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Integrating Biomass Conversion Technologies with Recovery Operations In-Woods: Modeling 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 in accessing harvesting sites and allows integration of BCT into forest management. The goal of this study was to examine the logistic effects of integrating a BCT into a CBRO, under different in-wood scenarios based on variations in travel time between the facility locations, amount of raw materials handled, intermediate storage capacity, and duration (number of days) of annual operations. Specific objectives included analyzing the effects of forest residue recoverability (BDMT, bone dry metric ton/ha), total transportation time from the harvest unit to the market, and the annual number of in-woods production sites on the overall efficiency of the BCT operations. 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 platform was utilized to model the scenarios and generate one-way travel times from the harvest site to final markets. Results from geospatial analysis showed that there were 89–159 and 64–136 suitable locations for the BCT for logistics model (LM) I and II, respectively. Total one-way travel time for all the models ranged between 1.0–1.7 h. Additionally, the annual numbers of BCT sites was inversely proportional to the total one-way travel time (i.e., harvest unit to market). 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 and entrepreneurs to identify sites for placing BCTs in the forest that minimizes transportation times.

Keywords: biomass logistics; briquetting; gasification; network analysis; timber harvesting operations; torrefaction; work plan; woody biomass

1. Introduction

1.1. Biomass Conversion Technology and Forest Operations

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 [1].

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 [2–7]. The inherent inefficiency of transporting low-value forest residues is the fundamental economic barrier to increased biomass utilization [8]. Therefore, supply in remote locations may not be suitable for extraction due to high access costs [9]. When transportation costs are taken into account, more expensive resources in close proximity may be more economically competitive than low-priced resources farther away [10].

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 [11]. Recently, this distance has gone up to 94 km (average one-way distance) [5,12–14]. However, even at 80 km or less, transportation costs alone can rise as high as $11 to $33/bone dry metric ton (BDMT) depending on the road conditions [6]. US Department of Energy [1] estimates around one-third of the recoverable forest residues (3.7 million BDMT) available throughout the nation can be extracted from the roadsides at $22/BDMT and the rest (approximately 11.1 million BDMT) at $33/BDMT. The report also states only 60% of the forest residues can be recovered due to inaccessibility.

These situations have necessitated the concept of 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 secondary transportation costs in terms of higher economic values, which is increasingly becoming an achievable approach [15]. Biomass conversion technologies (BCT) such as torrefaction, gasification, pyrolysis, and densification (palletizing and briquetting) can convert forest residues into more dense energy carriers, which could further enhance handling and transportation [16].

Integrating BCT equipment into the supply chain of regular harvesting operations typically comes with many stringent requirements set by the process itself (e.g., uniform particle size, low moisture content, and absence of contaminants in the feedstock) and other spatial attributes related to the locations of production (such as area, topography, forest managerial constraints, such as watercourse and lake protection zone (WLPZ)/equipment exclusion zones (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 [6,17]. Geospatial analysis has also been applied to identify potential sites for new facilities [18]. Along with these, a logistics model for work plans have been developed for centralized biomass recovery operation (CBRO) [19]. Spatial datasets along with other attributes, such as facility locations, road networks, hauling time, time-associated traveling over various road types, vehicles used, operational cost, etc., 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 [4,6].

1.2. Network Analysis on Supply Chain

Management of the transportation and logistics network has become major components affecting the supply chain valuation for industrial production [20]. For planning and managing biomass supply chains, several practical models have been developed with the help of tools such as operations research and mathematical optimization based on computer algorithms [21].

Location-allocation resolutions comprise a considerable amount of capital investment and can affect the long-term production and distribution of products [22]. Several location–allocation models (including fundamental transportation/assignment and linear programming formulations) have been developed to optimize spatial patterns with respect to location criteria, including cost, coverage, and access [21,23–26]. Apart from cost reduction, location-allocation algorithms have also accounted for several other factors such as availability of labor, proximity to raw materials and markets, market dimensions, government regulations, and environmental considerations [27].

Based on the physical locations of the operational sites involved, models can be broadly classified into two main categories based on the sites of operations: Single facility and multi-facility location [28]. The spatial and operational attributes of production facilities, along with workload capacity and distribution of task among them, influences transportation efficiency and productive machine or delay time, thereby effecting the overall transportation cost [29]. Therefore, the determination of location and size of biomass conversion sites is vital to network design [30].

The size and location of CBRO incorporating various BCTs has rarely been examined in terms of the logistics aspect. Past studies have shown that the mobilization of woody biomass for energy production demands a high level of integration between the various stakeholders that extract and convert the feedstock [31]. There is a strong technical merit for identifying and incorporating optimal system balances in centralized BCT processing. The primary goal of this study was to model two different settings integrating BCT and CBRO based on their physical location (in-woods) and understand the operational challenges within the workflow associated with each case. The specific objectives were to examine the effects of forest residue recoverability (BDMT/ha), overall transportation time from the harvest unit to the market, storage space at the in-wood facility, and the annual number of production sites (re-location) on the overall efficiency of the BCT operations. Furthermore, attempts were made to evaluate the model with respect to on-ground timber harvesting conditions. These models can equip forest engineers, procurement foresters, natural resource managers, and entrepreneurs to identify sites for placing BCTs within the forest that 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. Explanation of Concepts/Terminology 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 modeled for the study are operated in-woods and include 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: The procedure of converting wood biomass into smaller particles or fragments, typically using a chipper, grinder, shredder, hammer, or other equipment. For this study, comminution attributed to reduction of size by a chipper. The end product of this process becomes the feedstock for the BCT, which are characterized by uniform size distribution, low contamination, and low moisture content.

Coupled operation: When one operational task (e.g., BCT) is totally dependent on the task prior to it. Any delay effecting the former task will have a direct ripple effect on the task following. For example, in a coupled system if the CBRO operation stalls, this will directly stop the working of BCT as the latter no longer gets its input feedstock.

Forest residues: Woody materials present on the forest floor including logging residues generated from timber harvesting operations that are typically of lesser or no economic value. Forest residues were further classified into tree-tops, limbs, chunks, small-diameter trees, and non-merchantable trees [32,33].

Permanent road: Two-lane graveled roads 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) [32–34].

Watercourse and lake protection zone (WLPZ)/equipment exclusion zones (EEZ): Areas in which timber harvesting operations are restricted due to legal aspects or environmental concerns.

2.2. 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 Coast Redwood (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga menziesii*), Western Hemlock (*Tsuga heterophylla*), and Tanoak (*Notholithocarpus densiflorus*).

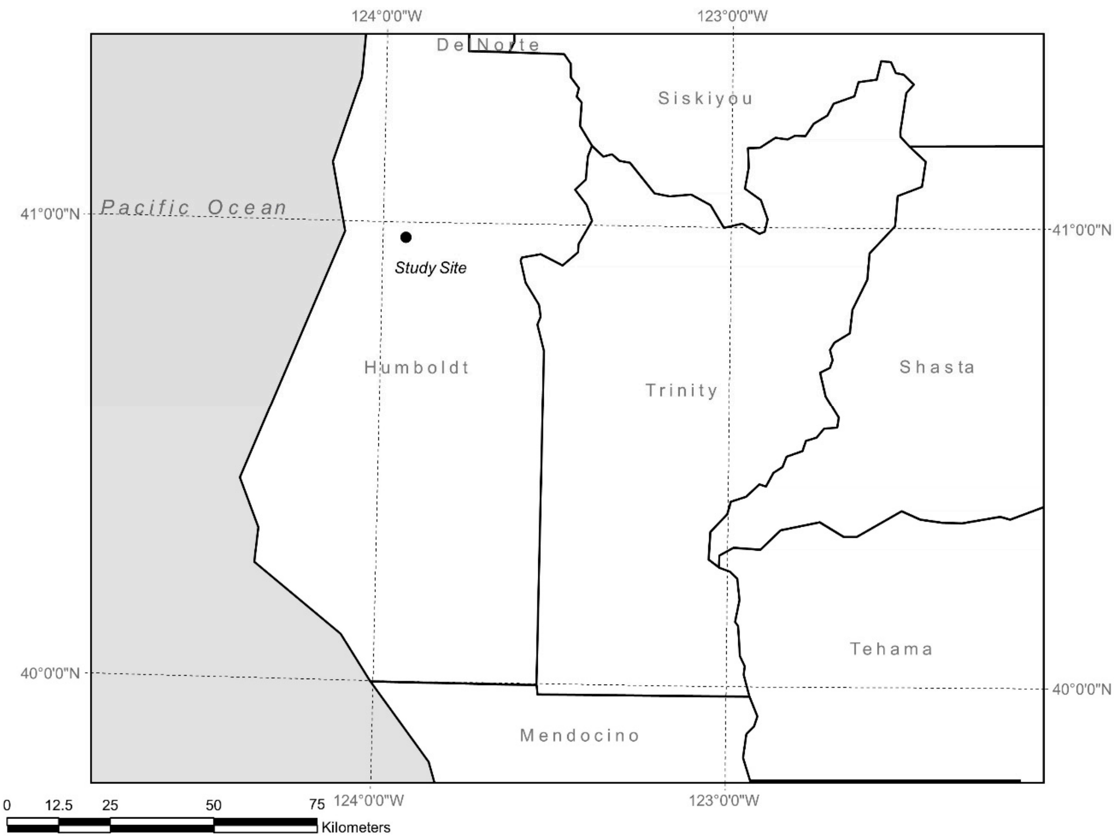

Figure 1. Study area for the integrated centralized biomass recovery operation and biomass conversion technology model in Humboldt County, California.

Integrated harvesting, generating both forest residues and sawlogs, is the common practice in the region and even-age stand 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. The timber harvesting operations are whole-tree operations typically consisting of feller buncher or hand fallers (for steep terrains), followed by extraction using shovel loaders or skidders. Processing is done at the landing by a dangle head processor, pull-through delimber, or chainsaws (when the landing is restricted by space).

2.3. Description of Biomass Recovery Operation

Forest residues generated from the timber harvest were skidded 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 using a loader. 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 [35–37]. 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 h long. This ensured at least a one-day supply of processed tree-tops are 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 each chosen site within the supply chain will represent one potential move for that season, e.g., two BCT sites represents two moves, five BCT sites represents five moves, and so on.

2.4. Models and Scenarios

This study was designed to model an integrated CBRO and BCT operation in northern California based on the physical location and by incorporating aspects of current timber harvesting techniques adopted for the region. 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. The models were based on methods using traditional facility location analysis techniques, such as basic quantitative and quantitative criteria. Two models were developed to evaluate the logistics of the supply chain based on physical location of the CBRO and BCT process. Both models began at the harvest units, where processed tree-tops were picked up from roadside decks, comminuted at the CBRO sites, BCT converted, and ended with delivery of 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 that occurred at separate locations. Consequently, here the chipped material moves from CBRO site to BCT conversion sites in a chip van (Figure 2). The payload for both self-loading log truck and modified dump truck was set at 18 MT (Metric tons). Volume of payloads was not considered because the trucks were generally limited by weight due to a legal weight restriction of 36 MT in California, USA.

Based on information from foresters and BCT experts, LM I and II were based on an annual biomass recovery operation of 200 and 100 days, respectively. This restriction of 100 days in LM II (decoupled system) was grounded in the fact that CBROs were conducted off roads (in-woods), which were closed during mud (non-harvesting) seasons. 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 was based on the amount of feedstock processed (Table 1). The space for equipment and storage varied between 0.3 and 5.1 ha and depended on whether the site had a storage space for feedstock or not. As the biomass recovery days were not similar to the BCT operation days, additional space for storing the biomass at the BCT sites was considered in both models. Different space was allocated for the models and scenarios based on footprint calculations regarding the needs of a BCT site and assumptions based on field-based observations [38].

Three potential scenarios were developed for LM I in terms of recoverable biomass per hectare: (1) Scenario I—high (112 BDMT/ha); (2) Scenario II—moderate (67 BDMT/ha); and (3) Scenario III—low (33 BDMT/ha). Similarly, for LM II: (4) Scenario IV—high (112 BDMT/ha); (5) Scenario V—moderate (67 BDMT/ha); and (6) Scenario VI—low (33 BDMT/ha). The amount of recoverable biomass per harvest unit was obtained by multiplying the total harvest unit acres by the BDMT/ac of recoverable biomass for each scenario [39].

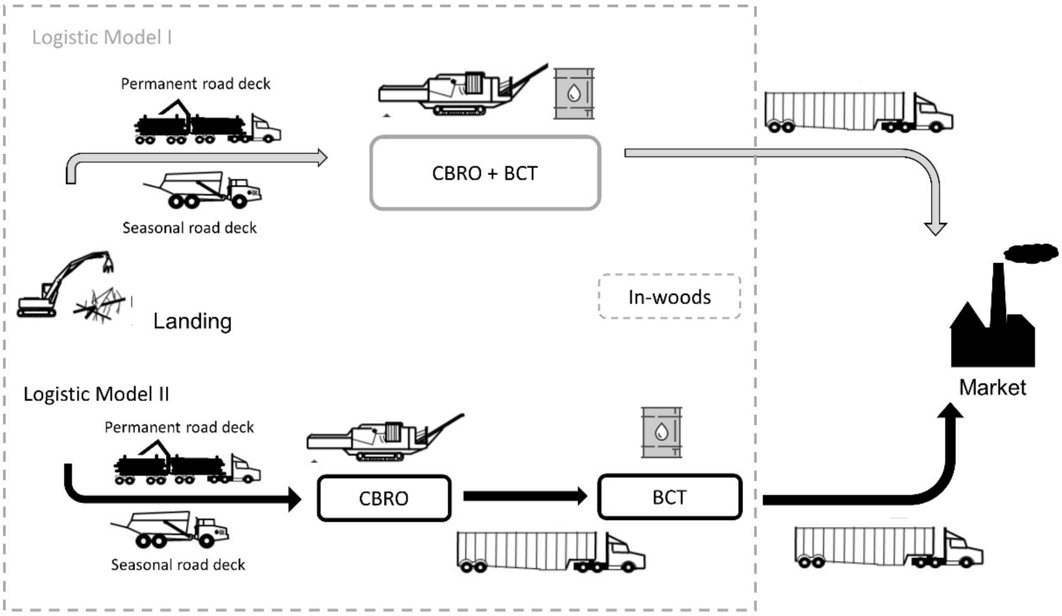

Figure 2. Graphical representation of the two logistics models (LM) I and II.

Table 1. Spatial requirements (in hectare) associated with each logistics model (LM) and associated scenarios adopted from Biomass Research Development Initiative final report [38]. CBRO and BCT denotes centralized biomass recovery operation and biomass conversion technology, respectively.

		Without Storage [1]		With Storage	
		CBRO Sites	BCT Sites	CBRO Sites	BCT Sites
LM I	Scenario I	N/A [2]	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

[1] Without storage (coupled operation) implies sites that had only area for stationing machines and space to store feedstock for one hour of operation. [2] N/A: Not applicable. In LM I; CBRO and BCT operates at the same site.

2.5. Spatial Dataset

The GIS data were comprised of digital elevation model (DEM), hydrology shapefile (distinguishing Stream Classes I, II, and III), roads shapefile based on surface type (paved, rocked, un-paved), and harvest-unit (including all silvicultural management plans and boundaries of harvest units 2014–2015). 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).

2.6. 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 [19].

2.7. 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 WLPZ: Achieved by drawing buffers around the WLPZ and removing areas which overlapped with the harvest units;
3. Steepness of the terrain less than or equal to 3% slope: Digital elevation models were classified;
4. Access to permanent road: Union function was used to find harvest areas that overlapped with permanent roads.

2.8. 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 time of traveling between demand point (candidate harvest units) and facility location (CBRO/BCT/market) to haul all final products (tree-tops/comminuted feedstock/BCT products). Travel time was intentionally selected (rather than travel distance) because most forest trucking operations are limited by the number of daily truck loads. Further, loaded travel time varies considerably based on the type of roads used [6,40]. Maximize market share function was used to select facilities to maximize the market share for 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 specified 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 at 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. In other words, increasing the number of sites past this number will not return a better solution set. This number was found to be in line with a similar study, which cited biomass contractors moved the CBRO locations 24 times per work year [19].

An average travel speed on graveled forest roads was set at 23 km/h [2]. The public road (paved) had legal speed limits ranging between 24 to 89 km/h and averaged 40 km/h.

3. Results and Discussion

There were 138 candidate timber harvest units that met all the criteria, i.e., sites not within a WLPZ and EEZ that 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 (Figure 4). Based on the spatial analysis, LM II had 236 CBRO sites that were located for all scenarios. There were 89–159 and 64–136 sites located for the BCT for LM I and II, respectively (Table 2).

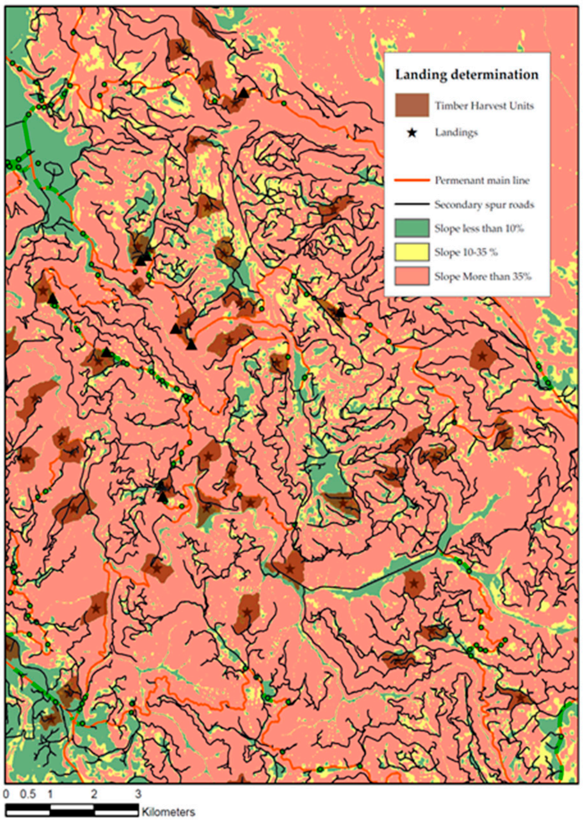

Figure 3. Centralized biomass recovery operation (CBRO) and biomass conversion technology (BCT) sites were determined through a series of geospatial process, which were then used to locate, calculate, and display the locations of recoverable biomass (per harvest unit and CBRO) and harvesting method. Road distance was used to calculate haul route distance.

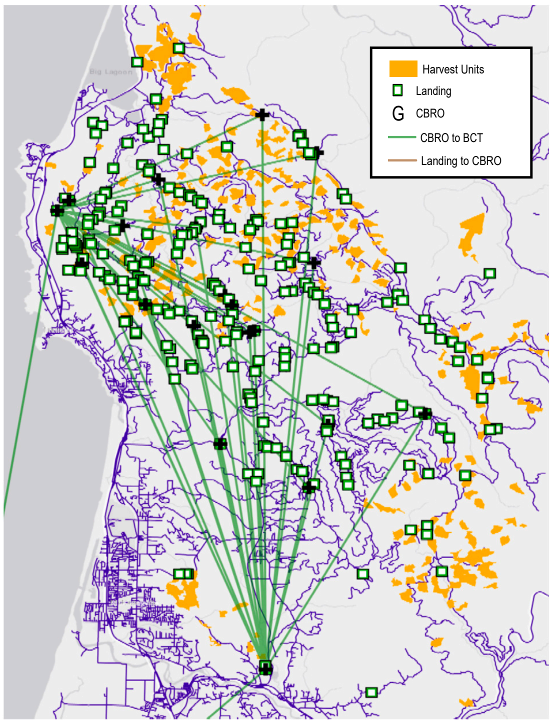

Figure 4. Network analysis results for location-allocation tool for scenario VI. Straight lines are for visualization and haul distances are calculated using road distance.

Table 2. The number of centralized biomass recovery operation (CBRO) and biomass conversion technology (BCT) sites for each scenario within logistics models (LM) I and II, respectively.

		CBRO Sites	BCT Sites
LM I	Scenario I	N/A [1]	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 the BCT sites from the CBRO sites as needed, then Scenario IV and V (LM II) had a storage space of greater than 2.83 ha 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. In other terms, as Scenario I, IV, and V generated higher volumes per ha, the space required to store the large amount of processed feedstock posed as another hindrance for the system to decouple. Further on, the chipper (at the CBRO, for LM I) 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 3). It is to be noted that this travel time would have a drastic impact, as traveling is done on forest roads [6]. However, this could often be 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 were 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) was reduced. Even though logistics were modeled for five moves per season, for actual working conditions, more than two moves per season was not feasible due to the expense incurred during machine movement and site preparation.

Table 3. 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	200	0.64	N/A [1]	N/A	0.82	0.41	201	1.05
	Scenario II	197	0.65	N/A	N/A	0.92	0.46	198	1.11
	Scenario III	510	0.40	N/A	N/A	1.19	0.60	511	0.99
LM II	Scenario IV	1850	0.63	17	0.43	1.18	0.59	1869	1.65
	Scenario V	1124	0.51	20	0.51	1.01	0.50	1145	1.52
	Scenario VI	1468	0.59	22	0.54	1.15	0.58	1491	1.70
5 BCT									
LM I	Scenario I	463	0.61	N/A	N/A	3.15	0.63	466	1.24
	Scenario II	278	0.51	N/A	N/A	3.27	0.65	281	1.16
	Scenario III	510	0.40	N/A	N/A	3.46	0.69	513	1.09
LM II	Scenario IV	1047	0.50	37	0.37	3.18	0.64	1087	1.51
	Scenario V	1017	0.49	55	0.55	2.95	0.59	1075	1.63
	Scenario VI	1211	0.52	52	0.52	3.29	0.66	1266	1.69

[1] N/A: Not applicable for LM I because CBRO and BCT operates at the same site.

3.1. Temporal Nature of the Supply Chain

The supply chains were modeled for 200 (LM I) and 100 days per year (LM II). This represented the actual annual working timeframe in the Pacific Northwest United States because of operational windows for the biomass harvesting. The 200-day-per-cycle working frame was practiced 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 roadsides near or within harvest units. The duration of tree-tops placed at this location shall range 6–11 months, with the intention of minimizing the moisture content to around 9–12% [35–37]. Past research has shown that pre-hauling processed tree-tops from harvest units to permanent road sides can effectively accumulate forest residues at CBRO sites at reduced costs while providing efficient, all year-round access to forest residues [2]. Additionally, the wood residue transportation was much more cost efficient if trucks maximized their usage of permanent roads [40]. 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.

Regarding workflow in such instances, biomass recovery operations in harvest units accessed by seasonal road only will have to be prioritized, as it is only accessible during appropriate season. Following which, units next to permanent roads can be harvested because they would have year-round access.

3.2. Enhancing Efficiency of the Supply Chain

Operational efficiency for the BCT models developed was dependent on the travel time and roads types. Past research has shown that the transportation efficiency of woody biomass was enhanced if trucks maximized their usage of highways [6]. The maximization of desired road type also reduced the repair and maintenance cost for the trucks. However, most of the timberlands were only accessible by gravel or unpaved roads. On the other end of the spectrum, the final markets (i.e., powerplants) had good access to the highways and paved roads. Furthermore, the DEM revealed of the 15,000 km^2 in the county, almost 5300 km^2 had a slope of 30% or more, which would further increase travel time. For this study, the elevation component was not taken into account. Other factors found to influence the efficiency of supply chain logistics of BCT products are as follows.

3.2.1. Scaling Effects

Reducing unit cost of supplying BCT products by increasing the weight or volume of payload. This increased payload can substantiate increase in travel time for transportation to the market. However, total payload weight is subjected to state laws and often acts as an impediment [5,12].

3.2.2. Unit Effect

Reducing cost of transportation by eliminating functions or increasing the economic value of a function. This can be achieved in two aspects: (a) BCT products have higher economic value compared to the conventional forest residue products and (b) back hauling opportunities through cooperation between entities, either within the same industry or between different industries or with suppliers. Studies have shown that backhauling could reduce as much as 20% of the total transport costs [41].

3.2.3. Efficiency Effect

This method involves lowering supply cost without increasing the volume increasing, but by increasing efficiency of various processes within the supply chain. Utilizing better vehicles and routes along with reduction in the loading time and delay at the mills can be a major contributor. It has been confirmed that mill/power plant delay are often very long, especially during peak time, which restricts the number of loads delivered per day [13,14].

3.3. Implications of the Supply Chain on Timber Harvesting Operations

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 [32–34]. This practice has been proved to effectively minimize organic contamination and ash content of feedstock, ultimately improving the final quality of BCT feedstock [42].

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 \$55/BDMT [6]. However, the stump-to-truck cost in industrial timberland operations could range from \$29 to 39/BDMT depending on a variety of reasons including harvesting system, silvicultural prescriptions, and terrain [2,42]. Costs for mobilization of equipment, overhead, and profit allowance were not included in these stump-to-truck cost figures as it can vary between operations and is the standard procedure for estimating harvest operational cost. Hence, under current market price, the procurement area for traditional feedstock is limited to less than 130 km unless the operation is compensated by other financial resources [6]. Here, BCT operation 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. These enhanced values for the energy-densified products could potentially increase the round-trip up to 160 km [43]. 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 [44]. This practice also ensures nutrient recycling. Even though these slash mats are recoverable, the material would be contaminated, therefore not suitable as feedstock 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 137 BDMT/ha), there was still about 73 and 79 BDMT/ha of down woody material left on site for the shovel and cable yard units, respectively [39].

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 that are 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 trucks 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 existing mill sites or industrial log yards favoring a permanent BCT location. This can help in scaling up the production, thereby reducing the total cost of operation. Another benefit of placing BCT equipment at permanent 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.

4. 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 self-loading short log trucks or modified dump trucks can more effectively accumulate forest residues at reduced costs while providing efficient access to forest residues for year-round supply of raw material. Two models, within which were six scenarios, were tested to determine the optimal biomass recovery systems in order to reduce costs and increase productivity of biomass recovery for BCTs. Conclusive results show that all scenarios within each logistics model exhibit either more or less travel time than the other. However, 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 at both the CBRO and BCT locations. However, arranging the CBRO and BCT operations at the same in-wood location reduced the average travel time.

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