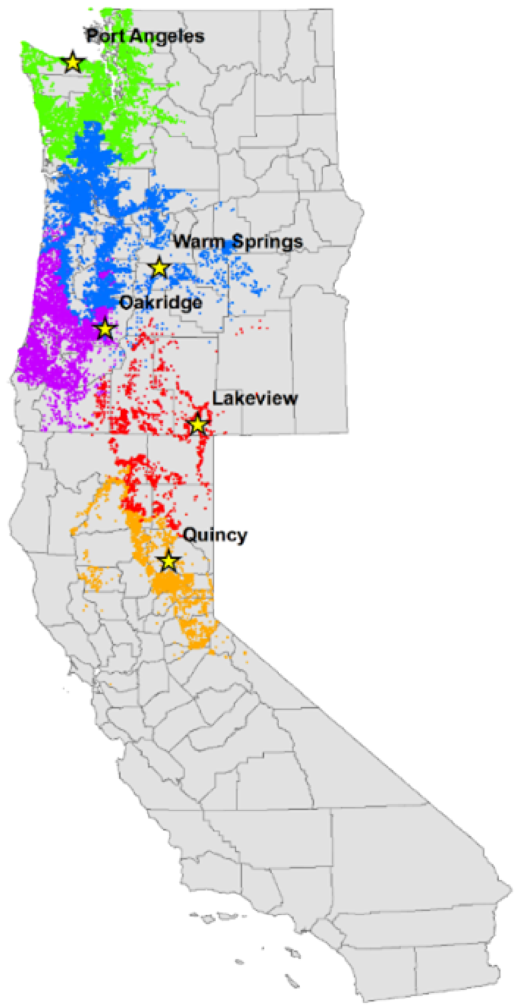
Table 1 Total harvested acres and volumes for Washington, Oregon, and California.

	Harvest Acres	Saw timber MMBF*	Roadside Tons** Pulp	Roadside Tons** Tops	Roadside Tons ** Branches	Roadside Tons** Total	Tons** /Acre
5 Year Total	1,507,621	32,225	19,187,073	2,295,345	28,544,372	50,026,790	33.2
Annual	301,524	6,445	3,837,415	459,069	5,708,874	10,005,358	33.2

* MMBF – million board feet ** Tons here are metric tons (t)

However, most of potentially available biomass is not recoverable as it is too far from existing and potential 'in town' processing facilities. Using five scenario locations (Figure 1) we assess potentially available biomass for three distance and time alternatives: a four-hour one-way haul (4hr); and a two-hour one-way haul (2hr) to 'in town' processing locations; and a shorter haul to a remote Bioconversion Technology (BCT) site located at the watershed centroid associated with each parcel. Limiting the haul distance to a two-hour one-way haul (vs 4hr) reduces potentially available biomass by 85% on average across the five scenario locations. A 2hr haul is comparable to the average time/distance that sawlogs are hauled in the region and therefore likely represents an upper bound for hauling low-value biomass for wood-to-energy uses. In order to access the other 85% of potentially available biomass, new alternatives are required. The option of developing a network of remote BCT sites to densify and aggregate material for eventual transport to markets or energy plants may well be necessary to meet the goals of the Billion Ton Update (2016).

Figure 1 Scenario Locations for Waste to Wisdom Biomass Recovery Analysis



In order to understand the potential environmental tradeoffs of establishing remote BCT sites, a range of scenarios for remote BCT site operations were analyzed using life cycle assessment (LCA) techniques when producing biochar (Puettmann et al 2017), and briquettes and torrefied wood (Alanya-Rosenbaum and Bergman 2017a, 2017b) . Chapter 2 of this report uses upstream data from the spatial network analysis and the forest inventory analysis to develop scenarios for a forest resource recovery cradle to gate life cycle inventory (LCI) and LCA in Task 4.7. That cradle to gate LCI is then used as upstream data for the LCI's on biochar, briquettes and torrefied wood. Life cycle impact assessment (LCIA) results are reported using the TRACI method (Bare 2011) to determine comparable environmental footprints from harvest to utilization for several collection alternatives. The forest resources LCIA includes options for utilizing pulp quality logs as a bioenergy feedstock in areas that do not have pulp markets. This scenario is particularly relevant in more rural areas that have no milling infrastructure and where fire risk reduction activities are conducted on federal lands. The quantity of residues that are produced from these activities are substantial (Figure 2) and the environmental impact of burning them to reduce fire risk is quantified for all parcels across the region.

Figure 2 Forest Residues remaining on site after fire risk reduction activities

(Photo Credit: John Sessions, Oregon State University)

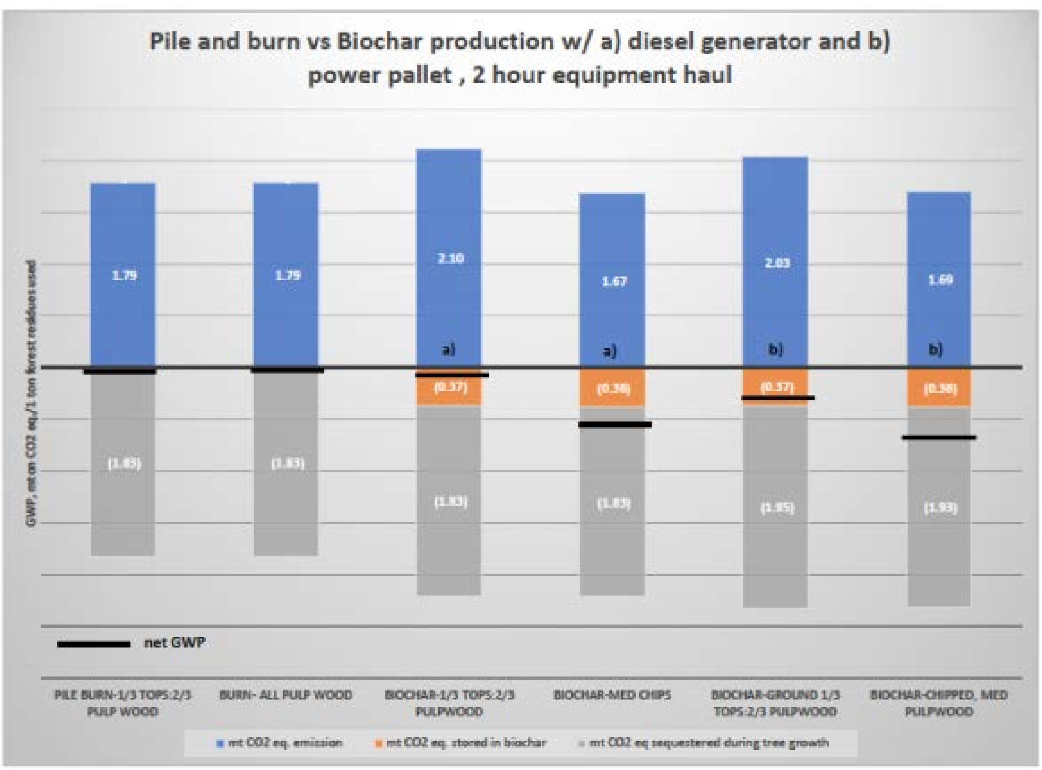
In addition to examining the potential to recovery pulp quality material for use in bioenergy applications, we also examine the LCIA of collecting tops and limbs that remain after forests are harvested for sawtimber (Figure 3a), and which would otherwise be burned to reduce fire risk (Figure 3b). Alternatives that were assessed included operations that recovered only the waste material from landing and roadside piles, as well as operations that collected additional residuals and low-value pulp from harvest units as were tested in other parts of the Waste to Wisdom project (Bisson and Han, 2016; Kizha and Han 2016).

Figure 3a and 3b Post Harvest Residues available for use in biobased products or burned to reduce fire risk

(Photo Credit: Elaine Oneil, University of Washington)

Chapter three provides a comparative analysis of forest residue collection for use as a feedstock relative to disposing of it through open burning. The comparison links the likely emissions from residue recovery versus open burning at different utilization rates. It also examines the environmental consequences of open burning of residues relative to the LCIA of biochar production to complement other reported outcomes on Task 4.2 (Figure 4).

Figure 4 Comparative Analysis of producing biochar vs open burning.



The comparative analysis of biochar production relative to open burning provides an answer to the question: To Burn or Not to Burn? The analysis shows that despite the many challenges of producing biochar in remote locations, there are complementary benefits in providing long term storage of recalcitrant carbon. Those benefits can be measured by avoided emissions from open burning. If efforts are conducted at scale, then the opportunity exists to generate real benefits from reducing fire risk by utilizing large amounts of waste wood. The avoided emissions are directly relevant to human health effects (Sifford 2016) as well as impacting wildfire behavior. Economic analysis (Sahoo and Bilek 2017a, 2017b) shows there are still many challenges to overcome, but if we truly want to embark on the vision as embraced by the Billion Ton Update, more work on remote BCT is a step in the right direction.

The volume of forest residues that are potentially available as feedstocks for bio-based products is significantly influenced by the recovery options that are available. Using a spatial database that is based on parcel level data and extant road networks shows that there is potentially 10 million BDT per year available in currently unused woody forest residues from forest operations in Washington, Oregon, and California. The total amount available is constrained by accessibility, recoverability, economics, and most importantly by distance to processing facilities. Using a subset of data for 5 scenario locations and limiting recovery to roadside piles on those areas that had more than 10 BDT/acre of residues generated estimates of 6.3 million BDT available within a 4-hour one-way haul distance. If that haul distance is constrained to a maximum of 2 hours one way, only about 15% of the feedstock is potentially recoverable. This travel distance limitation likely overestimates potentially available supply as prior research shows that a 2-hour haul distance is the average for sawlogs which have a substantially higher market value than forest residues. Biomass recovery operations have a relatively small carbon footprint relative to the amount of carbon sequestered in the wood. Combustion of that wood to generate long term storage in biochar, or to generate energy from biomass rather than fossil fuels can have positive environmental outcomes, but the opportunities to use large volumes of residues is limited by a scale mismatch in the recovery and utilization technologies currently available. The appropriate scale for converting large amounts of forest residue to usable biomass is likely to be found in technologies that are appropriately sized to the resource. That suggests the need to develop technologies that are somewhere between the very small-scale technologies explored in the Waste to Wisdom project, and large scale technologies that are needed for efficient generation of biofuels or bioelectricity.

Keywords: biobased energy products, forest residue, western USA, life cycle assessment, feedstock supply, wildfire

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CHAPTER 1: A HIGH-RESOLUTION SPATIALLY EXPLICIT DATABASE FOR QUANTIFYING FOREST PRODUCTS, FIRE, CARBON, AIR QUALITY AND ECONOMICS IN THE PACIFIC COASTAL STATES

Final Report On Task 4.8 - Evaluate Impacts On Fire Reduction And Forest Productivity Gains

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1 OVERVIEW

Task 4.8 of the Waste to Wisdom project used GIS spatial analysis to evaluate the potential timber and biomass feedstock volumes available from forests in the Pacific coast states of Washington, Oregon and California. The database includes all of California but only Northern California has any significant amount of harvest, so the results could also be considered a good proxy for Northern California as well. The spatial database was cross-linked to harvest scenarios that were developed to represent typical harvest methods and patterns by owner type and forest type across the region. The study examined the volume of residual forest biomass that can be collected from working forests in the region under various management and economic scenarios. Task 4.8 had three primary goals: first, to estimate the volume of forest biomass; second, to assess biomass availability based on various cost and price considerations; and third to use these data as inputs to life cycle assessment (Oneil and Puettmann 2017a), open burning comparison (Oneil and Puettmann 2017b), and optimization modeling efforts (Berry and Sessions 2017). For this section of the report, details are provided on the methodology used to develop the spatial database and generate biomass estimates. Its use for LCA and comparative analysis with open burning impacts are addressed in subsequent chapters of this report.

1.1 Methodology

The methods used to develop these data for the three state region follows the process developed for Washington Biomass Assessment project (Perez-Garcia et al 2012) with updates for Washington inventory along with a complete analysis for Oregon and California as part of this project. Rather than repeat the 30+ pages of detailed methodologies from Perez-Garcia et al (2012) we recommend a thorough review of that document to augment the summary methodology provided herein.

In brief, the process for arriving at feedstock estimates relies on a series of nested calculations that build on the base data provided for each forested parcel in the three state region. The parcel database was built using data layers complete with metadata incorporated into a GIS database framework. The data layers included: tax parcel information including ownership, tax status, and acreage; land attributes such as slope, elevation, geology and topography; watershed boundaries; streams, lakes, and wetlands; regulatory overlays such as stream buffers and unstable slopes; roads; satellite imagery; and forest inventory (Figure 1). These forested parcels were 'populated' with forest inventory using contiguous Gradient Nearest Neighbor (GNN) modeling (Ohmann and Gregory 2002). GNN modeling takes discreet inventory points collected by the USFS Forest Inventory and Analysis unit and links it to spatial data including topography, geology and climate to create a seamless overlay of forest cover with attributes of the original plot as illustrated in Figure 2. GNN data are normalized to 2012. To capitalize on prior work, in this project inventory developed from the Gradient Nearest Neighbor (GNN) method were integrated with ownership and physical characteristics of the land from the Advanced Hardwood Biofuels Northwest - Natural Resource Lands Database to create a granular and extraordinarily flexible framework for modeling forest resources.

This methodology has been shown to significantly improve the resolution and detail of the inventory. It also allows for the development of spatially explicit transportation models rather than county level summaries. Taken together these model components were used to generate a detailed analysis of road networks, link them to estimates of feedstock volume by forest type, owner type, and parcel, and calculate distance to a large number of potential facilities to accurately model economics, product and emissions outputs.

Figure 5: Input Layers for GIS analysis

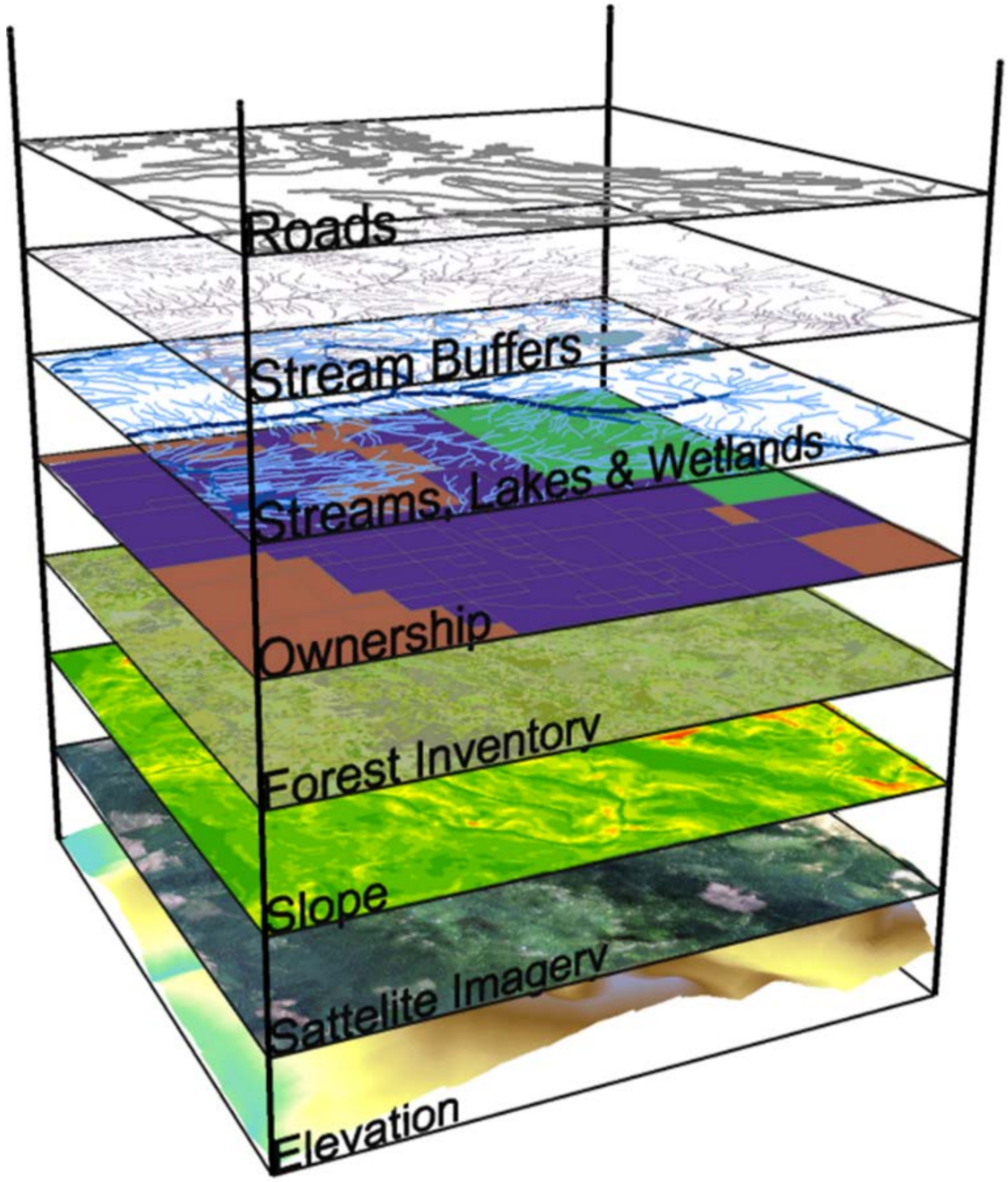
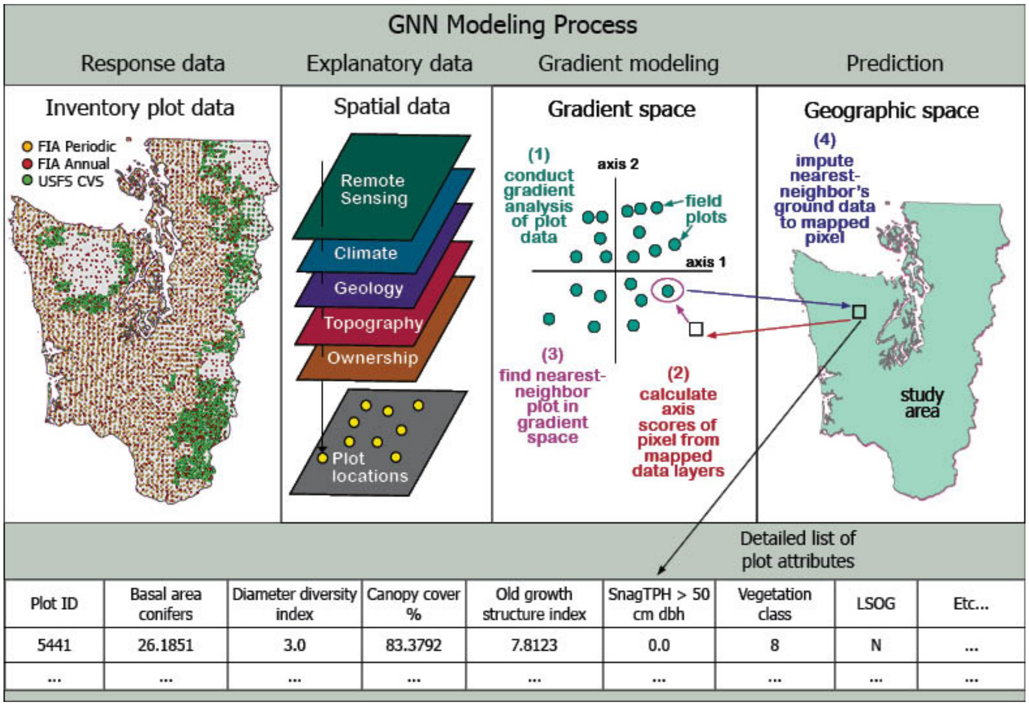


Figure 6: GNN Modeling Process



The multi-terabyte spatial database developed during the assessment was then summarized consistent with the needs of other Waste to Wisdom researchers to better characterize harvest scenarios, timeline, geography, infrastructure, costs, and prices. The outputs were used to provide a better understanding of forest residuals and biomass market availability. Figure 3 through Figure 9 provide the general context for how these estimates were developed using Washington State data as an example. An identical process ensued for Oregon and California.

To illustrate how the integrated GIS spatial database populated with GNN data is used, data from the original Perez-Garcia et al (2012) study were used to display the netdown factors that are included in arriving at a final biomass supply estimate. Based on their analysis, there are an estimated 2.7 billion tons of biomass in the trees in all of Washington's forests (Figure 3). This estimate is based on inventory data covering all forests and all trees regardless of whether those forests are reserved from harvest, or are available for harvest. This estimate is therefore a reasonable estimate of standing biomass that can be used for purposes of calculating carbon storage within Washington State. In order to assess the amount of biomass that is potentially available for bioenergy uses, a series of netdowns are required. First, of that 2.7 billion tons of biomass, almost 1 billion tons is not available for harvest (Figure 4). This biomass is reserved from harvest in land uses including parks, wilderness, stream buffers, and other regulatory set-asides.

Figure 7: Total Forest Biomass in Washington State

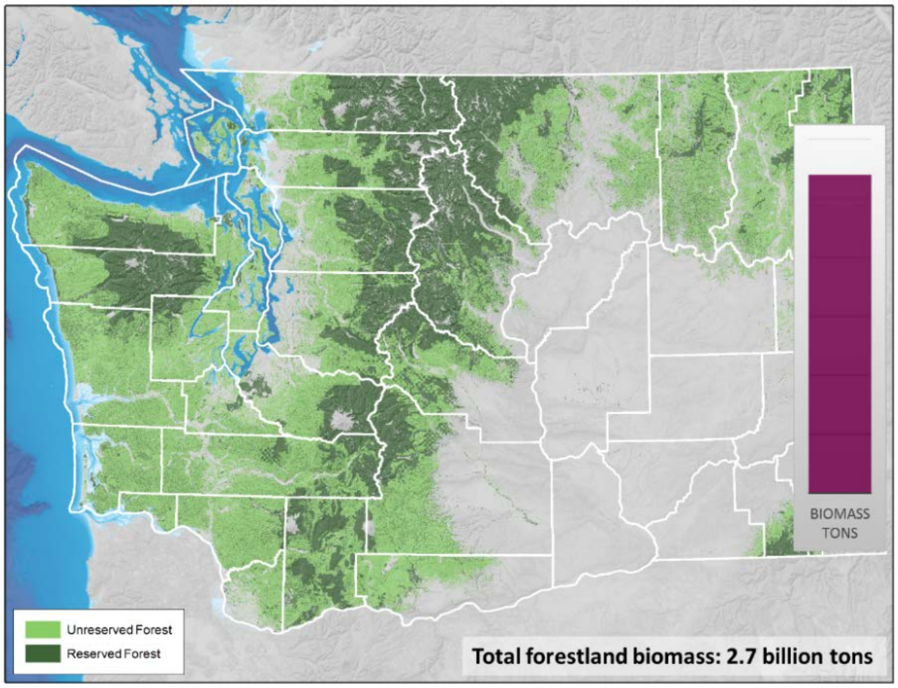
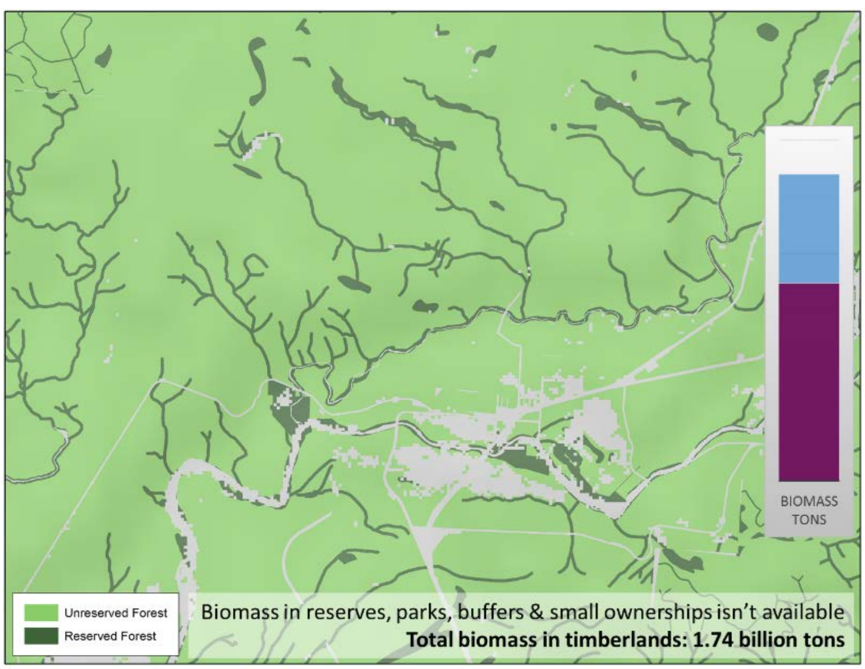
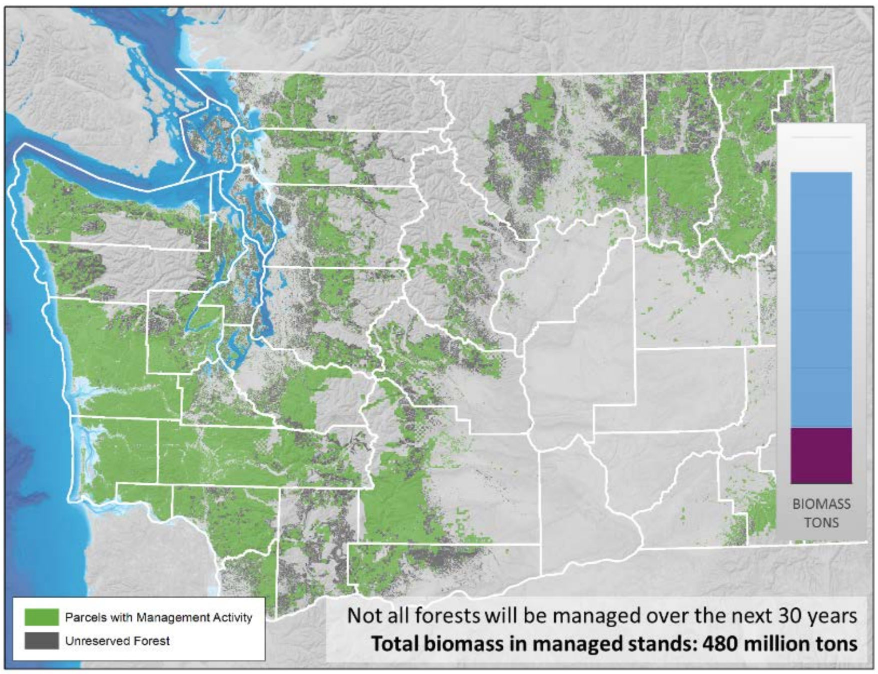


Figure 8: Unreserved biomass in Washington State



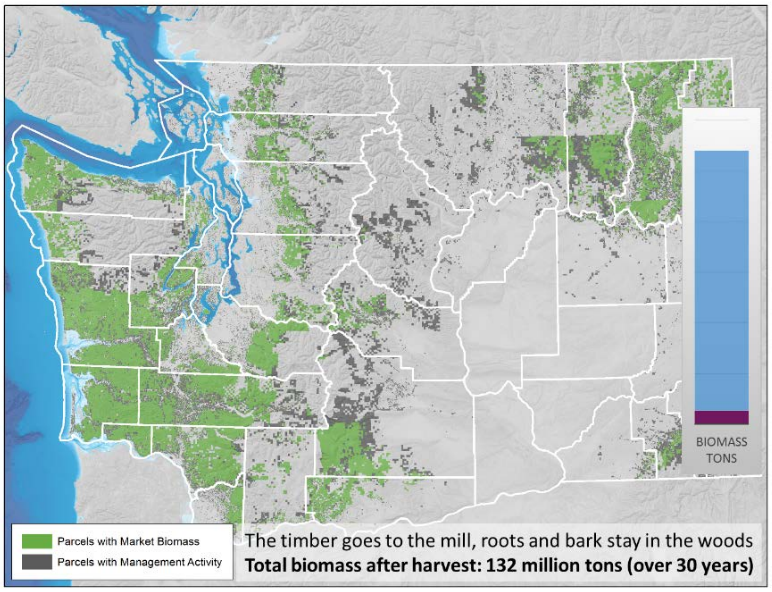
After netting out large reserves such as parks and wilderness, the total estimated biomass in Washington State's forests is 1.74 billion tons. A large percentage of these forests are not managed for timber or biomass removal based on owner surveys and historical harvest activity. Of those that are managed for timber harvest and/or biomass removal, only a portion of the forest is harvested in any given year. This situation arises as forests take anywhere from 35-80 years to reach maturity depending on the management intensity and ecological growth potential of their location. Data on existing inventory, growth rates, harvest rates and management intensity were used to generate estimates of annual harvest over a 30 year time horizon in this example. Over that 30 year time horizon, an estimate of 480 million tons of biomass would be available in Washington State (Figure 5).

Figure 9: Total Biomass in managed forests of Washington State



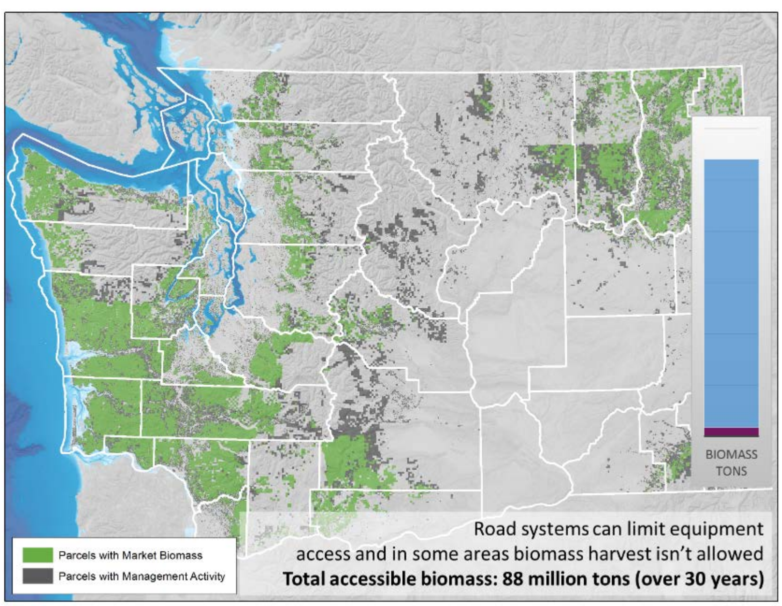
Timber harvests are primarily designed to supply logs to markets that manufacture lumber, plywood and engineered wood products. Less common reasons for harvest include fire risk reduction treatments where small diameter trees are removed to reduce fire risk. Regardless of what happens to the harvested tree, the roots, some of the bark and the tops remain in the woods. After accounting for all these other uses, an estimate of 132 million tons of biomass would be potentially available for biomass to energy uses (Figure 6).

Figure 10: Washington State forest biomass allocated to wood products



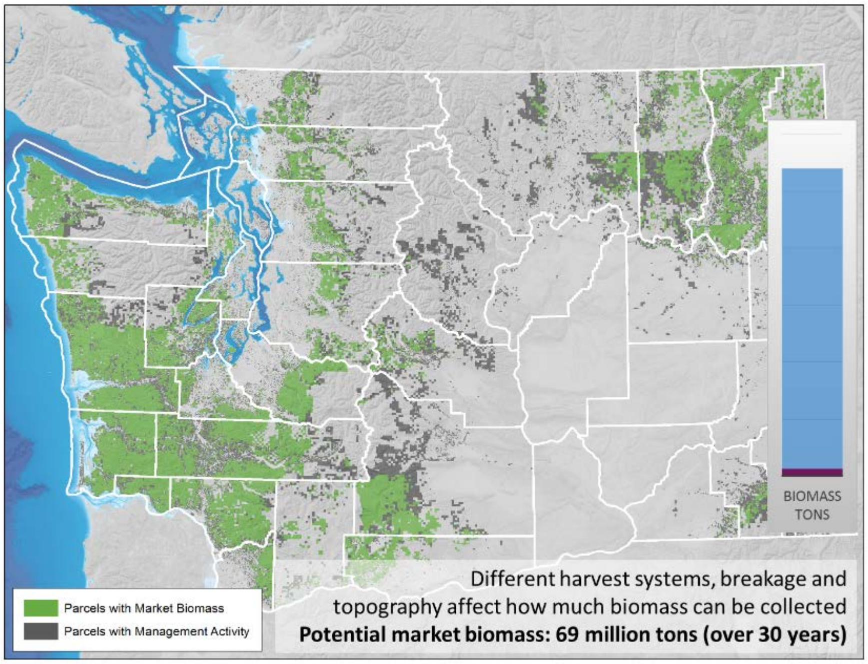
However, further netdowns of available biomass feedstock supply occur because of access limitations and regulations on biomass recovery. Based on road network analysis, the amount of biomass that can be technically recovered using existing technologies (road networks, equipment types) is about 67% of the total biomass that remains after a harvest operation is complete, reducing the total potentially available biomass to 88 million tons over a 30 year time horizon (Figure 7).

Figure 11 Accessible biomass



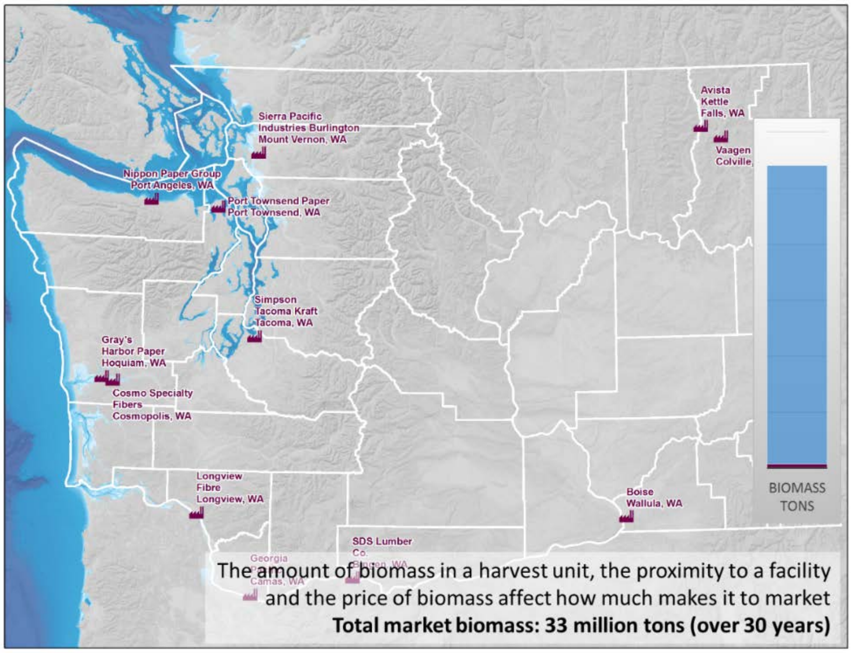
On the harvest sites that chip vans could access to recover material, not all biomass makes it to the landing or roadside where it could be accessible for shipping. This reduces the potentially available supply by an additional 22%, or a total of potentially marketable biomass of 69 million tons over 30 years (Figure 8).

Figure 12 Biomass Feedstock available at the roadside with suitable road access.



Finally, economics plays a substantial role in determining the total amount of forest biomass that would be available for use as a feedstock for wood to energy endeavors. Using market analysis and detailed survey data, Perez-Garcia et al (2012) determined that the total available marketable biomass available in Washington State is estimated at 33 million tons over 30 years or approximately 1.1 million tons per year (Figure 9).

Figure 13: Estimated Biomass Feedstock Available over 30 Years (Washington State).



The 1.1 million tons per year estimated for the Perez-Garcia et al 2012 study included tree tops and branches, plus a waste and breakage factor with all other material considered as economically recoverable as sawlogs and pulp logs. A re-examination of Figure 7 through Figure 13 shows that the reductions in available biomass for each subsequent netdown factor are non-uniform. Using this spatially explicit methodology results in more granularity in assessing where available biomass is likely to exist on the landscape. This methodology is therefore able to generate refined predictions for haul distance, harvest intensity and timing, amount of material at roadside, and recovery potential.

2 RESULTS

For the current study, there were modifications to the input processes to reflect updated waste and breakage factors relative to those used in Perez-Garcia et al (2012), adjustments to the economic recovery of pulp logs reflecting lack of (and loss of) manufacturing infrastructure for that product, and implementation of onsite recovery advances as reported by Waste to Wisdom scientists in Task 2. Using these revised input factors, an estimated volume of forest harvest and forest residues for the three state region is given in Table 2. The values in Table 2 are representative of the biomass available at roadside akin to those values for Washington State as represented in Figure 12. Because of the additional pulp log component, these estimates are higher than those generated for the Washington Biomass Supply study (Perez-Garcia et al 2012). For comparison, since 2000 the reported harvest volume in Oregon averages 3.8 BBF (billion board feet), in Washington it averages 3.1 BBF, and in California it averages 1.5 BBF. All values are derived from individual state timber tax reports that also report timber harvest volume.

Table 2 Total harvested acres and volumes for Washington, Oregon, and California.

	Harvest Acres	Saw timber MMBF	Roadside Tons Pulp	Roadside Tons Tops	Roadside Tons Branches	Roadside Tons Total	Tons/ Acre
5 Year Total	1,507,621	32,225	19,187,073	2,295,345	28,544,372	50,026,790	33.2
Annual	301,524	6,445	3,837,415	459,069	5,708,874	10,005,358	33.2

In Table 2 the sawtimber harvest volume is reported in million board foot volume and is based on merchandizing trees to a 6" top diameter less estimates for defect of 10%. Pulp volume is measured in metric tons and includes all volume between the 6" top diameter of the sawlog and a 4" top of the same tree plus the defective sawlogs not counted as sawtimber. Tops are the tree stem less than 4" and are reported in tons/acre. In the full dataset, branches, tops, and pulp biomass are reported for those amounts left scattered in the unit (residual biomass) as well as those amounts that are piled at the landing or roadside as part of a commercial harvest operation. In Table 1 only roadside amounts are provided as those volumes are the most easily accessible and economical for recovery. The values in Table 2 do not account for the economics of recovery, so are similar to Total Roadside Tons in Table 3.

Table 3 Washington State Biomass Study Volumes (Perez-Garcia et al 2012)

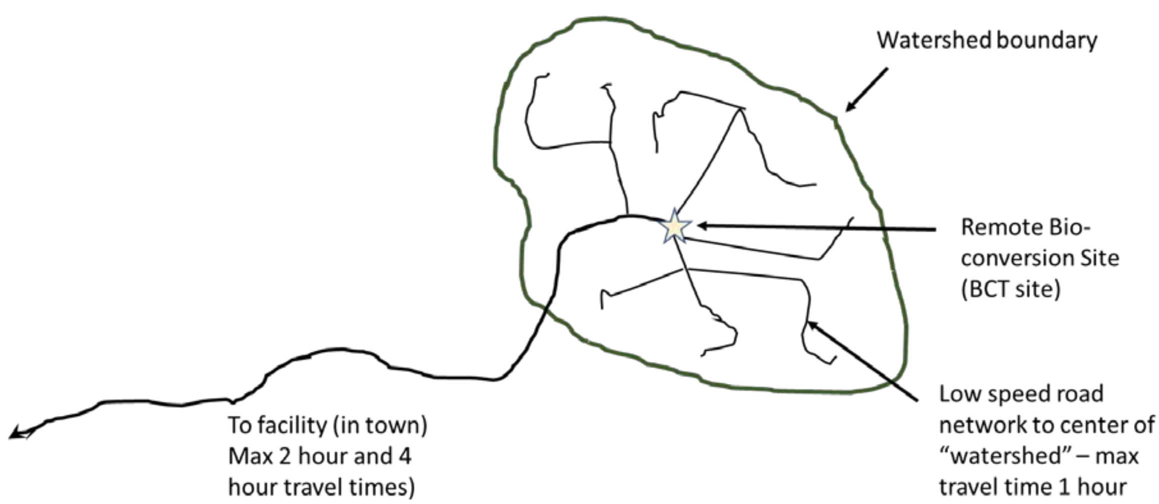
Washington example	Total residuals (Tons)	Total accessible (Tons)	Total Roadside Tons	Economically Accessible (Tons)
30 year	132,000,000	88,000,000	69,000,000	33,000,000
annual	4,400,000	2,933,333	2,300,000	1,100,000

Total roadside tons from the Washington study (Table 3) (using slightly different assumptions) suggest about 23% of the total residues come from Washington State with the remainder coming from Oregon and Northern California. Overall, average harvest volumes since 2000 are marginally higher than the modeled estimate, but that estimate is based on higher volume allocations to pulp wood that is directed towards bioenergy uses and consequently lower allocations to sawlog volume. If the pulp figures are converted to sawlog volumes using the WA Department of Revenue scale conversion rates of 9 tons/MBF, then the pulp volume represented in Table 2 equals the average yearly volume harvested in WA and OR since 2000.

2.1 Scenario Analysis

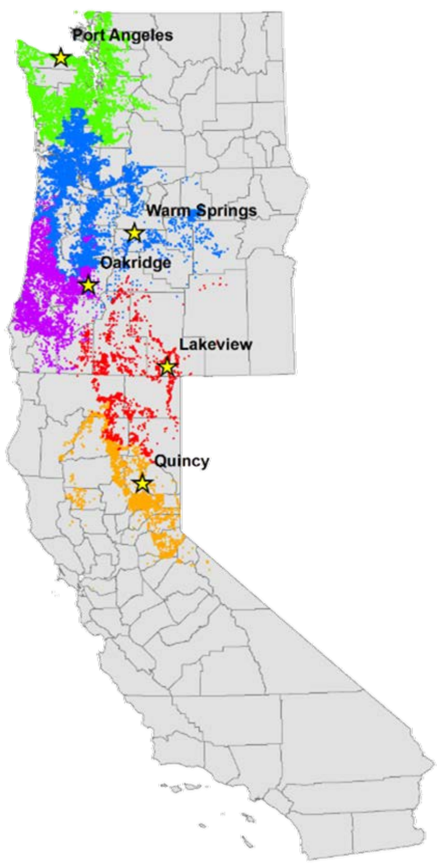
The Waste to Wisdom project was designed to assess the viability of developing small scale biomass conversion technologies (BCTs) that could be mobilized to remote sites, thereby addressing major limitations on recovery identified in prior studies. Therefore data on biomass supply not only included distance and time to travel from individual parcels to chosen facility locations, it also included distance and time from the parcel to the watershed (HUC10) centroid (the theoretical remote BCT site), and watershed centroid to facility in Figure 14. The parcel to watershed centroid was based on Euclidean distance, whereas all other distances were based on road network routing. HUC10 watersheds are approximately 10,000 to 50,000 acres in size. The database permits evaluation of specific locales across the region for their suitability as feedstock supply areas based on economic and environmental criteria under various alternative scenarios.

Figure 14: Road Network Analysis Framework



The spatial database forms the underpinning of the comparative LCA for forest resources that allows for the examination of the tradeoffs between feedstock recovery for production of biobased products, economics of recovery, and open burning impacts. Watershed level inventory were generated using GNN data and then harvested under a series of management assumptions. Outputs from the system included timber volume, biomass volume at the roadside and in the woods, biomass characteristics, and average haul distance and time to the watershed centroid, and to the nearest population center. Haul time was based on average road speeds for the travel path of the biomass moving from its harvest site along in-woods roads, county roads, and highways to the nearest population center and also to the watershed centroid. Data were gathered for all forested parcels in the three state region. To explore variation within these data, five scenario locations were chosen for detailed analysis. These locations were Port Angeles, Washington, Warm Springs, Lakeview, and Oakridge, Oregon and Quincy, California. The geographic location of the parcels that were included in each database by location are shown in Figure 15. It also shows that differences in road networks, ownership pattern, areas of reserved timberlands, forest cover, and harvest operability, the areal extent of parcels, and their distribution across the landscape varies substantially across the 5 scenarios that were analyzed.

Figure 15 Five Scenario Locations with Parcel Locations



Data were aggregated to a specific scenario location based on haul time, not haul distance using road network analysis and average road speed characteristics to calculate one-way haul times. All parcels within 4 hours travel distance to these centers were summarized in databases that reported out on a range of characteristics as shown in Table 2.

2.2 Haul Distance Analysis

The choice to use time rather than distance as the relevant parameter for hauling is based on prior analysis, including the WA biomass supply study (Perez-Garcia et al 2012), the Washington Log Trucking Industry Study (Mason et al 2008) , and the California redwood LCA study (Han et al 2014), all of which integrated both distance and time metrics for hauling. These studies determined that time provided a clearer picture of economic recovery potential than distance. The trucking survey data in Mason et al (2008) is particularly compelling as it is a near census of log trucking activity across the state at that time. They found that, on average, the log truck drivers worked 12.3 hours per day and hauled 2.9 loads per day, or about 4.2 hours round trip per load including loading and unloading. This would equate to less than a 2 hour one way haul time. Average haul distance for high value sawlogs was 67.1 miles (one way), with 82.8% of the distance on pavement and the remainder on gravel roads across the entire state. Using that distance travelled as the determining factor ignores the impact that road quality, and therefore road speed, has on overall recovery of residues.

Using the network analysis from the forest land database, aggregated by one way travel times of 2 hours and 4 hours, we see a substantial variation in haul distances for the same maximum time across the 5 scenario locations (Table 4). The time distance factors are non-linear in that there is only a 38-48% reduction in haul distance when haul time is reduced by 50%.

Table 4 Average haul distance and speed by Scenario Location and Haul Time

Scenario location	Haul time scenario	Average km from parcel to town	Average km/h - parcel to town	Average km - parcel to remote BCT location	Average km/h - parcel to remote BCT location
Pt Angeles	4hr	172.90	63.50	21.00	43.40
Pt Angeles	2hr	71.10	54.40	22.30	43.80
Pt Angeles	2hr/4hr (%)	41.10	85.70		
Lakeview	4hr	235.00	77.10	17.40	45.10
Lakeview	2hr	89.30	65.80	24.10	50.50
Lakeview	2hr/4hr (%)	38.00	85.20		
Quincy	4hr	163.60	62.70	19.50	47.70
Quincy	2hr	78.00	60.60	16.10	51.60
Quincy	2hr/4hr (%)	38.00	85.20		
Warm Springs	4hr	204.90	67.80	17.00	43.00
Warm Springs	2hr	93.50	55.30	16.30	38.00
Warm Springs	2hr/4hr (%)	45.60	81.50		
Oakridge	4hr	205.80	74.80	16.80	44.10
Oakridge	2hr	98.50	66.70	18.30	51.80
Oakridge	2hr/4hr (%)	47.90	89.20		
All Locations weighted av.	4hr	99.10	70.10	18.00	44.60
All Locations weighted av.	2hr	89.30	61.90	19.20	48.10
All Locations weighted av.	2hr/4hr (%)	2.70	85.90	113.10	108.80

The impact on potentially available biomass volume is much greater than the distance impact. There is a 69-94% reduction in available volume when constraining haul times from 4 hours to 2 hours (Table 5) with a weighted average reduction of 85%. This enormous reduction in potential biomass recovery based on haul distance to the nearest town in our 5 scenario locations substantiates the critical need for this project to identify technologies, optimized systems, and markets that would make remote BCT sites economically and technically feasible. Otherwise, most of the potentially available forest residues, even of pulp quality (like Figure 2), will remain in the woods as waste, rather than contributing to rural economic health and greenhouse gas mitigation goals.

Table 5 Potentially Available Biomass by Haul Time Scenario and Location

Maximum drive time from BCT to point of sale	4 hours	2 hours	time/distance impact on recoverable volume
Scenario Location	volume (BDT at roadside)		
Pt Angeles	831,273	150,759	18%
Warm Springs	1,457,766	91,926	6%
Oakridge	2,121,756	313,326	15%
Lakeview	897,293	61,576	7%
Quincy	972,936	297,890	31%
All scenarios	6,281,024	915,476	15%

The forest residues include a range of piece sizes and quality. The forest inventory data, in conjunction with data on slope, species mix, owner group, harvest type, and expectations for markets for pulp quality material, were used to estimate the characteristics of the forest residues, including the amount that would be left at the landing after harvest and the amount that would remain in the woods. For each of these two locations (in woods and at the roadside), estimates of the amount that was pulp quality, tops, and branches were individually summed for each parcel. The total amounts were summed for each scenario location and haul time (Table 6).

Table 6 Potentially Available Biomass by type, location and haul time scenario

Scenario location	Haul time scenario	ha/ year	pulp quality (BDT)	<4" tops only (BDT)	branches only (BDT)	total residues (BDT)	BDT/ ha
Port Angeles	4hr	3,053	87,203	10,801	196,663	294,668	96.5
Port Angeles	2hr	538	15,760	1,738	37,902	55,400	102.9
Port Angeles	2hr/4hr (%)	17.6%	18.1%	16.1%	19.3%	18.8%	
Lakeview	4hr	3,982	117,557	10,151	117,985	245,693	61.7
Lakeview	2hr	212	4,520	473	3,954	8,947	42.3
Lakeview	2hr/4hr (%)	5.3%	3.8%	4.7%	3.4%	3.6%	
Quincy	4hr	3,974	157,870	12,599	156,118	326,587	82.2
Quincy	2hr	211	7,730	535	8,112	16,377	77.6
Quincy	2hr/4hr (%)	5.3%	4.9%	4.2%	5.2%	5.0%	
Warm Springs	4hr	5,264	132,274	19,240	229,087	380,601	72.3
Warm Springs	2hr	331	7,678	742	7,829	16,250	49.1
Warm Springs	2hr/4hr (%)	6.3%	5.8%	3.9%	3.4%	4.3%	
Oakridge	4hr	6,992	168,358	28,776	312,718	509,852	72.9
Oakridge	2hr	1,170	29,465	5,665	52,946	88,076	75.3

Oakridge	2hr/4hr (%)	16.7%	17.5%	19.7%	16.9%	17.3%	
All Locations wgt av.	4hr	5,053	138,991	19,330	224,422	374,792	74.2
All Locations wgt av.	2hr	755	19,273	3,952	39,574	61,815	81.9
All Locations wgt av.	2hr/4hr (%)	14.9%	13.9%	20.4%	17.6%	16.5%	

CHAPTER 2: LIFE CYCLE ASSESSMENT OF FOREST RESIDUE RECOVERY FOR SMALL SCALE BIOENERGY SYSTEMS

Final Report on
Task 4.7 Forest Resource LCA

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1 INTRODUCTION

Task 4.7 of the Waste to Wisdom project developed a cradle to gate attributional life cycle inventory (LCI) for forest collection processes and conducted a life cycle assessment (LCA) using the TRACI method (Bare 2011) to determine comparable environmental footprints from harvest to utilization for several collection alternatives.

Data on feedstock characteristics, including the amount that is pulp quality material and the amount that was comprised of branches and tops was calculated using the spatial database as described in Task 4.8. Data outputs were aggregated across the three state region for five scenario locations: Port Angeles, Washington, Warm Springs, Lakeview, and Oakridge, Oregon and Quincy, California. Each of these scenario locations has a distinct forest type, land ownership pattern, and road network. They also vary substantially in overall productivity of the forest, and hence in the amount of potentially available biomass that could be used as a feedstock for bioenergy or bio-based products.

Outputs from the spatial database included ninety-seven different variables for each parcel. These variables identified the parcel by county, state, ownership, location, and size. They also reported on a wide range of stand metrics, the type of harvest operation that was simulated, slope class, the harvest volume by species and the residual biomass separated into bins to account for its physical characteristics. Finally the variables described the distance to the watershed centroid, to the scenario location (e.g. Port Angeles) and the time it took to haul the material to these locations. The number of parcels per scenario location ranged from approximately 5000-18000 individual locations. Data were aggregated based on a series of assumptions related to haul distance and economically viable recovery amounts as outlined under Forest Resources LCI Model Assumptions. The major factors of interest were the maximum distance from the parcel to the remote BCT site and the maximum distance to the in-town processing facility.

All data were generated for each scenario location and then aggregated using a weighted average based on total biomass volume. These values were used as the input values for the LCI and LCIA.

2 LIFE CYCLE ASSESSMENT GOAL AND SCOPE DEFINITION

The goal of this work was to quantity the attributional life cycle inventory of generating woody biomass feedstocks from forest waste for use in bioconversion technologies. Attributional life cycle assessments quantify inputs and outputs that are directly attributable to the production of a specific product and rely on average data and allocation between processes to quantify burdens (UNEP 2011). While the biomass material could be used for any bioconversion technology, the target parameters for comminution and the locations evaluated were designed to link to other parts of the Waste to Wisdom project that focused on characterizing bio-conversion technologies that could be semi-mobile with locations in remote sites to facilitate transportation of low density material.

The scope is limited to the evaluation of the inputs and outputs as defined by the system boundary both at the parcel (Figure 16) and at the BCT facility (Figure 19). Since the two locations are separated in space, a range of hauling alternatives were also evaluated as part of the LCI and LCIA. Evaluation of landscape level impacts of forest operations and the potential impacts to soil carbon and biodiversity are outside the scope of this analysis.

3 SYSTEM BOUNDARY

The system boundary (Figure 16) includes alternatives for two potential biomass recovery operations: those that include in forest processes and those that exclude in forest operations. For all biomass operations, activities that deal with aggregating the biomass, densifying it by either chipping or grinding, and loading are included within the boundary. These activities take place at the landing or forest road, or in some cases at the BCT site. They are clearly attributable to the recovery of the biomass when it is considered a waste product of forest operations that are designed to remove sawlogs for commercial purposes.

The system boundary can be expanded to include in-forest operations when a) additional biomass such as limbs, tops, small diameter material and other residues that would normally be left on the site are yarded to the landing or roadside in preparation for being densified and hauled to facilities for processing into bio-based products. The system boundary can also be expanded to include in-forest operations when the activities are clearly not related to commercial forest operations, but do result in woody biomass being yarded to the roadside for disposal. An example that is common in the Pacific coast states is when forest stands are thinned to increase fire resiliency and the material has no current commercial market, but is yarded to the roadside for burning or to reduce fire risk. In this case, the felling and yarding of pulp quality material was included in the expanded system boundary as an ‘in-forest’ operation. Because some operations occur at the forest site and some occur at the BCT site, hauling alternatives are also included in the system boundary (Figure 19).

Hauling is reported in this analysis as an average across five scenario locations, but is treated separately for the two major types of forest biomass: pulp quality logs and ground residues (tops, limbs, and branches) because the equipment used, and its fuel usage per BDT of material hauled are substantially different. Hauling is summarized separately to facilitate gate to gate analysis for individual BCT operations. Inputs include fuel, lubricants and woody biomass. Outputs include emissions related to the production of 1 metric bone dry ton (BDT) of biomass destined for the BCT site and densified biomass at the reactor throat.

4 FUNCTIONAL UNIT

The results are based on 1 metric ton of biomass ready for the reactor throat, either located at a remote BCT site at a regional manufacturing facility. All input and output data were allocated to the functional unit of product based on the mass of products and co-products in accordance with International Organization for Standardization (ISO) protocols (ISO 2006). The allocation is based on a bone dry metric ton (or tonne) of biomass.

5 BIOMASS RECOVERY

5.1 LCI Model Assumptions

1. All data are based on weighted average volume available from the 5 scenario locations
    1.1. Weighting of volume is corrected for the following assumptions
        1.1.1. Only sites with greater than ten bone dry metric tons per acre (> 10 BDT/acre) are economically operable. This assumption is based on recovering approximately one truckload/acre as the lowest amount that is viable for a commercial thin operation, with 10 BDT being approximately equal to one truckload/acre at 50% moisture content.
        1.1.2. Of the sites with > 10 BDT/acre, only 50% will be technologically accessible due to terrain/ turnout limitations/ and other recovery limitations based on survey data from the Washington state biomass study (Perez-Garcia et al 2012)
    1.2. Weighting of distance is corrected for the following assumptions
        1.2.1. Haul time is limited to a maximum of 60 minutes from the harvest unit to a centrally located BCT site (remote BCT site) with the haul time and road network analysis is used to derive travel distance in miles.
        1.2.2. Haul time is limited to a maximum of 120 minutes (2 hour) or 240 minutes (4 hour) from the BCT site to the scenario location (i.e. Port Angeles, Warm Springs, Lakeview, Oakridge, Quincy)
2. Hauling operations were separated into two distinct operations – one for pulp quality material and one for tops/branches
    2.1. Material is hauled at the moisture content it has in field conditions and trucks are weight limited to the total of the weight of water plus the weight of wood, but the calculations for tkm is based on BDT of wood.
    2.2. Pulp was hauled to BCT site as whole logs using a mule train (truck plus trailer with short logs)
        2.2.1. Mule train trucks average 5 mpg over average road conditions
        2.2.2. Mule train trucks are limited to 57,183 pounds of payload (weighted average of trucks operating in the region)
        2.2.3. Pulp is 50% moisture content by weight which converts to 12.99 bone dry metric tons (BDT)/load
    2.3. Tops and branches were ground at the landing and hauled to BCT site using a dump truck with hoist
        2.3.1. No end dump with higher capacity because of technology limits at conversion site
        2.3.2. Weight limited to 30,000 pounds (6.82 BDT) carrying capacity for truck and 32,000 pounds (7.27 BDT) for trailer (where applicable)
        2.3.3. Truck only – no extra trailer due to terrain constraints for cable ground.
        2.3.4. Truck plus trailer for ground based harvest areas.
    2.4. Weighting of different haul methods based on percent ground and percent cable for hauling to in-woods BCT only
    2.5. Assume that a 2-hour or 4-hour haul to town would only be feasible with a truck and trailer combination, as hauling only 6.82 BDT/load in a truck would be economically prohibitive.
3. Comminution
    3.1. Pulp was chipped, screened, and loaded into BCT dryer
    3.2. Tops and branches were ground, screened and loaded into BCT dryer

5.2 Model Structure

Four distinct scenarios for biomass recovery were modeled as part of this project. They were 1) recovering pulp logs for biomass as a waste left at the landing (i.e. excluding 'in forest' operations); 2) recovering pulp logs from within the harvest unit (i.e. including 'in forest' operations); 3) recovering forest residues (tops and branches only) as a waste left at the landing (i.e. excluding 'in forest' operations); and 4) recovering forest residues as a co-product of harvest by loading and hauling from the harvest unit to the roadside (i.e. including 'in forest' operations). The flow diagram for the steps in each scenario are shown in Figure 16.

Figure 16 System Boundary for in woods and near woods operation with options for both including and excluding in forest operations.

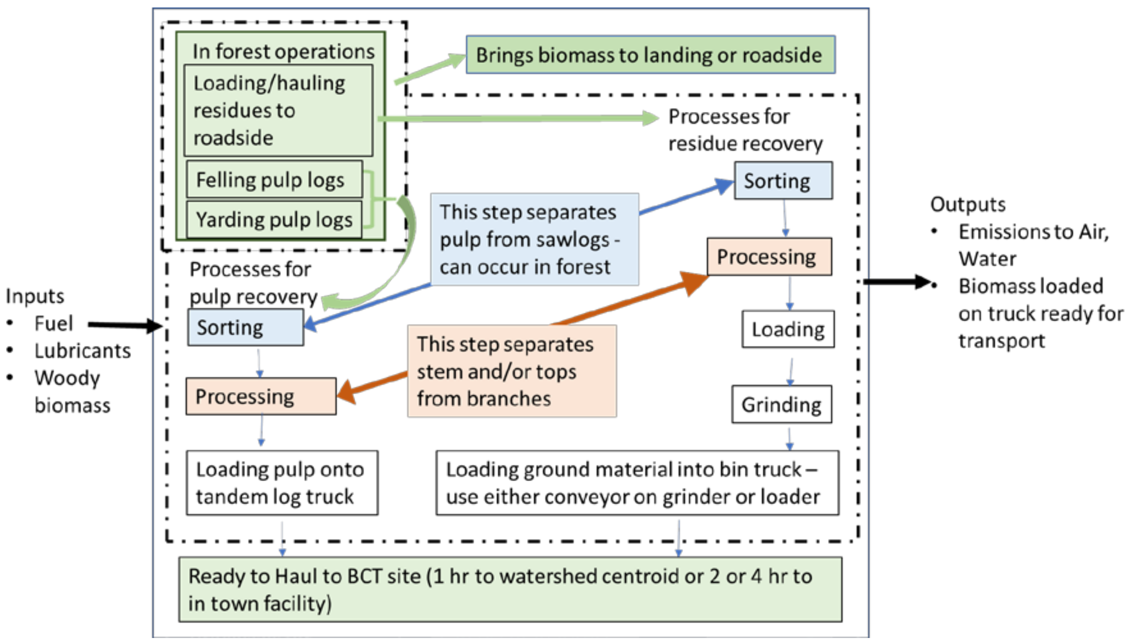


Figure 16 also shows the two system boundaries that represent the processes involved if 'in forest' operations are included or if they are excluded. The rationale regarding the choice to exclude or include these 'in forest' operations is based on whether or not the material is characterized as a waste. According to ISO 14044, allocation of inputs and outputs can only be made between co-products. If a material is a waste, then it carries no upstream burden. Therefore, if biomass is recovered from the landing or roadside as a waste product from the harvest of sawlog materials, the boundary excludes *in forest* processes that are allocated to the sawlog which is then considered the only product recovered from the operation. If the biomass is considered a *co-product* of harvest operations that were designed to obtain sawtimber or reduce fire risk, then *in forest* operations are included in the system boundary. If additional onsite tops and branches that normally would not be yarded to the roadside, are loaded and hauling to the roadside, then these 'in forest' operations are included in the system boundary as part of the upstream recovery though the felling process is not because it is 100% allocated to the harvested sawlog. In all cases, allocation is on a mass basis.

Once the biomass is loaded and ready for transport to the BCT site, there were several scenarios modeled in the next stage of the biomass recovery operations. The model assumes that pulp logs can be removed from all locations where sawlogs can be removed because the equipment configurations are similar. However, as many forest roads include steep gradients, sharp turning radii, and limited turnaround capabilities, ground feedstocks can only be removed with a single dump truck from steep harvest units, and potentially with a truck and transfer on flatter terrain that would have adequate locations to turn the truck and trailer combination around and travel safely along the return route. Because of the economics of hauling long distances, and the low payload on a dump truck, hauling from the harvest unit to in-town BCT sites was assumed to use a truck and transfer for ground material or a mule train for the pulp quality material. This meant that hauling from cable harvested units was constrained for the woods to town scenarios.

Figure 17 Bioconversion Technology Site Location Scenarios

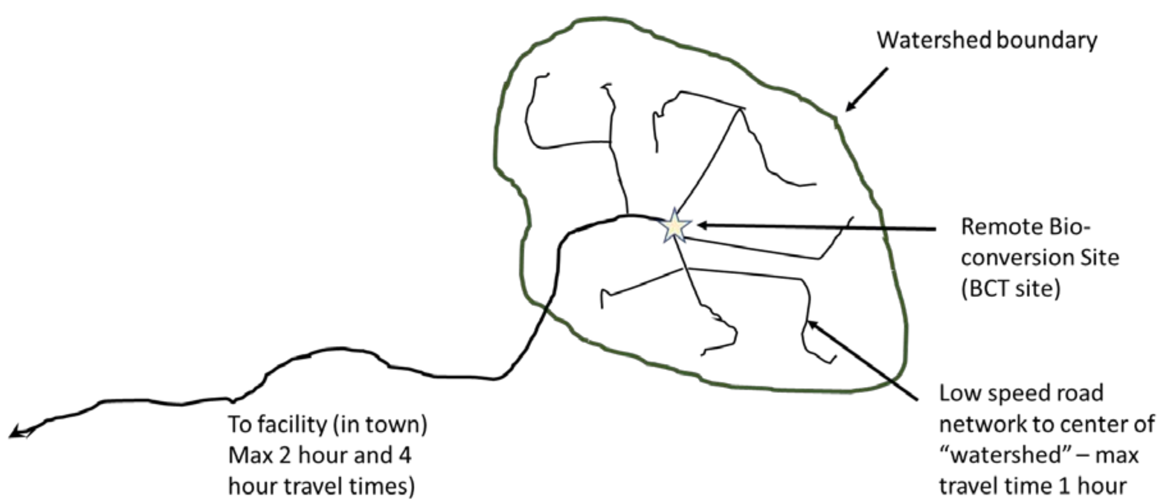


Figure 18 Hauling Distance and Trucking Type by Travel Time and BCT site location

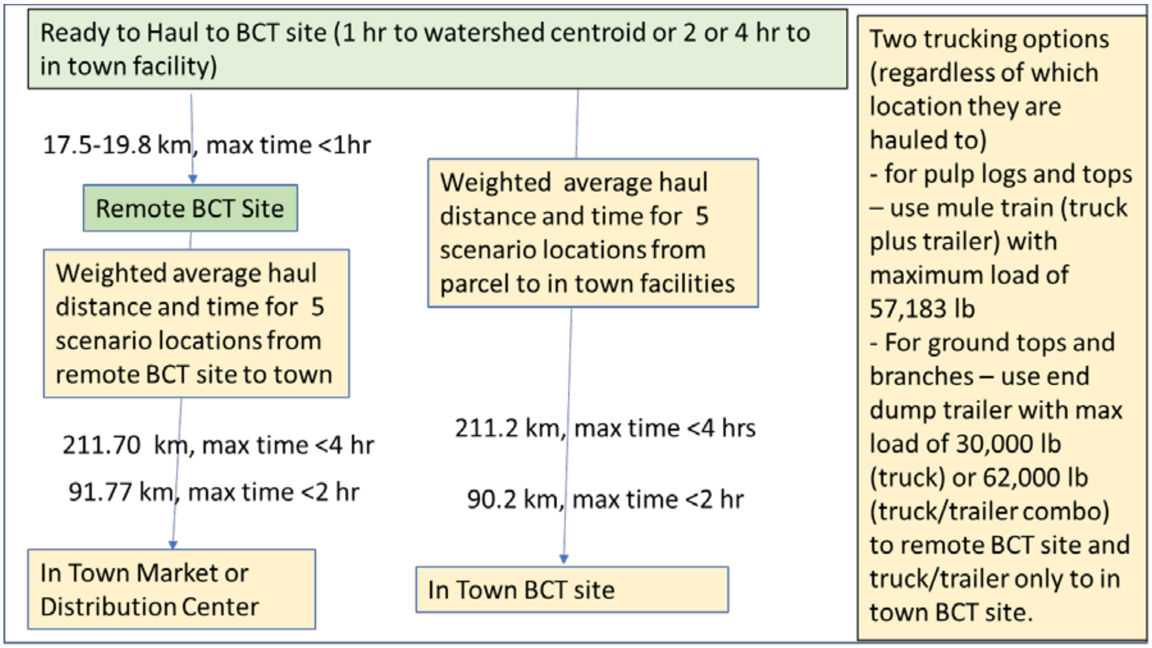
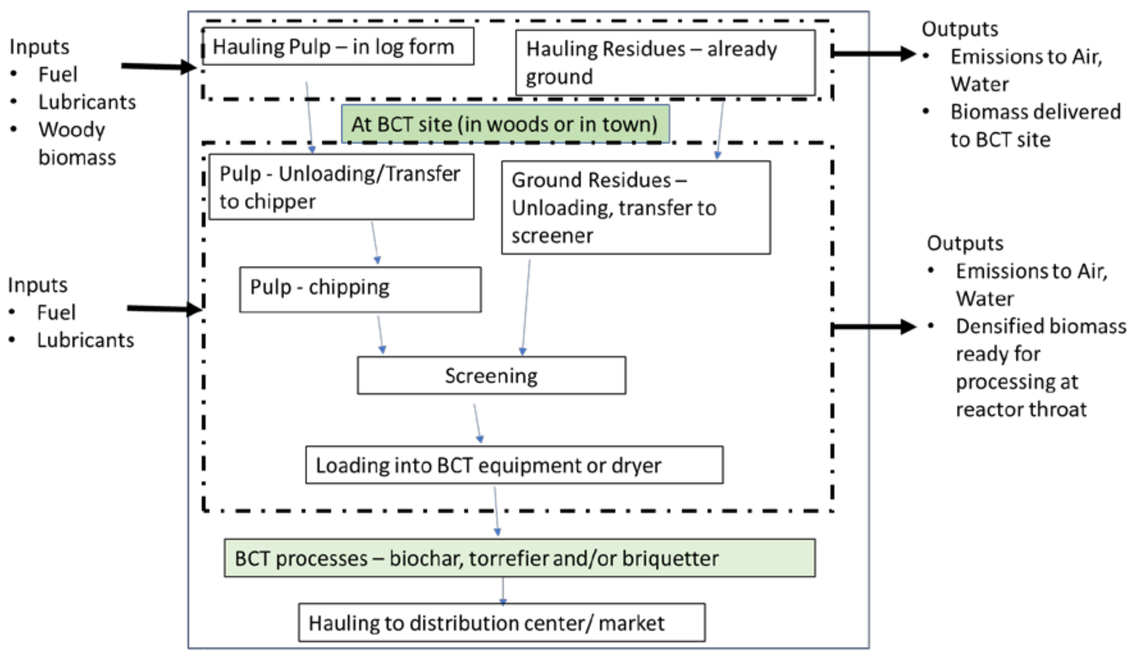


Figure 19 System Boundary and Operations at Bioconversion Technology (BCT) Site.



5.3 Biomass Recovery Equipment

Data from Kizha and Han (2016), Bisson and Han (2016) and Han et al (2014) were collated into systems that reflect the range of model alternatives that were explored in the LCA on biomass recovery (Table 7). Data were converted to common units of fuel use per BDT for ease of analysis. Lubricant consumption was assumed at 1.8% of fuel consistent with assumptions used by Johnson et al (2012). While many values from these sources were reported in tons, some were reported as fuel usage per hour and or fuel usage per MBF (thousand board feet – a measure of sawlog volume). Conversions to BDT were based on average values per productive machine hour for those values given on an hourly basis. Conversions to BDT from MBF were based on conversion factors from MBF to tons for pulp quality material as used for taxation purposes by the Washington State Department of Revenue. For scenarios that include in-forest operations, the in-forest fuel use was additive to the fuel use for recovery from the landing for each type of feedstock. Comminution can occur either at the landing or at the BCT site. Several alternatives were explored, with results presented for grinding operations occurring at the landing and chipping operations occurring at the BCT site. This distinction between locations is largely driven by efficiencies in hauling log quality material over ground material in situations where that is possible.

Table 7 Harvest and Biomass Recovery Equipment and Fuel Use

Recovery Location and Equipment Used	Equipment Model (where available)	fuel (l/BDT)	lubricants (l/BDT)
Pulp recovery to landing (include in forest operations)			
Fellerbuncher	John Deere 959K	0.7707	0.0139
Shovel yarder	Caterpillar 568	3.5589	0.0641
subtotal		**4.3167**	**0.0777**
Pulp recovery from landing (exclude in forest operations)			
Loader for sorting	John Deere 2954D	0.3458	0.0062
Processor	John Deere 2454D	1.0115	0.0182
Loader for loading	John Deere 2954D	0.7075	0.0127
subtotal		**2.1090**	**0.0380**
Unload/Process at BCT site (remote or in town)			
Loader for unloading	John Deere 2954D	0.7075	0.0127
Morbark Chipper	875 HP	0.5461	0.0098
Deck Screener	Peterson Pacific	1.5939	0.0287
Loader in unit and with grinder or chipper	250 HP	0.5971	0.0107
subtotal		**3.4445**	**0.0620**
Total without hauling (excluding in forest operations)		**5.5535**	**0.1000**
Total without hauling (including in forest operations)		**9.8702**	**0.1777**
Residue (tops and branches) recovery to landing (include in forest operations)			
Loader for sorting	John Deere 2954D	0.3458	0.0062
AWD modified Dump Truck from unit to landing		0.6512	0.0117
subtotal		**0.9970**	**0.0179**
Residue (tops and branches) recovery from landing (exclude in forest operations)			
Loader in unit and with grinder or chipper	250 HP	0.5971	0.0107
Horizontal Grinder	Peterson Pacific 5700C	2.9853	0.0537
AWD Tractor from landing to staging site		0.2860	0.0051
subtotal		**3.8684**	**0.0696**
Unload/Process at BCT site (remote or in town)			
Loader for unloading	John Deere 2954D	0.7075	0.0127
Deck Screener	Peterson Pacific	1.5939	0.0287
Loader in unit and with grinder or chipper	250 HP	0.5971	0.0107
subtotal		**2.8984**	**0.0522**
Total without hauling (excluding in forest operations)		**6.7668**	**0.1218**
Total without hauling (including in forest operations)		**7.7638**	**0.1397**

5.4 Data Analysis

Biomass recovery data described above were aggregated, weighted to reflect allocation among treatment types, and input into the SimaPro software package (PreConsultants, 2012) which was used to conduct the LCI. LCI data were then aggregated to develop a LCIA using the TRACI method (Bare et al 2011). The TRACI method groups emissions to air, water and land into impact categories such as global warming potential, ozone depletion, and smog creation. The method converts emissions to a common unit using a built-in characterization model. In this way, emissions that have differing impacts can be converted to 'reference' units and reported out as a single factor. For example, global warming potential (GWP) is commonly reported using a reference unit of carbon dioxide equivalents (CO2e or CO2 eq). The emission of 1 unit of CO2 is thus 1 with the emission of other heat trapping gases, such as methane, are relative to this unit. Within the characterization model in SimPro, methane (CH4) has a GWP value of 25 whereas CO2 has a GWP value of 1, meaning one unit of methane contributes 25 times more to GWP than one unit of CO2. Table 8 shows the TRACI impact categories, their reference units, and what they are measuring as an environmental impact. These categories are reported for all processes that were modeled for the biomass recovery LCIA.

Table 8 Selected impact indicators, characterization models, and impact categories.

Impact Indicator	Characterization Model	Impact Category
Greenhouse gas (GHG) emissions	Calculate total emissions in the reference unit of CO_2 equivalents for CO_2, methane, and nitrous oxide.	Global warming
Releases to air decreasing or thinning of ozone layer	Calculate the total ozone forming chemicals in the stratosphere including CFC's HCFC's, chlorine, and bromine. Ozone depletion values are measured in the reference units of CFC equivalents.	Ozone depletion
Releases to air potentially resulting in acid rain (acidification)	Calculate total hydrogen ion (H+) equivalent for released sulfur oxides, nitrogen oxides, hydrochloric acid, and ammonia. Acidification value of H^+ mole-eq. is used as a reference unit.	Acidification
Releases to air potentially resulting in smog	Calculate total substances that can be photo-chemically oxidized. Smog forming potential of O_3 is used as a reference unit.	Photochemical smog
Releases to air potentially resulting in eutrophication of water bodies	Calculate total substances that contain available nitrogen or phosphorus. Eutrophication potential of N-eq. is used as a reference unit.	Eutrophication
Releases to air potentially causing mortality in humans	Human toxicity potential expressed in comparative toxic units (CTUh) which estimate increase in morbidity in the total human population, per unit mass of a chemical emitted	Carcinogens
Releases to air potentially causing mortality in humans	Human toxicity potential expressed in comparative toxic units (CTUh) which estimate increase in morbidity in the total human population, per unit mass of a chemical emitted	Non-carcinogens
Releases to air potentially resulting in particulate matter less than 2.5 microns	Calculate total substances that create airborne particulate matter. Respiratory effects uses PM2.5 eq as a reference unit	Respiratory Effects
Releases to water potentially impacting aquatic species	Expressed in comparative toxic units (CTUe), an estimate of the potentially affected fraction of species (PAF) integrated over time and volume, per unit mass of a chemical emitted.	Ecotoxicity

6 LIFE CYCLE ASSESSMENT RESULTS

Table 9 provides the LCIA for four different alternatives that can be used to recover forest residues for use as feedstocks for the production of bioenergy or biobased products. The results report on emissions and impacts up to the point that the biomass is loaded on the truck and ready for hauling to the BCT site. The difference in boundary condition when including versus excluding the in-forest operations is readily apparent in Table 9. Recovering pulp logs from the slash piles is approximately 32% of the impact of harvesting them from the forest. Likewise, recovering ground slash from the roadside piles is approximately 76% of the impact of adding in-forest recovery as part of the boundary. Recall that tops and branches are ground on site to increase their density before hauling, whereas pulp logs are not comminuted until they reach the BCT site, therefore a comparison of pulp to residue is not particularly information at this stage in the analysis.

Table 9: per metric ton LCIA by residue type, with and without in forest operations. (Excludes biogenic CO_2)

Impact category	Unit	Pulp recovery from landing (exclude in forest operations)	Residue recovery from landing (exclude in forest operations)	Pulp recovery from landing (include in forest operations)	Residue recovery from landing (include in forest operations)
Ozone depletion	kg CFC-11 eq	2.726E-10	5.108E-10	8.444E-10	6.757E-10
Global warming	kg CO2 eq	6.529E+00	1.223E+01	2.022E+01	1.618E+01
Smog	kg O3 eq	2.863E+00	5.365E+00	8.867E+00	7.096E+00
Acidification	kg SO2 eq	9.029E-02	1.692E-01	2.796E-01	2.238E-01
Eutrophication	kg N eq	5.399E-03	1.011E-02	1.672E-02	1.338E-02
Carcinogenics	CTUh	9.850E-08	1.845E-07	3.050E-07	2.441E-07
Non carcinogenics	CTUh	9.454E-07	1.771E-06	2.928E-06	2.343E-06
Respiratory effects	kg PM2.5 eq	1.858E-03	3.480E-03	5.753E-03	4.604E-03
Ecotoxicity	CTUe	1.824E+01	3.418E+01	5.649E+01	4.520E+01
Fossil fuel depletion	MJ surplus	1.288E+01	2.414E+01	3.990E+01	3.192E+01

Table 10 provides the LCIA of the different hauling alternatives on a per ton-kilometer (tkm) basis. Because each hauling configure has a different weight limit, and different accessibility constraints, they will all be viable alternatives in certain cases. The largest challenge in the analysis is in determining what the most likely percentage of time that higher weight alternative are chosen given specific road configurations and their limitations on access.

Table 10 Comparison of Trucking Alternatives – LCIA per tonne-km (tkm).

Impact category	Unit	Truck, ground material	Truck and transfer, ground material	Mule Train, pulp logs
Ozone depletion	kg CFC-11 eq	8.787E-12	4.252E-12	4.610E-12
Global warming	kg CO2 eq	2.303E-01	1.115E-01	1.209E-01
Smog	kg O3 eq	3.764E-02	1.822E-02	1.976E-02
Acidification	kg SO2 eq	1.375E-03	6.656E-04	7.217E-04
Eutrophication	kg N eq	7.663E-05	3.710E-05	4.022E-05
Carcinogenics	CTUh	3.155E-09	1.527E-09	1.655E-09
Non carcinogenics	CTUh	3.039E-08	1.471E-08	1.594E-08
Respiratory effects	kg PM2.5 eq	2.395E-05	1.160E-05	1.257E-05
Ecotoxicity	CTUe	5.878E-01	2.844E-01	3.084E-01
Fossil fuel depletion	MJ surplus	4.152E-01	2.009E-01	2.178E-01

Table 11 provides a more complete comparison of the use of pulp and residues from tops and branches including hauling to a remote (in-woods) BCT site. The average haul distance modeled for Table 11 is 18.77 km from the harvest unit to the BCT at the watershed centroid. This is a weighted average of all 5 scenario locations. At this point it is relevant to compare the different feedstocks because they would both be collected, loaded, comminuted to a suitable size, screened, and ready to enter the BCT reactor throat. Because hauling pulp logs is more efficient than either of the methods for hauling ground material, the pulp recovery carrying a 16% lower footprint than the residue recovery when considering only the operations from the landing to the BCT throat. When adding in the in-forest operations, that relationship switches, and residue recovery is 22% more efficient than recovering pulp. This shift arises because the boundary expansion for in-forest recovery of residues accounts for only the additional effort to recover the branches and tops that would normally be left on site and away from the road. In other words the residues are still a true waste. By contrast, the in-forest operations for collecting pulpwood account for the cutting of the material and yarding it to the road. In this case, the wood is not considered a true waste, because it would otherwise not be harvested. Instead, it is considered a co-product of harvest, or in most cases, a co-product of fire risk reduction thinning. These alternatives are not likely to solve the arguments for and against considering the pulp logs a waste generated from fire risk reduction thinning, but they do provide data that can help inform the debate.

Table 11 Per metric ton LCIA results with Trucking to remote BCT site.

Impact category	Unit	Pulp Recovery, landing to BCT site, exclude in forest operations	Residue Recovery, landing to BCT site, exclude in forest operations	Pulp Recovery, forest to BCT site, with in forest operations	Residue Recovery, forest to BCT site, with in forest operations
Ozone depletion	kg CFC-11 eq	8.142E-10	9.734E-10	1.386E-09	1.138E-09
Global warming	kg CO2 eq	1.969E+01	2.352E+01	3.338E+01	2.747E+01
Smog	kg O3 eq	8.013E+00	9.636E+00	1.402E+01	1.137E+01
Acidification	kg SO2 eq	2.545E-01	3.059E-01	4.439E-01	3.605E-01
Eutrophication	kg N eq	1.516E-02	1.823E-02	2.648E-02	2.149E-02
Carcinogenics	CTUh	2.940E-07	3.514E-07	5.005E-07	4.110E-07
Non carcinogenics	CTUh	2.823E-06	3.374E-06	4.805E-06	3.946E-06
Respiratory effects	kg PM2.5 eq	5.194E-03	6.246E-03	9.089E-03	7.369E-03
Ecotoxicity	CTUe	5.447E+01	6.513E+01	9.273E+01	7.615E+01
Fossil fuel depletion	MJ surplus	3.847E+01	4.599E+01	6.549E+01	5.378E+01

Table 12 shows the alternative of collecting residues and pulp logs from the landing and roadside and hauling them either 2 hours one way or 4 hours one way to an in-town BCT processing facility. The longer the distance, the more the differences between the hauling alternatives washes out as a 2 hour haul for pulp is 66% of the GWP impact of a 2 hour haul of forest residues, but it is 91% of the impact to haul pulp 4 hours to the processing facility relative to the ground residues. Comparing LCIA data from the remote BCT site to the in-town BCT site, it is 30-54%% more efficient to get the pulp logs to the reactor throat at the remote site than to either the 2 hour haul and 4 hour haul respectively. The LCIA of the ground material is more of a mixed outcome as the hauling assumption for long distance hauls includes a shift from hauling from steep ground with a truck only, to hauling all material with a truck and trailer. This will require some equipment modifications to ensure that the transfer can be picked up at a site that is accessible for both truck and transfer. Even with this change to the hauling method between the two scenarios, preparing, hauling, and processing ground material ready for use at a remote BCT site is still 25% more efficient than hauling it 4 hour to an in-town facility from a GWP perspective.

Table 12 Per metric ton LCIA results with Trucking to intown processing site under two distance scenarios.

Impact category	Unit	Pulp Recovery, landing to in town facility, exclude in forest operations, 2 hour haul	Pulp Recovery, landing to in town facility, exclude in forest operations, 4 hour haul	Residue Recovery, landing to in town facility, exclude in forest operations, 2 hour haul*	Residue Recovery, landing to in town facility, exclude in forest operations, 4 hour haul*
Ozone depletion	kg CFC-11 eq	1.143E-09	1.701E-09	1.263E-09	1.777E-09
Global warming	kg CO2 eq	2.832E+01	4.295E+01	3.110E+01	4.459E+01
Smog	kg O3 eq	9.422E+00	1.181E+01	1.087E+01	1.308E+01
Acidification	kg SO2 eq	3.060E-01	3.933E-01	3.511E-01	4.317E-01
Eutrophication	kg N eq	1.803E-02	2.290E-02	2.075E-02	2.524E-02
Carcinogenics	CTUh	4.121E-07	6.124E-07	4.552E-07	6.400E-07
Non carcinogenics	CTUh	3.961E-06	5.890E-06	4.374E-06	6.154E-06
Respiratory effects	kg PM2.5 eq	6.091E-03	7.612E-03	7.035E-03	8.438E-03
Ecotoxicity	CTUe	7.649E+01	1.138E+02	8.446E+01	1.189E+02
Fossil fuel depletion	MJ surplus	5.402E+01	8.038E+01	5.965E+01	8.396E+01

* truck and transfer used for hauling

These results are based on input data reflecting average fuel usage as reported by Task 2 of the Waste to Wisdom team. Those input data are based on equipment efficiency values and survey responses, but they reflect a relatively narrow range of operational conditions. It is likely that in other locations, and especially in locations in the drier parts of the region, they would not achieve as high an efficiency. As a result, these results may under estimate the impacts of forest residue recovery, particularly for small diameter logs.

CHAPTER 3: TO BURN OR NOT TO BURN: WHERE, WHEN AND HOW TO BURN TO MINIMIZE ENVIRONMENTAL IMPACTS

Final Report on
Task 4.2 Avoided Costs and Environmental Benefits of Biochar Application

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1 OVERVIEW

Several components of the Waste to Wisdom project examined the value of producing and using biochar as a soil amendment, (Page-Dumroese et al 2015, 2017). A life cycle assessment (LCA) of producing biochar (Puettmann et al 2017) was also developed as part of the project and was based on test results from the small scale biochar machine manufactured by Biochar Solutions Inc (hereafter BSI machine) as described by the Schatz Energy Report Center (2016). In this report we integrate these elements using a comparative analysis approach to quantify the environmental costs and benefits that accrue from using material that would otherwise likely burn as part of fire risk reduction activities, or during a wildfire that might occur after operations are complete.

The work conducted on the ecological sustainability of using biochar as a soil amendment, with a focus on its impact on forest soils demonstrates that the largest gains are likely to come from increasing soil water holding capacity in dry western forests. This benefit is described in detail in Page-Dumroese et al (2015, 2017) and will not be addressed here. The emission profiles associated with producing biochar for a range of alternative woody feedstocks, moisture contents, and equipment configurations are fully developed in the life cycle assessment (LCA) of Puettmann et al (2017) based on trials conducted on the BSI machine. Results from Puettmann et al (2017) show that it takes a very large amount of woody residues to produce biochar with input/output ratios of 6.4:1 to 7.9:1 ton of feedstock input per ton of biochar output depending on the type of material used, its moisture content, and the BSI machine configuration. Running the BSI machine generates an emission profile that, when taken together with emissions associated with obtaining the feedstock can be used to produce a GWP for producing biochar. Similarly, emission profiles for open burning of woody residues were developed as part of this project to compare/contrast current ‘business as usual’ (BAU) scenarios with recovery of forest residues for use in the biochar equipment.

1.1 Characterization

Emissions are grouped according to the potential impacts they have on the environment using impact indicators from TRACI (Bare et al. 2011). The impact indicators include emissions to air noted above, plus other emissions to the soil and water that provide quantifiable measures of potential environmental impacts. The target impact indicator, the impact category, and means of characterizing the impacts are summarized in Table 13.

Table 13 Selected impact indicators, characterization models, and impact categories.

Impact Indicator	Characterization Model	Impact Category
Greenhouse gas (GHG) emissions	Calculate total emissions in the reference unit of CO_2 equivalents for CO_2, methane, and nitrous oxide.	Global warming
Releases to air decreasing or thinning of ozone layer	Calculate the total ozone forming chemicals in the stratosphere including CFC's HCFC's, chlorine, and bromine. Ozone depletion values are measured in the reference units of CFC equivalents.	Ozone depletion
Releases to air potentially resulting in acid rain (acidification)	Calculate total hydrogen ion (H+) equivalent for released sulfur oxides, nitrogen oxides, hydrochloric acid, and ammonia. Acidification value of H^+ mole-eq. is used as a reference unit.	Acidification
Releases to air potentially resulting in smog	Calculate total substances that can be photo-chemically oxidized. Smog forming potential of O_3 is used as a reference unit.	Photochemical smog
Releases to air potentially resulting in eutrophication of water bodies	Calculate total substances that contain available nitrogen or phosphorus. Eutrophication potential of N-eq. is used as a reference unit.	Eutrophication
Releases to air potentially causing mortality in humans	Human toxicity potential expressed in comparative toxic units (CTUh) which estimate increase in morbidity in the total human population, per unit mass of a chemical emitted	Carcinogens
Releases to air potentially causing mortality in humans	Human toxicity potential expressed in comparative toxic units (CTUh) which estimate increase in morbidity in the total human population, per unit mass of a chemical emitted	Non-carcinogens
Releases to air potentially resulting in particulate matter less than 2.5 microns	Calculate total substances that create airborne particulate matter. Respiratory effects uses PM2.5 eq as a reference unit	Respiratory Effects
Releases to water potentially impacting aquatic species	Expressed in comparative toxic units (CTUe), an estimate of the potentially affected fraction of species (PAF) integrated over time and volume, per unit mass of a chemical emitted.	Ecotoxicity

Each impact indicator value is stated in units that are not comparable to others because they are measuring different aspects of potential environmental impact, therefore indicators should not be combined or added. Emission factors as noted in Table 13, and data on the level of complete combustion expected in piled slash were used to generate the LCIA for open burning of slash piles as shown in Table 15.

1.2 Emissions and Life Cycle Inventory Assessment

Emissions from open burning were derived from the literature (Battye and Battye 2002, Prichard et al. 2006) and calculations of the amount of coarse and fine material that is likely to be left piled at landings and roadsides post harvest. The emission profiles from the literature cover a range of chemical species including particulate matter (PM10, PM2.5), carbon monoxide (CO), carbon dioxide (CO2), methane (CH4), non-methane hydrocarbons (NMHC), elemental carbon, organic carbon, oxides of nitrogen (NOx), ammonia (NH3), volatile organic carbon (VOC), sulfur dioxide (SO2), methanol, and formaldehyde. Some of the factors are constants and some rely on a number of coarse scale relationships that vary depending on burn stages (flame, smolder, and residual). Taken together, these variables were used along with assumptions about total fuel consumption, the ratio of fine to coarse materials, and total material available to arrive at emissions from pile burning as shown in Table 14.

Table 14 Emission Profile from Open Burning of Slash including biogenic carbon emissions (per ton (1000kg) of slash)

Emissions to Air	Unit	Average slash mix – cable harvest	Average slash mix – ground harvest
Ammonia	kg	0.47	0.45
Carbon dioxide, biogenic	kg	1688.75	1693.76
Carbon monoxide, biogenic	kg	64.5	62.2
Formaldehyde	kg	1.03	1.00
Methane, biogenic	kg	4.46	4.23
Methanol	kg	0.64	0.62
Nitrogen oxides[1]*	kg	2.50	2.50
Non-methane volatile organic compounds (NMVOC)	kg	4.05	3.96
Particulates, < 10 um (mobile)	kg	4.36	4.23
Particulates, < 2.5 um	kg	3.86	3.75
Sulfur dioxide*	kg	0.83	0.83
VOC, volatile organic compounds	kg	5.48	5.29

Table 15 Life Cycle Assessment Impacts from Open Burning of Slash including biogenic emissions (per metric ton of slash)

Impact category	Unit	Average slash mix – cable harvest	Average slash mix – ground harvest
Ozone depletion	kg CFC-11 eq	0.000E+00	0.000E+00
Global warming	kg CO_2 eq	1.788E+03	1.788E+03
Smog	kg O_3 eq	9.185E+01	9.087E+01
Acidification	kg SO_2 eq	3.464E+00	3.426E+00
Eutrophication	kg N eq	1.665E-01	1.641E-01
Carcinogenics	CTU_h	1.380E-05	1.340E-05
Non carcinogenics	CTU_h	1.827E-07	1.773E-07
Respiratory effects	kg $PM_{2.5}$ eq	3.983E+00	3.871E+00
Ecotoxicity	CTU_e	2.775E+01	2.694E+01

The alternative to open burning is to collect the slash, process it for use as a feedstock for energy or biochar, and move it to the production location. As noted in Task 4.7, the processing can occur at the harvest site, or at the BCT site with efficiencies identified for either case depending on the feedstock type. Collection, processing, and hauling all take energy and all have a quantified LCA footprint. Upstream data from the forest resources LCA was used to generate an LCIA that reflects the energy inputs for 1 ton of feedstock that could be used to produce biochar at a remote BCT site. For comparison with biochar

[1] * constants from Battye and Battye equations, all others calculated from Battye and Battye equations

scenarios from Puettmann et al (2017) Table 16 is based on the recovery from a weighted average of ground and cable harvest sites across the 5 scenario locations, assuming that 1/3 of the material was tops and branches, and 2/3 was the bole or pulp wood. Tops and branches were collected from landings and roadsides, ground into a higher density material onsite, loaded into trucks on cable harvest sites, and onto truck and transfer units on ground based harvest units, and hauled to the BCT site where it was screened for size and input into the biochar machine. The boles or pulp wood was collected from landings and roadsides, loaded onto mule train trucks, hauled to the BCT site, then processed into chips, screened, and loaded into the biochar machine. This combination of activities in these ratios generated the LCIA results in Table 16.

Table 16 Life Cycle Impact Assessment of Slash Recovery (at BCT site) (per metric ton of slash)

Impact category	Unit	Biochar feedstock
Ozone depletion	kg CFC-11 eq	-8.666E-10
Global warming	kg CO2 eq	-2.097E+01
Smog	kg O3 eq	-8.547E+00
Acidification	kg SO2 eq	-2.714E-01
Eutrophication	kg N eq	-1.617E-02
Carcinogenics	CTUh	-3.129E-07
Non carcinogenics	CTUh	-3.004E-06
Respiratory effects	kg PM2.5 eq	-5.540E-03
Ecotoxicity	CTUe	-5.798E+01
Fossil fuel depletion	MJ surplus	-4.095E+01

1.3 Comparative Analysis

These upstream data in Table 16 were input into the biochar LCIA (Puettmann et al 2017) to generate the results for the BSI machine that produces biochar as compared to open burning in Table 17. Since the remote BCT sites do not have grid electricity, alternative electrical generation sources are required. For this study, the BSI machine used to make biochar was tested using both a portable biomass gasifier (i.e. power pallet) and a portable diesel generator.

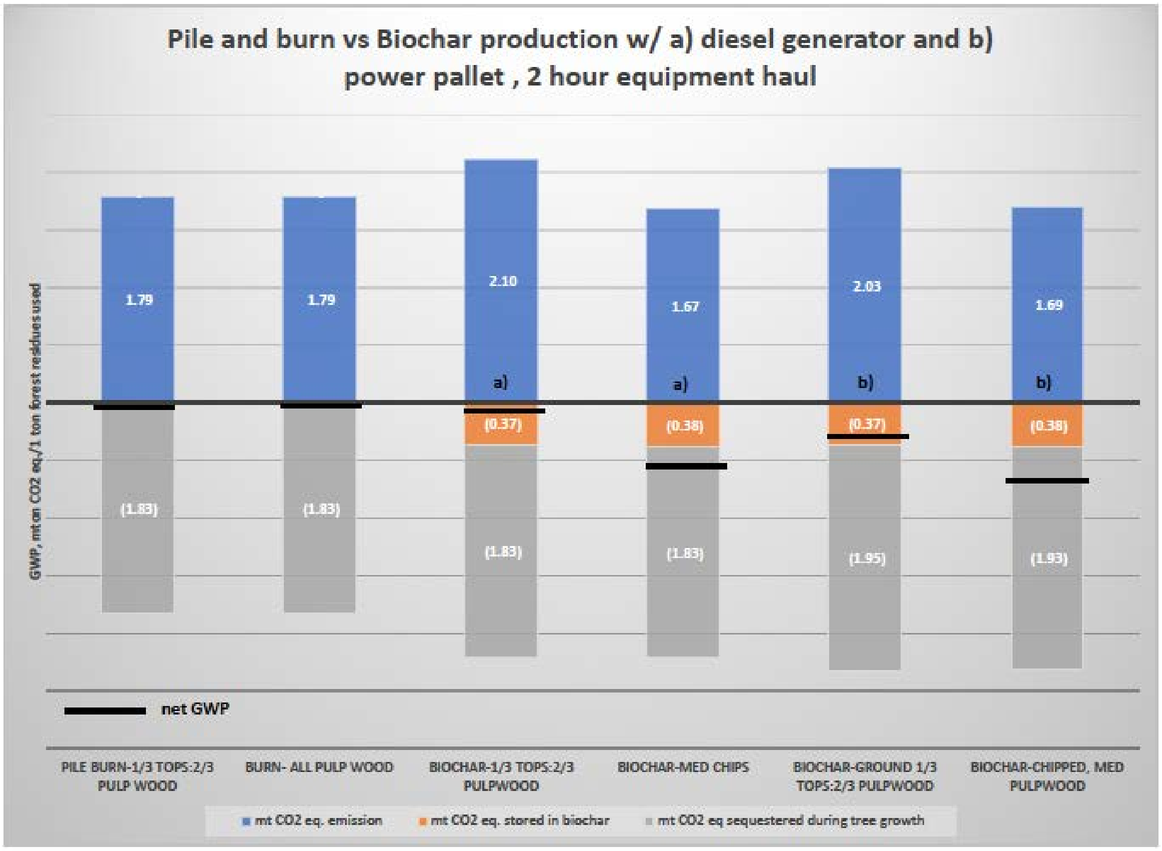
Table 17 Global Warming Potential per ton of feedstock used under three scenarios and two feedstocks

Equipment Type			**Using Diesel Generator**		**Using A Power Pallet**	
Feedstock type	Pile burn-1/3 tops: 2/3 pulpwood	Pile Burn-all pulpwood	Biochar-ground 1/3 tops: 2/3 pulpwood	Biochar-medium chips from pulpwood	Biochar-ground 1/3 tops: 2/3 pulpwood	Biochar-medium chips from pulpwood
mt CO2 eq. emission	1.79	1.79	2.10	1.67	2.03	1.69
mt CO2 eq. stored in biochar	-	-	(0.37)	(0.38)	(0.37)	(0.38)
mt CO2 eq sequestered during tree growth	(1.83)	(1.83)	(1.83)	(1.83)	(1.95)	(1.93)
Net mt CO2 eq	(0.04)	(0.04)	(0.10)	(0.54)	(0.29)	(0.63)

In Table 17 GWP includes biogenic CO2 emissions from open burning of wood residues using the factors for open burning from Table 13. The carbon dioxide absorbed from the atmosphere during growth of the wood residues is also provided for the 1 ton of residues that are burned to produce biochar using either a diesel generator or a power pallet to produce electricity at the remote BCT site. Using data provided by Schatz Energy Research Center (2016) on the input/output volumes of different feedstock types, and the LCA assessment of their data by Puettmann et al (2017), an average of 7962 kg of medium chips are required to produce 1 t of biochar. Similarly, an average of 6374 kg of ground residues are required to produce 1 t of biochar. Puettmann et al (2017) show that differences in moisture content are part of the reason behind the differences in input requirements. They also show that these two types of biochars have different amounts of fixed carbon so may not be completely interchangeable as marketable commodities. However, for purposes of integration and comparison with open burning alternatives, this range of inputs/outputs is sufficient.

The BSI using a power pallet for electricity generation shows a higher carbon dioxide absorption because wood is used to generate the electricity as well as for biochar production, regardless of feedstock used. The calculated conversion rate for wood to energy for the BSI machine is 0.044 kg of wood to feed the power pallet for every 1.0 kg of feedstock used in the production of biochar with a 58% efficiency applied (Puettmann et al 2017). Comparing the GWP to absorption for each process generates an estimated net GWP (Table 17) as shown graphically by the net (black) line in Figure 20.

Figure 20 Net GWP comparison of producing biochar using a) diesel generator, b) power pallet vs open burning of residues



The biochar scenarios considered both a 2 and 4-hour equipment haul distances (distance from town) to the remote BCT site. The difference between 2 and 4 hours equipment haul times was insignificant, therefore results using the 2-hour equipment haul distance are provided for comparative purposes. The pile and burn options are nearly carbon neutral with a Net GWP emission of -0.04 t CO_2 eq per ton of biomass burned. While the production of biochar is slightly net positive. Net GWP emission for 1 metric of feedstock are -0.29, -0.63 for biochar produced with ground tops and pulpwood and biochar produced with medium chips using a diesel generator. When diesel generator is used, there is a 66 percent decrease in NET carbon storage for the tops/pulpwood biochar system and 14 percent decrease in biochar system that used chipped pulpwood. The use of the biomass gasifier (power pallet) to supply the energy for the biochar machine stored an additional 7 percent CO_2 during forest growth and lower CO2 eq emissions by 3 percent over the diesel generator for biochar produced with tops and pulpwood.

Other scenarios for biochar production using different feedstocks are provided in Puettmann et al (2017). In all cases carbon sequestration in the feedstock was counted as were emissions in burning that feedstock so that the net GWP reflects both uptake and emissions to the atmosphere. Because biochar contains carbon that was sequestered by removing carbon dioxide from the atmosphere the outcomes demonstrate the extent to which biochar serves as a carbon sink similar to wood products when they are in service. However, biochar is expected to be a more decay resistant and therefore recalcitrant form of carbon sequestration than wood products. It also has the co-benefit of reducing the need for fertilizer, improving moisture holding capacity of soils, and therefore is expected to increase tree growth when applied under conditions where moisture and soil fertility are limiting factors (Page-Dumroese et al 2017).

1.4 Scale Mismatch

There is a substantial volume of woody feedstocks available from commercial forestry operations throughout the region as shown in chapter 1, but the distances that residues need to be hauled to reach a major center constrain recovery operations. The idea explored during this research was to examine the potential to use small scale technologies that could be moved from location to location to reduce haul time for low density, low value forest residues. That would certainly improve utilization of the available supply, but there is still a scale mismatch that has to be overcome. For the most part, the recovery equipment used to collect biomass can process 26-40 BDT/hour; the equipment to haul it can move 9-12 BDT/hour, but the BSI machine and other small scale technologies tested were operating at capacities less than 1 BDT/hour. Clearly any substantial recovery of available biomass resides is well outside the size limitations for a single small scale biochar machine to utilize. Options to co-locate several BSI machines together, or co-locate biochar producing machines that produce waste heat with small scale torrefier or briquette making machines were explored as part of Task 3 of the Waste to Wisdom project. The benefits of co-location include opportunities to use waste heat from the biochar machine to dry wood for the torrefier and briquette making machine. Options such as developing a depot model to stockpile material for continuous year round production of biochar need to be further explored to overcome this scale mismatch between the recovery operations and the utilization operations. Otherwise, we have found that small scale biomass utilization operations are equally unlikely to be a good match for the available supply, any more than large scale centrally location operations can utilize widely dispersed, low density material as is generated during forest operations in the Pacific coast states.

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