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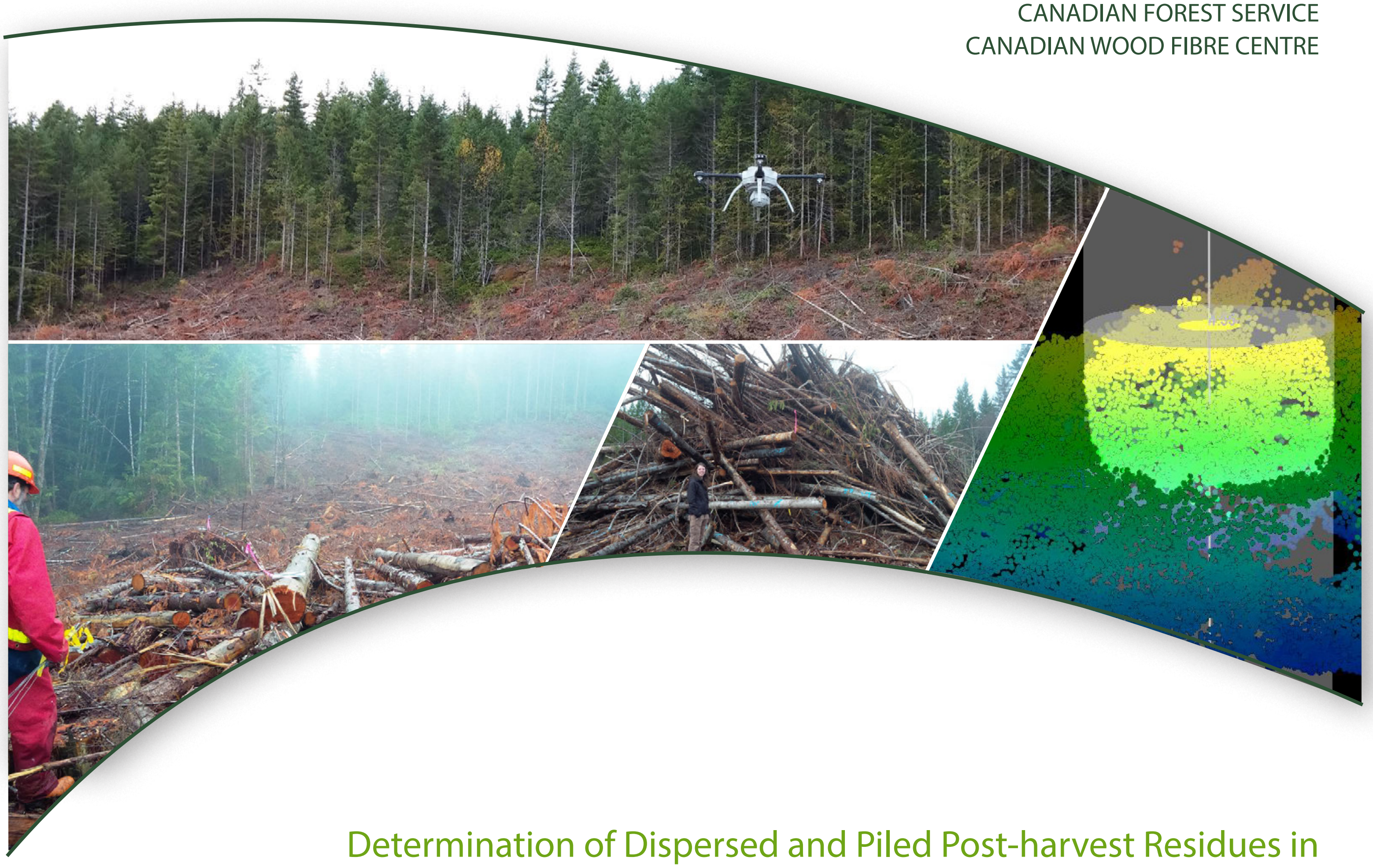

Determination of Dispersed and Piled Post-harvest Residues in Coastal Douglas-fir Cutblocks Using Unmanned Aerial Vehicle Imagery and Ground-based Surveys

J.A. (Tony) Trofymow, François Gougeon, and Jason Kelley

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Cover photos: Unmanned aerial vehicle flying over Northwest Bay harvest block, assessing pre-piling residues in experimental heavy accumulation plot, post-piling residue pile from experimental plot, Side view of normalized image point cloud of a residue pile.

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Abstract

After forest harvesting, significant amounts of woody residues are left dispersed on cutblocks, with some subsequently piled and burned. Quantification of these residues is required to estimate carbon budgets, billable waste, harvest efficiency, bioenergy potential, and smoke emissions. Currently, various sample-based field methods are used to assess post-harvest residues. Geospatial methods based on LiDAR and high-resolution imagery allow for a complete measurement of a site, enhancing forest stand inventories. These methods could also improve assessment of post-harvest residues.

In this study, ground-based and geospatial methods are compared to estimate amounts of woody residues for two cutblocks in the Northwest Bay area on Vancouver Island, British Columbia. Before and after burn pile construction, high-resolution colour photography was acquired using an unmanned aerial vehicle in 2014–2015. Dispersed waste and residue survey plots, and pile or accumulation plots were georeferenced and measured. Images were analyzed with an improved semi-automated log delineation method that better accounted for log overlaps. Image point clouds, digital surface models, and digital elevation models were created to determine bulk pile volumes, packing ratios were calculated for sample piles, and piled wood volumes derived from image point clouds were compared to values derived from field surveys.

Analysis showed field methods used to determine pre-piling stratum areas obtained values that differed by 5–20% compared to those obtained using geospatial methods on orthophotos. Analyses of cutblocks that use high-resolution imagery have greatest value in determining the post-harvest areas of the block, roads, and various strata of interest. The semi-automated method was best at determining dispersed residues under well-lit and good flight conditions on logs without obscuring branch foliage. Under such conditions, dispersed wood volumes derived using this method for an entire cutblock were comparable to those derived by the sample-based waste and residue survey method. The semi-automated log delineation method was not suitable for determining residue volumes in accumulation or piles. Field and geospatial method differences in stratum and block-level total residue volumes were affected by the estimates of stratum areas, with the geospatial values more consistent and preferable. For geospatial methods, pre- to post-piling differences in total residue volumes of the pile and accumulation strata were mostly related to the semi-automated log delineation method's poor estimates of wood in accumulations. Post-piling total residue volumes were more similar among field and geospatial methods than pre-piling, although volume distribution among strata differed with method. Within a method, post-piling volumes were generally less than pre-piling volumes, even though no wood had been removed from the blocks; however, the change in volume was not significant for most methods because of the high variance in plot density or packing ratios. Nevertheless, results suggest the best method for determining residue volumes will require a combination of geospatial and field measurements. Field measurements are still required to determine the site-specific packing ratios used to calculate piled and accumulation residue volumes, and to determine wood species and grade to calculate wood biomass.

Résumé

L'exploitation forestière produit dans son sillage de grandes quantités de résidus ligneux qui sont dispersés dans l'ensemble des blocs de coupe. Une partie de ces résidus sont par la suite mis en piles et brûlés. Il est nécessaire de quantifier ces résidus pour estimer le bilan du carbone, les déchets facturables, l'efficacité de la récolte, le potentiel bioénergétique et les émissions provenant de la fumée. On utilise à l'heure actuelle diverses méthodes de terrain fondées sur des échantillons pour évaluer la quantité de résidus après récolte. Des méthodes géospatiales utilisant le LiDAR et l'imagerie à résolution fine permettent d'effectuer des mesures complètes d'un site, améliorant ainsi les inventaires des peuplements forestiers. Ces méthodes pourraient également affiner l'évaluation des résidus après récolte.

Dans le cadre de la présente étude, les chercheurs ont comparé des méthodes terrestres et géospatiales afin d'estimer les quantités de résidus ligneux dans deux blocs de coupe de la région de Northwest Bay, dans l'île de Vancouver, en Colombie Britannique. En 2014–2015, des photographies en couleurs à résolution fine ont été prises au moyen d'un véhicule aérien sans pilote, avant et après la mise en piles des rémanents. Des mesures ont été prises dans des parcelles d'étude de résidus et de déchets dispersés ainsi que dans des parcelles où les déchets se sont accumulés ou ont été mis en piles. Ces données ont aussi été géoréférencées. Les images furent analysées au moyen d'une méthode améliorée de délimitation semi automatique des troncs qui tient mieux compte des chevauchements. De plus, à partir de nuages de points provenant des images, des modèles numériques de surface et d'élévation ont été développés afin d'établir les volumes externes des piles. Le taux d'entassement a été échantillonné sur certaines piles puis, les volumes de bois mis en piles établis d'après les nuages de points ont été comparés aux valeurs découlant des relevés de terrain.

L'analyse a révélé que les méthodes de terrain ayant servi à déterminer la superficie des strates avant la mise en pile des rémanents donnaient des valeurs qui variaient de 5 à 20 % par rapport aux résultats obtenus au moyen des méthodes géospatiales fondées sur les orthophotographies. Les analyses des blocs de coupe faites à partir des images à résolution fine présentent une valeur certaine pour l'établissement de la superficie après récolte des blocs, ainsi que celle des routes et des diverses strates d'intérêt. Lors de bonnes conditions d'éclairage et de survol et, avec des troncs dépourvus de feuillage sur leurs branches, la méthode semi automatique est celle qui a permis le mieux de déterminer les résidus dispersés. Dans ces conditions, les volumes de bois dispersés pour un bloc de coupe entier calculés au moyen de cette méthode étaient comparables à ceux obtenus au moyen de la méthode de de relevé des résidus et des déchets fondée sur des échantillons. La méthode de délimitation semi automatique des troncs ne convient pas à l'établissement des volumes de résidus accumulés ou mis en piles. Les différences constatées entre les méthodes géospatiales et celles de terrain pour ce qui est des volumes totaux de résidus dans les strates et pour l'ensemble d'un bloc ont été attribuées aux différences d'estimations de la superficie des strates, les valeurs obtenues au moyen de la méthode géospatiale étant plus uniformes et préférables. Quant aux différences notées dans les volumes de résidus totaux des strates d'empilement et d'accumulation, avant et après la mise en pile des résidus, elles étaient associées pour la plupart à des estimations erronées de la quantité de bois accumulé obtenue par la méthode de délimitation semi automatique des troncs. Les volumes de résidus totaux obtenus par les méthodes géospatiales et de terrain après la mise en piles s'apparentaient davantage que ceux établis avant la mise en pile, mais la distribution des volumes entre les strates était différente. Dans le cadre d'une méthode, les volumes étaient généralement inférieurs après la mise en pile qu'avant, même si aucune quantité de bois n'avait été enlevée des blocs. Cependant, cette variation volumétrique n'était pas significative pour la plupart des méthodes en raison de la variance élevée de la densité dans les parcelles ou des taux d'entassement. Néanmoins, les résultats donnent à penser que la meilleure méthode pour déterminer les volumes de résidus devra allier des mesures géospatiales et des mesures sur le terrain. D'ailleurs, il est toujours nécessaire de prendre des mesures sur le terrain pour établir les taux d'entassement propres à un site et utilisés pour le calcul des volumes de résidus accumulés et mis en piles et, pour établir les essences et les catégories de bois à des fins de calcul de la biomasse ligneuse.

Key Points

- Geospatial analyses of cutblocks using high-resolution imagery have greatest value in determining the post-harvest areas of the block, roads, and various other strata of interest.
- For the pre-piling roadside and scattered dispersed strata, waste and residue survey (WRS) plot sample values were higher than those obtained using the semi-automated log delineation (SLD) method for the Fall 2014 imagery; this was mainly related to limitations in the detection of whole logs.
- The better lighting, image quality, and loss of obscuring branch needles evident in the Summer 2015 imagery resulted in SLD sample-based values that were comparable to WRS sample-based values; however, as used, the SLD method was not suitable for determining heavy accumulation stratum residue volumes.
- The SLD method has good potential to determine wood volumes; however, this method involves calibration with field plot measurements and needs a minimum number of field measurements if the species and grade of residues are also required.
- Branches with adhering foliage on post-harvest residues also limit success of the SLD method; to use this method effectively, images would need to be acquired several months after harvest is complete and needles dropped, thus delaying how soon residue volumes could be estimated.
- For the heavy accumulation and piled strata, image point clouds can be obtained from low-altitude oblique images acquired from unmanned aerial vehicles (UAVs) and used to determine bulk volumes (and areas) for all pile and accumulation objects.
- The same image point cloud should be used to generate the needed digital surface and digital elevation models, with the latter prepared from the image point cloud edited to remove points on accumulations, piles, or leave areas. Even with additional ground control points, it was not possible to adequately register a previous LiDAR digital elevation model against that generated from the image point cloud.
- The most practical and repeatable method to determine site-specific sample packing ratios for piles and accumulations will involve scaling wood in WRS sample plots to a measured fixed depth, and calculating the bulk volume measured (plot area x depth). The sample packing ratios are then used with the bulk volumes to calculate wood volumes for all pile and accumulation objects.
- Good image quality is critical to the image analysis and generation of image point clouds, and will depend not only on the UAV camera resolution but also flight conditions, UAV speed, and speed of image storage.
- The apparent changes in wood volumes in the combined heavy accumulation plus piled strata after piling, even though no wood has left the site, suggests all methods give poor estimates of wood volumes in residue piles. In practice it would likely be best to use only the wood volumes determined for the accumulation stratum prior to piling as determined from a combination of geospatial (orthophoto areas and image point cloud bulk volumes) and field (scaled wood in fixed area plots to determine plot density or packing ratio) methods. Once piled, assume that all wood in the pre-piling accumulations is in piles minus wood remaining in any accumulations. Since field scaling of wood volumes and grades in accumulations is less problematic than in piles, this will result in a better and consistent estimate of wood in the piled stratum.

1. Introduction

After forest harvest, significant amounts of woody residues are left dispersed on site to decay or can be subsequently piled and burned. Quantification of residues remaining after harvest is required to estimate carbon budgets, billable waste, harvest efficiency, bioenergy potential, and smoke emissions.

Ground-based methods are currently used to determine the amount of woody debris or post-harvest residues on a site. All are based on sampling, where all wood in fixed-area ground plots is measured. In British Columbia, a standardized waste and residue survey (WRS) methodology is used which first prescribes a systematized layout of ground plots within each defined stratum of a cutblock (B.C. Ministry of Forest and Range 2005). Strata include roadside residues, accumulations from log processing, piled residues, and dispersed residues in the rest of the cutblock area. The method then prescribes the number of plots per hectare that should be assessed in each stratum to reach a desired confidence level.

Other ways to assess woody debris include those based on the line intersect sampling method developed by Van Wagner (1968) to assess fuel loads for fire hazard assessment. These methods, also called "plane intercept methods" (Brown 1974), can present logistical problems. For example, Hazard and Pickford (1986) found that to achieve estimate values within ±10% of the 95% confidence level for actual wood volume would require measuring 235 lines, each 38.10 m long (a total of 8953 m of lines). In addition, non-random distribution of logs can lead to overestimates of woody debris if sampling lines are laid perpendicular to the orientation of woody debris in a study area (Stahl 1998; Brissette et al. 2003). Despite such limitations, line intersect sampling methods are routinely used to assess amounts of woody debris in various national (Canadian Forest Inventory Committee 2008; Forest Inventory and Analysis 2011) and provincial forest inventories (Ontario Ministry of Natural Resources 2013; Alberta Biodiversity Monitoring Institute 2014).

Line intersect sampling methods are generally not suitable when assessing wood volumes in residue piles. Hardy (1996) developed a system of applying simple geometric shapes to piles to determine bulk pile volume. When combined with tables of field-based estimates for packing ratios (wood volume/bulk pile volume) and wood species specific gravity, this system provides estimates of wood biomass for the prediction of smoke emissions; however, when piles reach sizes greater than 5 m3, their shapes become increasingly irregular and do not conform to simply geometric forms (Wright et al. 2009). In addition, packing ratios are a function of the method used to define the bulk pile volume and thus different methods used to assess bulk pile volumes will require different packing ratios (Trofymow et al. 2014). The WRS method assesses wood volumes in residue piles by determining plot density (wood volume/plot area). This is accomplished by placing fixed area plots on a set of sample piles, scaling wood to a measurable depth, and then adjusting wood volumes by the total depth of the pile at plot centre (B.C. Ministry of Forest and Range 2005).

Geospatial methods using imagery acquired through remote sensing and orthophotos have long been used to assess forest and land cover types as well as to delineate areas affected by disturbances, such as harvest, fire, and deforestation. More recently, airborne laser scanners (also referred to as "LiDAR," or Light Detection and Ranging) and high-overlap stereo imagery have been used to produce LiDAR- or image-based point clouds, respectively. The resulting point clouds are then used to derive digital surface models of vegetated or ground surfaces for vegetated or bare ground areas (Næsset et al. 2004; Lalonde et al. 2006; White et al. 2013a; Maltamo et al. 2014). Data from airborne laser scanners includes returns from the top surface, within-canopy, and ground, which can be filtered to separate ground returns from canopy returns. Accurate digital elevation models are then derived from the ground surface point clouds. For forested areas, the difference between LiDAR digital surface and digital elevation models yields a normalized canopy height model from which the determination of various stand height statistics is possible. When combined with ground plot data, these statistics are used to determine detailed information such as tree volume and basal area for timber stands over large areas (Lalonde et al. 2006; White et al. 2013a; Maltamo et al. 2014). Point clouds acquired via high-resolution imagery or LiDAR have been used to delineate tree crowns, assess heights, species, and stand density (Leckie et al. 2003; White et al. 2013b).

Applications of geospatial methods for assessing woody debris have been more limited. Eamer and Walker (2010), used orthophotos and LiDAR to study the sand storage capacity of large woody debris (LWD) on beaches. They created two digital elevation models to delineate the difference between spectral signatures of sand and LWD but were unable to delineate individual logs or their length. Richardson and Moskal (2016) used LiDAR and image-based analysis to detect LWD and delineate and size individual logs larger than 30.5 cm diameter in streams at multiple study sites, using both automated and manual log delineation methods. Blanchard et al. (2011) used LiDAR point cloud data to conduct a rule- and object-based image analysis to classify downed logs. Trofymow (et al. 2014) compared geospatial methods using LiDAR to ground-based WRS methods for piled residues in the Oyster River area of coastal British Columbia (Figure 1) and found the WRS methods underestimated piled residue wood volumes by 50–65%, primarily related to underestimates in the pile areas or bulk volumes, whereas the U.S. Forest Service volume method overestimated pile wood by 50% when site-specific packing ratios were not used (Hardy 1996).

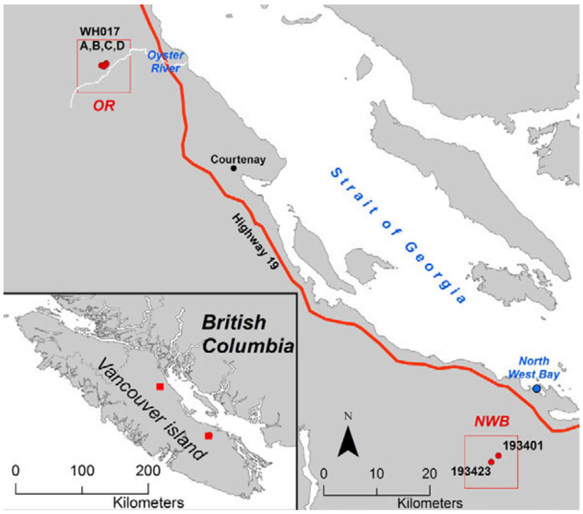

Figure 1. Location of Oyster River cutblocks (OR; WHO17 A, B, C, D) and Northwest Bay cutblocks (NWB; 193401, 193423) on Vancouver Island, B.C.

As part of the Trofymow et al. 2014 study, a preliminary semi-automated log delineation (SLD) method was developed in PCI Geomatica®[1] to analyze orthophotos and isolate logs larger than 10 cm in diameter to determine dispersed residues and offer a comparison to WRS methods. Across four cutblocks, residue volumes derived using the SLD and WRS methods were correlated (R^2 = 0.69), although SLD volumes were 2.5 times larger than those derived using the WRS method. Methods for dispersed residues could not be properly compared as individual WRS plots were not geo-referenced, only 12 plots were sampled, and low-resolution images poorly resolved the logs. The authors recommended developing the method further using higher-resolution imagery and comparing its estimates to the ground-based WRS method for a greater number of sample plots.

1.1 Objectives

In this study, we compare ground-based and geospatial methods to estimate amounts of woody residues in two cutblocks soon after harvest and later after mechanical piling. We further develop the semi-automated log delineator method for dispersed residues by using high-resolution imagery obtained through unmanned aerial vehicle (UAV) flights and compare these values with those measured using ground-based waste and residue survey methods for many sample plots on the pre-piled blocks. We then examine the utility of image point clouds derived from post-piling, UAV-acquired imagery to determine bulk pile volumes and then use of field-based measurements of wood volumes from experimental piling plots and WRS pile plots to derive sample packing ratios to convert pile bulk volumes to pile wood volumes. Finally, we compare the ground-based and geospatial method estimates of total block-level residue wood volumes before and after piling. We hypothesize that within a method these values should be identical for a cutblock as no wood has been removed from the sites.

[1] PCI Geomatics. 2015. Geomatica [software]. Markham, Ont. http://www.pcigeomatics.com/geomatica-help/.

2. Study Sites

The Northwest Bay study area is located within the very dry maritime Coastal Western Hemlock (CWHxm) biogeoclimatic subzone, at 49°11′7.9″N, 124°19′46.6″W on Vancouver Island, British Columbia, Canada (Figure 1). The two cutblocks—193401 (18 ha) and 193423 (23 ha), located southwest of Northwest Bay on lands owned by Island Timberlands (Figure 1)—were harvested by feller-buncher and yarded by hoe-chucking in the summer and fall of 2014. Before harvesting, both blocks were dominated (43–63%) by second-growth Douglas-fir (*Pseudotsuga menziesii*), with secondary components of western hemlock (*Tsuga heterophylla*) or western redcedar (*Thuja plicata*). Pre-harvest cruise volumes were 484 and 273 m^3/ha in 193401 and 193423, respectively, with lower volume areas on the periphery of each block. Block 193401 had a low slope, southerly aspect, and an elevation range of 450–470 m, whereas block 193423 had a moderate slope, northeast aspect, and an elevation range of 560–680 m. Machine piling on these blocks was completed by Island Timberlands in early 2015. Waste and residue survey measurements and high-resolution colour aerial photography was acquired on the two cutblocks by UAV flights before and after pile construction (Figure 2).

Figure 2. Aeryon SkyRanger unmanned aerial vehicle with roadside, heavy accumulations, and scattered dispersed residues at a Northwest Bay block after harvesting.

3. Methods

3.1 Waste and Residue Survey

Following harvest and piling operations, an Island Timberlands contractor completed both the before (October 2014) and after (February 2015) waste and residue surveys according to provincial guidelines to determine woody residues in roadside ("RBX"), heavy accumulations (1–3 m deep) left after log processing ("RBH"), scattered dispersed ("SBX"), and piled ("PBX") strata by measuring strata areas (hectares) and scaling wood in sample plots in each stratum to determine the plot density (i.e., residue wood in cubic metres per hectare). These data were then used to calculate residue wood volume in the stratum and block (B.C. Ministry of Forest and Range 2005). Across both blocks, 57 WRS dispersed and 24 accumulation or pile plots were measured in the field with plot centres georeferenced to less than 30 cm (most < 10 cm) horizontal accuracy, using a Trimble® GeoXH 6000 with post-processing differential correction using Trimble Pathfinder® software. [2]

The pre-piling areas of each stratum were measured in the field (Figure 3). The roadside areas were determined as a constant width (15 m) from road edge, excluding accumulations or leave areas. The accumulation areas were determined by hip-chain measurements of the length of each area along the roadside boundary and width of the accumulation. The dispersed areas were calculated from the difference of the planned block area (net of roads) and the roadside and accumulation areas. Both roadside and accumulation plots were circular in shape with a radius of 3.99 m (i.e., 0.005 ha). The dispersed plots were circular with a radius of 11.28 m (i.e., 0.04 ha), except in some cases where plots overlapped another stratum or leave areas, in which case plots were D-shaped with a 15.96 m radius (i.e., 0.04 ha). All residues 10 cm or larger in diameter were scaled and put into three classes based on length and the condition of the ends. "Logs" (L) are defined as any residues 10 cm or larger in diameter and 3 m or longer in length. Residues 0.2–3 m in length are

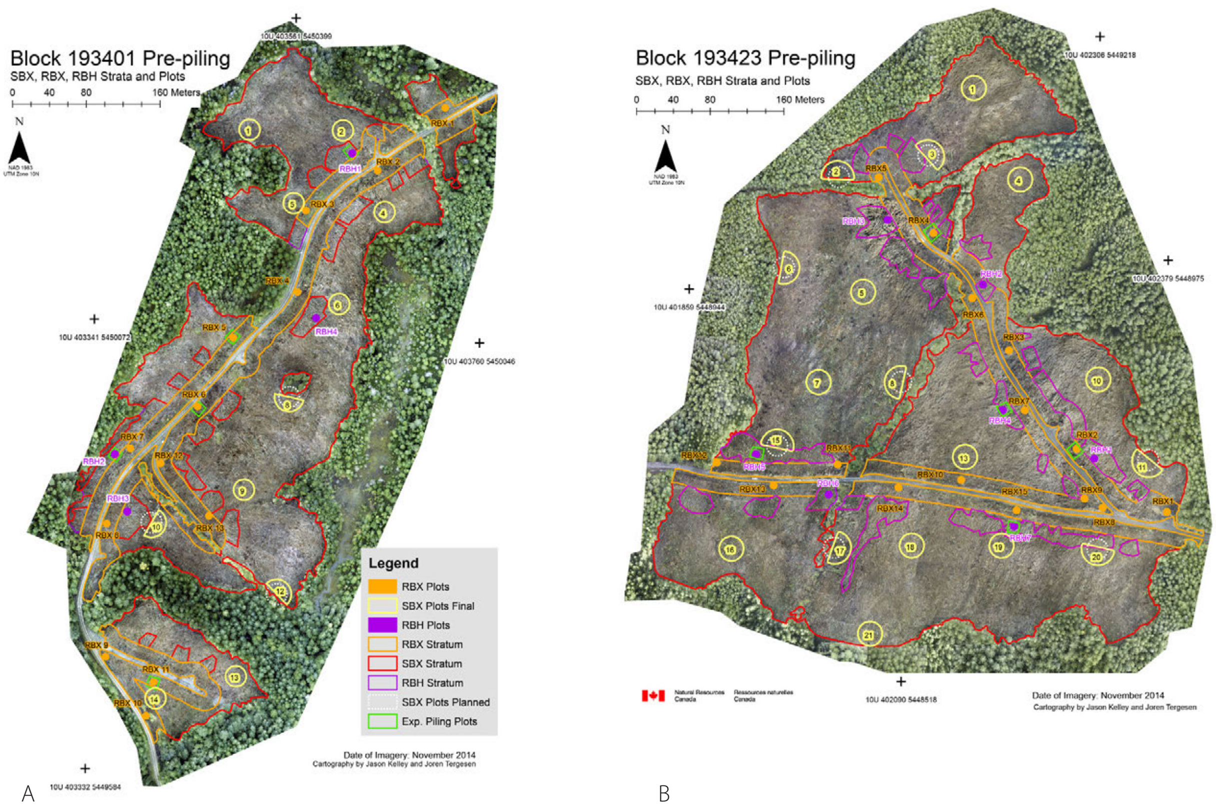

Figure 3. Orthophoto mosaic with pre-piling strata and plots for blocks (a) 193401 and (b) 193423 at Northwest Bay, B.C. Strata acronyms: roadside (RBX), heavy accumulations left after log processing (RBH), scattered dispersed (SBX), and piled (PBX).

[2] Trimble Inc. 2017. Pathfinder [software]. Sunnyvale, Calif. http://www.trimble.com/mappingGIS/PathfinderOffice.aspx?tab=Technical_Support.

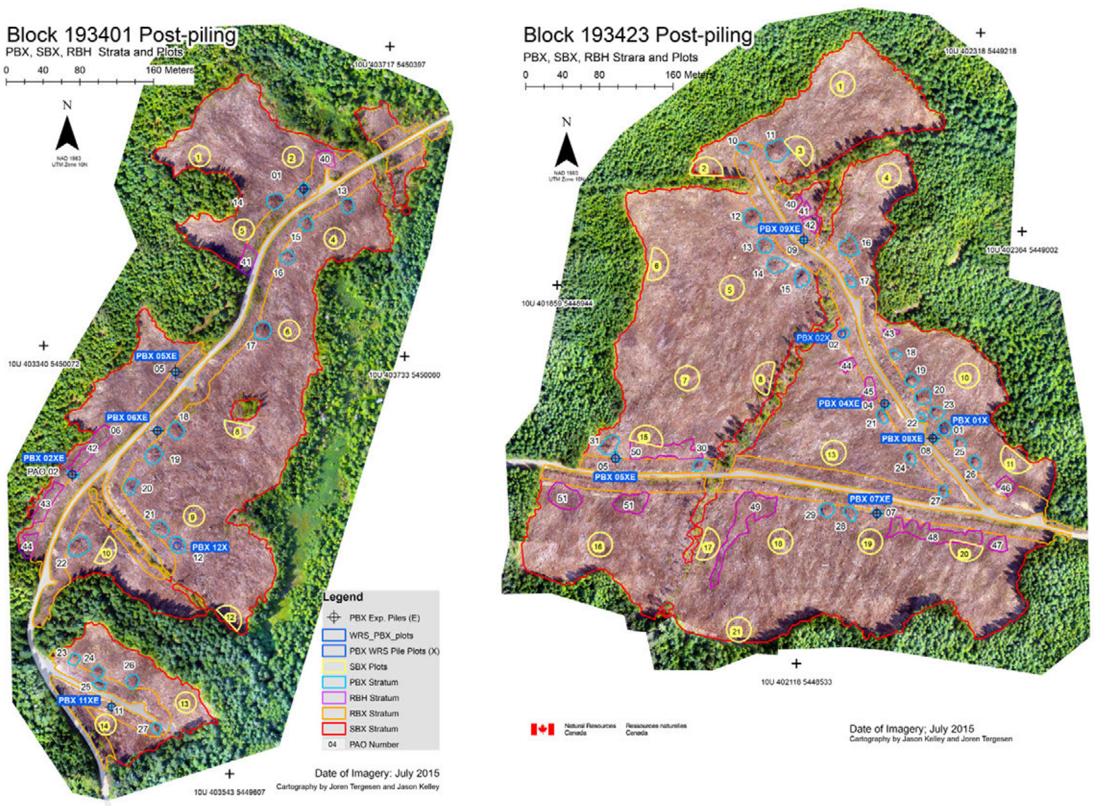

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Figure 4. Orthophoto mosaic with post-piling strata and plots for blocks (a) 193401 and (b) 193423 at Northwest Bay, B.C. Strata acronyms as in Figure 3.

defined as "bucking waste" (W) if the piece has a cut end, or as "breakage" (B) if the piece had a broken end (B.C. Ministry of Forest and Range 2005). In accumulation plots, the total depth at plot centre and depth scaled were determined to calculate a percent measured value that was used to derive the plot density (residue wood in cubic metres per hectare).

After piling, most of the accumulations and some roadside residues were in piles, whereas the dispersed residues remained intact. The areas of the roadside, accumulation, and piled strata were re-measured in the field and new 3.99 m radius plots were located on individual sample piles, the wood was scaled, and the total and scaled depth determined to calculate a percent measured value, and the piled plot density calculated. The area of the piled stratum was determined in the field by estimating the width of each pile, calculating its area as a square, and summing the area of all piles.

In addition to the field measurements of stratum areas, areas were also determined by digitizing each stratum on orthophoto mosaics prepared from UAV imagery taken during the pre- (Figure 3) and post-piling (Figure 4) flights. The roads and perimeter of the actual cutblock were first digitized with geographical information system (GIS) software. For the roadside stratum, a 15-m buffer was applied from the road edge and then edited to exclude leave areas and accumulations or piled objects, each of which were individually digitized. The remaining area was designated as the scattered dispersed stratum.

To compile the data, the contractor used ENFOR software,[3] which produces plot, stratum, and block summaries for residues by species and grade as well as individual plot tallies of species, grade, length, top diameter, and butt diameter. A single database containing all data for each plot was created from the WRS data. Since the field-based and ortho-digitized stratum areas can differ, the WRS stratum and block-level residue volume totals were calculated and reported using both the field and GIS stratum areas.

[3] Enfor Consultants. 2015. Enfor waste survey software. North Vancouver, B.C. http://www.enfor.com/?Page=/software/waste/.

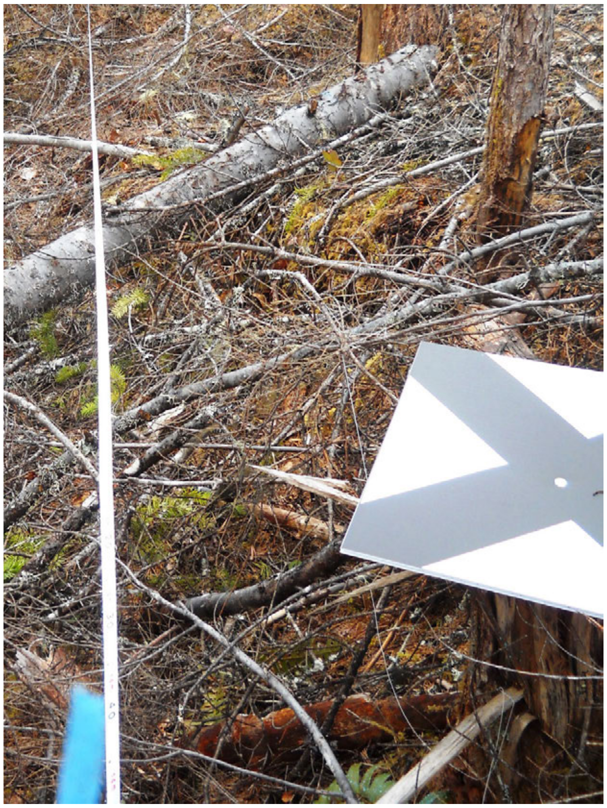


Figure 5. Residues and target in scattered dispersed plot (SBX2) on block 193401.

3.2 Image Acquisition and Processing

The UAV flights were completed by Integrated Information Systems (http://i2s.ca/) using an Aeryon SkyRanger quadcopter equipped with an SR-3SHD 15MP camera that captured colour (RGB) imagery at 1.2–2.4 cm resolution, depending on the flight. Table 1 provides the UAV flight and image acquisition parameters. Before the flights, 30 x 30-cm targets (Figure 5) were nailed to stumps or logs adjacent to the WRS plot centres, georeferenced, and used to assist in preparation of the orthophoto mosaics.

The first pre-piling flight of both blocks was conducted in October 2014. The presence of shadows and mist in block 193423 led to an additional flight in December 2014. An orthophoto mosaic was delivered that combined images from the first and second flights; however, this revised mosaic still had problems that prevented analysis, so another flight occurred in February 2015. The final pre-piling orthophoto mosaic for block 193423 was created with images from all three flights to produce the highest image quality. The final pre-piling mosaics are referred to as the "Fall 2014" orthophoto mosaics. All mosaics were prepared by Integrated Information Systems using Pix4D software. [4]

The post-piling flight was conducted in June 2015 and the acquired images were used to create the "Summer 2015" post-piling orthophoto mosaics. Although images for the pre-piling flights were captured as digital negative (DNG) files, the post-piling flights were captured as JPG files. Since DNG files required more time to store, flight speeds had to be slower; in many cases, the periphery of the image was out of focus, especially with flights conducted under windy conditions. For the post-piling flights, lateral overlap was increased from 60% to 80% to allow for the creation of an image point cloud from the stereo images using Pix4D software. The image point cloud was used to create a digital elevation and digital surface models for later analysis of pile bulk volumes.

Table 1. Flight and image acquisition parameters for UAV flights before and after piling.[a]

Parameter	193401 before piling	193423 before piling flight 1	193423 before piling flight 2	193423 before piling flight 3	193401 after piling	193423 after piling
Date	24-Oct-14	24-Oct-14	08-Dec-14	11-Feb-15	09-Jun-15	09-Jun-15
Time	13:00	09:00	12:00	09:00	14:00	10:30
Weather	Overcast	Overcast	Rain/high winds	Overcast	Sunny, clear skies	Sunny, clear skies
Photo resolution (cm)	2.3	1.22	1.22	1.22	2.4	1.8
Lateral overlap (%)	60	60	60	60	80	80
Image format	DNG	DNG	DNG	DNG	JPG	JPG
Flight speed (km/hr)	5	5	5	5	12	12

[a] All UAV flights were conducted using an Aeryon SkyRanger sUAS quadcopter equipped with an SR-3SHD 15 MP camera having a 46° x 34° field of view. All flights were at 120 m altitude with 80% forward overlap. Data were processed with Pix4D Mapper (Version 1.4.46) and ArcGIS (Version 10.2.2) using a NAD83 Albers projection.

Geospatial analyses for all orthophoto mosaics were done using NAD83 Albers projection and NAVD88 CVGD28 geoid within ArcGIS™ (Version 10.2.2).[5] For the pre-piling image processing and initial post-piling image processing and IPC creation, five differential GPS ground-control points were used in each block.

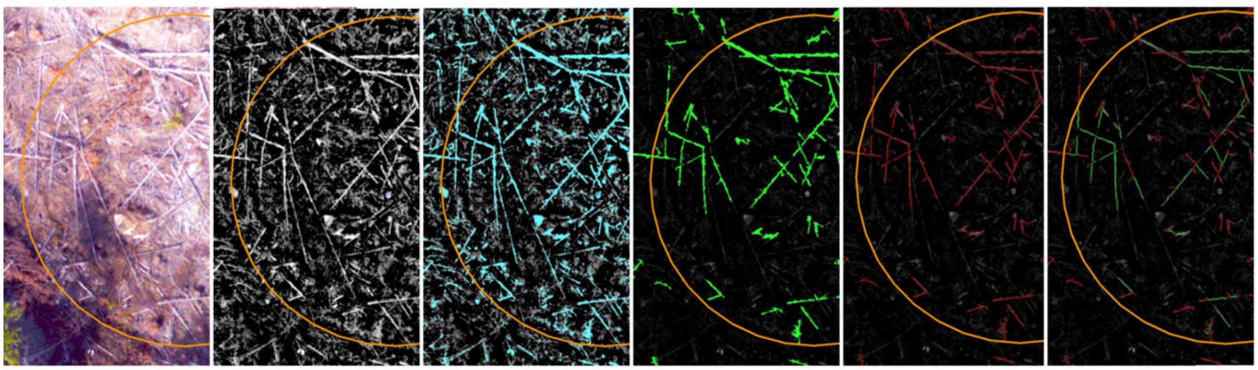
3.3 Semi-automated Log Delineation

The semi-automated long delineation (SLD) procedure uses some modified programs and procedures from the Individual Tree Crown suite of programs (Gougeon and Leckie 2003). Appendix 1 contains a flowchart of the SLD procedure (Table A1.1). To reduce file size for further processing and to increase log continuity, image resolution was resampled from ~2 cm to 5 cm and images clipped using a 2-m buffer around each plot (Figure 6a). Images were delivered by Integrated Information Systems in a BigTiff file format and converted into a PCI Geomatica 8-bit format (.pix). Once the .pix file was created using the same number of pixels and lines, the georeferencing was then copied from the original image. Because the original image contained 8-bit data (0–255) stored in a 32-bit range, the data was scaled from all three channels of the original image into an 8-bit range in the three channels of the PCI image.

After the image was prepared, the Individual Tree Crown program "HOMOGEN" program was used to create a mean of the blue channel. HOMOGEN used a 7 x 7 kernel on the first pass and a 31 x 31 kernel on the second pass to generate a mean image of the blue channel. This mean blue image was then subtracted from the blue channel to create a normalized blue channel image (Figure 6b). A threshold run on the normalized blue channel created a bitmap containing any pixels with a digital number (DN) of 25 or greater (Figure 6c).

The resulting bitmap from the threshold was then used in the "CWDSFIL" program to filter out any odd pixels, circular objects (stumps), and small chunky debris that did not meet the minimum size (i.e., < 10 cm diameter and < 1 m length). The sizeable objects left contained mostly logs and multi-log objects and were saved to a bitmap (Figure 6d).

The CWDSFIL bitmap was processed with the "skeletonize" utility in the Fiji software (Schindelin et al. 2012) to produce skeletons of the log objects; the software's "analyze skeletons" utility was then used to identify log skeletons, intersections of logs, and end points of logs. The result of this analysis was imported back to Geomatica and a threshold was run to remove the intersection points separating multi-log objects into individual logs (Figure 6e).



A B C D E F

Figure 6. Example (from scattered dispersed plot SBX14; Summer 2015) of image processing for semi-automated log delineation, including: (a) resampling to 5 cm; (b) normalization; (c) thresholding; (d) CWDSFIL program to obtain objects longer that 1 m in length and greater than10 cm diameter; (e) Fiji skeletonization; and (f) LOGIVOL program to keep proper logs and report their size and position.

The resulting skeleton was input to the "LOGIVOL" program that followed the skeletons and used the objects from the CWDSFIL program to assess the diameter of each object and to remove objects failing to meet either the average diameter or length requirements. Objects selected by the LOGIVOL program were placed in a bitmap for visual analysis (Figure 6f) and exported to a text file that contained individual log co-ordinates, lengths, diameters, areas, and volumes for subsequent statistical analysis.

4. Pix4D. 2015. Pix4Dmodel [software]. Lausanne, Switzerland. https://pix4d.com/product/pix4dmodel/.

5. ESRI. 1995–2014. ArcGIS Desktop, Version 10.2.2 [software]. Redlands, Calif. http://resources.arcgis.com/en/help/main/10.2/.

The SLD procedure was used in the analysis of pre-piling roadside, accumulation, and dispersed sample plots, as well for analysis of the full area of the dispersed stratum in the Fall 2014 orthophoto mosaic. In addition, to test how image quality affected estimates of dispersed residue volumes, the SLD procedure was used in the analysis of the dispersed plots and full area of the dispersed stratum in the Summer 2015 orthophoto mosaic. The post-piling image in both blocks appears to be better lit and with the loss of obscuring needles from the branches, entire logs were more visible.

meet the 10 cm minimum diameter were not selected for the final volume calculation by the LOGIVOL program. We found that these minor changes in parameter values did not improve the overall fit and so original default parameter values were used for the SLD procedure in further calculations.

3.4 Manual Log Delineation

Manual log delineation (MLD) involved digitizing (in ArcGIS 10.2.2), on the original 1.2–2.4-cm resolution orthophoto

A B

Figure 7. Example of manual log delineation for: (a) Fall 2014; and (b) Summer 2015 images for a scattered dispersed plot (SBX14), illustrating how the delineation changes seasonally with the loss of obscuring foliage and better illumination.

3.3.1 Parameter Exploration

To optimize the results of the SLD method, several parameters were explored with the pre-piling images to find the best fit regression in SLD versus WRS data (see below). The first parameter was the DN value used when thresholding from the normalized blue band. The values tested were the original DN ≥ 25, and DN ≥ 20. This was to test whether increasing the amount of pixels selected from the threshold improved the final volume calculations. The second parameter tested was changing the minimum diameter value in CWDSFIL from the original 10 cm to 7 cm. This was to test whether increasing the number of objects selected by the CWDSFIL would improve the final volume calculations. Objects that did not

mosaic, the perimeter of all logs within a plot that appeared to meet the size criteria (≥ 10 cm diameter, ≥ 1 m length). A script was then used to calculate the longest straight line inside the log polygons, providing log length.[6] The log-length value was used with the reported area of each log object to calculate an average diameter, as well as a calculated volume for each log object. The MLD was done for all roadside plots in both blocks of the pre-piling image but not the post-piling image, as most roadside plots were destroyed during piling operations. Manual log delineation was also done on the dispersed plots for both blocks in both pre-piling and post-piling orthophoto mosaics (Figure 7); however, because of the larger size of these plots, only a subset was chosen for the delineation.

[6] Jenness Enterprises. 2007. Longest straight line, version 1.3a [script]. Flagstaff, Ariz. http://www.jennessent.com/arcview/longest_lines.htm.

3.5 Pre-piling Comparisons

Method comparisons for the pre-piling (Fall 2014) orthophoto mosaic were made at the plot level (residue wood in cubic metres per plot), and for stratum-level plot density (residue wood in cubic metres per hectare). Table 2 provides a description of the methods and how these were calculated. Regressions were calculated of residue volumes per plot for the SLD method(s) versus WRS method, the MLD method versus WRS method, and the MLD method versus SLD method for each stratum (RBX, RBH, SBX), for all plots in each block, and for all plots in both blocks combined. Regressions were also done for the dispersed plots using the Summer 2015 orthophoto mosaic. Regression results were inspected and repeated with data for outlier plots removed. Regression equations were considered significant with a $P < 0.05$.

For the stratum-level method comparisons, plot wood volumes were normalized by plot area and the sample-based mean (and standard error) plot density (residue wood in cubic metres per hectare) for the stratum calculated using data for all plots within a block. As noted above, the SLD method was also applied to the entire roadside and dispersed stratum areas for the Fall 2014 orthophoto mosaic and for the dispersed stratum area for the Summer 2015 orthophoto mosaic to give a full measure of residue wood volume in the stratum and divided by GIS area to give a mean (no standard error) plot density for the stratum. In cases where the plot-level SLD versus WRS regressions were significant and positive, the regression equation was used as a correction factor for the full-measure SLD method and the regression parameter error propagated to the estimated mean (and standard error) residue density for the stratum.

3.6 Generation of Digital Elevation Model from Post-piling Image Point Clouds

To determine bulk volumes of pile or accumulation objects from LiDAR point clouds or UAV image point clouds, a suitable digital elevation model (DEM) must be prepared to normalize the digital surface model and calculate the object volumes. Terra Remote had been previously flown the full treed Northwest Bay sites with LiDAR in 2011 as part of the same acquisition done for Island Timberlands over the Oyster River site, as described in the residue pile study by Trofymow (et al. 2014). For the Northwest Bay site, Island Timberlands provided the LiDAR ground-hit point cloud and the 2-m

Table 2. Summary of field and geospatial methods used to estimate woody residue volumes (cubic metres) in ground plots and mean plot density (cubic metres per hectare) for a stratum.

Method (acronym)	Description
WRS	Waste and Residue Survey – Scale logs > 3 m length and breakage, waste bucking ≥ 0.2 m length, all ≥ 10 cm butt and top diameter on RBH and RBX (3.99 m) and SBX (11.28 m) plots. Data included, by species and grade, the log length, top and butt diameter of each piece.
SLD	Semi-automated Log Delineation – Procedure that normalizes and processes orthophotos for log objects ≥ 10 cm width and ≥ 1 m length (see Section 3.3) and returns list of log objects with length, width, area, and volume.
MLD	Manual Log Delineation – Digitize polygons of logs ≥ 10 cm width and ≥ 1 m length (Longest Straight Line routine; see footnote 6) and list log objects with length, width, area, and volume.
WRSs	WRS sample-based mean residue volume per hectare for all plots in stratum = (∑ ((scaled wood volume ÷ (measure% ÷ 100)) ÷ plot area))) ÷ *N* plots. Not all logs can be scaled in RBH plots and are adjusted by percent age of total depth measured (75–99%).
SLDs	SLD sample-based mean residue volume per hectare for all plots in a stratum.
SLDf	SLD full measure of residue volume in the entire stratum ÷ stratum area = volume per hectare.
SLDfc	SLD full measure of stratum residue volume per hectare, "corrected" using equations from significant plot-level WRS vs. SLD volume regressions.

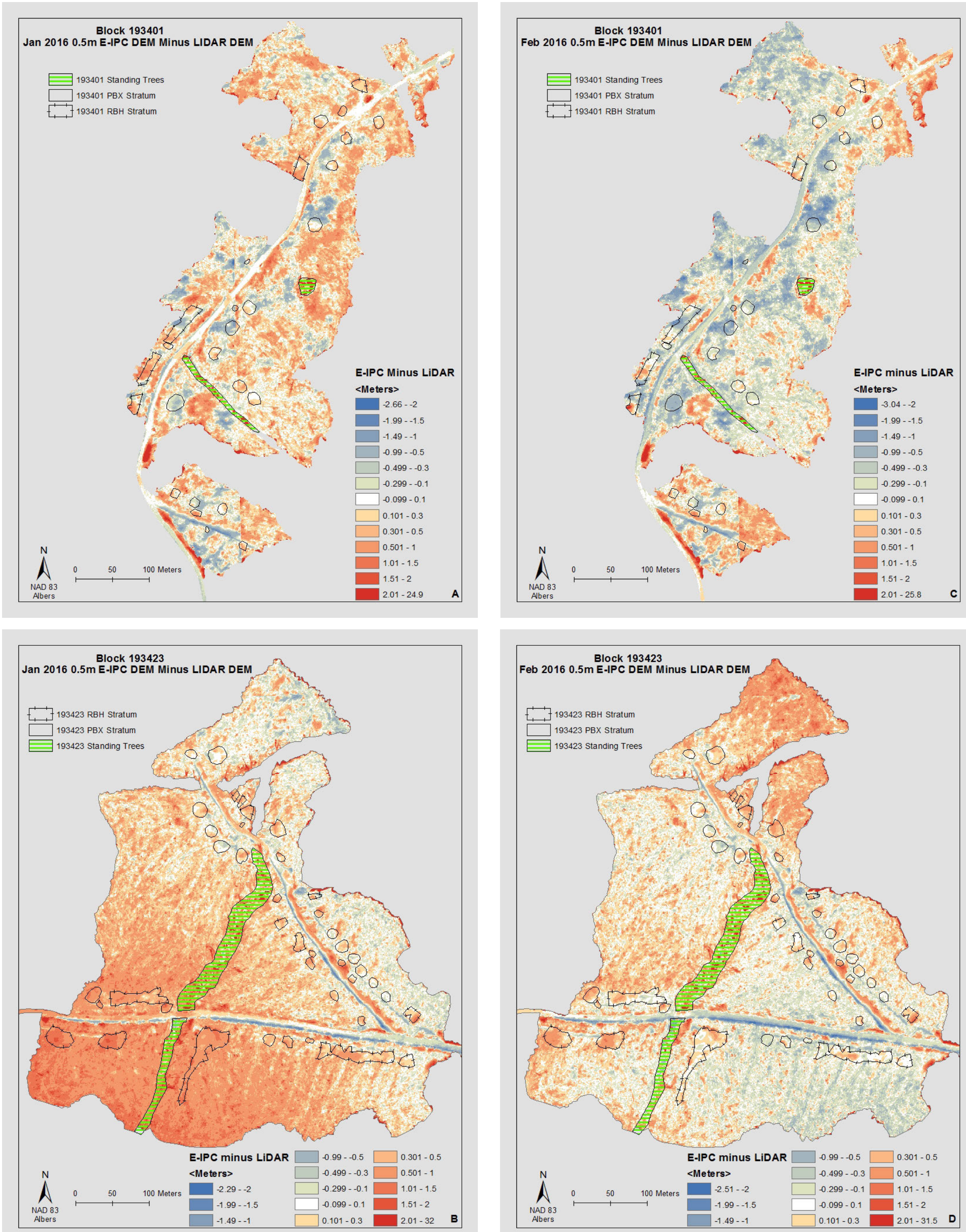


Figure 8. Differences between the digital elevation models generated from 2015 UAV image point cloud and 2011 LiDAR ground hits data, using (a, b) differential GPS elevations at five ground control points in each block, or using (c, d) ground control points identified from the 2015 orthophoto mosaic for each block (12 points for block 193401, 14 points for block 193423) with elevations from 2011 LIDAR digital elevation model offset for stump height (targets) derived from UAV the image point cloud.

resolution LiDAR digital elevation model prepared by their GIS department in 2011. A digital elevation model of the cutblock was also prepared from the June 2015 UAV image point clouds (generated using five differential GPS ground control points in each block), by first editing in Fusion[7] to delete points in the UAV image point clouds (E-IPC) located within the digitized boundaries of the pile and accumulation objects, as well as all points in leave tree areas, and then processing the E-IPC using the ArcGIS LASD routine to create a 0.5 m rasterized pseudo-digital elevation model (pDEM) representing the ground surface.

Initial block-level comparisons of the two digital elevation models showed that a significant bias existed between the E-IPC pDEM and the 2011 LiDAR DEM (Figure 8a, 8b): –2 m to 2 m differences were evident in block 193401 and 1–2 m differences in block 193423, with the bias increasing from the north to south end of block 193423. To better register the image point clouds with the 2011 LiDAR DEM, 12 and 14 new ground control points were added for blocks 193401 and 193423, respectively, using the x and y differential GPS target positions and the corresponding LiDAR DEM elevation at that point. As ground control point targets were located on top of stumps, the height of the stump (Figure 5) above adjacent ground, obtained from the UAV image point cloud, was added to the LiDAR DEM elevation to determine the ground control point elevation. The combined set of ground control points was used to reprocess the UAV images for each block in Pix4Dmodel, prepare a revised second image point cloud (IPC2), and a revised second pseudo-digital elevation model (E-IPC2 pDEM2). The differences between this revised model and the LiDAR DEM were less (i.e., greater area with differences from –0.2 m to 0.2 m) although still significant, with a greater area of negative differences in block 193401 but less slope bias in block 193423 (Figure 8c, 8d). Features associated with road building and yarding activities became more evident. Therefore, we deemed the 2011 LiDAR DEM unsuitable for use in determining pile and accumulation object bulk volumes.

3.7 Residue Pile and Accumulations Bulk Volumes and Area

Because the block-level differences between the revised second digital elevation model and the LiDAR digital elevation model for the entire cutblock were large enough to influence

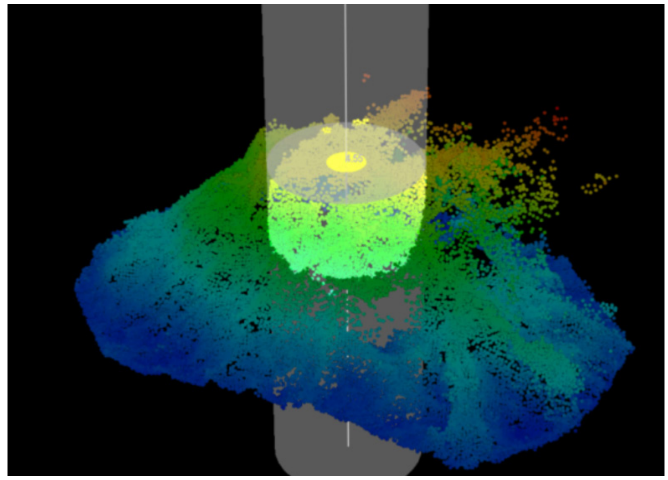


Figure 9. Top view of normalized image point cloud, showing waste and residue survey pile-plot location and image point cloud 95th percentile height at pile-plot centre (4.2 m) (plot PBX01XE, block 193401).

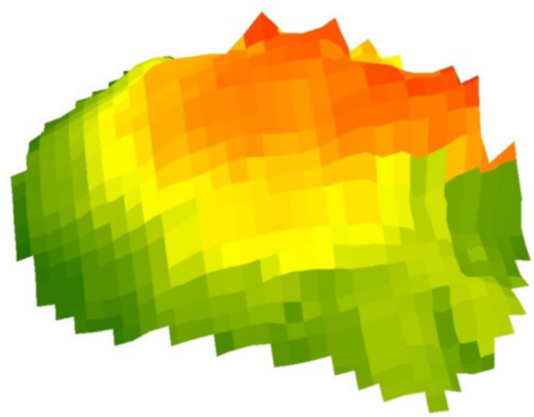


Figure 10. Raster (0.5-m resolution) for pile plot used to determine bulk pile volume (plot PBX01XE in block 193401).

the bulk pile volumes, the difference between the pseudo-digital elevation model and digital surface model generated from the revised second image point cloud was used to calculate the bulk volumes for each pile and accumulation object.

The 2015 UAV revised second image point cloud (IPC2) was processed to create pseudo-digital elevation models and digital surface models using three different software packages.

[7] U.S. Department of Agriculture. Introduction to Fusion [website]. Forest Service, Remote Sensing Applications Center, Salt Lake City, Utah. https://www.fs.fed.us/eng/rsac/fusion/launch/fusionbkg.htm.

[8] ESRI. 1999–2011. ArcGIS Desktop, Version 10 [software]. Redlands, Calif. http://help.arcgis.com/en/arcgisdesktop/10.0/help

[9] Ibid.

[10] ESRI. Ibid.

1. ArcGIS Terrain Feature[8] to create two pseudo-digital elevation models (minimum and mean) from the E-IPC2 and a digital surface model from the full IPC2. This was the same method used in Trofymow et al. (2014) to determine bulk pile volumes at the Oyster River blocks.
2. Fusion[9] using the E-IPC2 to generate two 0.5-m resolution pseudo-digital elevation models (minimum and mean) and the full IPC2 to create a 0.5-m resolution digital surface model.
3. ArcGIS LASD[10] : the E-IPCs and full IPC2 were imported to ArcGIS as LAS data sets and used to produce two 0.5-m resolution pseudo-digital elevation models (minimum and mean) and a 0.5 meter-m resolution digital surface model.

All methods used maximum height in each 0.5 m cell to generate the digital surface model. The pseudo-digital elevation models and digital surface models for all three methods were then clipped to the pile and accumulation object boundaries (Figure 9) using a PYTHON script developed for the Oyster River site. The script takes the digital elevation model (before) and the digital surface model (after) clipped to the individual pile and accumulation objects and uses the ArcGIS cut/fill tool to determine bulk volumes for each object. Results tables for all objects are merged into a single table for export to Microsoft® Excel®. The cut/fill tool in ArcGIS compares the raster surfaces (Figure 10) of the digital surface and digital elevation models and, cell by cell, calculates the difference in elevation between them and the area of the cell to assign a change in volume to the output cell. Appendix 2 provides a summary of the digital elevation model and digital surface model generation workflow for the pile and accumulation objects.

After bulk volume methods were compared, the bulk volumes and areas for only one method were used for subsequent analyses of stratum- and block-level residue wood volumes.

3.8 Residue Pile Packing Ratios

To convert bulk pile volumes into pile wood volumes, a packing ratio (PR = wood volume/bulk pile volume) is required. For this study, three different methods of calculating packing ratios were compared. These methods used data from pre-piling measurements of plot density (PD) in the experimental piling area (Figure 3) or post-piling measurements of plot density and heights in WRS sampled piles (Figure 4). The experimental pile packing ratio (prx) used measurements from five experimental piling areas (~11 x 11 m) staked in the field for each block (Figure 11). Each experimental piling area contained a WRS plot on which PD was measured and used to estimate the wood volume in the entire piling area. During piling, machine operators were instructed to make piles out of wood only located within the experimental piling area (Figure 12). Packing ratios were calculated for the 10 experimental piles by dividing the wood volume from the experimental piling area by the image point cloud bulk pile volume.

Figure 11. Pre-piling residues in experimental heavy accumulation piling plot (plot RBH1, block 193401).

Figure 12. Post-piling residues in experimental pile (plot PBX01XE, block 193401).

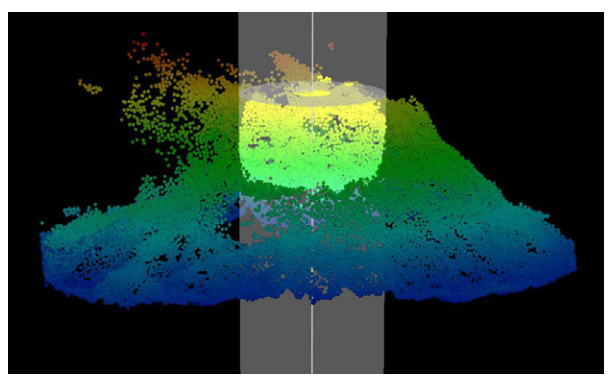


Figure 13. Side view of normalized image point cloud, showing waste and residue survey pile-plot location and image point cloud 95th percentile height at pile-plot centre (4.2 m) (plot PBX01XE, block 193401).

The second method used to calculate packing ratios used the WRS pile measurements (prw). The scaled wood volume in the WRS pile plot was divided by the bulk volume of the pile plot cylinder (area of WRS plot x WRS pile height at plot centre). The third method used to calculate packing ratios was similar to the second but multiplied the area of the WRS plot by the 95th percentile of pile height (Figure 13) calculated from the IPC (prwih). A summary of the different methods and calculations to determine the different packing ratios is given in Table 3.

3.9 Pre- and Post-piling Strata and Block Residue Wood Volumes

Piles (PBX) were created from wood contained within the area of the pre-piling heavy accumulation (RBH) stratum, although after piling some accumulations remained as steep and saturated soil conditions in some places meant that the machine could not work (C. Linklater, ProFor Consulting, pers. comm., November 17, 2014). In post-piling orthophotos, cleared areas of the pre-piling accumulation stratum were assigned to the dispersed stratum, and pile areas were digitized and designated as the piled stratum. Since no wood was removed from the site, stratum-level comparisons were made of each method for wood volumes in the pre-piling accumulation stratum versus wood volumes in post-piling, summed RBH + PBX strata.

Table 3. Summary of field and geospatial methods used to estimate block-level woody residue volumes (cubic metres per block) by stratum for blocks 193401 and 193423.

Method (acronym)	Description
WRSs	WRS sample-based mean residue volume per hectare in each stratum; ((∑ ((scaled wood volume ÷ (measure% ÷ 100)) ÷ plot area))) ÷ N plots) × WRS area of stratum. Not all logs can be scaled in PBX and RBH plots and are adjusted by percentage of total depth measured.
WRSs_gis	WRS sample-based mean residue volume per hectare for stratum; ((∑ ((scaled wood volume ÷ (measure% ÷ 100)) ÷ plot area))) ÷ N plots) × GIS area of stratum. Not all logs can be scaled in PBX and RBH plots and are adjusted by percentage of total depth measured.
SLDs	SLD sample-based mean residue volume per hectare for all plots in a stratum × GIS area of stratum.
SLDf	SLD full measure of residue in the entire stratum area in the orthophoto mosaic.
SLDfc	SLD full measure of stratum residue "corrected" using equations from significant plot-level WRS vs. SLD volume regressions.
IPCprx	Image point cloud PBX bulk volumes × experimental pile packing ratio mean; that is, ∑((experimental plot WRS PD × experimental plot area) ÷ IPC bulk pile volume)) ÷ *N*
IPCprw	Image point cloud PBX bulk volumes × WRS packing ratio mean; that is, ∑((scaled wood volume ÷ (measure% ÷ 100)) ÷ (WRS PBX plot area × WRS pile height)) ÷ *N*
IPCprwih	Image point cloud PBX bulk volumes × WRS + IPC packing ratio mean; that is, ∑((scaled wood volume ÷ (measure% ÷ 100)) ÷ (WRS PBX plot area × IPC pile height)) ÷ *N*
GISpx	GIS PBX stratum area × experimental piles plot density mean; that is, ∑((experimental plot WRS PD × experimental plot area) ÷ pile area) ÷ N
IPCprxb	Image point cloud bulk volume for both PBX and RBH objects × experimental pile packing ratio mean; that is, ∑((experi mental plot WRS PD × experimental plot area) ÷ IPC bulk pile volume)) ÷ *N*

Stratum wood volumes (residue wood in cubic metres per stratum) were calculated from the mean stratum plot density (m3/ha) multiplied by stratum area for all WRS strata in both the pre-piling and post-piling state. For the geospatial methods in the pre-piling state, the plot density for the roadside, dispersed, and accumulation strata was multiplied by the stratum area. For the post-piling state, the plot density for the roadside and dispersed strata was multiplied by the stratum area, whereas for the piled and accumulation strata (depending on method), mean packing ratio was multiplied by bulk stratum volumes, or mean plot density was multiplied by stratum area.

Block-level total wood volumes (residue wood in cubic metres per block) were determined by summing the residue wood volumes for each stratum in a block. These should remain constant from the pre-piling to the post-piling date as no wood was removed from the sites and thus differences for a method between dates reflects the changes in stratum area and wood volume estimates in the piled and accumulation strata. Overall, six different methods for calculating the total stratum wood volumes in each block were used (see Table 3).

4. Results

4.1 Pre-piling Plot-level Comparisons

4.1.1 Roadside Residues

The 0.005 ha roadside (RBX) stratum plots were used to determine residues within ~15 m of the road (Figure 14). The semi-automated log delineation (SLD) method generally underestimated wood volume (and log lengths, not shown) compared to the waste and residue survey (WRS) method. The WRS versus SLD regressions were mostly not significant; the block 193401 volume regression was significant ($p < 0.05$) and used to correct the SLD full measure. The block 193423 regression, although significant, was negative and not used (Figure 16a). The manual log delineation (MLD) method overestimated wood volumes (and log lengths, not shown) compared to the WRS method, and the volume regression in 193401 and both-block log length regression (not shown) were significant (Figure 16b). The MLD method generally overestimated wood volume (and log lengths, not shown) compared to the SLD method, although the both-block volume regression was significant (Figure 16c).

Figure 14. Residues in roadside plot (plot RBX5, block 193401).

Figure 15. Residues in roadside heavy accumulation plot (plot RBH1, block 193401).

4.1.2 Roadside Heavy Accumulations

The 0.005 ha roadside heavy accumulation (RBH) stratum plots were used to determine wood volumes in accumulations of residues, up to 1–3 m deep, left after trees were processed into logs, ready for piling and burning (Figure 15). The SLD method underestimated wood volume (and lengths, not shown) compared to the WRS method; although the length regression (not shown) in block 193423 was significant, volume regressions were not significant (Figure 16d).

4.1.3 Scattered Dispersed Residues

The 0.04 ha scattered dispersed (SBX) stratum plots were used to determine the dispersed residues that occupied most of the block (Figure 5). Using the Fall 2014 imagery, the SLD method underestimated log volume compared to the WRS method (Figure 17a), whereas when using the Summer 2015 imagery, the SLD method overestimated log volume (Figure 17b). The both-block and block 193423 regressions were significant for both sets of imagery and were used to correct the full SLD measure. Because the dispersed plots were larger, the MLD method was only applied to six plots. Although mean MLD volume was similar to that obtained with the WRS

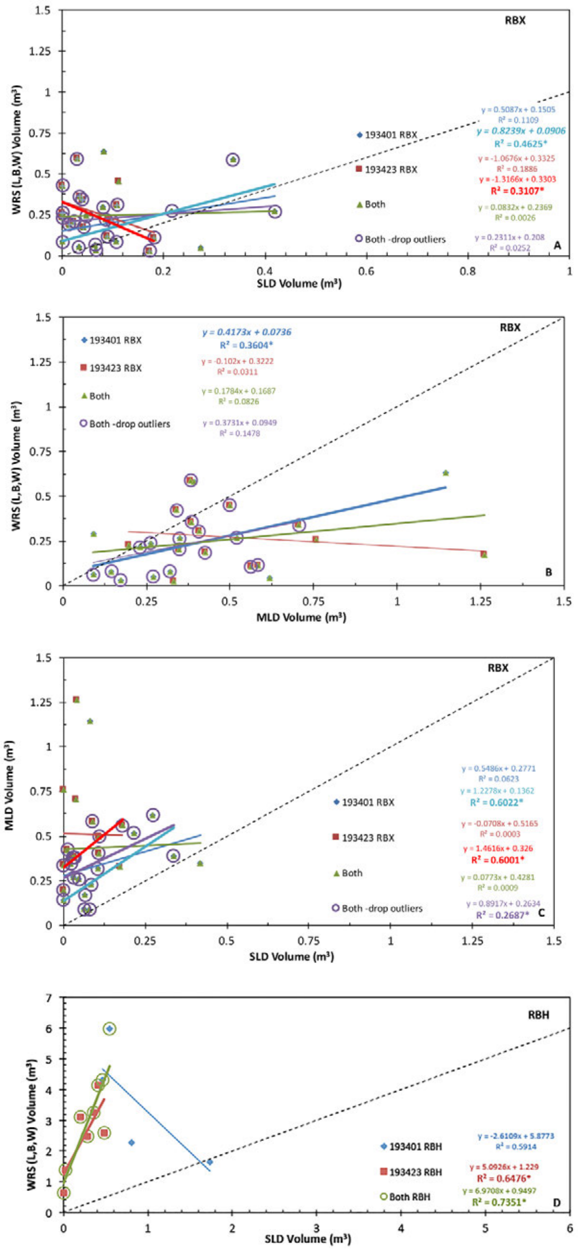


Figure 16. Plot-level comparison of geospatial and ground methods used to determine residue wood volumes (cubic metres per plot) for roadside (RBX) plots: (a) waste and residue survey (WRS) vs. semi-automated log delineation (SLD); (b) WRS vs. manual log delineation (MLD); (c) MLD vs. SLD; and for heavy accumulation (RBH) plots, (d) WRS vs. SLD, using Fall 2014 imagery. WRS volumes include logs (L), breakage (B), and waste (W). See Table 2 for a description of the different methods.

method, the WRS vs. MLD regressions were not significant for either image date (Figure 17c, d). The MLD method tended to overestimate volumes compared to the SLD method, although the MLD vs. SLD regression for Fall 2014 was significant (Figure 17e).

4.2 Pre-piling Stratum-level Comparisons of Mean Plot Density

Plot means for a method within each stratum and block were used to derive a “sample”-based measure (i.e., mean ±SE; WRSs, SLDs, MLDs; see Table 3) of plot density (i.e., residue volume per hectare). The waste and residue survey sample-based (WRSs) plot density values in the accumulation stratum (RBH; 452–643 m3/ha) were 10 times greater than those in the roadside (RBX; 44–53 m^3/ha) or dispersed (SBX; 33–41 m^3/ha) strata (Figure 18c, d). Within a stratum, the WRSs value was similar between blocks, although plot density tended to be higher in block 193401 than in block 193423. Within a stratum, the semi-automated log delineation sample-based (SLDs) values were less than the WRSs values, especially in the RBH stratum (43–147 m^3/ha); however, the SLDs values (46–59 m^3/ha) in the dispersed (SBX) stratum using the post-piling, Summer 2015 imagery were the same or greater than the WRSs values (Figure 18g, h) and were 2–6 times higher than the SLDs values using the pre-piling, Fall 2014 imagery (9–22 m^3/ha; Figure 18e, f). The manual log delineation sample-based (MLDs) values in the roadside (RBX) stratum (70–100 m^3/ha) were greater than the WRSs or SLDs values (Figure 18a, b).

The semi-automated log delineation method was applied to the image for the entire stratum to obtain a “full” measure of residue density (i.e., residue volumes per hectare; SLDf). Within a stratum and block, the SLDf value was in almost all cases identical to the SLDs value. Where the regression correction could be applied, the SLDfc value was not significantly different from the WRSs value, although the propagated error was high because of the high variance for parameters in the original regressions.

Fall 2014 Imagery

Summer 2015 Imagery

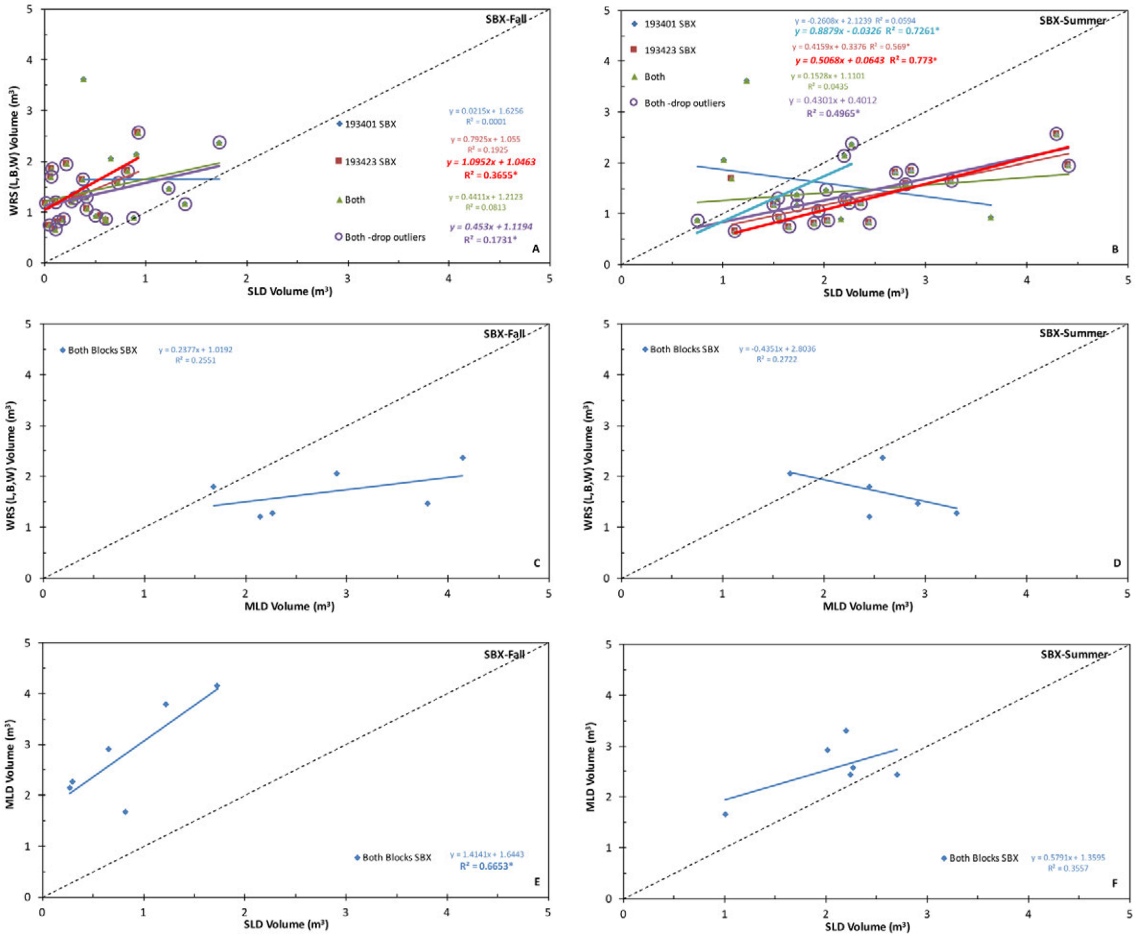


Figure 17. Plot-level comparison of geospatial and ground methods used to determine residue wood volumes (cubic metres per plot) for scattered dispersed (SBX) plots using Fall 2014 imagery: (a) waste and residue survey (WRS) vs. semi-automated log delineation (SLD); (c) WRS vs. manual log delineation (MLD); (e) MLD vs. SLD; and Summer 2015 imagery: (b) WRS vs. SLD; (d) WRS vs. MLD; and (f) MLD vs. SLD. The WRS volumes include logs (L), breakage (B), and waste (W). See Table 2 for a description of the different methods.

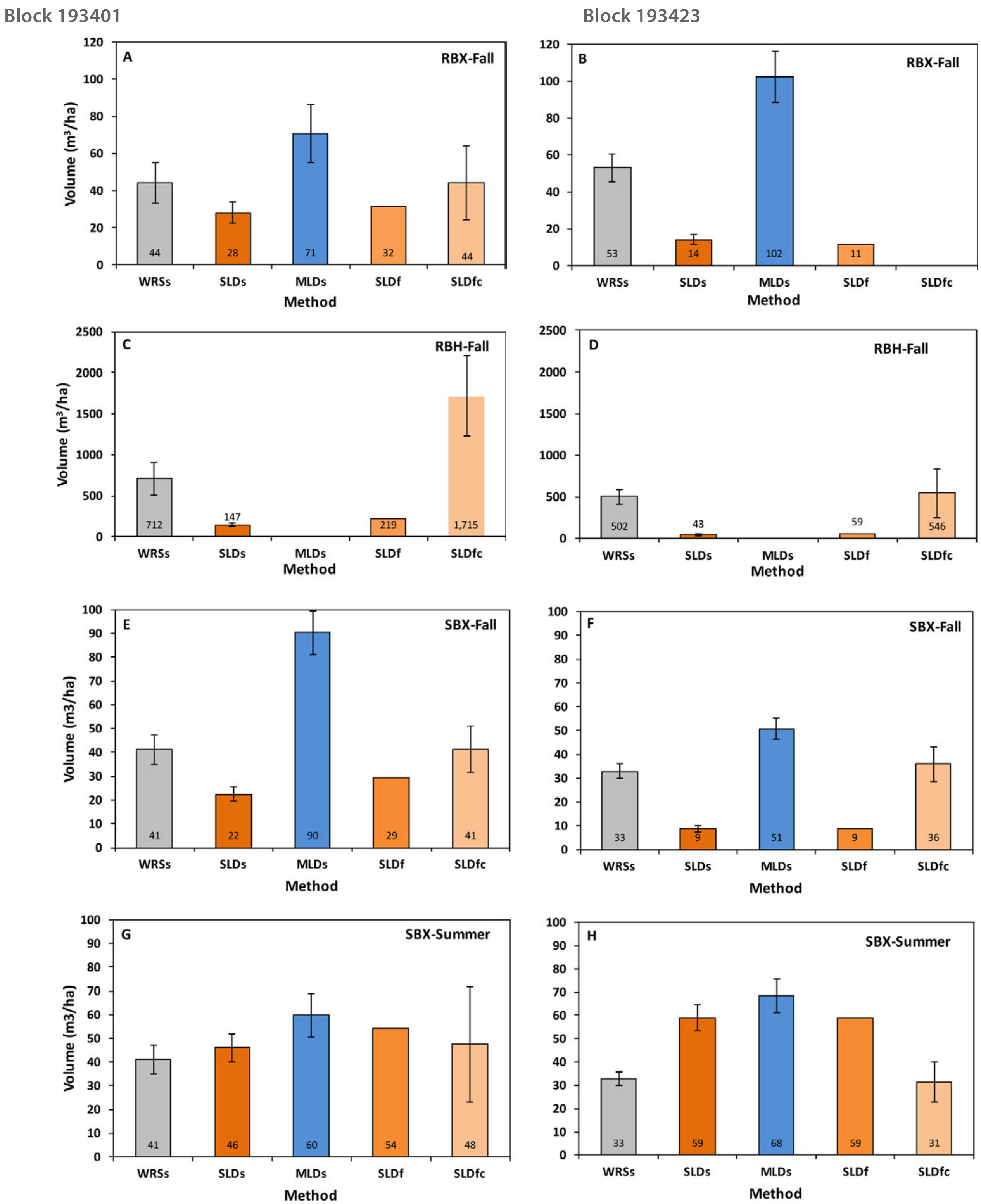


Figure 18. Comparison of ground (WRSs) and geospatial (SLDs, MLDs, SLDf, SLDfc) methods used to determine mean (±SE) woody residue plot densities (cubic metres per hectare) in Northwest Bay blocks 193401 and 193423 for: (a, b) roadside (RBX) and (c, d) heavy accumulation (RBH) strata using Fall 2014 imagery; and for scattered dispersed (SBX) strata using Fall 2014 (e, f) or Summer 2015 (g, h) imagery. See Table 2 for a description of the different methods.

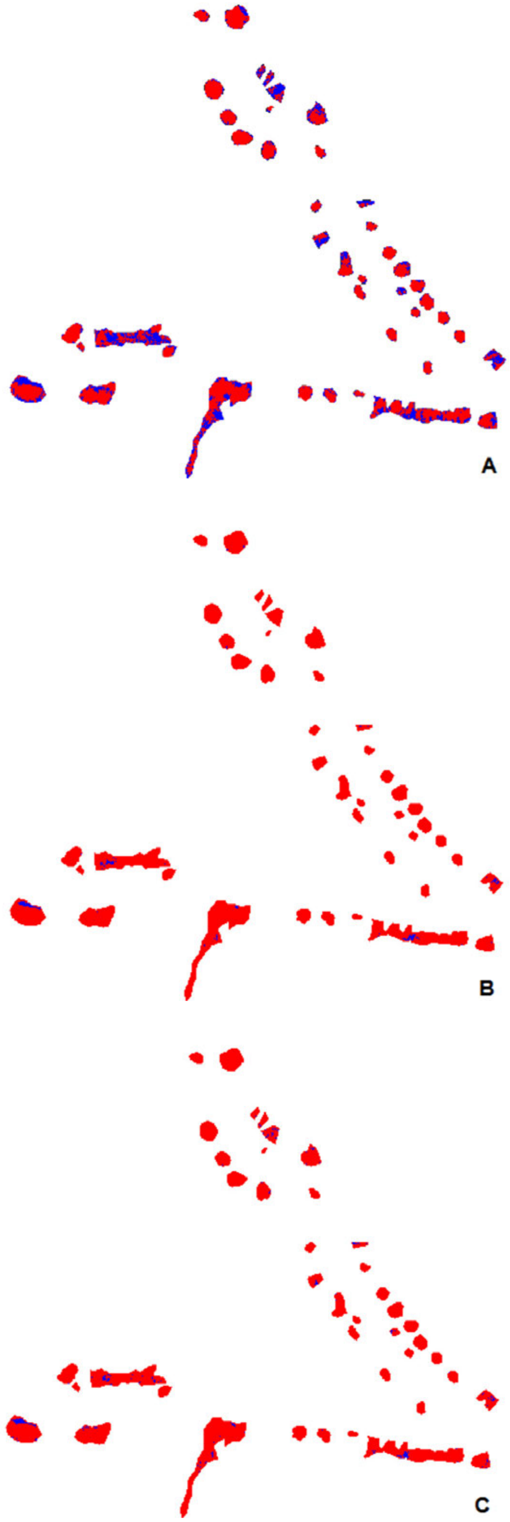


Figure 19. Pile and accumulation object positive (red) and negative (blue) net volumes determined using ArcGIS cut/fill tool for block 193423 and the three software methods (a) ArcGIS Terrain, (b) Fusion, and (c) ArcGIS LASD used to generate digital elevation and digital surface models.

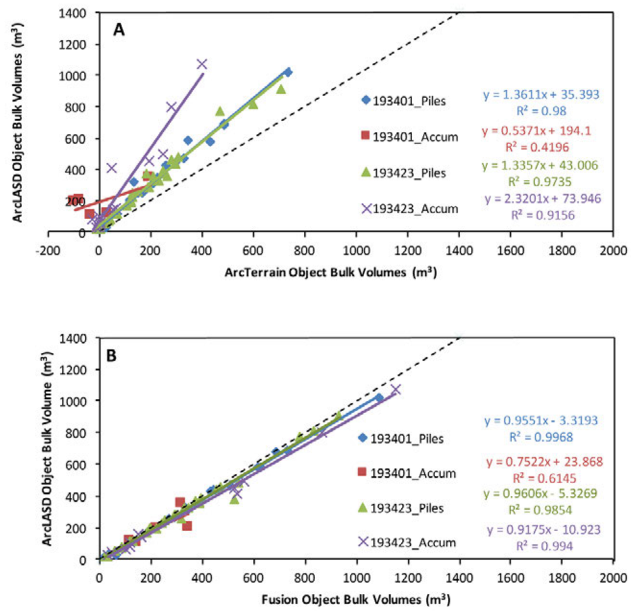


Figure 20. Comparison of pile and accumulation objects' bulk volumes determined using different software methods: (a) ArcLASD vs. ArcTerrain; and (b) ArcLASD vs. Fusion. Block 193401 pile objects (blue); block 193401 accumulation objects (red); block 193423 pile objects (green); block 193423 accumulation objects (purple).

4.3 Post-piling Residue Piles and Accumulations

4.3.1 Bulk Volumes

As noted in Section 3.6, block-level differences between the E-IPC2 pDEM and the LiDAR DEM for the entire cutblock were found to be large enough to influence the bulk volumes; therefore, bulk volumes for each pile and accumulation object were determined by the difference of the digital surface model and pseudo-digital elevation model generated from the respective, full and edited 2015 UAV image point clouds.

The pile and accumulation object bulk volumes in each block, as determined by three software methods (calculated using the cut/fill tool in ArcGIS), differed in their estimates of net object volume gain and net object volume loss as illustrated for block 193423 (Figure 19). Only minimum raster heights were used for the calculation of the pseudo-digital elevation model as use of mean raster height resulted in more negative volumes. All objects with ArcGIS Terrain method were affected, some had little area of net loss and some had large area of net loss, and thus reported as negative object bulk volumes (Figure 19a). For the Fusion and ArcGIS LASD methods, less overall net loss was evident, with most of the net loss class occurring in the accumulation objects (Figure 19b, c).

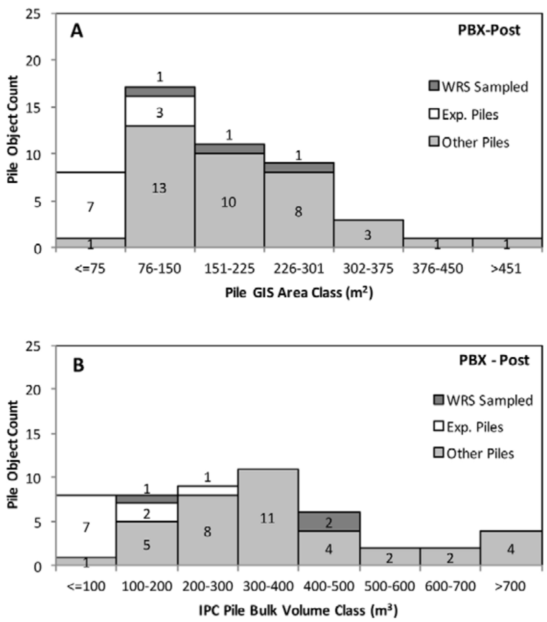


Figure 21. Frequency distributions of pile object (a) areas and (b) bulk volumes for waste and residue survey sampled piles (dark grey), experimental piles (white), and all other piles (light grey).

Bulk pile and accumulation object volumes for the ArcGIS LASD method were highly correlated to the other two methods; however, the bulk volumes generated by the ArcGIS Terrain method were ~30% less than those with the ArcGIS LASD method and ~40% less than those with the Fusion method (Figure 20). Additionally, the Terrain method produced negative volumes for several accumulation objects. The ArcGIS LASD method produced slightly lower bulk volumes than the Fusion method (Figure 20b). Terra Remote, the company that acquired the 2011 LiDAR data for Island Timberlands, indicated the ArcGIS LASD method gives comparable results to their proprietary Terrasoft software (D. Mostyn, General Manager, pers. comm., February 4, 2016). Thus, the ArcGIS LASD method was used in all further analyses to determine bulk pile volumes.

The piles sizes across both blocks determined by the geospatial methods ranged from 27.25 to 458.34 m^2 for pile areas, and from 20.99 to 1020.95 m3 for bulk pile volumes (Figure 21). The experimental piles were from lower pile size classes than those for the waste and residue survey method, which sampled over a greater range of size classes; however, all sampled piles were generally smaller in area and volume than most piles in the two blocks. Pile heights at plot centres on the 10 experimental piles, determined in the field using the WRS method and from the image point cloud (Table 4), were similar, with IPC heights slightly, but not significantly, lower than the WRS heights (paired two-tail t-test, $P = 0.088$).

Table 4. Waste and residue survey (WRS) and image point cloud (IPC) estimated above-ground heights (metres) at the pile-plot centres for the 10 experimental piles. Measured depth is the depth to which wood was scaled in the WRS. Locations of experimental piles (PBX#) are shown in Figure 4.

Block	PBX #	IPC pile height	WRS pile height	Measured depth
193401	1	4.2	5	2.3
193401	2	3.2	2.7	2.4
193401	5	1.4	1.3	1.3
193401	6	1.2	2.2	2.1
193401	11	1.5	1.7	1.6
193423	4	3.1	3.4	3.2
193423	5	1.2	2.7	2.6
193423	7	2.4	3.3	3.1
193423	8	2.2	1.6	1.6
193423	9	0.9	1.5	1.5
Mean		2.1	2.54	

4.3.2 Pile Packing Ratios

Packing ratios for all three methods were not significantly ($P > 0.05$) correlated with pile bulk volume (prx = –2E – 06x + 0.00543, $r^2 < 0.01$; prw = 0.0001x = 0.005, $r^2 = 0.26$; prwih = –0.00001x + 0.045, $r^2 = 0.04$). The mean packing ratio determined from the experimental piling area wood volumes and experimental pile bulk volumes (prx = 0.0541, SE = 0.0179) was greater than that determined from the WRS pile plot wood volumes and WRS or IPC heights (prw = 0.022, SE = 0.0044; prwih = 0.033, SE = 0.0094); however, the variance for all three was large. The differences in packing ratio methods affected the piled (PBX) post-piling stratum level wood volumes with PBX wood volumes determined from the prx (404, 491) twice that determined using the prw method (170, 203); however, the high variance in the mean packing ratio meant PBX wood volumes for the three methods were not significantly different from each other.

4.4 Pre- and Post-piling Comparisons of Total Residue Wood Volumes

Both before and after piling, the area of each stratum obtained using the waste and residue survey method differed from that obtained by GIS digitization (Table 5). Before piling, stratum area differences were 5–20%, mostly related to block area. After piling, wood in much of the accumulation (RBH) areas and some of the roadside (RBX) areas was piled to become part of the piled (PBX) stratum. The WRS piled stratum areas were 20% less than those determined using the GIS area, whereas WRS values for the remaining RBH areas were 40–200% greater than those determined for the GIS area. Since the RBH and PBX strata have the greatest plot densities, differences in area will affect total wood volumes. Thus, WRS total wood volumes were calculated using both the field and GIS stratum areas.

4.4.1 PBX and RBH Strata Using Different Pile Packing Ratios

The waste and residue survey pre-piling, accumulation (RBH) wood volumes were less using field versus GIS stratum areas in both blocks; however, the high variation in RBH plot density meant that total RBH wood volumes did not significantly differ with area method (Figure 22a, b). As noted previously, the geospatial semi-automated log delineation sample-based (SLDs) method gave lower plot densities than the WRSs method and, consequently, RBH wood volumes were significantly lower than with the WRSs_gis method. Since the same geospatial method was used, the pre-piling RBH values are repeated just to ease comparison with the post-piling results within a method.

The WRS post-piling total wood in the combined accumulation and piled strata were greater when field versus GIS areas were used, mainly because of the lower GIS area for the RBH stratum (Figure 22c, d). Nevertheless, because of the high variation in the waste and residue survey accumulation and piled strata plot densities, the total wood volumes within a block obtained using the WRSs or WRSs_gis did not significantly differ between dates. The accumulation wood volumes using the SLDs method were all significantly lower than those obtain with the WRSs_gis method, again related to the lower plot densities, and post-piling RBH wood volumes were less than the pre-piling because of the reduced area of the RBH stratum.

The combined accumulation and piled post-piling wood volumes for all geospatial methods were significantly higher than the pre-piling wood volumes. The packing ratio method with the lowest mean packing ratio (i.e., prw) gave the lowest piled total wood volume and the highest packing ratio (i.e., prx) gave the highest. For the IPCprxb method, total wood volumes in both the PBX and RBH strata were calculated using image point cloud bulk volumes for each and the mean prx packing ratio and, consequently, the RBH wood volumes were greater than those obtained using the SLDs method (Figure 22c, d). Nevertheless, because of the high variation in the mean prx packing ratio, the combined accumulation and piled wood volumes using the prx packing ratio did not significantly differ from the WRSs_gis values. Heavy accumulation and piled wood volumes using the prw packing ratios were significantly lower than the geospatial methods using

Table 5. Pre- and post- piling stratum areas (in hectares) determined by the waste and residue survey method (as input to ENFOR compilation software) and from digitization on the orthophoto mosaic prepared from the UAV imagery. The WRS scattered dispersed area is the difference of field measured strata area and planned block area, net of roads.

		Pre-piling		Post-piling	
Block	**Stratum**	**WRS area (ha)**	**GIS area (ha)**	**WRS area (ha)**	**GIS area (ha)**
193401	RBX	2.45	2.78	2.40	2.71
193401	RBH	0.85	1.09	0.73	0.23
193401	SBX	6.95	7.85	6.86	8.43
193401	PBX	0.00	0.00	0.26	0.35
193401	Total	10.25	11.72	10.25	11.72
193423	RBX	2.96	2.94	2.91	2.93
193423	RBH	1.45	1.89	1.02	0.71
193423	SBX	13.88	15.57	13.97	16.29
193423	PBX	0.00	0.00	0.39	0.48
193423	Total	18.29	20.41	18.29	20.41

the prx packing ratio and the WRSs_gis method, with values using the priwih packing ratio intermediate (Figure 22c, d). For subsequent calculation of all strata total volumes, only the prx packing ratio was used.

4.4.2 All Strata

The total strata wood volumes for both blocks pre-piling showed the difficulty the SLDs and SLDf methods had detecting residues from the poorer quality Fall 2014 imagery (Figure 23a, b). The large difference in accumulation volumes pre-piling in block 193401 for the SLDfc method is a result of the large variance in the regression parameters used to correct the full measure value (Figure 20a). The post-piling results show that total wood volumes within a block were similar among methods but distributions among the strata differed with method. For the waste and residue survey methods, within a block, pre-piling total wood volumes were not significantly different, although volumes using GIS area tended to be higher. The WRS post-piling wood volumes tended to be higher using field areas and lower using GIS areas; again, however, the differences were not significant. The post-piling results show that, with better image quality, the geospatial SLDs and SLDf methods were more comparable with the waste and residue survey methods for those strata using

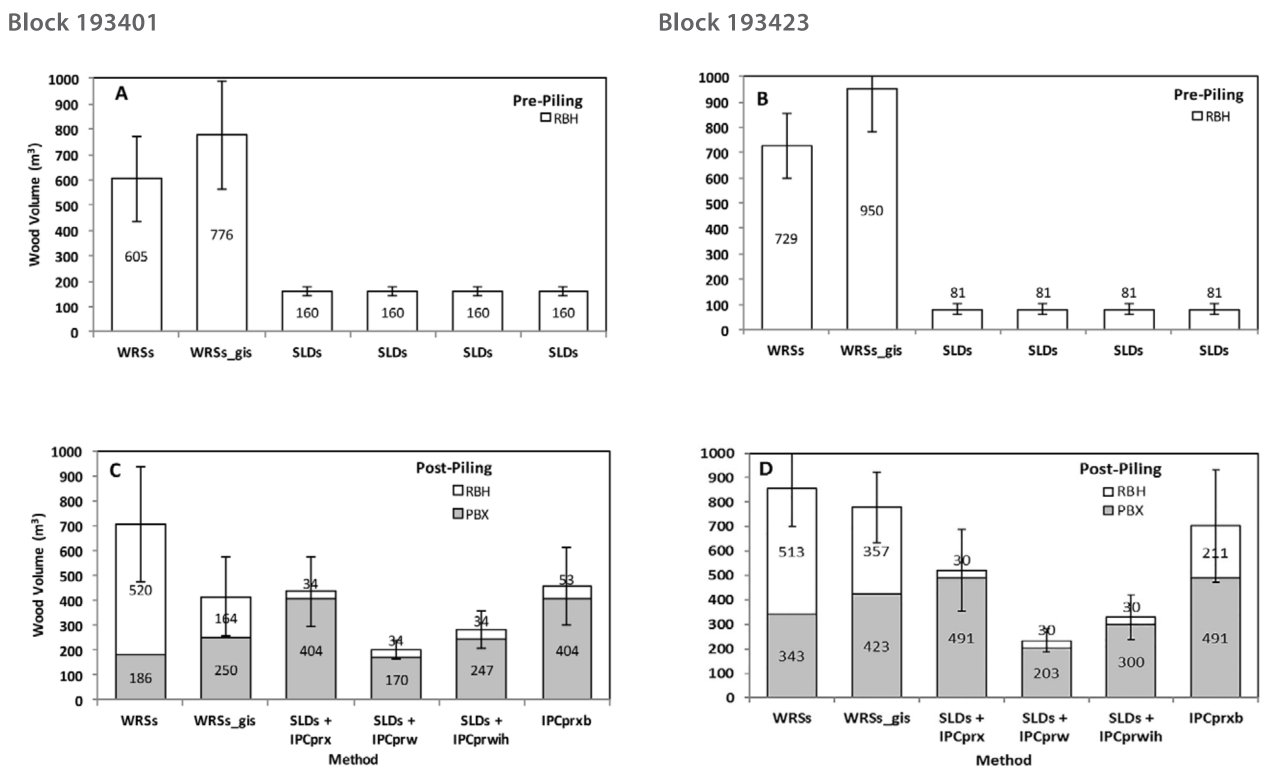


Figure 22. Block-level comparison of geospatial (SLDs, SLDs + IPCprx, SLDs + IPCprw, SLDs + IPCprwih, and IPCprxb [*see note below]) and ground methods (WRSs, WRSs_gis) for pre-piling (a, b) and post-piling (c, d) total (±SE) residue wood volumes (cubic metres per block) in heavy accumulation (RBH white) and pile (PBX grey) strata in blocks 193401 and 193423. See Table 3 for a description of the different methods. *The IPCprxb method uses the image point cloud bulk volumes and the mean prx packing ratio for residue volumes for both accumulation (RBH) and pile (PBX) objects.

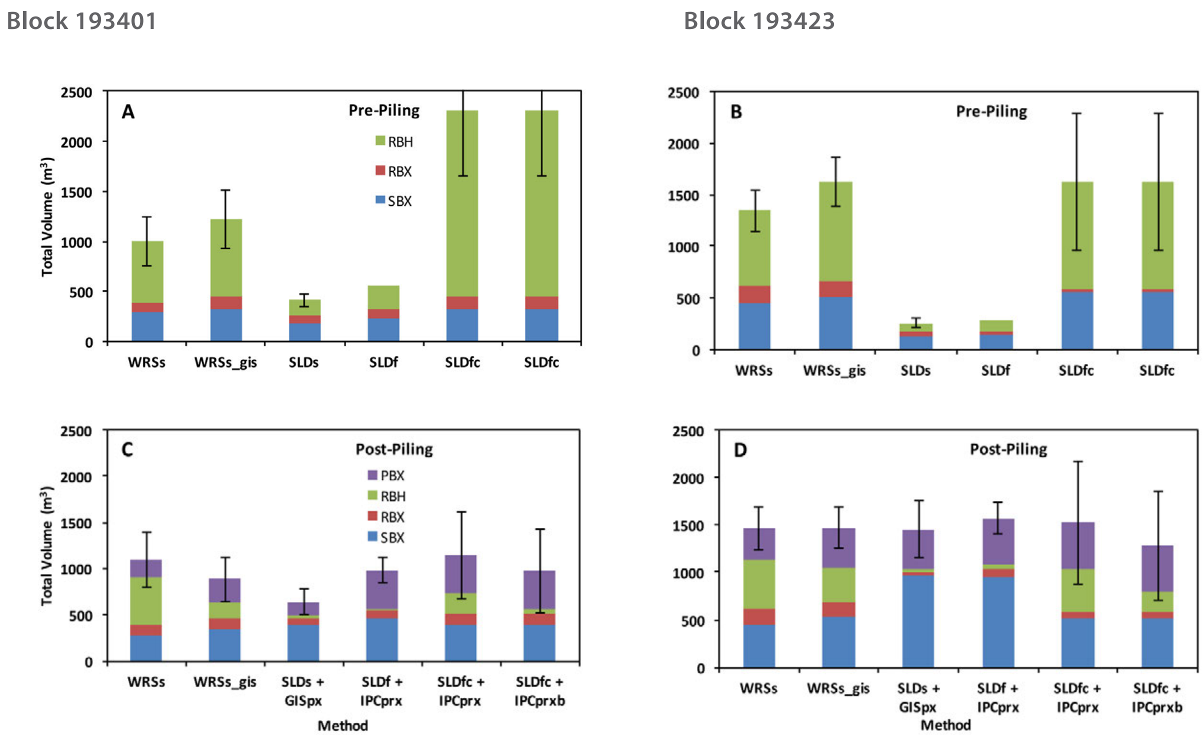


Figure 23. Block-level comparison of geospatial (SLDs + px, SLDf + IPCprx, SLDfc +IPCprx, and SLDfc + IPCprxb* [*see note below]) and ground methods (WRSs, WRSs_gis) for pre-piling (a, b) and post-piling (c, d) total (±SE) residue wood volumes (cubic metres per block) in heavy accumulation (RBH green), pile (PBX purple), roadside (RBX red), and scattered dispersed (SBX blue) strata in blocks 193401 and 193423. See Table 3 for a description of the different methods. *The IPCprxb method uses the image point cloud bulk volumes and the mean prx packing ratio for residue volumes for both accumulation (RBH) and pile (PBX) objects.

the semi-automated log delineation (RBH, RBX, SBX), except for plot 193423 in which SLD plot densities in the dispersed stratum were determined to be much higher in the post-piling than pre-piling imagery (Figure 20b, d). Applying the regression correction resulted in similar total volumes and strata volumes (SLDfc and IPCprx); however, as in the pre-piling, the high variance in regression parameters increased variance in the strata and total volumes. In all geospatial methods but the SLDs+GISpx, the piled stratum wood volumes are identical and, as noted in the previous section, larger than the WRS values. For the SLDs+GISpx methods, piled wood volumes were calculated using the pre-piling wood volumes of each experimental plot and its GIS area to determine individual and mean plot density for the experimental piles and multiplied by the piled stratum area (Table 3), resulting in lower wood volumes than that determined using packing ratio and pile bulk volumes. As noted in the plot density section (Section 4.2), the SLDs and SLDf values for the SBX, RBX and RBH strata within a block and condition were very similar, showing that the number and distribution of WRS plots were a good sample of the stratum.

5. Summary and Conclusions

Waste and residue survey field methods for pre-piling stratum areas differ by 5–20% from methods using GIS on orthophotos, and will contribute to differences in block and stratum total residue volumes; therefore, GIS methods would provide more accurate, consistent results. Analyses of cutblocks that use high-resolution imagery obtained from UAVs or aircraft have greatest value in determining the post-harvest areas of the block, roads, and various strata. Although UAVs could potentially acquire imagery under conditions unsuitable for aircraft, the costs of image acquisition per hectare may be higher, given the field travel time and slower rate of image acquisition by UAVs.

For the pre-piling roadside and dispersed strata, waste and residue survey plot sample values were higher than those obtained using the semi-automated log delineation method from the Fall 2014 imagery, mainly related to limitations in the detection of whole logs. The better lighting, image quality, and loss of obscuring branch needles evident in the Summer 2015 imagery resulted in semi-automated log delineation sample-based (SLDs) values that were comparable to waste and residue survey sample-based values; however, as used, the SLD method was not suitable for determining accumulation stratum residue volumes. Applying the SLDf method to the full stratum gave identical results to the SLDs, suggesting that the WRS plot sampling design used was good.

The semi-automated log delineation method has good potential to determine wood volumes; however, this method involves calibration with field plot measurements and needs a minimum number of field measurements if the species and grade of residues are also required. Good image quality is critical to the image analysis and will depend not only on the UAV camera resolution but also flight conditions, UAV speed, and speed of image storage. For example, the time needed to store DNG files meant the UAV flight was slower, less stable, and image quality poorer than if images had been acquired as JPG files. Branches with adhering foliage on post-harvest residues also limited success of the SLD method; to use this method effectively, image acquisition would need to occur several months after harvest is complete and needles dropped, thus delaying how soon residue volumes could be estimated.

For the piled and accumulation strata, image point clouds acquired from UAVs for pile and accumulation objects have the potential to be more detailed because low-altitude oblique images can be obtained. The same image point cloud should be used to generate the needed digital surface and digital elevation models, with the latter prepared from the image point cloud edited to remove points on accumulations, piles, or leave areas. Even with additional ground control points, it was not possible to adequately register a previous LiDAR DEM against the DEM generated from the image point cloud. Image point clouds are well suited to determine consistent pile and accumulation bulk volumes and use of either Fusion or ArcLASD software gave similar results, whereas ArcTerrain software gave lower volumes, or even negative volumes, for accumulations. Nevertheless, field-estimated, site-specific packing ratios are still needed to determine residue wood volumes in piles and accumulations. The most practical and repeatable method will involve scaling wood in waste and residue survey pile and accumulation plots to a measured fixed depth, and calculating the bulk volume measured (plot area x depth) and the packing ratio. This would assume that the packing ratio throughout the entire plot depth is relatively constant. Pile plots should cover the full range of pile sizes.

Although we hypothesized that no differences would occur between pre- and post-piling stratum and block-level wood volumes, the field and geospatial methods did generate some differences. In some cases, the differences were not significant because of the high variance associated with either the plot density or packing ratio values. The largest differences occurred when using the SLD method to obtain the pre-piling estimates; obscuring foliage and the quality of the Fall 2014 imagery limited the ability of this geospatial method to detect whole logs.

Results suggest the best method of determining total residue volumes requires a combination of geospatial and ground measurements. If the imagery used to assess post-harvest residues is obtained by UAVs, appropriate flight planning should ensure that good-quality images are captured in order to prepare the orthophoto mosaics used for delineating and analyzing roadside or dispersed residues, and to generate image point clouds for determining bulk volumes of accumulations and piles. Ground-based measurements of field plots are required to calculate mean packing ratios and calibrate plot densities. To choose appropriate specific gravity values for calculating amounts of wood biomass, field measurements in all strata are still needed to determine wood species and grade.

Additional research will help determine the optimal combination of geospatial and field methods necessary to assess residues and other attributes in post-harvest cutblocks. For example, the amount of residue lost following burning of piles and accumulations could be determined by calculating the change in their bulk volumes as assessed from geospatially generated image point clouds obtained before and after burning. The yarding effects on soils and vegetation could also be assessed from the same high-resolution imagery. In addition, less intensive line intercept methods could be used to determine wood species and grade as an alternative to scaling wood in fixed area field plots.

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Appendix 1.

Flow chart of semi-automated log delineation procedures

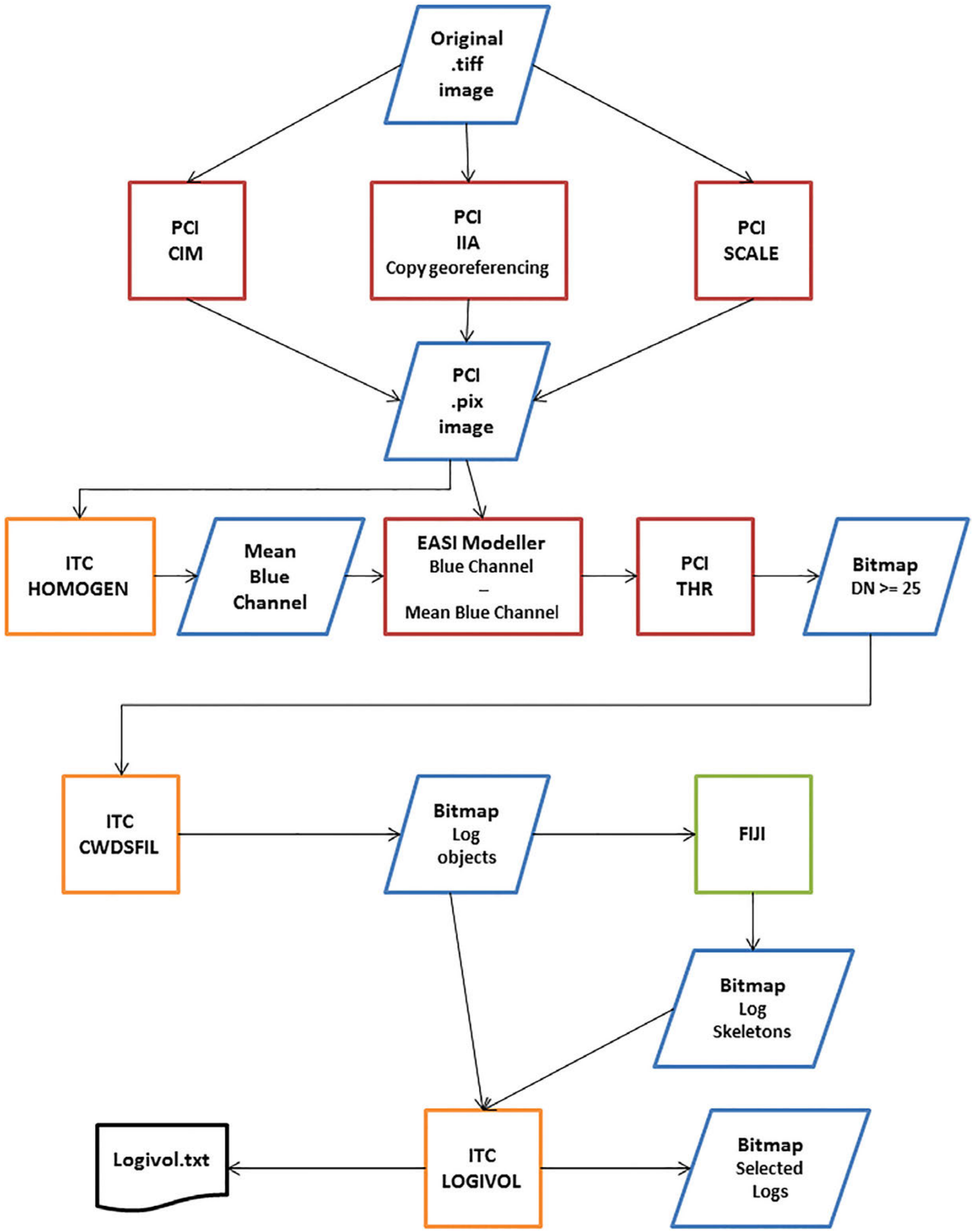

Figure A1.1. Flow chart of semi-automated log delineation procedures (blue: image/data; red: PCI Geomatica tool/process; orange: Individual Tree Crown [ITC] tool/process; green: Fiji utilities;

Appendix 2.

Summary of workflow for generation of digital elevation model and digital surface model for pile and accumulation objects using three different software packages

ArcGIS Terrain Workflow

Digital Elevation Model

- Convert **E-IPC** to multipoint feature
- Create terrain feature
- Add multipoints to terrain
- Add pyramids (min point-based thinning)
- Build terrain feature
- Generate 0.5 m raster surface

Digital Surface Model

- Convert **IPC** to multipoint feature
- Create terrain feature
- Add multipoints to terrain
- Add pyramids (max point-based thinning)
- Build terrain feature
- Generate 0.5 m raster surface

Fusion Workflow

Digital Elevation Model

- Create 0.5 m grid surface, using min point in grid, for **E-IPC** *(gridsurfacecreate)*
- Convert .dtm to .asc *(dtm2ascii)*
- Import to ArcGIS

Digital Surface Model

- Create 0.5 m grid surface, using max point in grid, for **IPC** *(canopymodel)*
- Convert .dtm to .asc *(dtm2ascii)*
- Import to ArcGIS

ArcGIS LASD Workflow

Digital Elevation Model

- Create LAS data set from **E-IPC**
- Convert LAS data set to 0.5 m raster, using min binned point in grid *(LAS to raster)*

Digital Surface Model

- Create LAS data set from **IPC**
- Convert LAS data set to 0.5 m raster, using max binned point in grid *(LAS to raster)*

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