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**Comparison of geospatial and ground-based methods for
determining post-harvest dispersed woody residues.**

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Abstract

Post-harvest woody residues are measured to estimate billable waste, bioenergy potential, fuel loadings, and carbon budgets. In fall 2014, a waste and residue survey (WRS) established 29, 0.4ha plots in the dispersed residue stratum on two cutblocks on Vancouver Island, British Columbia and measured woody residue “logs” $\geq 10\text{cm}$ diameter inside bark and $\geq 20\text{cm}$ length. A line-intersect sampling (LIS), spring 2015, measured all woody debris $\geq 10\text{cm}$ diameter outside bark (DOB) on 18 plots. High-resolution (2cm) photography was acquired in summer 2015, orthophotomosaics prepared and analyzed for residue “logs” $\geq 10\text{cm}$ DOB in 29 plots using semi-automated “log” delineation (SLD) and manual heads-up “log” digitization (MLD). After adjustment for bark thickness SLD values were still higher than WRS, due to inclusion of non-log pieces, though MLD values were not. LIS values were not different from WRS once adjusted for bark thickness, transect overlaps, and decayed or non-log pieces excluded. The LIS and pre-harvest forest cover species composition differed from the WRS. While the SLD geospatial method can census $\geq 10\text{cm}$ diameter residues in entire cutblocks, it was biased. Field-based methods may be required to correct SLD bias and measure species composition to determine bark thickness and wood densities to calculate biomass from residue volumes.

Keywords

Unmanned aerial vehicle, high resolution orthophotomosaics, automated log delineation, line-intersect sampling, forest waste and residue survey, woody debris

50 Introduction

51 Accurate estimation of post-harvest woody residues that are left dispersed on site is
52 critical for several reasons including: the calculation of bioenergy potential, determining harvest
53 efficiencies, calculation of billable waste, fire fuel loadings, and estimation of carbon budgets
54 (Trofymow et al. 2014, 2017). Post-harvest woody residues maybe left dispersed across a
55 cutblock or found in accumulations near the roadside where felled trees have been processed to
56 logs. Roadside residues may be subsequently piled and burned on site, decked for later removal
57 for use as firewood or chipped for transport to bioenergy facilities. Increased interest on
58 quantifying the amounts and use of post-harvest residues for bioenergy is occurring as they
59 represent one way that the forest sector can help mitigate climate change. Smyth et al. (2017)
60 estimated that for Canada, over a 33 year period that use of an estimated 7.1 TgC yr⁻¹ harvest
61 residues in local bioenergy facilities could have a positive cumulative mitigation potential of 429
62 Tg CO₂e by 2050. The primary benefit in use of residues for bioenergy comes from their potential
63 to offset emissions from burning fossil fuels, and, if otherwise slash burned, represented one of
64 the best of seven possible forest management strategies analyzed for climate change mitigation
65 in Canada (Smyth et al. 2014).

66 Amounts of post-harvest residues will vary with stand type and forest region. Dymond et
67 al. (2010) estimated for Canada’s managed forest below 60° latitude, production of 20 ± 0.6Tg
68 year⁻¹ of harvest residues available for bioenergy feedstocks (includes a 50% netdown for social
69 and ecological purposes). Gross harvest residue biomass densities (oven dry (OD) tonnes ha⁻¹)
70 were lowest in eastern boreal forests (10-20), intermediate in western boreal (20-35), and
71 highest in BC coastal forests (35-70). Harvest residue densities can vary over time as utilization
72 levels change. MacDonald (2009) found in four forest districts on Vancouver Island that the mean
73 biomass density of dispersed harvest residues tripled (22 ± 3.8 to 63 ± 12.5) over the period 2002
74 – 2007. The ratio of dispersed residue volume to merchantable volumes ranged from 7-11% in
75 old-growth stands and 8-10% in second-growth stands, however MacDonald (2009) noted that
76 ratios were higher in interior BC and Alberta stands as a greater fraction of the volume and
77 biomass of smaller trees was non-merchantable tops. Across the 110 supply areas on Vancouver
78 Island and South Coast, MacDonald estimated that the harvest of 19.6M m³yr⁻¹ in this region
79 resulted in 1.743M m³ dispersed, 1.163M m³ roadside and 0.4M m³ dryland sort harvest residues

(697,000, 465,000, 160,000 ODt yr⁻¹, respectively). Roadside and dryland sort represented ~half of the total harvest residues, but because of accessibility were likely to be the most economically viable source of residues for bioenergy purposes.

Field-based methods are the current norm for assessing the amounts of dispersed down woody materials on a site and the method and terminology used may be affected by the purpose of the inventory. Woody debris and forest fuels refers to all down woody materials on a site, derived from tree stems “logs”, tops, branches, twigs, and overturned stumps with attached roots (Woodall and Monleon, 2008) and in the National Forest Inventory (NFI) methodology, data are grouped by diameter class (eg. fine ≤ 1.0 cm, small > 1.0 cm to ≤ 7.5 cm, medium coarse > 7.5 cm to ≤ 30.0 cm, and large coarse woody debris > 30.0 cm) and decay class (eg. 1 – intact; 2- bark mostly intact, some sapwood decay; 3- trace bark, extensive sapwood decay, 4- no bark, heartwood decay, log mostly round and in full contact with ground; 5- no bark, extensive decay, log oval and sunken into ground) (Canadian Forest Inventory Committee 2008). Woody residues refers to down woody material left on site after harvest and in waste and residue surveys consists of stemwood pieces, “logs”, that meet a certain diameter and length criteria, and excludes pre-harvest decaying and small diameter wood. For some bioenergy inventories, branch wood is also included in assessments of post-harvest woody residues (Spencer and Röser, 2017). All are sample-based methods and include fixed area plots where all woody residues in a number of plots are scaled (B.C. Ministry of Forest and Range 2005, Forest Inventory and Analysis 2011) or point-based line-intersect samples to estimate woody debris volumes from diameter measurements taken where a piece crosses a transect line (Van Wagner 1968, Marshall et al. 2003, Gregoire and Valentine 2008) or plane (Brown et al. 1974). The British Columbia Waste and Residue Survey (WRS) (B.C. Ministry of Forest and Range 2005) uses a systematic random layout of 0.4ha fixed area plots for the scattered dispersed residues stratum, however this can be labour intensive and costly given the appropriate number sample plots needed to estimate the mean residue volume density ($\text{m}^3 \text{ha}^{-1}$) for a cutblock. Woldendorp et al. (2004) mapped all woody debris in 1ha plots to test efficacy of fixed-area sample plot size and found that a 20x20m quadrat was adequate in Australian forests but that a 50mx50m quadrat was needed in woodlands where woody debris was sparse.

Line-intercept sampling (LIS) methods were initially developed for measuring forest fuels to assess fire hazard from post-harvest slash (Van Wagner 1968), fuel consumption with prescribed burns (Ontario Ministry of Natural Resources 2013, Harrington 1987) as well as for quantifying amounts of woody debris in ground plots in national (Canadian Forest Inventory Committee 2008, Woodall and Monleon, 2008, Forest Inventory and Analysis 2011) and regional (Alberta Biodiversity Monitoring Institute 2014, Marshall et al. 2003) forest inventory programs. Obtaining accurate values with the method requires consideration of the total transect length (Harmon and Sexton 1996), number of lines used and the non-random distribution of logs in some harvest situations. Pickford and Hazard (1986) found that to estimate values within $\pm 10\%$ of the 95% confidence of actual wood volume, line intercept methods would require 235 lines, measuring 38.10m long each (8953.50m of line total). Others (Ståhl 2002, Brissette et al. 2003) have found that non-random distribution of logs can overestimate woody debris volume, if sample lines are laid perpendicular to the orientation of woody debris in a study area.

Geospatial methods could potentially be less labour intensive than field methods and would allow for a full census of residues in an entire cutblock. However, the efficacy of new methods requires testing and comparison with accepted methods. Data derived from manual digitization of logs from aerial imagery (Richardson and Moskai 2016, Blanchard et al 2011) or mapping of woody debris in the field (Woldendorp et al. 2004, Pesonen et al. 2009) have been used to verify or test the efficacy of other automated or field sample-based methods, respectively, for determining down woody debris. Using remote sensing technologies, Trofymow et al. (2014) presented a method to determine piled woody residue volumes in four cutblocks in the Oyster River area of Vancouver Island, using a combination of LiDAR-based measurements of bulk volumes of all residue piles and scaled log volumes in sample piles. They showed that geospatial estimates of piled woody residue volumes were much greater than those from two field-based methods. Trofymow et al. (2017) proposed that analysis of high resolution ($\leq 5\text{cm}$ pixel) air-photo images could be used as an alternative to the current WRS method for assessing dispersed woody residue volumes, and presented some initial results for a Semi-automated Log Delineation (SLD) geospatial method for two cutblocks in the Northwest Bay area of Vancouver Island. One limitation of geospatial methods is their inability to assess the trees species, decay state or other attributes of a residue "log" that could be determined by field inspection. Such

information is used to convert wood volumes to biomass or biomass C (Canadian Forest Inventory Committee 2008) as wood density (kg m^{-3}) and wood carbon concentration are related to tree species (Miles and Smith, 2009) and decay class (Preston et al. 1998, Woodall and Monleon, 2008). Species and decay class serve as proxy data, replacing direct measurements of wood density and carbon concentration of woody debris samples from a site.

The purpose of this research was to compare the effectiveness of methods for determining dispersed post-harvest woody residues in cutblocks in a second-growth Douglas-fir dominated forest, including two geospatial methods semi-automated log delineation (SLD) and manual log digitization (MLD) and variants of the field-based line-intersect sampling (LIS) method, as compared to values from a field-based waste and residue survey (WRS) method. The effect of differences in tree species composition on estimates of woody residue biomass was also examined.

Methods

Site description

The study site was located on Island Timberlands' private lands at Northwest Bay (NWB) approximately 30 km west of Nanaimo on Vancouver Island, British Columbia (Figure 1). The two cutblocks, 193401 (18 ha) and 193423 (23 ha), were logged in 2014 by feller buncher. The felled trees were moved to roadside through multiple passes by an excavator with thumb (hoe-chucking) to a roadside processor that cut remaining branches and non-merchantable tops and bucked logs to length from the merchantable stemwood (Trofymow et al. 2017). Woody residues would include <3m "logs" and butts, longer stemwood from unmerchantable standing dead trees or species felled during harvest, and overturned cut stumps with attached roots. Pre-harvest, both cutblocks had been dominated by second-growth Douglas-fir (*Pseudotsuga menziesii*) (193401 61%, 193423 53%) with components of western hemlock (*Tsuga heterophylla*) (193401 18%, 193423 23%) or western redcedar (*Thuja plicata*) (193401 13%, 193423 16%) with minor amounts of red alder (*Alnus rubra*) and white pine (*Pinus monticola*). Cutblock 193401 was divided into two sub-blocks (401-1, 401-2) and cutblock 193423 into three sub-blocks (423-1, 423-2, 423-3) to facilitate comparison of area-based (WRS, SLD, MLD) and point-based (LIS) estimates. The sub-blocks accounted for differences due to topographic features (slope and

road), machine operability during harvest, and linear or patch leave areas (streams or wetlands) within the cutblocks.

Field waste and residue survey (WRS) measurements and estimates

Field waste and residues surveys (WRS) were conducted in October 2014 by a contractor who measured scattered dispersed residues (SBX stratum) according to provincial guidelines (B.C. Ministry of Forest and Range 2005). This stratum excludes areas occupied by roadside residue accumulations (RBH stratum) or piles (PBX stratum) (Figure 1). Trofymow et al. (2017) describes in more detail the delineation of different strata and their wood volumes at the Northwest Bay blocks, however this paper is focused on the 29, 0.04ha fixed-area plots (193401 11 plots; 193423 18 plots) measured in SBX stratum. Circular 11.28 m radius plots were used, however if the plot would have overlapped another stratum, 15.96m radius D-shaped plots (0.04ha) were used. The center of each plot (Supplementary Table S1) was staked, a 60x60cm target placed, and coordinates georeferenced using post-processed differential GPS data collected using a Trimble GeoXH 6000 with 0.3 m accuracy. All stemwood residues at least 10 cm inside bark top and bottom diameter (DIB) and at least 0.2 m in length were scaled to determine the plot volume density (m^3ha^{-1}) and binned by species into three length or end condition classes (Logs, $\geq 3\text{m}$ any end; Bucking waste, $0.2\text{m} \leq x < 3\text{m}$ cut end; Breakage, $0.2\text{m} \leq x < 3\text{m}$ broken end). The WRS individual plot tallies of residue wood measurements and volumes (using Smalian's formula) was then compiled by the contractor using Enfor waste and residue software (Enfor Consultants, 2011) to produce plot, stratum, and block level residue volume summaries. The individual WRS plot volume (m^3ha^{-1}), length (mha^{-1}), and piece ($\#\text{ha}^{-1}$) densities were used for further analysis and comparisons.

Imagery for geospatial methods

Aerial imagery was obtained in the summer of 2015 by a contractor using an Aeryon Skyranger UAV. Details of image acquisition conditions and parameters are described in Trofymow et al. (2017). Imagery was processed by the contractor into an orthophotomosaic for each block using Pix4d (v 1.4.46) software (Pix4D 2015) resulting in image resolutions of 2.4 cm (193401) and 1.8 cm (193423). Image extents (NAD1983 (CSRS) BC-Albers) for block 193401 was Northeast 1122013m, 466196m; Southwest 1122532m, 465334m and for block 193423, Northeast 1120553m, 464966m; Southwest 1121227m, 464216m.

Geospatial manual log delineation (MLD) procedures and estimates

Manual log delineation (MLD) was done for all SBX plots using the full resolution imagery. All logs that appeared to be at least 10cm diameter and at least 1m in length were digitized in ArcGIS v10.5 (Figure 2a). Log lengths were manually added down the center of each log object rather than the longest line algorithm previously used (Trofymow et al. 2017) as that algorithm was found to overestimate actual log length by placing a diagonal line in a large number of cases. Digitized log length and area were used to calculate an average width and volume of each object. Objects that did not have an average width meeting the minimum criteria (10 cm) were dropped from further analysis (MLD method). Since manual log delineation can only detect DOB, an adjustment factor was created by estimating the mean Double Bark Thickness (DBT) for each sub-block using the WRS measurements of each piece and species-specific DBT regressions from Smith and Kozak (1967). Pieces that did not have an average diameter that was equal to 10 cm + mean DBT were excluded (MLD DIB method). This removed pieces that had borderline acceptable widths that may not have been scaled during the WRS as they would have been less than 10 cm DIB. Volume, length, and piece densities for the MLD and MLD DIB methods were used for further analysis and comparison.

Geospatial semi-automated log delineation (SLD) procedure and estimates

The semi-automated log delineation (SLD) procedure was developed using software derived from the Individual Tree Crown suite (Gougeon and Leckie 2003). An earlier version (SLD v1.5) was described in Trofymow et al. (2017), however improvements had been made since then. In the current version (SLD v3.7), programs were changed to make use of the GDAL library (GDAL/OGR contributors 2018) instead of the proprietary PCI library (PCI Geomatica 2017). The change to the GDAL library allows for the workflow from the threshold procedure to the final “LOGIVOL” procedure to be completed outside of the PCI environment. Additional changes included: improved gap jumping using skeleton intersection points and preventing 90° turns; improved length estimation using the Euclidean distance between object end points; and an improved width estimation using the average direction of the object skeleton. The SLD version 3.7 programs produces identical results as version 1.5 throughout the workflow until the volume estimation by the “LOGIVOL” procedure, where estimation calculations were updated (length, width). The following is a brief description of the image processing and analyses procedure.

Imagery from the summer 2015 UAV flights was resampled from their original resolutions to a 5 cm resolution to improve both log continuity and processing times. The blue band of the imagery was normalized by subtracting a mean blue image created by a 2-pass averaging kernel with a 7 x 7 pixel window and a 31 x 31 pixel window. The normalized blue band image was then used for all further processing (Figure 2b). Using the latest version of the SLD programs, v3.7, the normalized blue image for both blocks was thresholded using the reclassify method (Hijmans 2017) from the R v3.5.0 Raster library (R Core Team 2014) to extract pixels with a $DN \geq 25$ (Figure 2c). The resulting image was then filtered for log-like objects using the "CWDSFIL" program (Figure 2d). The filtered log-like objects were skeletonized using the Fiji image processing software (Schindelin et al. 2012) and resulting skeletons were georeferenced using the normalized imagery. Combined with the log-like objects from the "CDWSFIL" program, the skeletons were used by the "LOGIVOL" program to identify objects that meet final size specifications and calculate their volume (Figure 2e). The procedure provides an image of final selected skeleton "log" objects, as well as a list of objects with their coordinates and calculated volumes and lengths for the entire cutblock. The volume, length, and piece density were then determined for all objects within the boundaries of each WRS plot (SLD v3.7 method). Unlike the WRS method, the SLD geospatial methods can only detect outside bark diameter. In a separate run, the sub-block mean DBT adjustment, as described for the MLD method, was applied to the minimum diameter criteria and results reported as the SLD v3.7 DIB method. Volume, length, and piece densities for the SLD v3.7 and SLD v3.7 DIB methods as well as the previous SLD v1.5 method were used for further analysis and comparison.

Field line-intersect sampling (LIS) measurements and estimates

Field measurements of residue wood using the line-intersect sampling (LIS) were conducted by Canadian Forest Service staff at the centres of the 18 SBX circular field plots (193401 8 plots; 193423 10 plots) in the spring of 2015. National Forest Inventory (NFI) procedures were followed (Canadian Forest Inventory Committee 2008), with measurements made on two 30m perpendicular transects crossing at plot center and orientated north/south and east/west (Figure 3a). The outside bark diameter (DOB) (measured by caliper), tilt angle (measured by compass clinometer), species and decay class (as described for the NFI in the Introduction) of all pieces ≥ 7.5 cm diameter were recorded for the entire transect, and whether

they fell on or beyond the 22 m of each transect segment within the 11.28m radius WRS plot (Figure 3b). D-shaped plots were not sampled using LIS as their shape would not allow for the same NFI transect design. Transect lengths were corrected to horizontal distance using the mean slope of each plot determined from a digital elevation model, as slope distance was used in the field.

Two LIS datasets, one using the full 60 m (Figure 3a) of transect and the other using the subset 44 m of transect (Figure 3b), were used to estimate of residue volume (m^3ha^{-1}) and length (m ha^{-1}) density. Pieces that did not meet the 10 cm minimum diameter (DOB) were excluded and not used in any further analysis. The volume estimate for each piece was then calculated using the formula:

$$v = \frac{d^2}{\cos \lambda} \quad [1]$$

where v is the estimated volume of the piece, d is the diameter of the piece and λ is the tilt angle of the piece in radians (Marshall et al. 2003). For both the 60 m and 44 m LIS the total volume density at each plot was calculated using the formula:

$$V = \frac{\pi^2}{8L} \sum_{j=1}^{m_i} v_{ij} \quad [2]$$

where V is the total volume density at the plot in $\text{m}^3 \text{ha}^{-1}$, L is the total transect length, and v_{ij} is the volume of the j 'th piece on the i 'th transect (Marshall et al. 2003). The total piece length density was calculated using the formula:

$$tl_i = \frac{10000\pi}{2L} \sum_{j=1}^{m_i} \frac{1}{\cos \lambda_{ij}} \quad [3]$$

where tl_i is the length density of the i 'th transect in m ha^{-1} , L is the total transect length, and λ is the tilt angle in radians of the j 'th piece on the i 'th transect (Marshall et al. 2003).

Preliminary analysis of the 44 m transects results showed values were much larger than using the 60 m transects. This could be due to radial transect design where a piece or pieces near the centre could have been double counted and should have been excluded from one transect segment (Gregoire and Valentine 2008). This would have been more of an issue with the 44m

transect than the 60m transect. As overlap can only be determined *in situ* and not solely from the recorded data, a method was developed that avoid double-counting within the central overlap area. Data for the full 30 m transect segment in one of the two orientations (N-S, E-W), was combined with that from the two 4 m transect segments that fall outside of the plot boundaries on the other orientation, resulting in 38 m of transect (Figure 3c,d). The calculations for total volume for these transects were the same as described above and the average of the two split transect segments, the LIS 38m method, was used in further analyses and comparison. Since lengths of “logs” crossing the transects were not measured, piece density could not be determined.

The standard NFI LIS procedure involved DOB measurements of pieces of all decay classes that fall along the entire 60m of transect and thus included woody debris that would have existed pre-harvest as well as post-harvest woody residues (LIS 60m method). The WRS method measures diameter inside bark (DIB) for only woody residues, thus requiring two adjustments to be made to the LIS data. First, to ensure comparable volume estimations, LIS outside bark diameters were converted into DIB using species specific double bark thickness (DBT) regressions from Smith and Kozak (1967) and pieces <10cm DIB excluded. Second, pieces with a decay class > 1 or identified as stumps, were excluded and calculations made using DIB for the 60m transects (LIS 60m NS DIB method) and the 38m transects (LIS 38m NS DIB). Volume and length densities for the LIS 60m, LIS 60m NS DIB, and LIS 38m NS DIB methods were used for further analysis and comparison.

Method comparisons

A combined results database, prepared for the WRS field and the MLD and SLD geospatial methods, included volume density (m^3ha^{-1}), length density (m ha^{-1}), and piece density ($\# \text{ha}^{-1}$) for all 29 plots across the 5 sub-blocks. A second database of volume and length densities was also prepared for all four methods (LIS, WRS, MLD, SLD) for the 18 plot subset across the 5 sub-blocks. For both databases, the mean and standard error for each method was calculated within and across sub-blocks and differences between the WRS and each of the other methods were assessed from paired t-test or Wilcoxon tests. Pearson correlation coefficients and their significance were calculated between each method across all 29 or 18 plots. A one-way Analysis of Variance was used to test for differences among sub-blocks for the WRS method.

Regression analysis of volume density only, was conducted for area-based methods for all 29 plots. Comparisons included WRS versus MLD DIB, SLD, and SLD DIB methods and MLD-DIB versus SLD, and SLD DIB methods. Regressions were prepared with a fixed 0 intercept, a floating intercept, with and without outlier points included. Outliers were selected as points having a strong influence on the model identified using Cook's distance (Cook, 1977). Plots identified as outliers were then visually inspected to justify the reasoning for the removal from the regression analysis and included: shading/light conditions (193401-SBX 12), large overturned stumps (193401-SBX 09), and pieces being distributed away from transects (193401-SBX 05).

The species composition of residue wood volumes was calculated for the WRS and the LIS 38m NS DIB field methods for each of the 5 subblocks. The WRS used individual piece volumes by species available from the plot tallies in each sub-block. LIS volumes by species were estimated for the 38m transects using equation [1] adjusted to DIB in each sub-block. Comparisons of species volume composition for the two methods were made at the sub-block level and across all sub-blocks. For reference, species composition from the pre-harvest forest cover inventory were also calculated using the weighted area of each stand type in a sub-block.

Results

Comparison of WRS and geospatial area-based methods

Residue volume, length, and piece densities determined by the WRS method were not significantly different among sub-blocks (Table 1) and showed a similar amount of variation within a sub-block (Table 1a), though 401-2 tended to have higher values and variation than the other sub-blocks. Mean WRS volume and length densities across all 29 plots (36.0, 2145) slightly differed from those for the 18 plots (35.4, 2082) used for LIS measurements.

The MLD residue volume, length, and piece densities were significantly higher than those for the WRS for sub-block 423-1 (Table 1), but showed a similar amount of variation within a sub-block as the WRS with the exception of sub-block 401-2 (Table 1) which was heavily influenced by large overturned stumps. Adjustment for inside bark diameter, MLD DIB, decreased overall volume, length, and piece densities by 23%, 21%, 22% respectively, such that overall and sub-block values were not significantly different from WRS results with the exception of sub-block 423-1 (Table 1). Across all 29 plots, MLD and MLD DIB volume, length

and piece densities were significantly correlated with each other but neither were correlated with the WRS method (Table 2). The zero-intercept volume density regression of WRS vs MLD DIB (Figure 3d) was significant ($\text{WRS}=0.678*\text{MLD DIB}$, $p<0.001$, $R^2=0.665$), while the regression excluding outliers was marginally significant ($\text{WRS}=22.75 + 0.366*\text{MLD DIB}$, $p=0.042$, $R^2=0.150$) (Table S2).

Volume, length, and piece densities for SLD versions SLD v1.5 and SLD v3.7 were significantly higher than WRS values overall and for sub-blocks 423-1 and 423-3 (Table 1) and showed similar amount of variation within a sub-block as the WRS with the exception of sub-block 423-2 (Table 2). Adjustment for inside bark diameter, SLD v3.7 DIB, slightly reduced volume, length and piece densities but these were still significantly higher than WRS values overall and for sub-blocks 423-1 and 423-3 (Table 1). When compared to the WRS for all 29 plots, SLD v1.5, SLD v3.7 and SLD v3.7 DIB volume densities were 50%, 46%, 42% higher, respectively, than WRS values; length densities were 28% lower, equal, and 7% lower, respectively than WRS values, and piece densities were 38%, 69%, 55% higher, respectively than WRS values (Table 1). Across all 29 plots, volume, length, and piece densities for none of the SLD method variants were significantly correlated with the WRS method.

Volume densities for all SLD variants were significantly correlated with both MLD methods, length densities for SLD v1.5 were correlated with MLD, and volume, length and pieces densities for all SLD variants were correlated with each other (Table 2). The zero-intercept volume density regressions of WRS vs SLD v1.5 ($\text{WRS}=0.593*\text{SLD v1.5}$, $p<0.001$, $R^2=0.768$), SLD v3.7 ($\text{WRS}=0.614*\text{SLD v3.7}$, $p<0.001$, $R^2=0.762$), SLD v3.7 DIB ($\text{WRS}=0.628*\text{SLD v3.7 DIB}$, $p<0.001$, $R^2=0.759$) (Figure 4a, b, c, respectively) were significant, as was the SLD v1.5 regression accounting for outliers ($\text{WRS}=10.03 + 0.430*\text{SLD v1.5}$, $p<0.001$, $R^2=0.497$). All other regressions with WRS were not significant (Table S2). The zero-intercept volume density regressions of MLD DIB vs SLD v1.5 ($\text{MLD DIB}=0.704*\text{SLD v1.5}$, $p<0.001$, $R^2=0.747$), SLD v3.7 ($\text{MLD DIB}=0.742*\text{SLD v3.7}$, $p<0.001$, $R^2=0.769$), and SLD v3.7 DIB ($\text{MLD DIB}=0.760*\text{SLD v3.7 DIB}$, $p<0.001$, $R^2=0.768$) (Figure 4 e, f, g) were significant as were regressions with all data including outliers (Table S2).

Comparison of WRS and LIS field methods.

Large differences in volume and length densities were observed among the three LIS method variants (Table 1, 18 plot LIS dataset). Volume and length densities for the LIS 60 method were significantly greater (6 and 2.5 times, respectively) that of the WRS method overall and for 3 or 4 of the sub-blocks. With adjustments for decayed wood and inside bark diameter, the LIS 60m NS DIB volume and length densities were greatly reduced, however still significantly greater than the WRS method overall (60% greater) and for 1 or 2 of the sub-blocks (Table 1). Adjustments to reduce double-counting in the LIS 38 NS DIB method, decreased both volume and length densities such they were not significantly different from the WRS method overall and for all sub-blocks. However, variation in volume and length densities among sub-blocks was greater (80% greater overall) for the LIS 38m NS DIB versus the WRS method (Table 1, standard errors). Volume and length densities for both the LIS 60m NS DIB and LIS 38m NS DIB method were significantly correlated with the WRS method (Table 2).

Overall volume and length densities for each WRS, MLD, SLD method in the 18 plot subset were similar to those in full set of 29 plots (Table 1). Differences between the WRS methods and MLD or SLD methods noted for the 29 plots also occurred in the 18 plot subset. MLD DIB and SLD v3.7 DIB volume densities were slightly greater and length densities slightly less than the LIS 38m NS DIB values, however none were significant.

Comparison of WRS, LIS, and pre-harvest forest cover species composition

Species volume percentages estimated by LIS 38m NS differed from those from the WRS method overall and in some sub-blocks (Table 3). In general the LIS method overestimated Douglas-fir, underestimated hemlock and to a lesser extent redcedar percentages (sub-block 423-1, exception). In most sub-blocks LIS underestimated other species percentages with the exception of sub-blocks 401-2 and 423-3 where LIS values were greater than WRS. In all sub-blocks, species composition from the pre-harvest forest cover inventory differed from the WRS method, with a greater percentage of Douglas-fir, lower percentage of western hemlock (sub-blocks 401-1, 4023-3, exception) and overall lower percentage of redcedar and other species (Table 3).

Discussion

Geospatial method comparisons and capabilities

The MLD method serves as a proxy for how a perfectly intelligent SLD process would perform with the given imagery by using human judgement to resolve issues like changes in log brightness due to the loss of bark, log continuation through obstructions, and multiple log crossings. When compared to the WRS method, the MLD DIB method overestimates volume density, but not to the same degree as the SLD v3.7 DIB method. These results could be due to differences in perception of what logs are meeting the minimum size criteria, as bright objects tend to have a white glow around them making precise estimation of log edges difficult. Additionally, differences could be due to the log volume calculation with geospatial methods using an average log width, whereas for the WRS measurements bottom and top diameters are recorded and Smalian's formula is used to calculate the individual piece volume.

Changes made to the SLD method since v1.5 have offered improvements in the dispersed residue volume estimation compared to WRS values. Sub-block median values in block 193401 were closer to WRS values with newer SLD versions, while in block 193423 only the median values using the SLD v3.7 DIB method showed improvement over the SLD v1.5 method when compared to WRS values. In general across all sub-blocks the overestimations of residue density have changed from WRS values being 59% of the SLD v1.5 values to being 61% of the SLD v3.7 values and 63% of the SLD v3.7 DIB values. While these results indicate estimates were improved with use of a DIB correction, future research may consider recording, or at least using the double-bark thickness regression to calculate, both the DIB and DOB from WRS measurements, since the latter would be more comparable to diameters from geospatial methods. Even though this study shows that the best current SLD method (SLD v3.7 DIB) is a biased estimator of volume density at the plot level, the method's strength is that it can be used to prepare a full census of woody residues for an entire cutblock (Trofymow et al. 2017). Over both cutblocks, the full census SLD v3.7 DIB method (SLDF) estimated total dispersed residue volume as 1349.67 m³, giving a volume density of 54.5 m³ ha⁻¹, greater than the mean volume density for either the sample-based SLD v3.7 DIB or WRS methods, 51.3 ± 3.6 and 36.0 ± 3.0 m³ ha⁻¹ respectively. Given the error, the sample-based SLD volume was not significantly greater than the full census SLD volume, however the possibility remains the sample plots did

not detect the full range of volume densities in the cutblocks. Since fixed-area plot WRS values were directly comparable to geospatial values, the significant regression for the WRS vs SLD v3.7 DIB methods could be used to correct for presumed bias in the full census SLD value, and resulted in a volume density of $34.2 \pm 3.7 \text{ SE m}^3 \text{ ha}^{-1}$. Thus, a regression developed from volume densities measured on a number of fixed area plots might used to correct values from a full census geospatial method to more accurately determine cutblock woody residue volumes.

As summarized in Table 4, the capabilities and restrictions of MLD and SLD geospatial methods differ from those of either the WRS or LIS field methods. As Trofymow et al. (2017) noted when comparing SLD analyses of fall 2014 and summer 2015 imagery, the SLD method performs best under well-lit conditions for “logs” without obscuring branch foliage. Thus, if SLD is used to determine dispersed residues there could be a several month lag to acquire suitable imagery and analyze the images. This may limit the applicability of the SLD method for real time inventories of residues for bioenergy purposes (Spencer and Röser 2017). The geospatial method could still be useful for post-harvest waste assessments or for studies using spatial LiDAR (White et al. 2017) to estimate pre-harvest merchantable and unmerchantable volumes. Forest LiDAR volume or biomass studies typically measure trees in co-located fixed area plots in stands to train statistical models that are then applied to the larger forest area. However, in certain management areas it might be possible to use post-harvest measurements of merchantable volumes from the timber scale and unmerchantable volumes from full census geospatial methods for a cutblock(s) to test and develop *posteriori* volume models using pre-harvest LiDAR data for the cutblock(s) area.

Line-intercept sampling method comparisons and capabilities

Results with the LIS 38m NS DIB method as compared to the LIS 60m or LIS 60m NS DIB methods emphasis the importance of adjustments for inside bark diameter, exclusion of decaying wood and stumps, and removing the influence of overlap near plot center, in improving estimated residue volumes when compared to WRS values. This suggests that use of either longer single transects or an altered transect design for the LIS method could be a suitable alternative to the area-based WRS method for determining post-harvest woody residues. Although LIS 38m NS DIB method results support conclusions by Gregoire and Valentine (2008) that overlap within LIS designs may result in biased estimates, Woodall and

Monleon (2008, pg. 52) demonstrate that for large numbers (hundreds) of plots there was not any bias from double-counting for the “Y” LIS transects used in the USDA Forest Service FIA plots. Each arm of the FIA “Y” is treated as a separate segment and the plot estimate is determined as the average of the three segments. Additional study may be warranted to determine if overlap is a significant issue in the NFI LIS design if woody debris volumes are calculated from the total rather than means of the two 60m (or four 30m) perpendicular transects. Previous studies have emphasized bias due to transect orientation, especially when residues are in a non-random direction and transects are perpendicular (Brissette et al. 2003). Observations during field measurements and of the “log” objects in the image prepared after SLD processing suggest residues were not oriented in a single direction at the LIS transects.

In general, LIS is a more rapid method than a total scale on fixed area plots (Harmon and Sexton 1996) though it will depend upon the volume densities. On areas with low densities larger or more fixed area plots are needed (Woldendorp et al. (2004), increasing costs. However, Pickford and Hazard (1986) found that to estimate values within $\pm 10\%$ of the 95% confidence, LIS methods would require many more transects than used in this study or in general. Since LIS is a point-based estimate, values cannot be directly compared to the geospatial values for the area around that point. Comparisons can only be made at a block level. However, it would be useful to examine if estimates made using a multiple segment LIS method for a fixed-area plot, could then be used to develop a regression to correct for bias in the full-census SLD estimates for a cutblock.

Using residue or forest species composition to estimate woody residue biomass

The LIS (LIS 38m NS DIB) method results indicate that distribution of residue wood volumes by species may differ when compared to WRS method. The greatest differences were LIS overestimates of Douglas-fir and underestimates of hemlock, possibly partly from species misidentification as LIS was done spring 2015 after foliage had fallen from branches attached to the “logs and tops. Further research should investigate if a LIS method can be used instead of the WRS to accurately determine species composition, since a species wood density is an important factor in calculating residue wood biomass. In single species stands, the pre-harvest stand inventory should be adequate to estimate species volume composition of the harvest residues. However, in stands with a mix of species where overstory and subcanopy trees are

different species, then after harvest subcanopy species may form a greater proportion of the residue volumes. This was likely why the forest cover and WRS residues species composition differed for these cutblocks. If the subcanopy tree species had lower wood density (eg. redcedar) than the overstory species (eg. Douglas-fir), then residue biomass and carbon would be overestimated if just the forest cover species composition is used.

To test this, weighted wood densities based on species composition of the WRS or LIS residues or forest cover were calculated using oven dry mass/ green volume wood densities (kg m^{-3}) (Douglas-fir - 450, western hemlock - 420, western redcedar - 310, red alder- 370, western white pine - 360) from Miles and Smith (2009). Overall the LIS and Forest Cover weighted wood densities were 6 and 7% greater, respectively, than WRS values (Table 3) reflecting the mainly lower %Douglas-fir and higher %redcedar in the WRS species composition. As a result, estimates of residue biomass densities on all sub-blocks across both cutblocks using WRS volumes and WRS species composition (13.133 ± 1.076 SE tonnes ha^{-1}) were slightly lower than with forest cover species composition (14.089 ± 1.154 SE tonnes ha^{-1}) and much lower than using LIS volumes and LIS species composition (16.385 ± 2.038 SE tonnes ha^{-1}) or forest cover species composition (16.636 ± 2.070 SE tonnes ha^{-1}). However, differences among calculated biomass values were not significant, primarily due to sample-based error in the WRS or LIS volume estimates. Error in differences in wood densities due to species composition was low and had no effect on the biomass error. For example, the WRS biomass density error including and excluding weighted wood density error was 1.075900036 and 1.075900000, respectively. Residue biomass densities calculated using wood densities for WRS species composition and sample-based MLD (MLD DIB), sample-based SLD (SLD v3.7 DIB), full census SLD, and regression corrected full census SLD volumes, were 15.693 ± 2.337 , 18.884 ± 1.744 , 20.226 ± 0.0004 , 12.702 ± 1.335 tonnes ha^{-1} , respectively. The MLD, and corrected full census SLD biomass densities did not significantly differ from the WRS values, while the sample-based and full census SLD values did significantly differ. The full census SLD residue wood volumes had no sample plot error, however correction of SLD bias with the regression from WRS field plots measurements, introduced another source of uncertainty and error. More accurate estimates of cutblock biomass and carbon would require measurement of wood densities and %C from an *in situ* sample of residue logs from each plot (eg. Preston et al. 1998). From this the propagated

error and uncertainties for a block biomass estimates associated with the sample-plot residue volumes, species composition, and actual dry wood densities could be determined (Lo 2005). However, the results of this study suggest the greatest source of uncertainty in post-harvest woody residue biomass is due to error in residue volumes rather than wood densities, which are likely adequately estimated from species composition. Such would not be the case for estimates of woody debris biomass, as the variation in wood density will differ by species and decay class.

Conclusions

The SLD v3.7 method has improved since version 1.5 and when used with the DIB adjustment, had values more comparable, but biased to values determined by the fixed area plot WRS method. The WRS method measures only harvest woody residues at least 10cm DIB and thus a significant fraction of the total woody debris in a block is not measured. This makes comparisons with geospatial methods more problematic as DOB is measured. Although adjustments can be made for DIB for geospatial methods, the character (species, decay class, piece type) of the woody debris is not determined and so woody material other than post-harvest woody residue “logs” could be included. Some of these issues are overcome using the MLD method, however it is more labour intensive than the SLD method and likely only a sample could be digitized. Comparison of the amount of total woody debris volumes determined by default LIS methods suggests woody residues detected with geospatial methods included little if any pre-harvest woody debris. Results suggest that the use of a LIS method with a transect design that avoided overlaps may be an alternative to the more labour intensive fixed area WRS plot and could be used to determine species composition of post-harvest woody residues. Such data could then be used to determine a double-bark thickness adjustment factor for inside/outside bark diameters and weighted wood densities to calculate woody residue biomass from geospatial estimates of residue volumes. While the SLD geospatial method can provide a full census of dispersed post-harvest coarse ($\geq 10\text{cm}$) woody residue pieces, lengths, and volumes in an entire cutblock, corrections for bias may be needed. In mixed species forests, a combination of geospatial and field-based methods may still be required to convert woody residue volumes to biomass for applications in bioenergy inventories and carbon budgets.

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List of Figures

Figure 1: Location of the Northwest Bay blocks a) 193401 and b) 193423 with harvested areas, roads, scattered dispersed residue (SBX) stratum sub-blocks, and SBX plot locations.

Figure 2: Example of image processing from block 193401 SBX plot 14 including a) original image with objects digitized by MLD; b) SLD v3.7 processing for b) normalized blue band; c) thresholding; d) objects selected by 'CWDSFIL' (dark grey) from thresholded objects (light grey); and e) final objects selected by 'LOGIVOL' (black) from 'CWDSFIL' objects (light grey).

Figure 3: Line intersect sampling method transect design for: a) 60 m transect; b) 44 m transect; c) 38 m north modified transect; and d) 38 m west modified transect.

Figure 4: Regression models using either a fixed 0 intercept, a floating intercept, or a floating intercept with no outliers for: a) WRS vs SLD v3.7 (DOB); b) MLD DIB vs SLD v3.7 (DOB); c) WRS vs SLD v3.7 DIB; d) MLD DIB vs SLD v3.7 DIB; e) WRS vs LIS 60m NS; f) MLD DIB vs LIS 60m NS; g) WRS vs LIS 38m NS; and h) MLD DIB vs LIS 38m NS. See Table 2 for description of method acronyms.

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Table 1: Post-harvest woody residue volume, length and piece densities as estimated by field (WRS, LIM) and geospatial (MLD, SLD) methods for plots in each sub-block and across all sub-blocks.

Sub-block	N	WRS	MLD	MLD DIB	SLD v1.5	SLD v3.7	SLD v3.7 DIB	N	WRS	LIS60m	LIS60m NS DIB	LIS38m NS DIB
Volume density (m³ha⁻¹)												
401-1	5	35.2	35.0	25.6*	40.1	37.0	35.9	5	35.2	226.3*	66.0	49.7
401-2	6	46.0	80.0	66.4	51.1	51.3	49.7	3	36.9	199.2	57.8*	50.2
423-1	6	29.8	54.7**	40.9	53.6***	52.6*	52.0*	3	30.5	260.3*	29.3	19.8
423-2	6	33.7	50.6	38.7	53.5	50.1	48.7	3	36.1	221.3	63.4	42.2
423-3	6	35.2	41.7	29.8	69.3***	69.4**	67.5*	4	37.5	199.1*	56.4	41.7
All	29	36.0	53.0**	40.8	54.0***	52.6***	51.3***					
All	18	35.4	54.5*	42.3	53.9**	52.1**	50.9*	18	35.4	220.6***	55.9***	41.8
Length density (m ha⁻¹)												
401-1	5	2380	2228	1765*	1262***	1682***	1539***	5	2380	5501*	3307	2485
401-2	6	2722	3229	2777	1368	1928	1768	3	2215	5299	3779*	3201
423-1	6	1876	3490**	2994*	1679	2169	2031	3	1779	4467*	2129	1343
423-2	6	1752	2607	2123	1475	1909	1750	3	1651	5134**	2967	1926
423-3	6	2035	2432	1799	1978	2978*	2790*	4	2160	6810*	4123*	3083*
All	29	2145	2817**	2310	1562***	2148	1991					
All	18	2082	240.80*	2403	1511***	2126	1979	18	2082	5525***	3314***	2454
Piece density (# ha⁻¹)												
401-1	5	615	795	595	720	860	785					
401-2	6	900	1088	896	829	1054	950					
423-1	6	588	1200***	1004***	938***	1113**	1029**					
423-2	6	550	946	733	863*	975**	888**					
423-3	6	617	883*	608	1146**	1492**	1375**					
All	29	655	989***	773	905**	1107***	1013***					
Volume density (m³ha⁻¹) standard error												
401-1	5	5.7	6.3	5.0(.018)	5.5	5.9	5.7	5	5.7	35.1(.012)	14.9	10.8
401-2	6	9.4	15.0	14.8	8.7	7.8	7.8	3	6.6	63.6	7.5(.030)	8.9
423-1	6	3.5	4.9(.004)	4.5	4.5(.000)	2.1(.031)	2.2(.031)	3	0.5	22.2(.014)	4.4	4.5
423-2	6	4.9	8.6	7.1	11.8	8.2	7.8	3	6.0	43.2(.091)	19.3	12.8
423-3	6	6.2	3.9	3.6	8.4(.000)	8.5(.005)	8.6(.031)	4	8.1	19.7(.002)	11.9	9.5
All	29	3.0	4.9(.002)	4.5	4.1(.001)	3.7(.001)	3.6(.002)					
All	18	2.9	6.7(.038)	6.3	5.0(.002)	4.7(.008)	4.7(.011)	18	2.9	17.8(.000)	6.7(.000)	5.2
Length density (m ha⁻¹) standard error												
401-1	5	321	345	300(.019)	214(.001)	298(.000)	276(.001)	5	321	530(.010)	300	242
401-2	6	423	245	238	126	156	167	3	298	334	465(.028)	493
423-1	6	229	261(.005)	281(.023)	98	90	97	3	174	468(.039)	317	206
423-2	6	239	502	456	277	309	270	3	198	74(.004)	438	245
423-3	6	300	192	182	182	300(.028)	298(.042)	4	407	1214(.016)	802(.029)	636(.043)
All	29	154	171(.004)	166	97(.000)	138	132					
All	18	157	241(.011)	232	120(.001)	188	183	18	157	370(.000)	277(.000)	241
Piece density (# ha⁻¹) standard error												
401-1	5	53	141	105	106	147	132					
401-2	6	139	98	78	94	88	96					
423-1	6	83	91(.000)	86(.002)	51(.000)	52(.001)	57(.004)					
423-2	6	88	162	144	167(.031)	146(.004)	126(.004)					
423-3	6	83	73(.016)	67	107(.003)	135(.002)	135(.002)					
All	29	49	57(.000)	53	57(.002)	66(.000)	62(.000)					

Note: Significance of paired t-test of each method with WRS denoted by, *p<0.05, **p<0.01, ***p<0.001. Actual p values for those with p<0.05 are shown in parentheses next to the standard error for that comparison. See Table 2 for method acronym.

Table 2: Pearson correlation coefficients for volume, length, and piece density for different methods.

	WRS n = 29	MLD n = 29	MLD DIB n = 29	SLD v1.5 n = 29	SLD v3.7 DIB n = 29	LIS 60m NS DIB n = 18	LIS 38m NS DIB n = 18
Volume density (m^3ha^{-1})							
WRS	1					0.629**	0.585*
MLD	0.170	1				-0.028	-0.055
MLD DIB	0.157	0.994(.000)	1			-0.063	-0.081
SLD v1.5	0.172	0.479(.009)	0.448(.015)	1		0.004	-0.010
SLD v3.7	0.130	0.413(.026)	0.408(.028)	0.859(.000)	1	-0.218	-0.222
SLD v3.7 DIB	0.123	0.413(.026)	0.407(.028)	0.857(.000)	0.999(.000)	-0.212	-0.215
Length density (m ha^{-1})							
WRS	1					0.681(.002)	0.565(.015)
MLD	0.179	1				0.119	0.029
MLD DIB	0.202	0.973(.000)	1			-0.017	-0.067
SLD v1.5	0.187	0.369(.049)	0.277	1		0.527(.025)	0.403
SLD v3.7	0.193	0.128	0.063	0.859(.000)	1	0.427	0.330
SLD v3.7 DIB	0.174	0.129	0.059	0.847(.000)	0.993(.000)	0.455	0.370
Piece density ($\# \text{ha}^{-1}$)							
WRS	1					-	-
MLD	0.187	1				-	-
MLD DIB	0.214	0.947(.000)	1			-	-
SLD v1.5	0.125	0.278	0.185	1		-	-
SLD v3.7	0.135	0.138	0.089	0.853(.000)	1	-	-
SLD v3.7 DIB	0.106	0.129	0.077	0.845(.000)	0.988(.000)	-	-

Note: Actual p values for those coefficients with $p < 0.05$ are in parentheses next to the coefficient.

WRS- Waste and Residue Survey;

MLD- Manual Log Delineation using outside bark diameter;

MLD DIB- MLD adjusted for diameter inside bark;

SLD v1.5 – Semi-automated Log Delineation version 1.5; SLD v3.7 - SLD version 3.7;

SLD v3.7 DIB - SLD v3.7 adjusted for diameter inside bark;

LIS 60m- Line Intercept Sampling method using 60m transect no adjustment or exclusion;

LIS 60m NS DIB – LIS 60m adjusted for diameter inside bark; stumps and decayed wood excluded;

LIS 38m NS DIB – LIS 38m transect mean, adjusted for diameter inside bark; stumps and decayed wood excluded

Table 3: Percent species by volume for each and all sub-blocks from field-based WRS and LIS (LIS 38m NS DIB) methods for woody residues or from pre-harvest forest cover (FC). Weighted wood density calculated using species wood densities (oven dry mass / green volume) from Miles and Smith (2009). See Table 2 for method acronyms

Sub-block	Method	N	%Df	%Hw	%Cw	%Pw + Dr + Other	Wt. Wood Density kg/m3	LIS or FC: WRS ratio
401-1	WRS	5	22	44	23	11	359	1.00
401-1	LIS	5	53	26	19	2	412	1.15
401-1	FC	3.17	60	17	14	10	386	1.08
401-2	WRS	3	38	18	25	19	327	1.00
401-2	LIS	3	55	4	14	27	312	0.96
401-2	FC	5.27	57	16	20	7	391	1.20
423-1	WRS	3	30	43	16	12	364	1.00
423-1	LIS	3	35	40	25	0	407	1.12
423-1	FC	4.05	50	19	22	9	377	1.04
423-2	WRS	3	45	39	16	0	419	1.00
423-2	LIS	3	68	24	8	0	435	1.04
423-2	FC	6.26	64	16	17	3	411	0.98
423-3	WRS	4	35	17	46	3	373	1.00
423-3	LIS	4	51	21	24	4	395	1.06
423-3	FC	5.99	63	18	15	3	412	1.11
ALL	WRS	18	36 (2.1)	32 (3.2)	23 (2.9)	9 (1.8)	371 (7.9)	1.00
ALL	LIS	18	52 (5.2)	23 (5.7)	18 (3.1)	7 (5.1)	392 (11.1)	1.06
ALL	FC	24.74	60	17	18	6	398	1.07

Df- Douglas-fir, Hw- western hemlock, Cw- western redcedar, Dr – red alder, Pw – western white pine. N – Number of plots sampled (WRS and LIS methods) or area (ha) of a sub-block. Over all plots the standard error of %species and weighted wood density is shown in parentheses for the WRS and LIS methods.

Table 4: Capabilities and restrictions of the different field and geospatial methods for measuring post-harvest dispersed woody residues.

Capabilities	WRS	LIS	SLD	MLD
Sample based plots or points	X	X		X
Full census of entire block			X	
Volume density	X	X	X	X
Length density	X	X	X	X
Piece density – (LIS requires additional measurement of piece length)	X	x	X	X
Diameter Inside or Outside bark – (WRS could do both, but standard is DIB)	I	O	O	O
Residue wood species	X	X		
Piece grade and decay class – (standard WRS does not measure decaying wood)	x	X		
Restrictions				
Post-harvest stemwood woody residues measured	X	X	X	X
Measurements are time consuming	X	x		X
Many plots or transects needed to reduce error	X	X		X
Post-harvest conditions can restrict measurement. Eg. Obscuring branch foliage			X	X
Weather conditions can restrict measurements/image acquisition	x	x	X	X
Woody residue orientation or overlap can introduce bias		X	x	
Can distinguish non-“log” pieces (eg. overturned stumps, large branches)	X	X		x
Possible to measure woody residues or debris less than 10cm diameter	x	X		
Possible to measure pre-harvest woody debris	X	X		
Specialized equipment or software needed to acquire and prepare imagery			X	X
Specialized software needed to process data or imagery	x	x	X	x
Processing of data or imagery not easily done with open source software	X		x	X
Method volume density biased relative to WRS method at sub-block level			X	x

259x164mm (300 x 300 DPI)

116x261mm (300 x 300 DPI)

251x60mm (300 x 300 DPI)

321x423mm (300 x 300 DPI)