CAN BIOMASS CONVERSION TECHNOLOGIES BE INTEGRATED WITH RECOVERY OPERATIONS IN-WOODS?

- MODELLING THE SUPPLY CHAIN -

Waste to Wisdom: Subtask 2.5

Project Management

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Can Biomass Conversion Technologies be integrated with Recovery Operations In-woods? Modelling the Supply Chain.

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Abstract: Economic potential of feedstock generated low-valued forest residue can be enhanced by emerging biomass conversion technologies (BCT), such as torrefaction, briquetting, and gasification. However, for implementing these emerging processes within the woods several hurdles are to be overcome, among which a balanced supply chain is pivotal. Centralized Biomass Recovery Operation (CBRO) could be an economically viable solution to accessing harvesting sites and allows integration of BCT into forest management. The objectives of this study were to examine the logistic effects of integrating a BCT into a CBRO, in-woods. Concurrently, this study examined the forest managerial impacts due to such an integration. Location-Allocation tool (Maximize Market Share problem type) within the ArcGIS Network Analyst extension was utilized to model the scenarios and generate one-way travel times from the harvest site to final markets. Logistically, arranging CBRO and BCT operations to occur at the same in-woods site returned shorter total and average travel times than arranging the two activities at separate in-woods sites. The model developed for this study can be used by forest managers to identify sites for placing BCTs in the forest which minimizes transportation times.

Keywords: Briquetting, gasification, network analysis, torrefaction, work plan

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1. Introduction

1.1. Terminologies used in the article:

Biomass conversion technology (BCT): Technologies that can create higher value added energy densified feedstock from forest residues when compared to the traditional chipped material. The BCTs modelled for the study are operated in-woods and includes torrefaction, briquetting and gasification.
Biomass recoverability: The actual amount of forest residues extracted from the timber harvest units that will be further processed at BCT locations to generate value added products. The recovered biomass is delimbed and stored as tree-tops in decks at the landing.
Centralized Biomass Recovery Operations (CBRO): The process in which forest residues from several log landings are brought into one site (via self-loading short log trucks or Modified dump trucks) where it will be comminuted to generate feedstock for BCT operation.
Comminution: Processing of forest residues into wood chips by a chipper. The end products of this process becomes the feedstock for the BCT which are characterized by uniform size distribution, low in contaminants and low moisture content.
Coupled operation: When one operational work task (e.g. BCT) is totally dependent on the work task prior to it (e.g. CBRO). Any delay effecting the former component will have a direct ripple effect on the component following. For example, in a coupled system if the CBRO operation stalls this will directly stop the working of BCT as the later no longer gets its feedstock.
Forest residues: woody materials generated from timber harvesting operation (other than sawlogs) that are typically of lesser or no economic value. These were further classified into tree-tops, limbs, chunks, small diameter, and non-merchantable trees **[1]**.

Permanent road: Two-lane graveled that have low grades and were designed for high volume traffic. These roads are meant to be used year-long.

Tree-tops: The wood material within bole (main stem) from 15 cm diameter level onwards to the tip of the crown for both conifer and hardwood trees. Processed tree-tops are delimbed (foliage removed along the entire length) to the top 5 cm diameter (small-end).

Watercourse and Lake Protection Zone (WLPZ)/ Equipment Exclusion Zones (EEZ): Areas in which timber harvesting operations are restricted due to legal aspects.

Forest residues generated during timber harvesting operation can be viewed as a sustainable source for energy production. Presently in the United States, woody biomass is considered as one of the largest and most accessible domestic source of renewable energy which predominantly comes from timber harvest operation, forest products industries and urban wood wastes **[2]**.

One major concern regarding the financial viability for energy production from forest residues is the transportation cost, which is often regarded as the single largest cost component of the entire operation **[3–6]**. The inherent inefficiency of transporting a low value forest residues is the fundamental economic barrier to increased biomass utilization **[7]**. Therefore, supply in remote locations may not be suitable for extraction due to high access costs **[8]**. When transportation costs are taken into account, more expensive resources in close proximity may be economically competitive than low-priced resources farther away **[9]**.

The feasibility of any wood bioenergy production largely depends on the transportation costs to extract forest residues from comparatively remote location. Previously, transporting comminuted forest residues more than 80 km by road was not considered to be economically feasible **[10]**. Recently, this distance has gone up to 94 km (average one way distance) **[11]**. However, even at 80 km or less, transportation costs alone can rise as high as \$10 to \$30/ Bone dry ton (BDT) depending on the road condition **[5]**. US DOE **[2]** estimates around one-third of the recoverable forest residues (4.1 million BDT) available throughout the nation can be extracted from the roadsides at \$20/BDT and the rest (approximately 12.2 million BDT) at \$30/BDT. The report also states only 60% of the forest residues can be recovered due to inaccessibility.

These situation have necessitated to come up with more value-added products compared to the conventional hog fuels and /or wood chips for enhanced utilization of the forest residue. These products can substantiate the secondary transportation costs in terms of the higher economic value, which is increasingly becoming an achievable approach **[12]**). Biomass Conversion Technologies (BCT) such as torrefaction, gasification, pyrolysis, and densification (palletizing and briquetting) technologies can convert forest residues, into more dense energy carriers which further enhance handling and transportation **[13]**.

Integrating BCT equipment into the supply chain of regular harvesting operation typically comes with many stringent requirements set by the process itself (e.g., uniform feedstock particle size, low moisture content, and absence of contaminants in the feedstock) and other spatial attributes related with the location of production (such as area, topography, forest managerial constraints (such as Watercourse and Lake Protection Zone (WLPZ), and Equipment Exclusion Zone (EEZ)), and access to permanent roads. Efficient integration of woody biomass into energy generation requires information regarding spatial and temporal variations on the availability of forest residues. The availability of recoverable forest residues has been the focal point of various optimization studies **[5,14]**. GIS has also been applied to identify potential sites for new facilities **[15]**. Along with these, logistic model for work plans have been developed for Centralized Biomass Recovery Operation (CBRO) **[16]**. Spatial datasets along with other attributes, such as facility locations, road networks, hauling time, time associated travelling over various road types, vehicles used, operational cost, etc. can be can be used to create dynamic and realistic models of wood biomass supply chain logistics in ArcGIS Network Analyst, which can further predict the cost of transportation in various situations **[5]**.

The size and location of CBRO incorporating various BCTs has never been examined. There is a strong technical merit for identifying and incorporating optimal system balances in centralized BCT processing. The primary objective of this study was to model two different settings integrating BCT and CBRO based on their physical location and understand the operational challenges within the workflow associated with each case. The study further looks into the effect of forest residue recoverability, based on BDT/ha, on the overall transportation time from the harvest unit to the market. These models can equip foresters and natural resource managers to identify sites for placing BCTs in the forest which minimizes transportation times, the move in and move out costs, and increase transportation efficiency because high density energy products are more economical to haul than green wood chips. Additionally, the model developed could be easily be adapted to other regions where timberlands are actively managed.

2. Materials and Methods

2.1. Study Area and Timber Harvesting Operations

The study area is an industrial timberland owned and managed by Green Diamond Resource Company (GDRC) and encompasses approximately 41,000 ha in Humboldt County, California (40°52′13″N, 123°57′30″W) (Figure 1). The predominant tree species are *Sequoia sempervirens* (Coast Redwood), *Pseudotsuga menziesii* (Douglas-fir), *Tsuga heterophylla* (Western Hemlock), and *Notholithocarpus densiflorus* (Tanoak).

Integrated harvesting, generating both forest residues and sawlogs, is the common practice in the region and even-age management is the major silvicultural prescription. The harvesting system adopted is either shovel logging or cable yarding timber depending on slope (ranging from 0 to 68°) and environmental constraints.

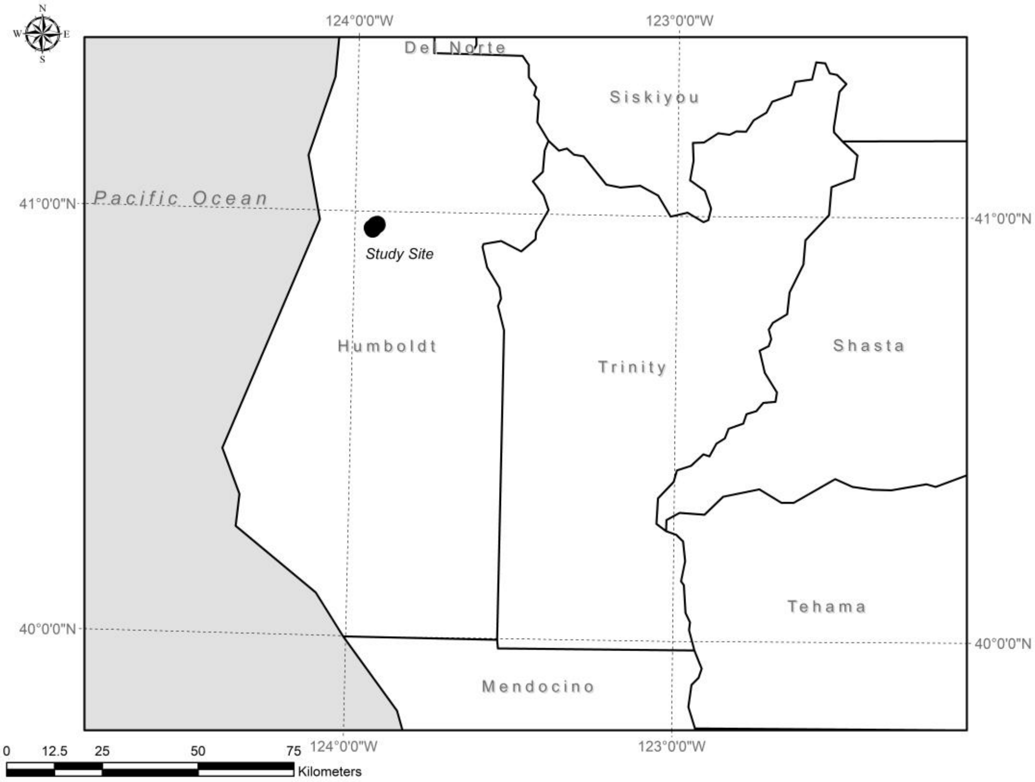

Figure 1. Study area for the integrated Centralized Biomass Recovery Operation and Biomass Conversion Technology model in Humboldt County, California

2.2. Description of Biomass Recovery Operation

Forest residues generated from the timber harvest were forwarded to landings along with the sawlogs. At the landing, selected forest residues (tree-tops, non-merchantable trees and small-diameter trees) are delimbed and piled in decks with a shovel. The processed forest residues (from here on referred to as tree-tops) are assumed to have an average moisture content of 12% after one year of drying [17]. Self-loading short log trucks are utilized to haul the tree-tops from the landings (having access to permanent roads) to CBRO sites where it will be chipped. For landings that had access via seasonal roads, a modified dump truck is used to haul to the landing. All CBRO sites had access to permanent roads. Delivery and comminution were decoupled by a one day supply. A typical workday for all equipment in the supply chain was 10 hours long. This ensured at least a one day supply of processed tree-tops available for use at the beginning of each work day. Star and deck screener are operated at the BCT sites to produce uniform sized feedstock. CBRO/BCT operations will only occur at one site at a time, and that each chosen site within the supply chain will represent one potential move for that season, e.g. 2 BCT sites represents two moves, 5 BCT sites represents 5 moves, and so on.

2.3. Models and Scenarios

Based on the amount of forest residues to be processed as well as if the operations within the supply chain are coupled or de-coupled, the scenario selected for the models had spatial requirements that varied quite significantly. Two models were developed to evaluate the logistics of the supply chain based on physical location of the CBRO and BCT process. Both model began at the harvest units, where processed tree-tops were picked up from roadside decks, comminuted at the CBRO sites, BCT converted and ended when delivered the BCT converted products to the market. The market (power plant) was 72 km away from the BCT sites. Logistics Model I (LM I) was based on situation that both CBRO and BCT occurred at the same centralized site. Logistics Model II (LM II) described CBRO and BCT activities occurred at separate locations. Consequently, here the chipped material moves from comminution site to BCT conversion sites in a chip van (Figure 2). The payload for both self-loading log truck and chip truck was set at 20 tons.

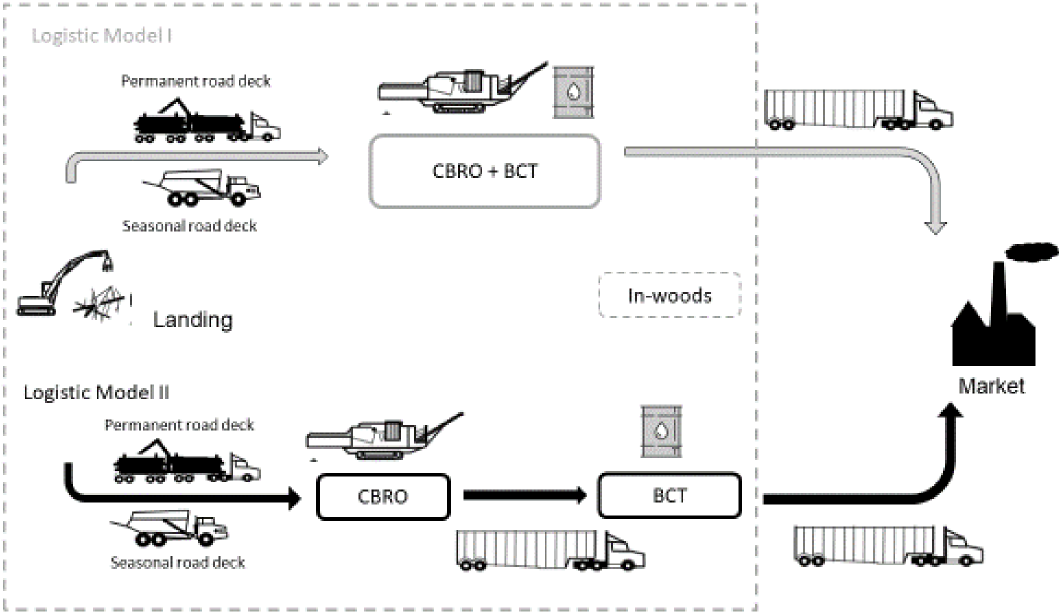

Figure 2. Graphical representation of the two Logistic Models (LM) I and II.

Based on information from foresters and BCT experts, LM I and II was based on an annual biomass recovery operations of 200 and 100 days, respectively. Both Models had BCT operations set at 250 days annually. The area for the comminution site was 0.22 ha without storage. The space for equipment and feedstock storage at the BCT sites were based on the amount of feedstock processed (Table 1). The space for equipment and storage varied between 0.45 and 5.01 ha, respectively. As the biomass recovery days were not similar to the BCT operation days, additional space for storing the biomass at the BCT sites were considered in both models. The space was evaluated based on footprint calculations regarding the needs of a BCT site and assumptions based on field based observations (SERC)

Three potential scenarios were developed for LM I in terms of recoverable biomass per acre: 1) Scenario I - high (124 BDT/ha), 2) Scenario II- moderate (74 BDT/ha), and 3) Scenario III- low (37 BDT/ha). Similarly for LM II: 4) Scenario IV – high (124 BDT/acre), 5) Scenario V- moderate (74 BDT/acre), and 6) Scenario VI- low (37 BDT/acre). The amount of recoverable biomass per harvest unit was obtained by multiplying the total harvest unit acres by the BDT/ac of recoverable biomass for each scenario.

Table 1. Spatial requirements (in hectare) associated with each Logistics Model (LM) and associated scenarios**.** CBRO and BCT denotes Centralized Biomass Recovery Operation and Biomass Conversion Technology, respectively.

		Without Storage*		**With Storage**	
		CBRO Sites	**BCT Sites**	**CBRO Sites**	**BCT Sites**
LM I	Scenario I	N/A	0.95	N/A	2.12
	Scenario II	N/A	0.59	N/A	1.32
	Scenario III	N/A	0.30	N/A	0.66
LM II	Scenario IV	0.09	1.44	0.09	5.10
	Scenario V	0.09	0.88	0.09	3.10
	Scenario VI	0.09	0.45	0.09	1.55

*Without storage (coupled operation) implies sites that had only area for stationing machines and space to store feedstock for one hour of operation.
N/A: not applicable. In LM I; CBRO and BCT operates at the same site.

2.4. Spatial Dataset

The GIS data comprised of Digital Elevation Model (DEM), hydrology shapefile (distinguishing Stream Classes I, II, and III), roads shapefile based on surface type (paved, rocked, dirt), harvest-unit (including all silvicultural management plans and boundaries of harvest units for 2014-15). Datasets on road, watercourse, harvest units, and silvicultural prescriptions were provided by Green Diamond Resource Company (GDRC). DEM were obtained from United States Geological Survey (USGS).

2.5. Developing logistics model

Developing the work plan for CBRO logistics was initiated by identifying the timber harvesting systems and forest residue collection points (log landings) through spatial analysis and calculation of forest residues recoverable per hectare. The locations for suitable landings for each harvest units were based on the distinction between the two harvesting systems (cable logging and shovel logging) employed to accurately model pre-haul routes and forest residue locations. The harvesting system for a unit was determined by a series of tasks, which included: 1) Converting DEMs to a slope vector layer, which was then clipped to the timber harvest unit's boundary; 2) developing a function of slope hectares to total unit hectares for each unit to determine the harvesting system employed. Slopes less than 23° permitted ground-based shovel logging and slopes exceeding 23° necessitated a cable yarding system *[16]*.

2.6. Centralized biomass recovery operation supply chain

A geo-spatial analysis was performed to identify candidate sites for CBRO that meet the various footprint and slope requirements for either model based on criteria such as:

1. Area equal to or more than 0.09 ha (without storage)
2. Eliminating areas that were included Watercourse and Lake Protection Zone (WLPZ) (via, Buffering)
3. Steepness of the terrain less than or equal to 3% slope (via, classifying DEMs)
4. Access to permanent road (via, union between permenant roads)

2.7. Network Analysis

The models were then developed in the Network Analyst (ArcGIS) using the Location-Allocation tool to estimate the total and average one-way travel times. Total one way travel time is defined as the total costs (based on time) of traveling between demand point (candidate harvest units) and facility (CBRO/ BCT/ market) to haul all final products (tree-tops/ comminuted feedstock/ BCT products). Maximize Market Share function was used to select facilities to maximize the market share of a given set of demand points in the presence of competing facilities. This assured that BCT sites were assigned with the most amount of biomass available under the set conditions. Impedance cutoff values were adjusted to access all demand points from the chosen facilities.

Setting the impedance cutoff at “1” minute helped in determining the number of demand points accessed in that time. The impedance cutoff was then increased until the model was able to access all of the given demand points.

The number of comminution sites across the project area was selected based on market location as the demand point and comminution sites as the facilities. The model then selected the best facility, increasing the number until the model returned “redundant results”, which was 20 for this study. Which meant that increasing the number of sites past this number will not return a better solutions set. This number was found to be in line with a similar previous study, which cited biomass contractors moved the CBRO locations 24 times per work year *[16]*.

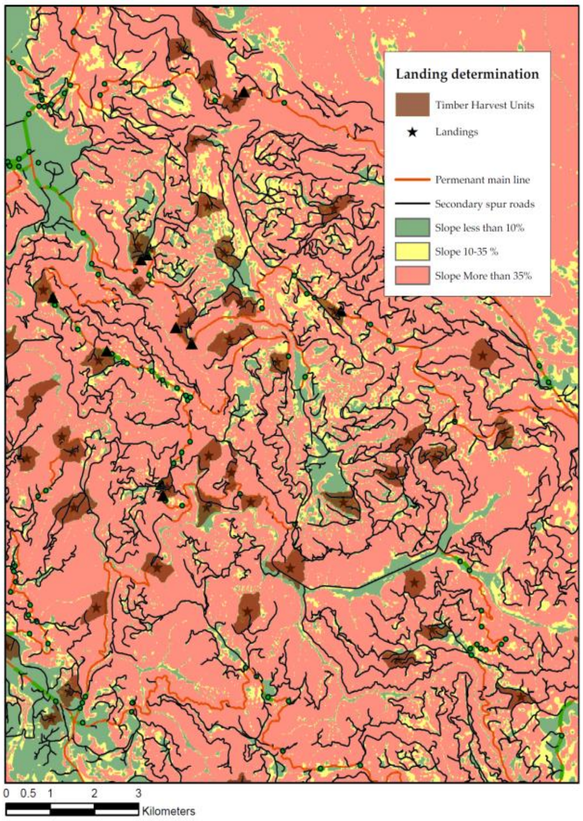

Figure 2. Centralized biomass recovery operation (CBRO) and Biomass Conversion technology (BCT) sites were determined through a series of geospatial process. Which were then used to locate, calculate, and display the locations of recoverable biomass (per harvest unit and CBRO), harvesting method. Road distance is used to calculate haul route distance

An average travel speed on graveled forest roads were set at 23 km/hr *[3]*. The public road (paved) had legal speed limits ranging between 24 to 89 km/hr and averaged 40 km/hr.

3. Results and Discussion

There were 138 candidate timber harvest units which met all the criteria, i.e, sites not within a WLPZ and intersected with road segments, of which 77 and 61 units utilized shovel and cable logging systems, respectively (Figure 3). These were assigned as the demand points for the location-allocation analysis. Based on the spatial analysis, LM II had 236 CBRO sites were located for all scenarios. There were 89- 159 and 64-136 sites located for the BCT for LM I and II, respectively (Table 3).

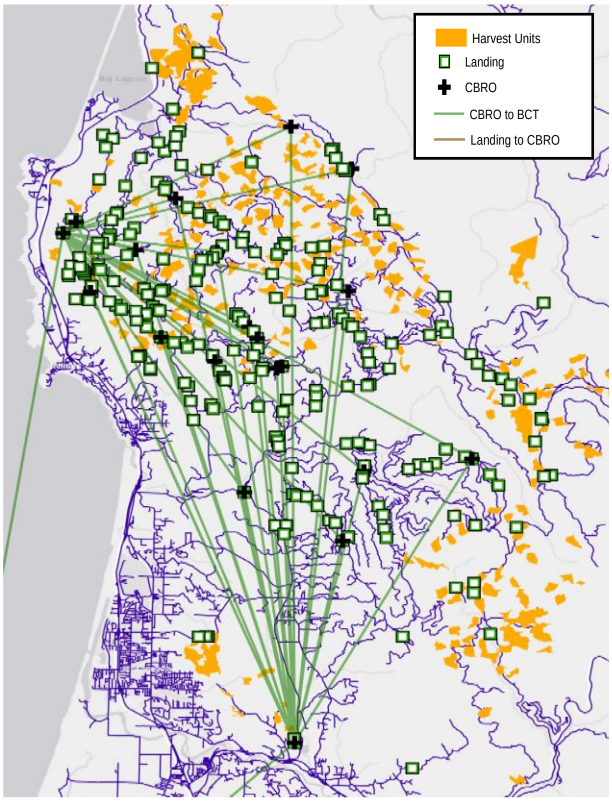

Figure 3. Network analysis results for location-allocation tool for scenario VI. Straight lines are for visualization, haul distances are calculated using road distance.

Table 3. The number of Centralized Biomass Recovery Operation (CBRO) and Biomass Conversion Technology (BCT) sites for each scenario within the Logistic Model (LM) I and II, respectively.

		CBRO Sites	**BCT Sites**
LM I	Scenario I	N/A	89
	Scenario II	N/A	114
	Scenario III	N/A	159
LM II	Scenario IV	236	64
	Scenario V	236	86
	Scenario VI	236	136

N/A: not applicable; In LM I, CBRO and BCT operates at the same site.

Results of the spatial analysis showed that a decoupled operation was not feasible for many situations due to the large storage space for the feedstock both at the CBRO and BCT. Therefore, if tree-tops were to be stored at the combined CBRO and BCT site (LM I), then Scenario I was the only option that had about 2.12 ha; however, if comminuted forest residues were to be delivered to BCT sites from CBRO sites as needed, then Scenario IV and V (LM II) had a storage space of greater than seven acres at the BCT sites (Table 1). This suggests that both models will have to assume that feedstock should be forwarded to BCT sites as needed, which couples the supply chain at the CBRO site. Further on, the chipper (at the CBRO) is likely needed to match with the production of the BCT, which would alleviate storage issues in the supply chain.

Eliminating a separate CBRO location within the supply chain (LM I) would also reduce total travel time, which can be attributed to the additional time required for hauling the comminuted biomass from the CBRO to BCT sites (LM II) (Table 4). It is to be noted that this travel times would be having a drastic impact as travelling are done on forest roads. However, this could be often an operational challenge in terms of the physical space required for the combined BCT and CBRO sites. The most favorable case would be if the BCT sites be located at the same site as CBRO, or should be placed further down the supply chain, e.g. closer to the market, in order to avoid the two activities compounding the transportation time as well as to facilitate extended hours of operations. In general, the models built for all scenarios (I- VI) using different numbers of BCT sites showed that as the number of BCT sites increased the total one-way travel time (i.e. harvest unit to market) reduced. Even though logistics were modelled for five moves per season, for actual working conditions more than two moves per season was not feasible.

Table 4. Average and total one-way travel times (in hours) for models having two and five BCT moves per work year. CBRO and BCT denotes Centralized Biomass Recovery Operation and Biomass Conversion Technology, respectively.

		Harvest site to CBRO		CBRO to BCT		BCT to Market		Harvest site to Market	
2 BCT		Total	Average	Total	Average	Total	Average	Total	Average
LM I	Scenario I	199.54	0.64	N/A	N/A	0.82	0.41	200.37	1.05
	Scenario II	196.94	0.65	N/A	N/A	0.92	0.46	197.86	1.11
	Scenario III	509.94	0.40	N/A	N/A	1.19	0.60	511.14	0.99
LM II	Scenario IV	1850.39	0.63	17.13	0.43	1.18	0.59	1868.70	1.65
	Scenario V	1123.67	0.51	20.40	0.51	1.01	0.50	1145.07	1.52
	Scenario VI	1468.30	0.59	21.54	0.54	1.15	0.58	1490.99	1.70
5 BCT									
LM I	Scenario I	463.19	0.61	N/A	N/A	3.15	0.63	466.34	1.24
	Scenario II	278.19	0.51	N/A	N/A	3.27	0.65	281.46	1.16
	Scenario III	509.94	0.40	N/A	N/A	3.46	0.69	513.40	1.09
LM II	Scenario IV	1047.02	0.50	36.94	0.37	3.18	0.64	1087.14	1.51
	Scenario V	1016.66	0.49	55.24	0.55	2.95	0.59	1074.85	1.63
	Scenario VI	1210.83	0.52	51.84	0.52	3.29	0.66	1265.95	1.69

N/A: not applicable; In LM I, CBRO and BCT operates at the same site.

3.1. Temporal nature of the supply chain

The supply chains were modelled for 200 (LM I) and 100 days per year (LM II). This represented the actual annual working time frame in the Pacific Northwest United States because of operational windows for the biomass harvesting. The 200 day per cycle working frame was practices if the biomass cycle was decoupled from the timber harvesting operations. In the 100 days per cycle (representing the coupled biomass and timber harvesting operations) models, the number of biomass collection days was less than the number of operable BCT days/year. As a result, a large area was needed for storing the additional volume of feedstock the BCT required to operate. This storage constraint can pose a significant setback in projects that exhibit steep topography such as the Pacific Northwest United States, and in some cases can make a project spatially unfeasible.

To address this situation, processed tree-tops can be decked on the permanent road sides near or within harvest units. Past researches have shown that pre-hauling processed tree-tops from harvest units to permenant road sides can effectively accumulate forest residues at CBRO sites at reduced costs while providing efficient, year-round access to forest residues **[3]**. Additionally, the wood residue transportation was much more cost efficient if trucks maximized their usage of permanent roads **[18]**. Results showed that 66% of the harvest units in the study area had permanent road access. Therefore, if the processed tree-tops could be forwarded to log decks on permanent roads, the storage constraint could be solved because collection and transportation with a self-loading log truck was possible year round. This being the case, managers only need to store one to two work days of tree top feedstock at the BCT site. This would also significantly reduce the overall footprint of the entire operation. From an operational point of view, this arrangement of the supply chain can maximize the utilization rates of all equipment, while minimizing the risk of challenges associated with access, seasonality, and storage of tree-tops.

With regards to the workflow in such instances, biomass recovery operations in harvest units accessed by seasonal road only will have to be prioritized, as it would be only accessible during appropriate season. After this, units next to permanent can be harvested because they would be having all year access

3.2. Implications of the supply chain on timber harvesting operations

This study was designed to model an integrated CBRO and BCT operations in northern California based on the physical location and by incorporating aspects of current timber harvesting techniques adopted for the region. The raw materials were derived from tree-tops that were processed down to 5 cm diameter (at small end) within the timber harvesting unit and sorted at the landing **[1]**. This practice has been proved to effectively minimize organic contamination and ash content of feedstock, ultimately improving the final quality of BCT feedstock **[19]**.

BCT integrated with CBRO systems can be incorporated into other forest managerial operations such as salvage, fuel reduction thinning, and stand conversion. Recent massive fire incidents have prompted many landowners to lower the fuel load on their timberlands. The major obstacle to this activity can be the cost of operations. In the region, the forest residues supplied to the conventional markets (power plant) were priced around $50/BDT **[5]**. However, the stump-to-truck cost in industrial timberland operations could range from $26 to 35/BDT depending on a variety of reasons including harvesting system, and terrain **[3,20]**. Costs for mobilization of equipment, overhead and profit allowance were not included in these stump-to-truck cost figures. Hence, under current market price the procurement area for traditional feedstock is limited to less than 130km unless the operations is compensated by other financial resources **[5]**. Here BCT operations becomes a promising option by increasing the economic value of the end products. This increased value for the BCT converted feedstock can substantiate the increment in trucking distance (also referred to as scaling effect). These enhanced value for the energy-densified products could potentially increase the round way trip up to 160km **[21]**. The improved price will also make biomass recovery operations economically feasible in previously inaccessible regions.

Historically, forest residues have been used as a “slash mats” for harvesting machines working in the timberlands to minimize soil compaction **[22]**. This practice also ensures nutrient recycling. Even though these slash mats are recoverable, the material would be contaminated, therefore not suitable as feedstocks for value added BCT products. The model was designed based on typical biomass recovery operation for the region which leaves 30-40 % of the forest residues on the floor. Nutrient impacts from biomass removal were of less concern because even after the forest residue recovery operation (especially Scenario I and VI-removing 124 BDT/ha), there was still about 67 and 72 BDT/ha of down woody material left on site for the shovel and cable yard units, respectively **[23]**.

The tree-tops could be shipped using self-loading short log trucks instead of the modified dump trucks (commonly used to transport non-comminuted forest residues in the region). Biomass recovery operations being seasonal in the region (roughly 100 days per year) are closed for the dump trucks during rainy seasons. In contrast, timber harvesting operations are year-round for cable logging and six months for shovel logging. Therefore, using short log trucks could extend the biomass recovery window for a much longer timeframe. Short log trucks are also more efficient than dump truck and can enhance the productivity of the entire operation.

This study considered an exclusively in-woods operations, however, it should be highlighted that in appropriate conditions, tree-tops can preferably be forwarded to an existing mill sites or industrial log yards favoring a permenant BCT location. This can help in scaling up the production there by reducing the cost of operation. Another benefit of placing BCT equipment at permenant sites is the availability of a power grid, which can support a reliable and continuous power supply. Such conditions could further avoid the financial and environmental costs associated with auxiliary diesel power generation. Similarly, positioning BCT equipment in such a way avoids many environmental constraints such as WLPZ/EEZ and fire restrictions, while simultaneously avoiding repetitive and expensive in-wood moves of BCT equipment.

5. Conclusions

CBRO has the potential to be an economically viable solution to access remote areas and allow integration of BCTs. Pre-hauling of processed tree-tops from harvest sites to CBRO using modified self-loading short log trucks or dump trucks can more effectively accumulate forest residues at reduced costs while providing efficient access to forest residues for year-round supply of material. Two models within which six scenario were tested to determine the optimal biomass recovery systems in order to reduce costs and increase productivity of biomass recovery for BCTs. Conclusive results shows that all scenarios within each Logistics model exhibit either more or less travel time than the other. However, analysis between the models showed that LM I eliminated additional travel time on forest roads between the CBRO and BCT sites. A decoupled operation was not feasible for many scenarios due to the large storage space for the forest residues both at the CBRO and BCT locations.

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References

1. Kizha, A. R.; Han, H.-S. Processing and sorting forest residues: Cost, productivity and managerial impacts. *Biomass Bioenergy* **2016**, *93*, 97–106, doi:10.1016/j.biombioe.2016.06.021.
2. US Department of Energy *2016 Billion ton report: Advancing Domestic Resources for a Thriving Bioeconomy*; Oak Ridge National Laboratory: Oak Ridge, TN, 2016; p. 448;.
3. Harrill, H.; Han, H.-S. Productivity and Cost of Integrated Harvesting of Wood Chips and Sawlogs in Stand Conversion Operations. *Int. J. For. Res.* **2012**, *2012*, 1–10, doi:10.1155/2012/893079.
4. Pan, F.; Han, H.-S.; Johnson, L.; Elliot, W. Net energy output from harvesting small-diameter trees using a mechanized system. *For. Prod. J.* **2008**, *58*, 25–31.
5. Kizha., A. R.; Han, H.-S.; Montgomery, T.; Hohl, A. Biomass power plant feedstock procurement: Modeling transportation cost zones and the potential for competition. *Calif. Agric.* **2015**, *69*, 184–190, doi:10.3733/ca.v069n03p184.
6. El Hachemi, N.; Gendreau, M.; Rousseau, L.-M. Solving a log-truck scheduling problem with constraint programming. In *International Conference on Integration of Artificial Intelligence (AI) and Operations Research (OR) Techniques in Constraint Programming*; Springer, 2008; pp. 293–297.
7. Windisch, J. Process redesign in development of forest biomass supply for energy. *Diss. For.* **2015**, *2015*, doi:10.14214/df.189.
8. Fischer, G.; Schrattenholzer, L. Global bioenergy potentials through 2050. *Biomass Bioenergy* **2001**, *20*, 151–159.
9. Langholtz, M.; Carter, D. R.; Marsik, M.; Schroeder, R. Measuring the economics of biofuel availability. *ArcUser Mag.* **2006**, 22–25.

10. Paine, L. K.; Peterson, T. L.; Undersander, D. J.; Rineer, K.; Bartlet, G.; Temple, S. A.; Sample, D. W.; Klemme, R. M. Some Ecological and Socio-Economic consideration for Biomass Energy Crop Production. *Biomass Bioenergy* **1996**, *10*, 231–242.
11. Koirala, A.; Kizha, A.; De Urioste-Stone, S. Policy Recommendation from Stakeholders to Improve Forest Products Transportation: A Qualitative Study. *Forests* **2017**, *8*, 434, doi:10.3390/f8110434.
12. Han, H.-S.; Halbrook, J.; Pan, F.; Salazar, L. Economic evaluation of a roll-off trucking system removing forest biomass resulting from shaded fuelbreak treatments. *Biomass Bioenergy* **2010**, *34*, 1006–1016, doi:10.1016/j.biombioe.2010.02.009.
13. Uslu, A.; Faaij, A. P. C.; Bergman, P. C. A. Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation. *Energy* **2008**, *33*, 1206–1223, doi:10.1016/j.energy.2008.03.007.
14. Perpiñá, C.; Alfonso, D.; Pérez-Navarro, A.; Peñalvo, E.; Vargas, C.; Cárdenas, R. Methodology based on Geographic Information Systems for biomass logistics and transport optimisation. *Renew. Energy* **2009**, *34*, 555–565, doi:10.1016/j.renene.2008.05.047.
15. Krukanont, P.; Prasertsan, S. Geographical distribution of biomass and potential sites of rubber wood fired power plants in Southern Thailand. *Biomass Bioenergy* **2004**, *26*, 47–59, doi:10.1016/S0961-9534(03)00060-6.
16. Montgomery, T. D.; Han, H.-S.; Kizha, A. R. Modeling work plan logistics for centralized biomass recovery operations in mountainous terrain. *Biomass Bioenergy* **2016**, *85*, 262–270, doi:10.1016/j.biombioe.2015.11.023.
17. Kizha, A. R.; Han, H.-S.; Paulson, J. S.; Koirala, A. Strategies for reducing moisture content in forest residues at the harvest site. *Appl. Eng. Agric.* **In press**, doi:10.13031/aea.12427.
18. Han, S.-K.; Murphy, G. Predicting Loaded On-Highway Travel Times of Trucks Hauling Woody Raw Material for Improved Forest Biomass Utilization in Oregon. *West. J. Appl. For.* **2012**, *27*, 92–99, doi:10.5849/wjaf.11-016.
19. Bisson, J. A.; Han, H.-S. Quality of Feedstock Produced from Sorted Forest Residues. *Am. J. Biomass Bioenergy* **2016**, *5*, 81–97, doi:10.7726/ajbb.2016.1007.
20. Bisson, J. A.; Han, S.-K.; Han, H.-S. Evaluating the System Logistics of a Centralized Biomass Recovery Operation in Northern California. *For. Prod. J.* **2016**, *66*, 88–96, doi:10.13073/FPJ-D-14-00071.
21. Mayhead, G.; Shelly, J. Woody Biomass Factsheet–WB4. *Electr. Woody Biomass* **2012**.
22. Oneil, E.; Lippke, B. *Eastern Washington biomass accessibility*; University of Washington: Seattle Washington, 2009; p. 40;.
23. Kizha, A. R.; Han, H.-S. Forest residues recovered from whole-tree timber harvesting operations. *Eur. J. For. Eng.* **2015**, *1*, 46–55.