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Forest Residues Recovered from Whole-tree Timber Harvesting Operations

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Abstract

Woody biomass in the form of forest residues is a potential source of sustainable renewable energy. However, the amount of these residues recovered from timber harvesting sites is far less than what is actually generated. This study focuses on estimating the amount of forest residues recovered from whole-tree harvesting sites using ground-based shovel logged and cable yarded harvesting systems in northern California. Inventories of standing trees along with pre- and post-harvest downed woody debris (DWD) surveys were used to estimate the total amount of aboveground biomass (AGB) in the study sites. Localized allometric biomass equations were used to estimate the pre-harvest AGB in standing trees. The amount of sawlogs and hog fuel recovered from the harvesting sites was collected from scale tickets. Forest residues delivered compared to the estimated amounts of forest residues generated were 70 percent for the shovel logged unit and 60 percent for the cable yarded unit. The amount of pre- vs. post-harvest DWD estimated from the inventory analysis for the cable and shovel units was increased by 42 and 23 percent, respectively. The methodology used for this study could be applied in other research focusing on determining a more accurate estimate of biomass recoverable from various harvesting systems.

Keywords: Biomass harvesting and supply, Cable yarding, Downed woody debris estimation, Even-aged stand management, Hog fuel recovered, Shovel logging

1. Introduction

Forest harvesting operations such as commercial timber harvest, fire hazard reduction, forest restoration, and pre-commercial thinning typically generate forest residues which are widely regarded as sustainable sources for renewable energy. These residues predominantly come in the form of dead trees, branches, tree tops, chunks, non-merchantable tree species, and small-diameter trees. A general assumption is that for every cubic meter of wood extracted from the forest, another cubic meter of forest residues is left behind (Enters, 2001). Another study - estimated approximately 421 oven dry metric ton (ODMT) equivalent of forest residues generated for every million cubic meters of merchantable timber harvested (Morgan, 2009). Excessive amounts of forest residues lying on the forest floor also pose fire risk and hinder site preparation for tree planting.

Several techniques have been developed to estimate the amount of forest residues left on site in various forest types, yielding a wide range of results. For large areas, remote sensing techniques have been preferred (Huang et al., 2009; Andersen et al., 2011). Other methods have involved models based on Forest Inventory Data, such as EVALIDator, and FIA DataMart tools in combination with allometric equations (Morgan, 2009; USDA, 2015). However, to empirically quantify the amount of forest residues after harvest, conventional techniques such as the planar intercept method are preferred, which employs multiple sampling plots and later extrapolating the downed woody debris (DWD) to the whole region (Oneil and Lippke, 2009).

From a biomass recovery perspective, it is critical to quantify the recoverable amount of forest residues generated in order to predict financial feasibility of the operation and potential revenue. Recoverable forest residues refer to the amount of forest residues extracted, processed, and utilized from timber harvesting operations. Several studies have documented forest residues recovered from timber harvest sites. Perlak et al. (2005) estimated recovery rates approximately 65 percent of forest residues with current timber harvesting practices. Another study based on the Biomass Opportunity Supply Model (BiOS), a software program developed to estimate recoverable forest residues, assessed between 5.5 and 50 percent recovery rates from whole-tree (WT) even-aged harvesting (Ralevic et

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al., 2010). In eastern Washington, USA, the average recoverable biomass across all regions, owners, and forest types was estimated at an equivalent of 43 green metric tons (GMT) per ha for commercial harvesting operations and 61GMT per ha for small-diameter tree harvests. In this case, even though 30 percent of the total forest residues harvested were accessible, only 20 percent were recoverable (Oneil and Lippke, 2009). These findings highlight that all accessible forest residues are not necessarily recoverable.

There are several limitations to the extraction of forest residues that can be broadly divided into three categories: technical, economic, and social/environmental constraints (Hohl et al., 2013; Parzei et al., 2014). Technical constraint is the inherent inability to access and/or process forest residues with current equipment. For example, it may not be feasible to harvest residues on steep slopes (more than 40 percent). In other cases, woody biomass could be accessed using current technologies, but it may be too far from a road or too dispersed throughout the harvest unit to make it economically feasible (i.e., operation cost being more than the market price). Finally, some biomass projects may be technically accessible and economically viable, but are unlikely to be socially or environmentally acceptable, such as forest residues harvested from late successional forest stands. Hence, models developed in the past to estimate the actual amounts of recoverable forest residues have incorporated a variety of "data filters" to address some of these constraints (Morgan, 2009). Factors affecting the recoverable quantity of forest residues include (Ralevic et al., 2010):

- Degree of utilization (species harvested, topping diameter, and merchantable products extracted)
- Silvicultural objectives, harvesting system and methods
- Regional or local conditions (site quality, stand conditions and species)
- Access, site conditions, seasonal factors, etc.
- Maximum allowable delivered price

Among the factors listed, harvesting system plays a significant role in determining the quantity of forest residues recovered. In ground-based harvesting systems utilizing whole-tree method, the majority of forest residues are concentrated at log landings, but some residues inevitably stay at the felling site and along trails. However, it is also a common practice to place some forest residues on the machine trails (referred to as a "slash mat") to minimize soil compaction (Mann and Tolbert, 2000). The resulting slash mat, while recoverable, may often be rendered unusable because of dirt, rocks, and other contamination (Oneil and Lippke, 2009). In cable yarded harvesting systems, located on steeper terrain (more than 40 percent slope), the units are often limited by landing space, thus making piling of biomass at the landing a challenge. The forest residues generated in these steep units are often windrow piled along road sides or pushed back into the units.

The objective of this study was to estimate and inventory the amount of forest residues that could be recovered from an integrated whole-tree even-aged management operation using cable yarded and ground-based shovel logging harvesting systems. The amount of DWD left on the ground from the operations were also compared between the two harvesting systems. While the results provided by the study might be more site specific, the methodology developed could easily be adapted to other locations and utilized by forest managers and researchers for estimating the actual amount of recovered forest residues from various harvesting systems and methods.

2. Materials and Methods

2.1. Definitions used in this study

Biomass: All biological material from living or dead trees present in the harvested units, including sawlogs, non-merchentable tree species and small-diameter trees, and forest residues.

Forest residues: All biomass other than sawlogs generated during the timber harvest. Grinded hog fuels were the final product from recovered forest residues.

Non-merchantable tree species: Hardwood species such as tanoaks (*Lithocarpus densiflorus*) and red alder (*Alnus rubra*) are currently not in demand in the sawlog market and can be comminuted to create hogfuels.

Small-diameter trees: Trees of both non-merchantable and sawlog species having a diameter at breast height (dbh) less than 20 cm that are available for comminution (processing) to produce hogfuels.

Sawlogs: Merchantable trees above 20 cm dbh, which will eventually be processed at a saw mill.

Standing trees: Sawlogs, non-merchantable tree species, small-diameter trees, and dead trees found in the stand.

Recoverable forest residues: Actual amount of forest residues that are comminuted and sent to the power plants for energy production.

2.2. Stand conditions and harvesting operations of sawlogs and biomass

The study sites were two even-aged management units on an industrial timberland property in Humboldt County, California (Figure 1). The site consisted primarily of even-aged (averaging 60 years) second- and third- growth coast redwood (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga menziessii*), western hemlock (*Tsuga heterophylla*), and tanoak (*Lithocarpus densiflorus*). The sites were about 220 to 460 m above mean sea-level and the terrain had ground slopes up to 111 percent (48°). The climate for the region is characterized by maritime influence from the Pacific Ocean, and receives approximately 1200 mm of rain annually, with an average temperature of around 11° C (Western Regional Climate Center, 2009)

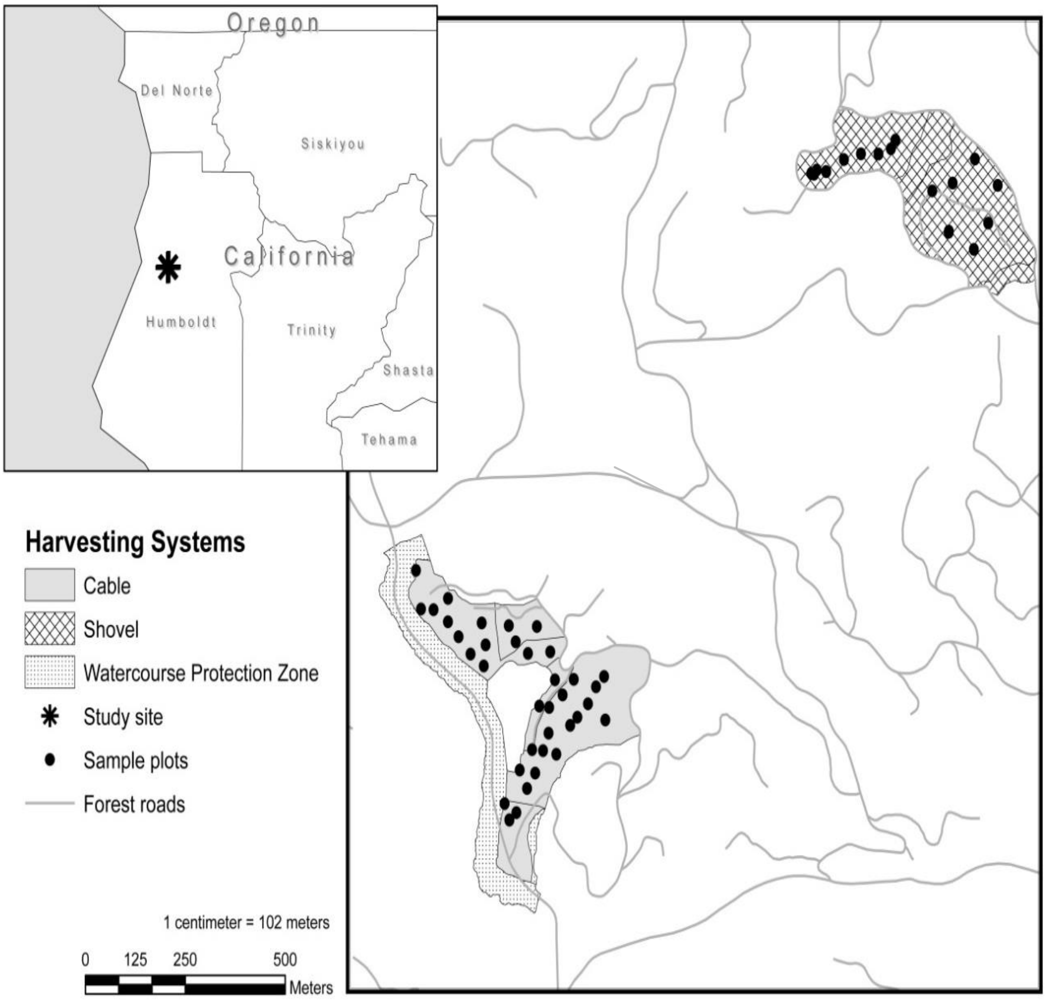

Figure 1. Study units for the biomass recovery study located in Humboldt County, California.

Two whole-tree harvesting systems were applied on the study units (Table 1): shovel and cable yarding. The harvest operations took place over two years starting in the fall of 2012. Operations for the shovel logged unit included falling and bunching with a feller-buncher, swinging the felled trees to the roadside with a John Deere 3554 shovel machine, and processing timber with a dangle-head processor at the roadside. In the cable yarded unit, tree felling was done manually using a chainsaw. A Skagit GT3 swing yarder was used for yarding the logs uphill and a Linkbelt 3400 Quantum loader was used for loading. Processing was done at the landing using a John Deere 892 with a dangle-head processor. For both units, non-merchantable species as well as small-diameter trees were brought along with the sawlogs to the landing. The main intention behind bringing the non-sawlog trees to the landing was to reduce fuel loads in the unit and further facilitate re-planting. Other forest residues left on the landing sites included residues from processing sawlogs and materials broken off during yarding.

During the biomass recovery operation in the ground-based shovel logging unit, a loader collected forest residues within the unit and landing. However, steep terrain in the cable yarded units was inaccessible to the loader. A modified dump truck was used to transport the forest residues from the unit to a grinding site. The ground materials (hog fuel) were later hauled to local wood-based power plants.

Table 1. Descriptive statistics related to terrain features of the study area.

	Shovel	Cable
Area (ha)	8.3	10.9
Ground slope range (%)	3-37	0-50
Average slope (%)	22	31
	Number of sampling plots taken	
Pre-harvest [a]	15	19
Post-harvest [b]	17	32

[a] *Downed Woody Debris (DWD) survey and timber cruise plots taken before harvest*
[b] *DWD plots sampled after harvest*

2.3. Data collection

Prior to harvesting, all units were sampled to estimate the total aboveground biomass (AGB). The AGB sampling was divided into standing trees and downed woody debris (DWD). The standing biomass (live and dead trees) was estimated by timber cruising, while DWD was estimated using the planar intercept method (Brown, 1974). Planar intercept method was chosen over line intersect method because DWD of all sizes was to be inventoried. Both components were sampled using 11m line transects for 0.04ha fixed-radius circular sampling plots. These plots were located at evenly spaced points 76m apart on transects lines drawn at random azimuths. The total amount of DWD was estimated from the number of intersections made by wood pieces with the transect line.

The line transects for the DWD summarized the surface biomass components into four diameter classes: Class I - less than 0.62cm, Class II - 0.62 – 2.51cm, Class III - 2.51– 7.59cm, and Class IV - above 7.62cm. The diameter and decay state for Class IV pieces were recorded. Decay states were largely qualitative indicators based on the physical appearance and structural integrity of individual pieces and were divided into sound and rotten. The slope of the transect line along with the depth of forest residues in the soil was also documented. The DWD estimates were calculated using the Equation 1 and 2 (Brown, 1974).

$$Amount\ of\ DWD\ (Class\ I\ to\ III) = \frac{11.64 \times n \times d^2 \times s \times a \times c}{Nl} \quad (1)$$

$$Amount\ of\ DWD\ (Class\ IV) = \frac{11.64 \times n \times \sum d^2 \times s \times a \times c}{Nl} \quad (2)$$

Where, n = total number of DWD material intersected with the transect; d^2 = squared average quadratic-mean diameters (Class I materials = 0.08cm^2, Class II = 1.79cm^2, and Class III = 18.26cm^2); for Class IV materials, Equation 2 was used where, $\sum d^2$ = sum of squared diameter of each intersected piece; s = specific gravity for conifers (Class I materials = 0.48, Class II = 0.48, Class III = 0.40, Class IV (Sound) = 0.40, and Class IV (Rotten) = 0.30); a = average secant of non-horizontal particle angles for correcting orientation bias for pre-harvest DWD materials (Class I = 1.15, Class II = 1.13, Class III = 1.10, and Class IV = 1.00), and for post-harvest DWD materials (Class I = 1.40, Class II = 1.13, Class III = 1.10, and Class IV = 1.00); Nl = total length of sampling line (Classes I and II = 2m, Class III = 3m and Class VI = 11m); and c = correction factor. Equations 1 and 2 estimated the DWD in tons per acre which was later converted to oven dry metric ton (ODMT) per ha assuming a 50 percent moisture content.

Following harvest, each plot was re-sampled using the same line transect for estimating post-harvest DWD. However, during timber harvest operation, large wood material (Class IV) was often relocated within the stand due to machine movement and tended to accumulate in greater densities at the landing or roadside due to processing. Therefore, additional transects were sampled at a higher sampling intensity to better capture the variation between the pre- and post-harvest DWD (Table 1). DWD amounts were also estimated from the inventory created for the forest residues and compared with the DWD survey estimates.

The timber cruise recorded species, height, and diameter at breast height (dbh) for all standing trees over 2.54cm (Table 2). Allometric equations for Northwestern Pacific region of the US were utilized to estimate standing AGB for individual tree species (Table 3). The major criteria (i.e., dbh range and ecoregion classification) were satisfied for all the localized biomass allometric equations used.

Table 2. A summary of timber cruise for the biomass recovery study units on a per hectare basis.

	Material *	Shovel	Cable
Basal area (m^2/ha)	S	9	9
	NM	4	2
	D	0.4	1
	SD	0.5	2
Trees density (number of trees per ha)	S	75	84
	NM	45	42
	D	17	23
	SD	126	194
Average DBH (cm)	S	35.4	37.1
	NM	30.5	24.7
	D	14.1	14.4
	SD	9.4	10.2

**S- Sawlog trees, NM– Non-merchantable tree species,*
D- Dead trees, SD– Small-diameter trees

Table 3. Allometric equations used to estimate the standing aboveground biomass for the major tree species for this biomass recovery study

	Regions	Total aboveground biomass	Biomass in tree component
Douglas-fir[a]	Pacific Northwest	= EXP(-2.8462+1.7009*LN(DBHcm))+	foliage
		EXP(-3.6941+2.1382*LN(DBHcm))+	live branch
		EXP(-3.529+1.7503*LN(DBHcm))+	dead branch
		EXP(-3.0396+2.5951*LN(DBHcm))+	bole wood (without bark)
		EXP(-4.3103+2.4300*LN(DBHcm))	bark
western hemlock[a]	Pacific Northwest	= EXP(-4.13+2.128*LN(DBHcm))+	foliage
		EXP(-5.149+2.778*LN(DBHcm))+	live branch
		EXP(-2.409+1.312*LN(DBHcm))+	dead branch
		EXP(-2.172+2.257*LN(DBHcm))+	bole wood (without bark)
		EXP(-4.373+2.258*LN(DBHcm))	bark
tanoak[b]	S.W. Oregon and N.W. California	= EXP(-0.3169+2.2774*LN(DBH inches))+	live crown
		EXP(-2.4895+2.0374*LN(DBH inches))+	dead branches
		(EXP(-3.2751+2.5010*LN(DBH inches)) *41.62)	total volume of bole
Pacific madrone[b]	S.W. Oregon and N.W. California	= EXP(-0.7881+2.4839*LN(DBH inches))+	live crown
		EXP(-2.3938+2.2936*LN(DBH inches))+	dead branches
		(EXP(-2.8331+2.2969*LN(DBH inches)) *40.33)	total volume of bole
red alder[b]	S.W. Oregon and N.W. California	= EXP(-1.329+2.6232*LN(DBH inches))+	live crown
		EXP(-4.3788+2.6243*LN(DBH inches))+	dead branches
		(EXP(-2.9326+2.4999*LN(DBH inches)) *25.58)	total volume of bole
coast redwood[c]	Northern California	= AntiLog10(-1.9123+2.3651* Log10(DBHcm)+0.0054)	total aboveground biomass

[a] *Gholz et al., 1979.*

[b] *Snell and Little, 1983.*

[c] *Kizha and Han, (submitted to For. Sci. Rev).*

Where EXP is exponential, LN is the natural logarithm, Log10 is the logarithm with base 10, DBH is diameter at breast height, and 666.7kg/m^3, 645.7kg/m^3, and 409.7kg/m^3 is the average oven dry density for tanoak, Pacific madrone, and red alder, respectively. Weights in oven dry kg were converted into ODMT.

Allometric equations for Douglas-fir and western hemlock estimated the AGB in green weight (Gholz et al., 1979), which was then converted to ODMT. For tanoak and Pacific madrone (*Arbutus menziesii*), the volume of bole derived from allometric equations was converted to ODMT using density factors (Snell and Little, 1983). For coast redwood, equations to predict AGB were developed using destructive sampling techniques. The amount of sawlogs and hog fuel hauled from the sites was obtained for each harvest unit from respective scale tickets.

2.4 Equations used for biomass inventory and recovery analysis

2.4.1. Forest products inventory

Several equations were used on a per hectare basis to inventory the amount of sawlogs and forest residues produced from the harvest units. Allometric equations were used to estimate the total amount of AGB for standing trees (Table 3).

Total amounts of forest residues were estimated by summing the total AGB in non-merchantable species, small-diameter trees, and dead trees, along with the residues generated during timber processing. The residues from timber processing (tops, limbs, chunks, and other slash material) were calculated as the difference between the estimated total biomass in sawlog trees and the sawlogs delivered to the mill obtained from scale tickets (Equ. 3). Forest residue recovery rate was calculated as a percent of the total forest residues delivered to the total amount estimated (Equ. 4).

The total standing biomass was the biomass present all of the standing trees. The total biomass recovery percentage was again calculated as a ratio of the total forest products delivered (sawlogs and hog fuel combined) to the estimated total standing biomass (Equ. 5).

$$\begin{aligned}&\mathit{Forest\ residue\ from\ timber\ processing} = \\ &\mathit{Total\ biomass\ in\ sawlog\ trees} - \mathit{Sawlogs\ delivered}\end{aligned} \tag{3}$$

$$\mathit{Forest\ residues\ recovery\ rate}\ \% = \frac{\mathit{Hog\ fuel\ delivered}}{\mathit{Forest\ residue\ estimated}} \times 100 \tag{4}$$

$$\mathit{Total\ biomass\ recovery\ rate}\ \% = \frac{\mathit{Forest\ products\ delivered}}{\mathit{Total\ standing\ biomass}} \times 100 \tag{5}$$

2.4.2. DWD inventory

DWD generated during the timber harvest operation was calculated using two approaches. At first, DWD on a per hectare basis was estimated from the planar intersect survey by finding the difference between the average post-harvest DWD and pre-harvest DWD from the sample plots (Equ. 6).

In the second approach, DWD left on the site after harvest was estimated from the inventory (Equ. 7). As the planar intersect survey could not efficiently estimate the overall amount of DWD generated due to the harvest, the total unaccounted DWD was calculated by subtracting the DWD (survey) from the DWD (inventory) and reported in ODMT per ha (Equ. 8). Additionally, a percentage of unaccounted DWD was also developed (Equ. 9).

$$DWD\ (survey) = Post\ harvest\ DWD - Pre\ harvest\ DWD \quad (6)$$

$$DWD\ (inventory) = Forest\ residue\ estimated - Hog\ fuel\ delivered \quad (7)$$

$$Unaccounted\ DWD = DWD\ (inventory) - DWD\ (survey) \quad (8)$$

$$Unaccounted\ DWD\ \% = \frac{DWD\ (inventory) - DWD\ (survey)}{Estimated\ amount\ of\ forest\ residues} \times 100 \quad (9)$$

2.5. Statistical analysis

Analysis of variance (ANOVA) was used to determine if significant differences ($p < 0.05$) existed in species composition, mortality, AGB for standing trees (ODMT per ha), and the various DWD classes (ODMT per ha) among the different units prior to harvesting. The post-harvest DWD means were later compared with the pre-harvest DWD means to examine if there was a significant difference due to the harvest. All the assumptions for parametric statistical tests were met. ANOVA was also done to analyse if differences existed in DWD, by diameter Classes I– IV and decay states, due to the treatments. If a significant difference was detected, Tukey-Kramer post-hoc test was performed to confirm where the differences occurred between groups. SPSS statistical software package (IBM SPSS Version 21) was used for all the analyses.

3. Results and Discussion

3.1. Actual hog fuel recovered

Higher amounts of forest residues were recovered from the ground-based shovel logged unit (157 ODMT per ha) compared to the cable yarded unit (110 ODMT per ha; Table 4). This situation can be attributed to better machine accessibility within the stand due to its gentle slope. The slash material left behind in the cable yarded unit could assist in stabilizing the forest soil in steeper terrain and further enhance the nutrient content in the soil (Brown et al., 2003).

The percentage of total forest products delivered versus total standing biomass estimated was 86 and 83 percent for the shovel and the cable yarded units, respectively (Table 4). Results from ANOVA done on the timber cruise showed there were no significant differences in the pre-harvest volume and mortality rate among the various units ($p = 0.423$ and 0.648). However, there was a significant difference in the species composition among the units ($p < 0.05$). Shovel logged units had more non-merchantable species compared to the cable yarded unit. Both shovel and cable units, were dominated by tanoak, coastal redwoods, and Douglas-fir (Figure 2). But both units had no difference in the AGB for the non-sawlog trees ($p = 0.562$) (Table 2).

Table 4. Inventory of forest residues recovered from two harvest units, shovel logged and cable yarded, in oven dry metric tons per hectare (ODMT per ha). Allometric equations were used to estimate the biomass values prior to harvest and delivered values from scale tickets.

	Shovel		Cable	
	Forest residues [a]	Total standing biomass	Forest residues [a]	Total standing biomass
	ODMT per ha			
Estimated	224	466	182	417
Delivered	157	399	110	345
	Percentage			
Recovery rate	70	86	60	83

[a] *Biomass generated from small-diameter trees, non-merchantable species(< 20 cm dbh), dead trees and limbs, tops, and chucks generated from sawlog processing.*

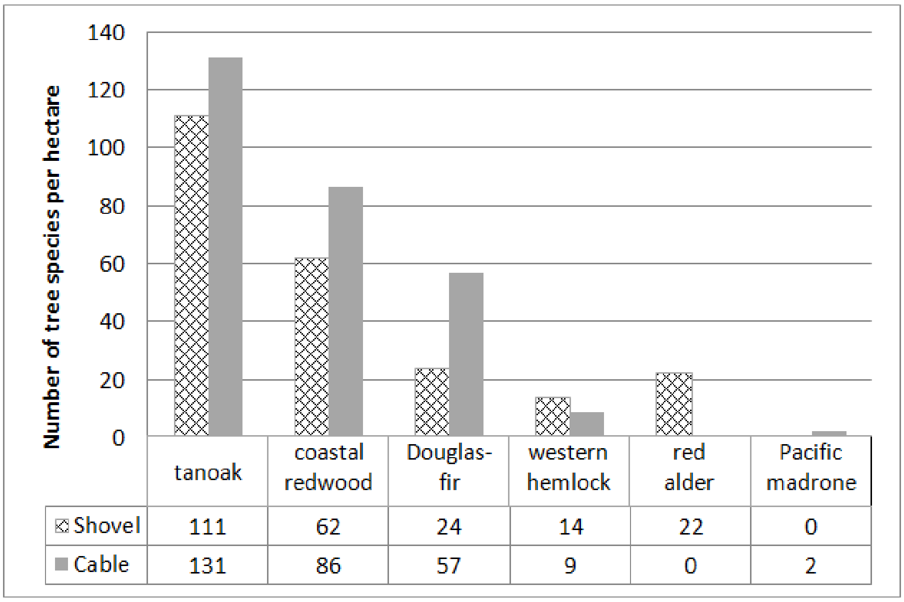

Figure 2. Species composition and stand density (number of trees per ha) for the two study units.

3.2. DWD survey

ANOVA done on the pre- and post-harvest DWD plots showed there was a significant difference for the first three diameter classes (Classes I to III: $p < 0.05$; Table 5). There was no significant difference in Class IV, and total amount of DWD for pre- and post-harvest for the two units ($p = 0.327$ and 0.942). This could be explained by closely observing the biomass recovery operation. In general, it was the large diameter wood pieces (Class IV) that were collected during the post-harvest biomass recovery operation, while other small wood pieces (Classes I to III) were usually left behind unless they were bundled. Again, there was a high probability for the small sized wood pieces (Classes I to III) to break off from the main branch and remain in the unit during the various timber harvesting operations, especially primary transportation (i.e., shovel swing or cable yarding).

The Tukey–Kramer post-hoc test showed a significant difference between the shovel logged and cable yarded post-harvest plots for the diameter Classes I, II, and III ($p < 0.05$) suggesting that increased amounts of small-diameter wood pieces were left on the ground in the cable yarded unit. These twigs along with the needles left on the ground were the tree components richest in nutrients. Furthermore, they decompose faster and could be considered as a significant source of nutrients (Wall and Hytönen, 2011).

While conducting this analysis, it was observed that the total DWD estimates in the pre-harvest DWD survey were highly influenced by a few or even one large diameter wood piece (>38 cm). These old logs were intentionally left behind from a previous operation, as a part of a habitat conservation plan and dead wood management plan. The majority of these large diameter wood pieces remained intact during operation; hence they were not of major concern in most sampling plots. However, in some plots these large wood pieces were moved (out of transect line) during operations. As a result, the total post-harvest DWD was less than that of the pre-harvest for the cable unit, which was contrary to the situation in the field.

Additionally, in the cable yarded unit, there were large diameter wood pieces surveyed during the pre-harvest that could not be accounted for in the post-harvest as they were buried over 75 percent in the soil. Hence, large diameter logs (>38cm) in the pre-harvest DWD survey which were buried in the ground or outside the transects in the post-harvest were noted. These plots were re-sampled to inspect these missing logs. The exclusion of these large diameter logs reduced the average pre-harvest DWD for all units by approximately 31 ODMT per ha.

High amounts of DWD were estimated for shovel units during post-harvest survey because five of the 15 plots were located in the landing area. Such cases have been reported in previous studies (Huang et al., 2009), where following major disturbance events (e.g. logging, fire, insect mortality, windstorms, etc.), large inputs of DWD occurred. Taking this into consideration, additional DWD plots were sampled post-harvest to increase the accuracy of the estimates because a limited number of sample plots may not provide reasonable estimates of the heterogeneity in DWD after a timber harvest operation (Birdsey, 2004).

The post-harvest DWD estimate from the planar intercept survey did not align with the DWD estimated by the inventory analysis (Table 6). This further led us to investigate the unaccounted DWD generated during the operation. Results showed that around 23 percent for shovel and 42 for cable units' total DWD present on the floor was not accounted for by the DWD survey. A good portion of the missing DWD could be potentially present in the piles left at the landing in both units. However, this could not be gauged as the piles were not sampled. Additionally this could also be attributed to the previously mentioned situation during the DWD survey.

Table 5. Average pre- and post-harvest downed wood debris (DWD) survey results estimated in oven dry metric ton per hectare (ODMT per ha).

	Shovel		Cable	
	Pre	Post	Pre	Post
Class I	0.85	0.70	0.61	1.52
Class II	2.79	4.39	2.23	4.77
Class III	2.70	7.57	2.34	8.37
Class IV Sound	86.80	65.32	37.80	22.53
Class IV Rotten	14.94	44.69	47.74	48.17
Total	108.08	122.68	90.72	85.36

Table 6. A summary of downed woody debris (DWD) surveys estimating the average amount of woody materials in oven dry metric ton per hectare (ODMT per ha) left on the forest floor post- and pre- harvest. The percent changes were calculated as a ratio of pre-harvest DWD to the post-harvest DWD.

	Shovel	Cable
	ODMT per ha	
Post-harvest survey	123	85
Pre-harvest survey	108	91
DWD (survey) [a]	15	-6
Percentage change	11%	-6%
DWD (inventory) [b]	67	72
Unaccounted DWD [c]	53	77
Percentage of unaccounted DWD	23%	42%

[a] *DWD (survey) = Post harvest DWD – Pre harvest DWD*
[b] *DWD (inventory)=Forest residues estimated – Hog fuel delivered*
[c] *Unaccounted DWD = DWD (inventory) – DWD (survey)*

3.3. Allometric equations

The accuracy in estimating the actual amount of biomass in standing trees was a crucial component for this study. While determining the percentage of the forest products recovered, the biomass in standing trees and the bole (stem) was needed to be accurate to predict the pre-harvest amounts. There were numerous allometric biomass equations available for predicting the total AGB. Therefore, priority was given to the dbh range, eco-region, stand condition, and R^2 during the selection. Comparison between the national-level allometric equations developed by Jenkins et al. (2003) and localized equations showed that the former was 16-20 percent more than the localized equation (Table 7). Previous studies have also recorded this inconsistency in AGB when using generalized equations for smaller areas (Fried and Zhou, 2008).

3.4. Impacts on management and limitations of the study

Recovery rates of forest residues could be effectively estimated using available allometric equations and information from scale tickets. However, forest products inventory and potential amount of forest residue supply based on models usually over-estimate the supply (Hohl et al., 2013; Parzei et al., 2014). This study showed that actual forest residues recovered from whole-tree timber harvesting sites were 40 and 30 percent less than the estimated forest residues generated for cable yarded and ground-based timber harvesting systems, respectively (Table 4). Nutrient impacts from biomass removal were of less concern because even after the forest residue recovery operation, the DWD (inventory) analysis showed that almost 67 and 72 ODMT per ha of biomass was left on site for the shovel and cable yard units, respectively (Table 6).

The planar intercept method (Brown, 1974) commonly used for estimating residual DWD, was not an effective method for this study. Several large diameter materials during post-harvest DWD sampling, were not accounted for because they were 75 percent buried in the ground. Furthermore, several plots were used for piled materials during the operation, especially in the shovel logged unit, which resulted in overestimates in some plots. Conversely, there were other plots used as spur roads during harvest, therefore having no DWD. Movement of large diameter logs within the sampling plots during the operation also influenced the total amount of DWD estimation.

Table 7. Comparing the total estimates predicted for the total standing biomass from national generalized Jenkins et al. (20003) equation (GE) and localized allometric equations (LE) in oven dry metric tons per hectare (ODMT per ha) using a systematic sampling method including 0.04 ha fixed-radius plots.

	Shovel	Cable
	OMDT per ha	
Generalized equation (GE)	554	521
Localized equation (LE)	467	417
Percentage difference [a]	16%	20%

4. Conclusion

Several studies have tried to estimate the forest residue generated from a timber harvesting operation using various models and methods. This study showed that the actual amount of forest residue delivered was less than the estimated amount. Therefore, forest products recovery rates should be based on both the estimates of standing tree biomass and actual amounts of forest products delivered. Additionally, the amounts of hog fuel recovered from the ground-based harvesting sites were higher than those from the cable yarded units. The DWD analysis done on the inventory of the forest residues showed an increase in total post-harvest DWD for the units. However, this trend was not captured in the DWD post-harvest survey for the cable yarded units. The study could be further strengthened by employing a DWD sampling method which allows accounting for the buried and dislocated large wood pieces within the plots.

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