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Evaluation of Area-Based Retention Using Remotely Piloted Aircraft Systems on Selected Harvest Sites in Nova Scotia

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Abstract

As part of Nova Scotia's paradigm shift to ecological forestry, the province has committed to implementing the Triad approach to forest management on Crown land. Management of forests in the ecological matrix zone of the Triad is based on the premise of maintaining, restoring, and enhancing ecological functions. Silvicultural methods employed through the Silvicultural Guide for the Ecological Matrix (SGEM) are intended to create and maintain multi-aged/mixed species forests. The complex spatial arrangement and retention requirements of silvicultural systems in the SGEM present a challenge for post-harvest monitoring to ensure prescription objectives were met, particularly those with area-based retention targets and irregular spatial arrangement. I used high overlap drone imagery collected on three harvest sites (two gap irregular shelterwoods and one partial overstory removal) to create orthomosaics and canopy height models (CHMs) derived from structure from motion (SfM) point clouds. Point cloud normalization using an SfM-derived digital terrain model (DTM) and an airborne laser scanning (ALS)-derived DTM were compared. I found that normalizing SfM point clouds to an ALS-derived DTM, using post-processed kinematic (PPK) images with sub-meter accuracy, produced more realistic CHM results in dense canopy. I compared an automated harvest/retention area delineation procedure to a manual harvest/retention area delineation procedure. The automated procedure employed a fixed-height threshold of 5 m to separate canopy (i.e., retention)- and non-canopy (i.e., harvested) CHM cells. The manual procedure used high-resolution orthomosaics to delineate harvested/retention areas. Compared to manual procedures, the automated procedure underestimated retention on two sites, and harvested area on one site. I found that as retention increased, the ability of the SfM-derived CHM to identify gaps was reduced. Both automated and manual procedures to identify retention percentages using drone imagery provided an efficient alternative to ground-based assessments, where a census of gap measurements would be otherwise unfeasible. An automated approach in high retention prescriptions should be augmented by manual delineation to ensure accurate gap characterization. Future efforts should focus on refinements to the fixed-height threshold approach to separate canopy and non-canopy in prescriptions with high retention, as well exploration of assessing basal-area based retention targets and other prescription objectives using drone imagery.

Keywords: Forestry, retention, drones, harvesting, canopy height model

Introduction

A key component of Nova Scotia's paradigm shift to ecological forestry, as recommended in the Independent Review of Forest Practices (Lahey, 2018), is the implementation of the Triad approach on Crown land. The Triad approach divides the forest into three zones: conservation, high production, and ecological matrix. The ecological matrix, which is the largest zone in the Triad approach, is a zone where conservation/biodiversity and resource production values are meant to be achieved (Lahey, 2018). The Silvicultural Guide for the Ecological Matrix (SGEM; McGrath et al., 2021) describes silvicultural methods to be used within the ecological matrix to meet conservation and production objectives. Management of forests in the ecological matrix is based on the premise of maintaining, restoring, and enhancing ecological functions. Silvicultural methods in the SGEM, broadly, are intended to promote uneven-aged management, creating and maintaining multi-aged/mixed species forests across a range of conditions that would be similar to those resulting from Nova Scotia's complex natural disturbance regimes (McGrath et al., 2021; Taylor et al., 2020), while recognizing that some sites are naturally subject to frequent, stand-replacing disturbances resulting in even-aged forest. Permanent reserve trees/retention in all silviculture systems is a key strategy in meeting biodiversity values of the ecological matrix.

Irregular shelterwoods are a novel silvicultural system on Crown land in Nova Scotia introduced through the SGEM. Irregular shelterwood systems are similar to traditional shelterwood and selection systems, where regeneration is established in shade. Unlike traditional shelterwood, where the overstory is retained for 5-10 years before removal, the overstory is retained for much longer periods. In contrast to selection harvesting where re-entries are uniform, re-entries in irregular shelterwoods are not necessarily uniform. Additionally, irregular shelterwoods may have non-uniform spatial arrangement. For example, patches of shorter-lived species (e.g. balsam fir [*Abies balsamea*]) that exist non-uniformly across a stand may be targeted for removal, while patches of longer-lived species (e.g. red spruce [*Picea rubens* Sarg.]) are retained, as opposed to uniform spacing between strips/gaps or a single post-treatment basal area (BA) target (McGrath et al., 2021).

The complex spatial arrangement and retention requirements of silvicultural systems in the SGEM present a challenge for post-harvest monitoring to ensure prescription objectives were met, particularly those with area-based retention targets and irregular spatial arrangement. In prescriptions with area-based retention targets, gap or retention patch size must be measured to calculate area-based retention. Measuring gap size on the ground accurately is time consuming, requiring GPS tracks to be recorded while walking edges. Gap diameter measurements can be taken and used to calculate area to save time, though this method is still time-consuming, and accuracy of size measurements decreases as gaps deviate from perfect circles. Gap measurements conducted on the ground are also likely to be a sample of all the gaps on a harvest site, introducing more uncertainty to the area-based retention calculation.

Advancements in remotely piloted aircraft systems (RPAS, referred to hereafter as drones) technology have facilitated on-demand collection of high-resolution imagery over areas ranging from 10's to 100's of hectares, depending on the drone (Smith-Tripp et al., 2024). Imagery collected from drones capable of executing pre-planned flight missions, during which images are collected at high overlap in a grid formation over the area of interest, can be used to generate high-resolution, up-to-date orthomosaics. Structure from Motion (SfM) is a technique where 3-dimensional (3D) structure is estimated from 2-dimensional (2D) imagery through perspective and triangulation between overlap images (Young et al., 2022). The structure can be represented as a point cloud, which can then be used similar to aerial laser scanning (ALS) point cloud data, producing digital terrain models (DTM's), canopy height models (CHM's), or updating forest inventory attributes (White et al., 2013). Highly overlapping images can be used to produce dense and high-quality point clouds (Dandois and Ellis, 2013).

White et al. (2018) used point clouds generated from traditional manned aerial photography (digital aerial photogrammetry [DAP] point clouds) to identify forest canopy gaps, with limited success compared to ALS-derived point clouds, especially with small gaps (with detected gap size averaging 56 m^2/0.0056 ha). The harvest gaps in irregular shelterwoods are much larger, with target size ranging from 0.1 to 0.3 ha (McGrath et al., 2021), and problems such as shadows and occlusion (White et al, 2018) may be less likely to obscure gap boundaries. Additionally, the increased density that is feasible when using drones to collect imagery facilitates the creation of higher density and higher quality point clouds compared to traditional aerial photography, which may better reflect the canopy (Dandois et al., 2015).

The objectives of this study were to explore the utility of drone-based imagery for assessing area-based retention in gap-based harvest treatments in three harvest sites of varying removals, where traditional ground-based measurements of retention were impractical.

Methodology

Study Area

All three sites were harvests completed on Crown land in 2024, each with a different prescription/retention target (Table 1).

Table 1. Summary of three sites of varying retention, harvested in 2024 on Crown land in Nova Scotia. Prescriptions were determined using the Silvicultural Guide to the Ecological Matrix (McGrath et al., 2021).

Site	Prescription	Retention Target (Removal Target)	Area (ha)	Gap Size Target (ha)
Pleasant River Lake	Medium Retention Gap Irregular Shelterwood (MIRG)	50% (50%)	21.8	0.2
Bear River	High Retention Gap Irregular Shelterwood (HIRG)	67% (33%)	22.8	0.2
Cox Brook	Partial Overstory Removal (POR 20)	20% (80%)	28.6	N/A

Pleasant River Lake

The Pleasant River Lake site harvest was a Medium Retention Gap Irregular Shelterwood (MIRG). The stand was dominated by red spruce and balsam fir. MIRG can be prescribed in areas with moderate amounts of long-lived, intermediate to shade tolerant (LIT) species present, and when horizontal structure is patchy or where windthrow hazard is high. Retention is 1/2 (50%) of the area (including trails), with 1/10 to 1/5 of the pre-treatment BA to be left as dispersed retention within gaps. Target gap size was 0.2 ha. The harvest block was approximately 22 ha.

Bear River

The Bear River site harvest was a High Retention Gap Irregular Shelterwood (HIRG). The stand was dominated by red spruce, red maple (*Acer rubrum*), and balsam fir. HIRG can be prescribed in areas with high amounts of LIT species present, and when horizontal structure is patchy or where windthrow hazard is high. Retention is 2/3 (67%) of the area (including trails), with 1/10 to 1/5 of the pre-treatment BA to be left as dispersed retention within gaps. Target gap size was 0.2 ha, and within-gap retention standards in the SGEM were intentionally exceeded. The harvest was completed with small harvesting equipment, allowing for narrow extraction trails and increased maneuverability to avoid damage to retention trees. The harvest block was approximately 23 ha.

Cox Brook

The Cox Brook site harvest was a Partial Overstory Removal with 20% Retention (POR 20). The stand was dominated by black spruce (*Picea mariana*). POR 20 can be prescribed on edaphic sites with low amounts of LIT, in stands dominated by red pine (*Pinus resinosa*), jack pine (*Pinus banksiana*), or black spruce, where regeneration establishment in full sun is likely to be successful. Though retention requirements in the SGEM for POR 20 are 1/5 (20%) of the pre-treatment BA, distributed with half in patches and the other half scattered/in small clumps (McGrath et al., 2021), retention was predominately left in patches on this site. The harvest block was approximately 29 ha.

Remotely Piloted Aircraft System

RGB imagery was acquired using a DJI Mavic 3M, which was equipped with a 20MP RGB camera. The DJI Mavic 3M was also equipped with a Real-time Kinematic (RTK) module, allowing for cm-level positioning through RTK corrections or post-processed kinematic (PPK) corrections.

Flight Parameters and Image Acquisition

Flight parameters were largely based on recommendations from Young et al. (2022), who found nadir imagery with high overlap (≥ 80% front and side) and high altitude (≥ 90 m) in forested areas improved CHM accuracy. Flight planning was completed with the DJI Pilot 2 App. Unless otherwise specified, default settings were used (Table 2). Image dewarping was turned off, shutter speed set to automatic, and camera pitch set to 0° (nadir) for all flights. The DJI Pilot 2 App automatically created flight routes based on these settings (Figure 1). The flight route can then be executed, and the drone captured images along the flight paths at intervals required to achieve the specified image overlap. Ground sampling distance (GSD) was approximately 3 cm for each of the three sites (Table 2).

Table 2. Flight parameters for imagery collection using a DJI Mavic 3M with the DJI Pilot 2 App for three harvest sites in Nova Scotia.

Site	Flight Speed (km hr^{-1})	Front Overlap (%)	Side Overlap (%)	Height Relative to Take-off (m)	GSD (cm $pixel^{-1}$)
Pleasant River Lake	29	90	80	115	3.08
Bear River	29	90	80	105	2.87
Cox Brook	29	90	80	105	2.87

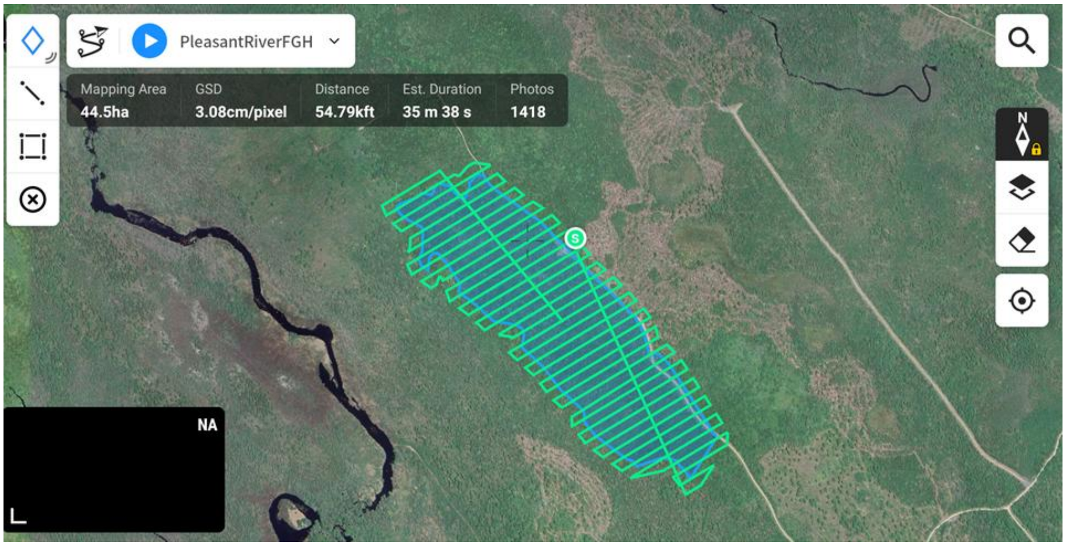

Figure 1. Flight route of the Pleasant River Lake Medium Retention Irregular Shelterwood harvest in Lunenburg County, Nova Scotia. Flight route was created using the DJI Pilot 2 App with a DJI Mavic 3M.

Flights were completed in summer and fall of 2024 (Table 3) and conducted in accordance with Part IX of the Canadian Aviation Regulations (CARs) (TC 2025). For the Bear River site, cloud conditions during the start of the flight were scattered and changed to overcast by the end of the flight. Wind conditions for Pleasant River Lake started as gentle but increased to moderate by the end of the flight.

Table 3. Flight conditions for imagery collection using a DJI Mavic 3M with the DJI Pilot 2 App for three harvest sites in Nova Scotia.

Site	Date	Time of Day (ADT)	Cloud Cover	Wind	# of Images	Mapped Area (ha)
Pleasant River Lake	16-07-2024	12:35-1:18	Clear - Scattered	Gentle - Moderate	1,418	44.5
Bear River	24-10-2024	11:52-12:36	Scattered - Overcast	Gentle	1,537	40.9
Cox Brook	28-08-2024	11:35-12:15	Clear - Scattered	Gentle	2,334	59.7

At the Pleasant River Lake site, 3 ground targets were placed before collecting imagery to use as ground control points (GCPs) and check points (CPs) during image processing (Figure 2). Target centers were located using a Hemisphere RTK GNSS Receiver Model S631 and Can-Net Virtual Reference Station (VRS) Network.

Figure 2. Ground targets as seen from the ground (left) and from drone imagery (right) of the Pleasant River Lake Medium Retention Irregular Shelterwood harvest in Lunenburg County, Nova Scotia. Targets are 30 cm in diameter.

PPK Geotagging

I post-processed image locations using Emlid Studio v. 1.9 (Emlid, 2024) and correction data from the nearest active control station. Correction data from the Can-Net VRS network was retrieved from Natural Resources Canada's Canadian Active Control System (CACS) online tool (NRCan, n.d.). See S1 for Emlid Studio settings and S2 for NRCan CACS RINEX observation data download settings. Only images where a fix (cm-level precision) or float (sub-meter precision) solution status was achieved were retained for further processing.

Photogrammetric Processing

Pix4Dmapper v. 4.9.0 (Pix4D, 2023) was used to create RGB orthomosaics and a SfM point cloud from the PPK aerial imagery. Refer to https://support.pix4d.com/hc/pix4dmapper for a description on Pix4Dmapper processing, and S3 for Pix4Dmapper settings. For the Pleasant River Lake site, I used the 3 ground targets as CPs to evaluate the precision of coordinates generated from uncorrected and corrected images. Vertical coordinates were adjusted to Canadian Geodetic Vertical Datum (CGVD) 2013 using a geoid height model (NRCan, 2024). The geoid height was relatively constant over the sites, so an average geoid height, to the nearest 0.1 m, specific to each site was used.

Point Cloud Post-Processing

SfM point clouds were post-processed in R (R Core Team, 2025), using the lidR package (Roussel et al., 2020). SfM point clouds were normalized to remove the influence of terrain on above-ground measurements, converting height above sea level values into height above ground values. For Pleasant River Lake and Bear River sites, I compared two methods for point cloud normalization. The first method employed a cloth simulation filter (CSF) algorithm to classify ground points in the SfM point cloud, which were then used to create a 1 m resolution DTM (Roussel et al., 2020). The second method used a 1 m resolution ALS-derived digital elevation model (DTM) to normalize the SfM point clouds. ALS-derived DTM tiles corresponding to the sites were downloaded from https://nsgi.novascotia.ca/datalocator/elevation/ (Service Nova Scotia, n.d.). Normalized point cloud height values < 0 m and > 40 m were discarded.

Canopy Height Model

Using normalized point clouds, various implementations of CHM algorithms and resolutions were tested, based on Roussel and Auty (2025). I found a 25 cm resolution CHM using a point to raster (p2r) algorithm and triangulated irregular network (TIN) to fill empty pixels produced realistic and efficient results (see S4 for sample R code to create the CHM). CHMs were visually evaluated against provincial photo-interpreted forest inventory heights.

Area-Based Retention/Removal Delineation

Manual Delineation

Harvest gaps/trails (Pleasant River Lake, Bear River) and retention patches (Cox Brook) were delineated manually in ArcGIS Pro (Esri, 2024), using only the orthomosaics generated with Pix4Dmapper. Manual delineation was used as a reference for automated delineation.

Automated Delineation

I employed a fixed-height threshold of 5 m (White et al., 2018) to identify canopy and non-canopy cells. Heights ≥ 5 m were considered canopy, and heights < 5 m were considered non-canopy. Cells were then converted to polygons, aggregating cells into canopy or non-canopy polygons based on whether they were canopy/non-canopy cells. For assessing removal percentage (Pleasant River Lake [MIRG] and Bear River [HIRG]), non-canopy polygons were analyzed. I attempted to remove natural canopy gaps, which do not count towards harvested area, by removing small polygons (< 50 m^2) (Figure 3). Retention trees within gaps (canopy polygons embedded within non-canopy polygons; Figure 4) were removed based on a size threshold of 200 m^2. For assessing retention percentage (Cox Brook [POR 20]), the methodology was similar, but canopy polygons (as opposed to non-canopy polygons) were analyzed. Scattered retention trees (canopy polygons < 50 m^2) within the treated area at the Cox Brook site, which do not count towards the 20% retention target, were removed in the same manner as above. See S5 for a workflow of geoprocessing tools.

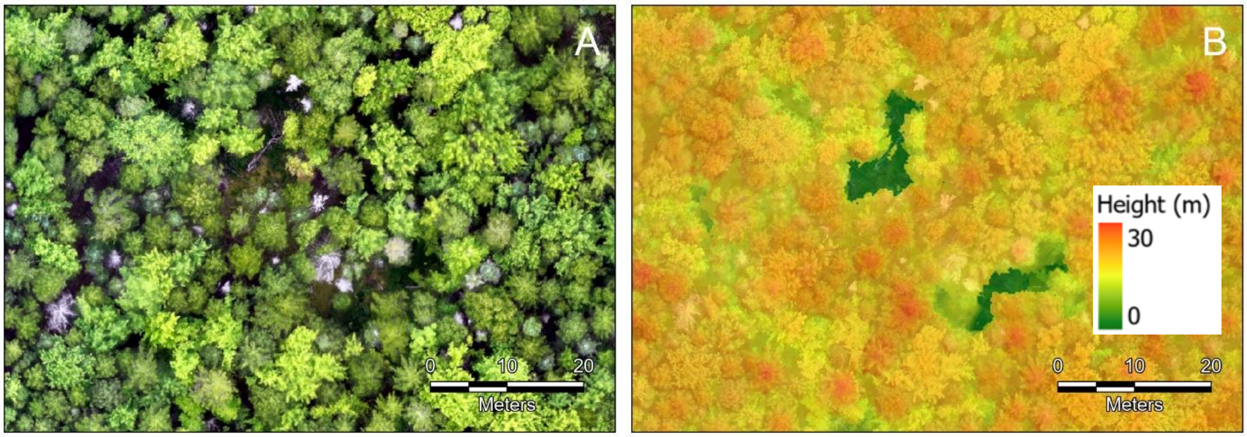

Figure 3. Natural canopy gaps, visible in the orthomosaic (Panel A) and the canopy height model (CHM) (Panel B) of the Bear River High Retention Irregular Shelterwood harvest in Annapolis County, Nova Scotia. Green CHM cells indicate heights < 5 m.

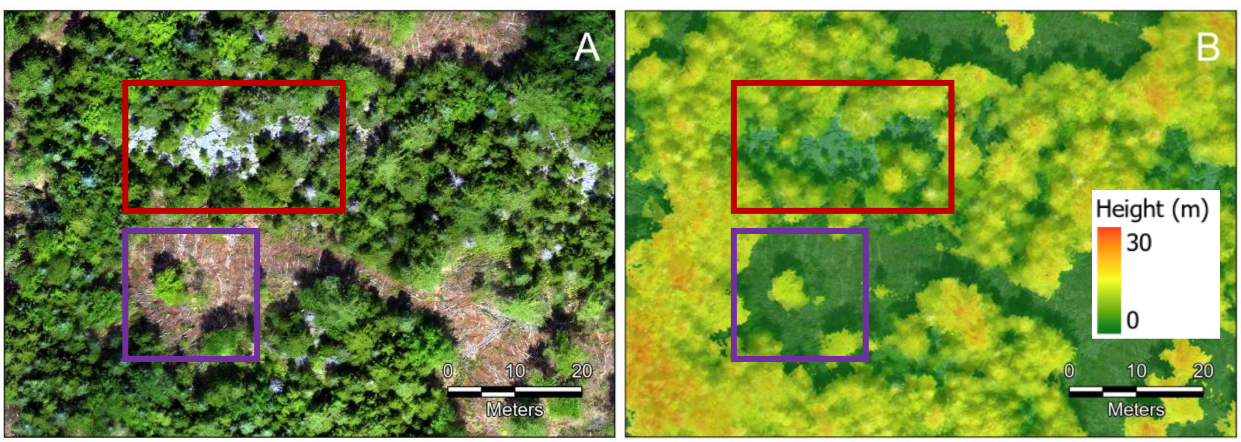

Figure 4. Rock outcrops (red box) and within-gap retention trees (purple box), visible in the orthomosaic (Panel A) and the canopy height model (CHM) (Panel B) of the Pleasant River Lake Medium Retention Irregular Shelterwood harvest in Lunenburg County, Nova Scotia. Green CHM cells indicate heights < 5 m, and yellow-orange cells indicate codominant canopy heights (≥ 10 m).

Results

Pleasant River Lake Georeferencing Accuracy

Average geolocation accuracy of original Pleasant River Lake imagery was 1.34 m horizontal and 2.40 m vertical. After PPK corrections, image geolocation accuracy was < 0.01 m (horizontal and vertical). Checkpoint accuracy in original imagery for X, Y, and Z coordinates was less than 1 m. Vertical errors were the largest at 0.67 m (Table 4). Checkpoint accuracy using PPK images was higher compared to original images, with horizontal coordinate accuracy < 0.10 m and vertical accuracy of 0.24 m (Table 4).

Table 4. Image geolocation and checkpoint accuracy of original images and post-processed kinematic (PPK) images of the Pleasant River Lake Medium Retention Irregular Shelterwood harvest in Lunenburg County, Nova Scotia.

Image Geolocation	Image Geolocation Accuracy (m)		Checkpoint Accuracy (RMSE[1], m)		
	Horizontal	Vertical	X	Y	Z
Original	1.34	2.40	0.22	0.37	0.67
PPK	<0.01	<0.01	0.02	0.09	0.24

[1]Root Mean Square Error

SfM- vs. ALS-Derived DTM Point Cloud Normalization

The SfM point clouds ranged in density from 63-96 points m^{-2}. Normalizing the point clouds using a DTM created from the SfM point cloud resulted in realistic CHM values where significant canopy openings were interspersed with closed canopy areas (Figure 5). However, in dense canopy without interspersion of harvest gaps, CHM values were much lower than expected. On the Bear River site, provincial photo-interpreted forest inventory height was 13 m in 2011, however the SfM-derived DTM resulted in CHM values of approximately 4 m (Figure 5B). When an ALS-derived DTM was used to normalize the SfM point cloud, resulting CHM values in dense canopy areas were closer to visual estimates and photo-interpreted forest inventory heights, with CHM values generally ranging from 14-17 m (Figure 5C). Subsequent analysis was completed using point clouds normalized to the ALS-derived DTM.

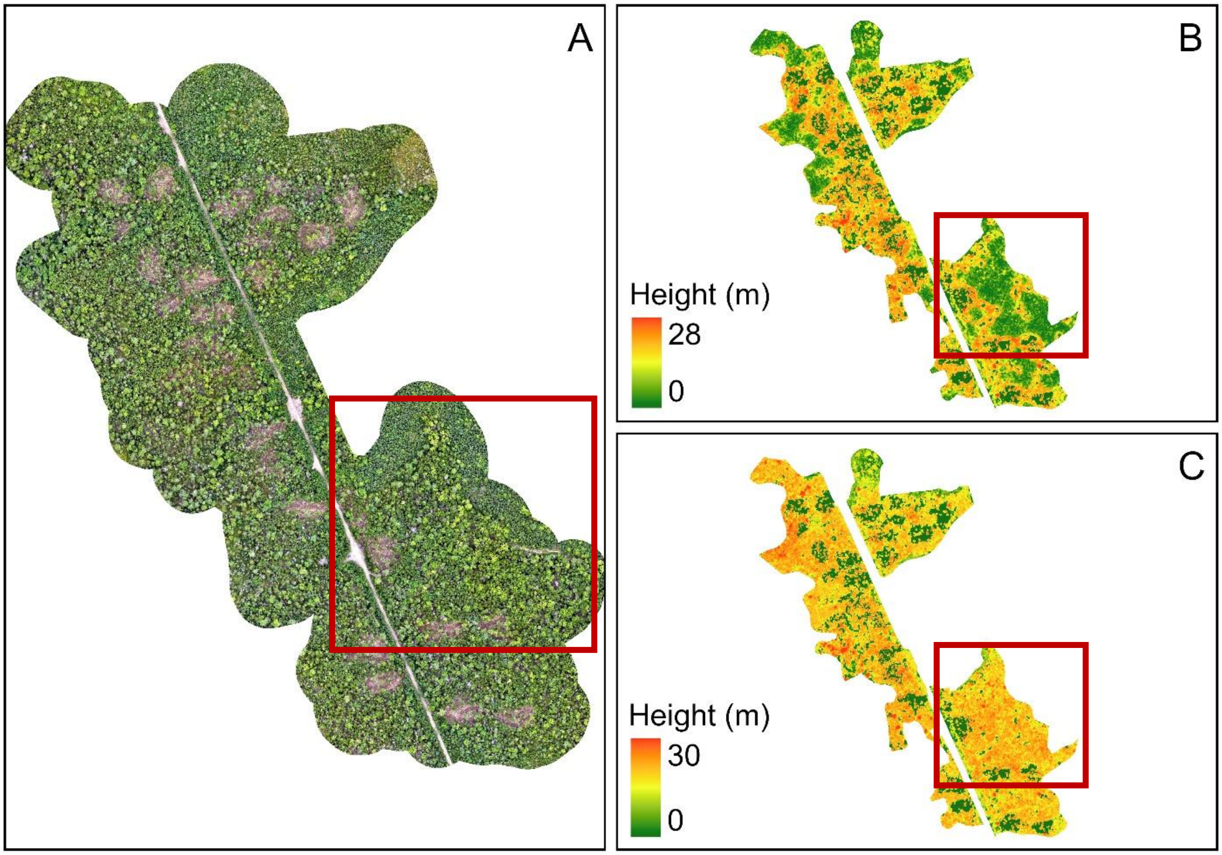

Figure 5. Orthomosaic (Panel A) and canopy height model (CHM) derived from a Structure from Motion (SfM) point cloud, normalized using an SfM-derived digital terrain model (DTM) (Panel B) and an airborne laser scanning (ALS)-derived DTM (Panel C) of the Bear River High Retention Irregular Shelterwood harvest in Annapolis County, Nova Scotia. Red boxes highlight an untreated area of dense canopy closure.

Harvest/Retention Area Delineation

On all sites, the automated delineation process underestimated treated (or in the case of Cox Brook, retained) area compared to the manual delineation process (Table 5, Figures 6-8). The automated delineation process for the Pleasant River Lake site appeared to identify every treated area and most of the trail system, though some of the identified trails between gaps in this process were not continuous (Figure 6). For the Pleasant River Lake and Cox Brook sites, gap/retention patch boundaries from both delineation methods were similar in shape and size, though the automated gap boundaries were generally more complex than the manually delineated gaps (Figure 9). Some of the differences were due to retention trees within gaps close to the edges, which should be considered treated area, but were not collapsed into treated polygons as they were not fully contained by the gap boundary (Figure 9C and Figure 9D). The automated gap delineation process for the Bear River site had difficulty identifying harvested area edges (Figure 9A and Figure 9B). Compared to Pleasant River Lake, gaps in this harvest block were smaller, had high within-gap retention and narrow trail widths, making the distinction between treated and untreated area less conspicuous. Trail widths were so narrow that they were also challenging to identify manually in the imagery. On the Cox Brook site, there was a high contrast between heights in retention patches (mature canopy) and treated areas (bare ground; Figure 8). Cox Brook had the smallest difference between automated and manual delineation retention estimates at 1% (Table 5).

Table 5. Comparison of post-harvest removal/retention calculations resulting from a manual delineation process and an automated delineation process, using orthomosaics and a canopy height model (CHM) derived from drone imagery collected with a DJI Mavic 3M on three harvest sites in Nova Scotia.

Site (Retention/Removal Target)	Area (ha)	Manual Gap/Retention Delineation		Automated Gap/Retention Delineation		Automated Delineation Error[1] (%)
		Area (ha)	%	Area (ha)	%	
Pleasant River Lake (50% removal)	21.8	9.9	45%	7.6	35%	-23%
Bear River (33% removal)	22.8	5.2	23%	3.3	14%	-37%
Cox Brook (20% retention)	28.6	4.9	17%	4.7	16%	-4%

[1] Error (%) = (Manual Delineation – Automated Delineation) / Manual Delineation x 100%

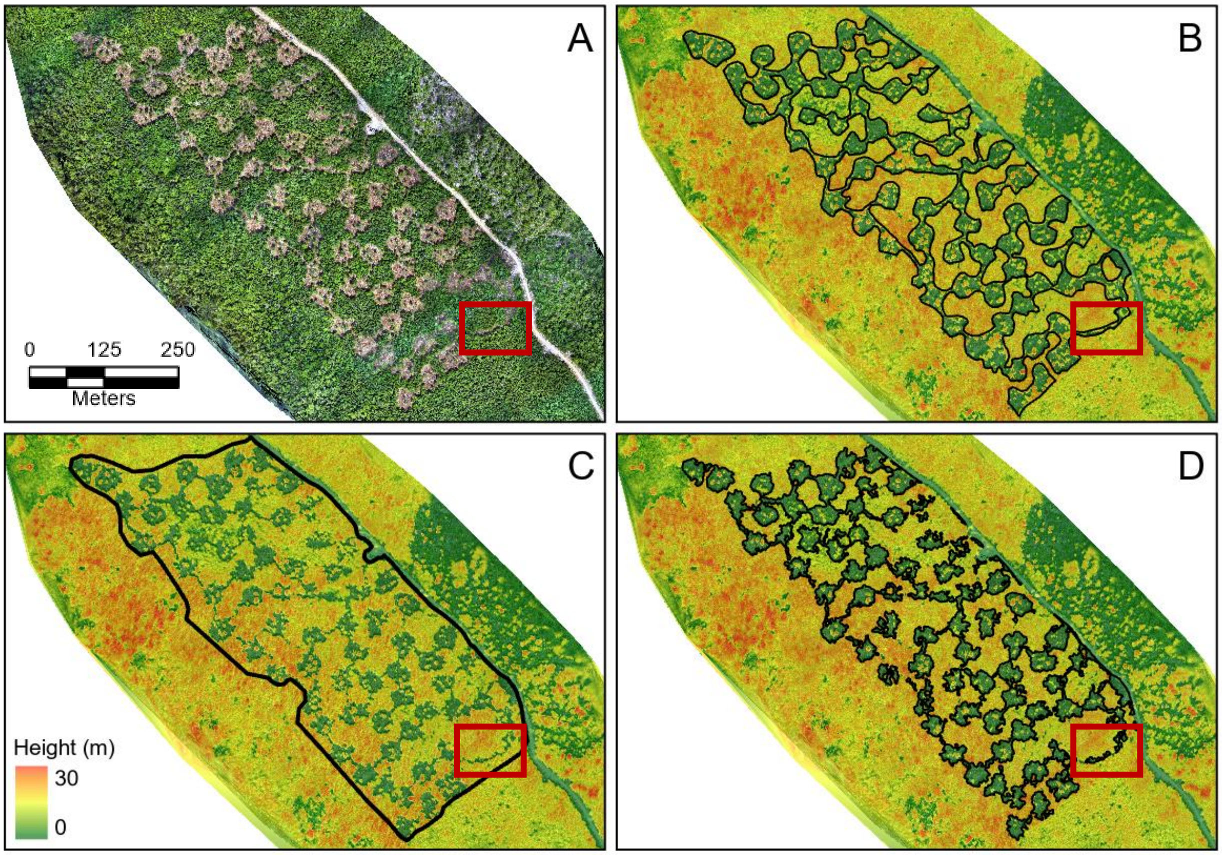

Figure 6. Orthomosaic (Panel A), canopy height model (CHM; Panels B, C, D), manual harvest gap delineation (Panel B), harvest boundary (Panel C), and automated harvest gap delineation (Panel D) of the Pleasant River Lake Medium Retention Irregular Shelterwood harvest in Lunenburg County, Nova Scotia. Red boxes highlight a section of trail that was not completely identified in the automated delineation process.

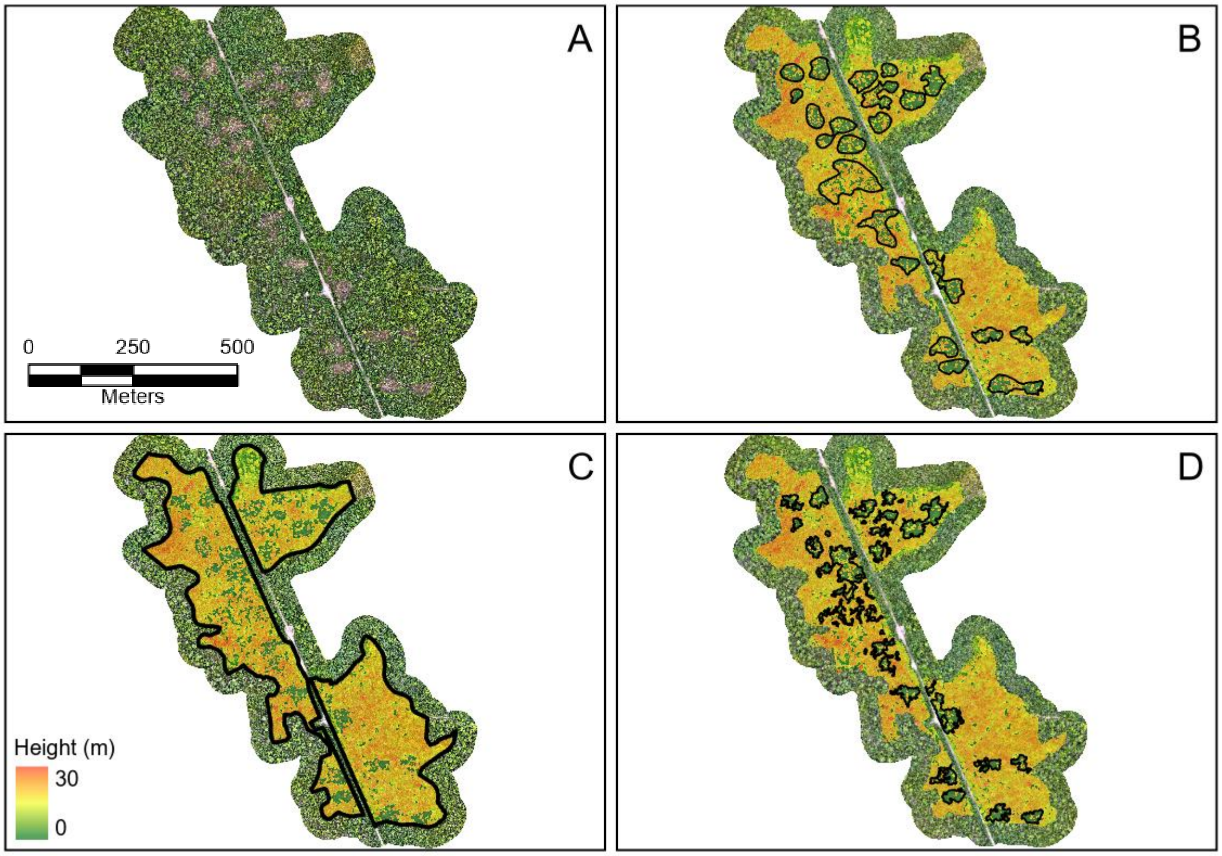

Figure 7. Orthomosaic (Panel A), canopy height model (CHM; Panels B, C, D), manual harvest gap delineation (Panel B), harvest boundary (Panel C), and automated harvest gap delineation (Panel D) of the Bear River High Retention Irregular Shelterwood harvest in Annapolis County, Nova Scotia.

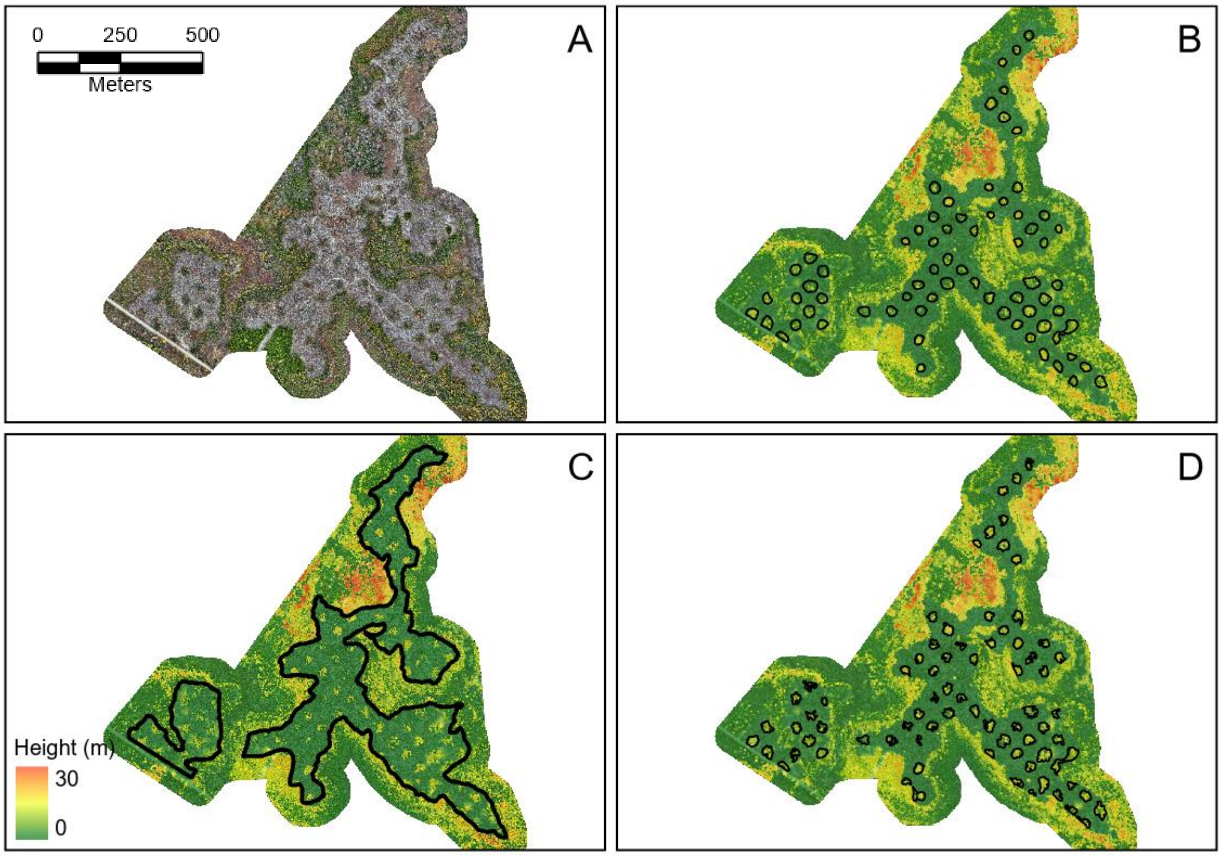

Figure 8. Orthomosaic (Panel A), canopy height model (CHM; Panels B, C, D), manual retention patch delineation (Panel B), harvest boundary (Panel C), and automated retention patch delineation (Panel D) of the Cox Brook Partial Overstory Removal harvest in Pictou County, Nova Scotia.

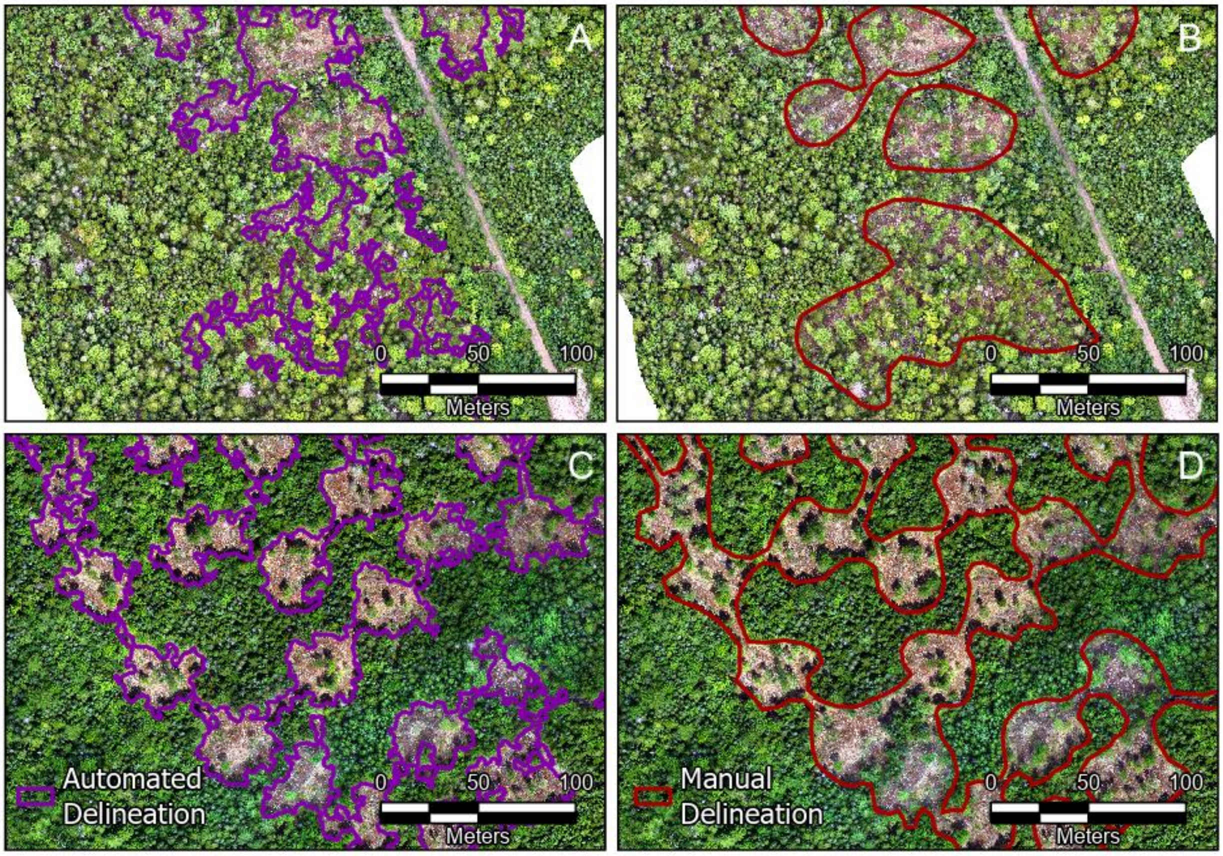

Figure 9. Automated harvest gap delineation (Panel A) and manual harvest gap delineation (Panel B) of the Bear River High Retention Irregular Shelterwood harvest, and automated harvest gap delineation (Panel C) and manual harvest gap delineation (Panel D) of the Pleasant River Lake Medium Retention Irregular Shelterwood harvest.

Discussion

Point Cloud Normalization

Though SfM point clouds were high density (63 to 96 points/m^2), they primarily characterize the canopy surface, producing very minimal ground points in closed-canopy forest (White et al., 2013). I found that using a DTM derived from the SfM point cloud produced unrealistic results in areas without nearby harvested gaps, as the SfM ground points were sparse (and in some cases, non-existent) in dense canopy. Interpolation across these larger areas does not reflect localized changes in topography between gaps. Utilizing an ALS-derived DTM to normalize the point cloud resulted in more realistic canopy height models, as ALS is capable of ground characterization in dense canopy (Goodbody et al., 2019), and the localized changes were more likely to be reflected in the ALS-derived DTM compared to an SfM-derived DTM. Given the province-wide coverage of the ALS-derived DTM, it should be used to normalize SfM point clouds, rather than relying on the SfM point cloud to generate a DTM.

Georeferencing Accuracy

When combining drone imagery with other datasets, < 1 m global accuracy (level 2 accuracy) should be achieved, requiring RTK or PPK drone capabilities or the use of GCPs (Smith-Tripp et al., 2024). Level 2 accuracy was achieved on all sites using PPK. PPK, in contrast with RTK, using correction data from NRCan (n.d.) does not require a subscription or internet connection to pass corrections to the drone. PPK accuracy typically decreases as distance from the control station increases (Chadwick et al., 2022), however coverage of control stations in Nova Scotia is well distributed, reducing the likelihood of distance to the nearest control station being an issue. Checkpoint accuracy for the Pleasant River Lake site was less than 1 m vertical and horizontal, validating that level 2 accuracy was achieved for that individual site. Chadwick et al. (2022) suggest that RTK/PPK can serve as a replacement for GCP's. Placing and locating ground targets can be a time-consuming process, and level 2 accuracy can often be achieved without ground targets (Chadwick et al., 2022), provided independent validation of accuracy is not required. When using RTK or PPK corrections, placing and locating one checkpoint in an easily accessible location may suffice for validating accuracy (Pix4D, 2017).

Harvest/Retention Area Delineation

Both the automated and manual delineation processes to identify harvested and retention areas appeared to identify a substantiable proportion of the areas of interest (either harvested area or retained area). In general, the ability of the automated approach to identify areas of interest was reduced as retention increased (i.e., reduced spatial contrast between canopy and non-canopy). White et al. (2018) found that DAP point clouds from manned aircraft were limited in their ability to characterize small canopy gaps (averaging 56 m^2/0.0056 ha). Increased retention arguably reduces the effective gap size, explaining the increased difficulty of the SfM point cloud to characterize canopy gaps with higher retention. However, the manual delineation process also becomes more challenging as retention increased. This was apparent with the Bear River site, where even with < 3 cm resolution imagery and a 25 cm CHM, trails were difficult to identify and the boundaries between harvested gaps and untreated areas were often inconspicuous. The target gap size on the Bear River site was 0.2 ha, however openings within the treated areas unobstructed by retention trees were much smaller than 0.2 ha.

I recommend a combined approach, where the automated process is first used to identify obvious gaps/retention, followed by manual adjustments, if required, to include or remove features the automated process omitted or erroneously identified. Features that may require special attention during manual adjustments include rock outcrops, natural canopy gaps, retention trees on edges of treated areas, narrow trails, and harvested areas with high/complex retention patterns.

The fixed-height threshold approach I employed was limited to area-based retention assessments. The SGEM includes several prescriptions that have BA-based retention targets (McGrath et al., 2021). Individual tree detection methods using SfM point clouds (e.g. Young et al., 2022) may be more suited towards assessing BA-based retention and should be investigated.

Aerial Imagery vs. Ground Based Assessments

The current alternative to drone-based imagery for assessing post-harvest removal/retention percentages was to measure or map gap boundaries on the ground. On the Pleasant River Lake site, there were over 60 gaps and approximately 10 km of perimeter (from manually delineated gaps). Using a ground-based approach, it would be unrealistic to assess the entire area. Measuring gap dimensions (width and length) is less time consuming than mapping gap boundaries, however the accuracy of area calculations using gap dimensions decreases as gap shapes deviate from a perfect circle. Also, as not all gaps were the same size and shape, measuring a subset of gaps may have provided an accurate representation of the entire site. Given the high accuracy of the imagery (< 1 m), delineating gap boundaries, either automated or manually, using imagery and a CHM should be as accurate as ground-based measurements, with the advantage of efficiency and complete site coverage. Alternatively, time on site could be spent assessing other prescription objectives (e.g., retention tree quality, soil damage mitigation; McGrath et al., 2021).

Image Acquisition Challenges

Weather and Season

Occlusions and shadows in imagery can have a substantial negative impact on image tie point matching, potentially reducing density and accuracy of SfM point clouds (Baltsavias, 1999). Direct lighting on sunny days can increase contrast in images, allowing for easier tie point matching, but depending on sun angle, shadows may be more prevalent (Chadwick et al., 2022). Shadows are also more prevalent when solar angle is low (i.e. early morning, late afternoon, fall, and winter; Dandois et al., 2015). On sunny days, care should be taken to fly close to solar noon to avoid excessive shadows. Overcast days are likely to produce images with lower contrast, however Dandois et al. (2015) found that canopy height estimates from imagery collected on overcast days compared to sunny days were not significantly different and suggest overcast days are suitable for imagery collection (and depending on time of day and season, perhaps preferrable, as shadows caused by solar angle don’t need to be considered).

Strong winds can lead to decreased SfM point cloud density or accuracy errors, as the tie point matching assumes that only the camera has moved – not features between images (e.g. branches or leaves swaying in the wind may be in different locations between images; Young et al., 2021). I did not experience any apparent issues due to wind speed (e.g. blurry/rippled images). If possible, images should be acquired on days with low winds to avoid potential issues associated with strong winds.

Imagery acquired during leaf-off conditions in hardwoods could reduce the ability of an SfM point cloud to accurately characterize the canopy surface. Complex branching structures, normally obstructed/smoothed by foliage (Olson et al., 2025), could negatively affect tie point matching, reducing point cloud density/accuracy over hardwood trees (Dandois et al., 2013). Conversely, imagery in hardwood or mixedwood stands acquired during leaf-off conditions could produce improved ground visibility, resulting in more accurate SfM-derived DTM's (Dandois et al., 2013). However, given the province-wide availability of an ALS-derived DTM, producing an accurate SfM-derived DTM was less important than an accurate CHMs. For accurate CHM's in mixedwood/hardwood stands, imagery should be acquired during leaf-on conditions, if canopy surface characterization is the primary interest.

Regulatory

Previously, CARs restricted basic RPAS operations to within visual line of sight (VLOS) (TC, 2025), and a special flight operations certificate (SFOC) was required to conduct beyond visual line of sight (BVLOS) operations. Maintaining VLOS can be challenging in forested areas, limiting the area that can be flown in compliance with federal regulations. Turnarounds or large landings can serve as take-off/landing points and provide a less obstructed view than a resource road right-of-way, however trees often quickly obstruct VLOS. Placement of visual observers throughout the flight area can be used to maintain VLOS, though also decreasing efficiency of the flights by requiring more personnel to complete the operation. Changes to Part IX of the CARs that took effect November 2025 included regulations for low risk BVLOS operations, without the need for an SFOC. These changes will allow more area to be flown in compliance with federal regulations, with fewer personnel involved in the operation.

Alternative Methods

Using either manual interpretation done by stereo-photo interpretation (see Reid & Hagens, 2023) or image classification methods (see Yang et al., 2015) to delineate gaps/retention areas, satellite or traditional manned aircraft imagery could provide an alternative means of image acquisition that avoids many of the challenges described above. I did not explore any automated image classification using RGB values, or stereo-photo interpretation as part of this analysis. Costs of acquiring satellite or manned aerial imagery are highly dependent on number, clustering, and size of stands requiring assessment (Reid and Hagens, 2023). The province of Nova Scotia collects aerial photography on a 10-year cycle. A DAP point cloud from the imagery is used to build a CHM, which could be substituted for the CHM derived from drone-based imagery. However, depending on geographic location the DAP CHM could be up to 10 years out of date. Using out of date imagery to analyze canopy gaps could result in the underestimation of removal percentages as the canopy closes in over gaps and trails, or the overestimation of removal percentages due to windthrow/stem breakage along trails and gap/retention patch edges following harvesting (McGrath and Ellingson, 2009). The widespread distribution and relatively small size of harvest blocks requiring this type of assessment, in addition to assessments needing to be completed annually, would require annual imagery of the entire province. Drone-based image acquisition appears to be a cost-effective and timely method of acquiring high-resolution imagery for small, scattered harvest block assessments.

Conclusion

As forest management evolves and harvest prescriptions become increasingly complex to meet a wide range of ecological, social, and economic values, effective and efficient harvest monitoring is central in ensuring values are met. Traditional ground-based assessments of harvest prescriptions become increasingly difficult as treatment complexity increases (mainly concerning spatial arrangement of gaps and retention levels). I presented a successful use-case of drone-based imagery in assessing one key prescription objective (area-based retention in gap irregular shelterwoods and partial overstory removals), where ground-based assessments were infeasible given the heterogeneity of the prescriptions. An automated approach using a fixed-height threshold to identify treated area and non-treated area to calculate retention percentage underestimated retention compared to manual delineation. I suggest a combined approach, where an automated approach is used to identify the majority of treated/untreated areas, supplemented by a manual delineation and adjustment of automated boundaries. The accuracy of the automated approach decreased with increasing treatment complexity, so extra scrutiny to automated results should be applied in those cases. Though alternative methods to acquire imagery (e.g. traditional manned aircraft photography, satellite imagery) exist, the widespread, small-scale and annual requirements of harvest prescription assessments make these sites ideal for drone-based image acquisition. Weather and seasonality challenges restrict the number of suitable days for acquiring imagery, but updates to regulations around BVLOS operations in Section IX of the CARs will allow for more efficient imagery collection. Extensive coverage of a VRS network combined with PPK corrections provide adequate accuracy to combine SfM point clouds derived from drone imagery with an existing ALS-derived DTM. Refinements to the fixed-height threshold approach, and exploration of other image classification and individual tree detection methods using SfM point clouds will improve accuracy and expand the utility of drone-based imagery for assessing retention in a wider range prescriptions and potentially assessing objectives other than retention.

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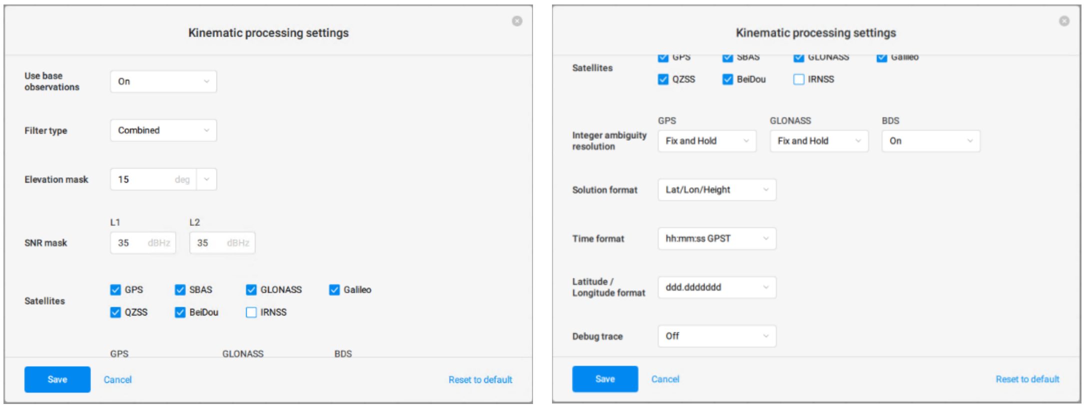
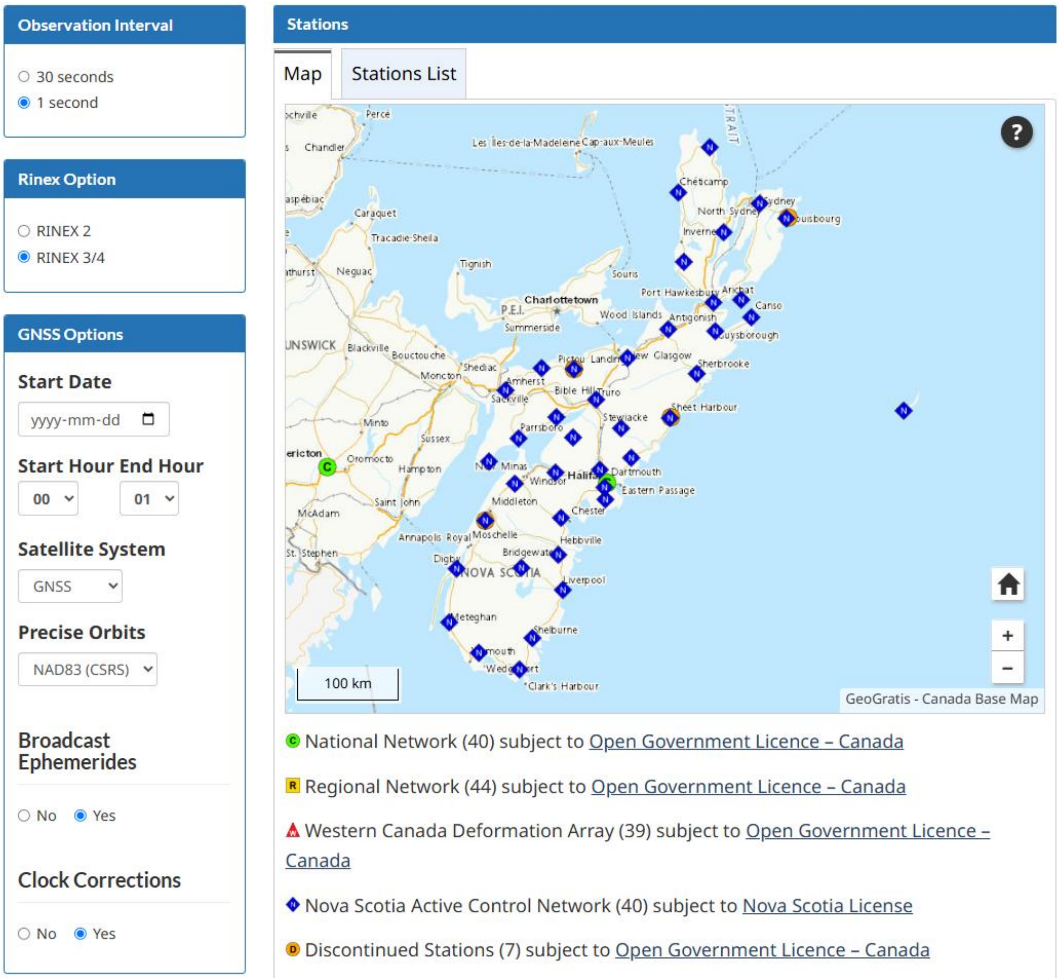
Supplemental

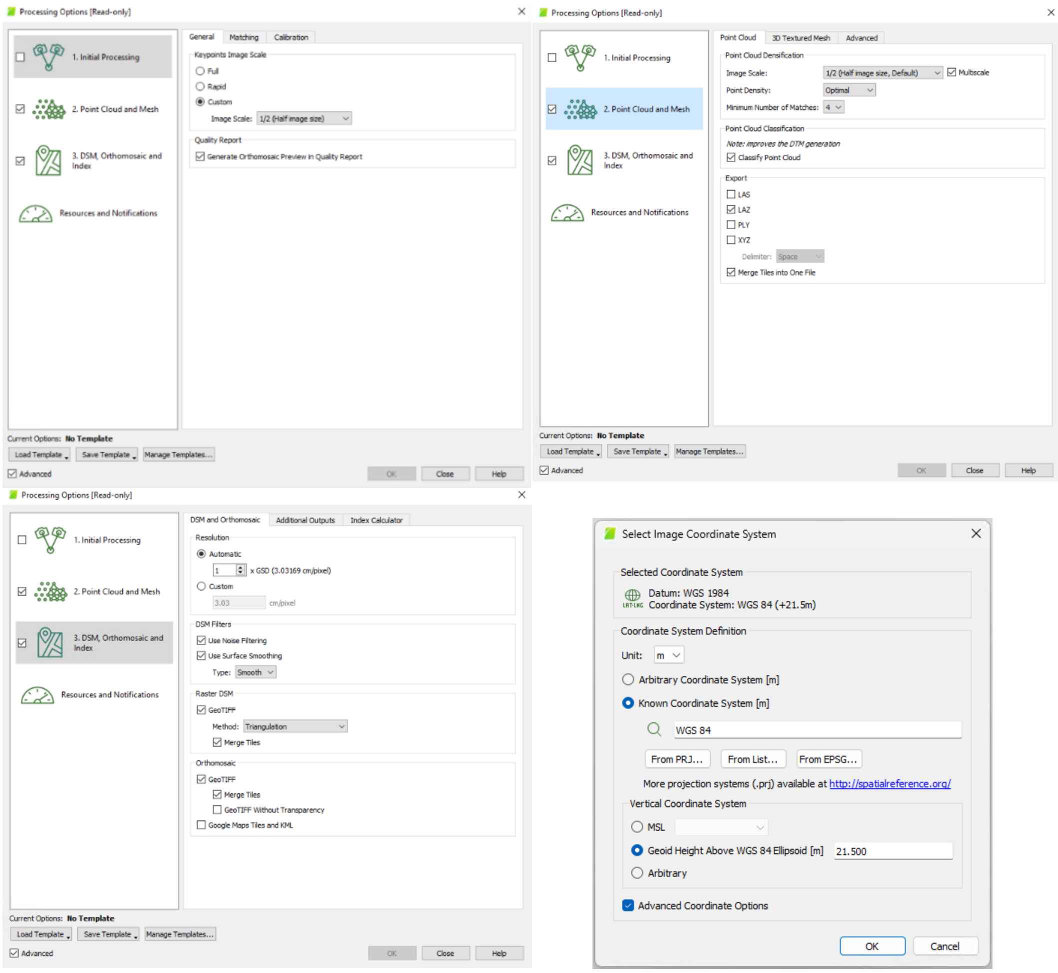
S1. Emlid Studio (v 1.9) settings used to post-process drone imagery collected on three harvest sites in Nova Scotia.



S2. Natural Resources Canada's Canadian Active Control System (CACS) online tool RINEX observation data download settings used to post-process drone imagery collected on three harvest sites in Nova Scotia. Available at https://webapp.csrs-scrs.nrcan-rncan.gc.ca/geod/data-donnees/cacs-scca.php.



S3. Pix4Dmapper settings used to create orthomosaics and point clouds from drone imagery collected on three harvest sites in Nova Scotia, Canada.

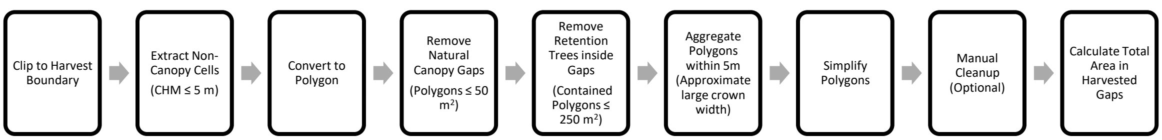


S4. Sample R code used to create canopy height models using structure from motion point clouds derived from drone imagery collected on three harvest sites in Nova Scotia.

```
library(lidR) library(sf)
las <-readLAS("SfM_point_cloud.laz") las <-st_transform(las, 2961)
boundary <- read_sf("harvest_boundary.shp") boundary <-st_transform(boundary,2961)
las <-clip_roi(las, boundary)
las <-classify_ground(las = las, algorithm = csf(sloop_smooth = TRUE, class_threshold = 0.5,
cloth_resolution = 0.5, time_step = 0.65))
dtm <-rasterize_terrain(las_ground, res = 1, algorithm = knnidw()) #uses SfM DEM
dtm <-rast("LiDAR_DEM.tif") #uses LiDAR DEM
dtm <-mask(dtm, boundary)
nlas <- normalize_height(las, tin(), dtm = dtm) nlas <-filter_poi(nlas, Z >= 0 & Z <= 40)
chm <- rasterize_canopy(nlas, res = 0.25, algorithm = p2r(na.fill = tin())) chm <-mask(chm, boundary)
writeRaster(chm, "chm_25cm.tif", overwrite=TRUE)
```

S5. Workflow used to identify gaps/retention in ArcGIS Pro from a canopy height model, using fixed-height threshold approach on three harvested sites in Nova Scotia.

Removal Percentage Workflow



Retention Percentage Workflow