Height growth of regeneration in boreal forest canopy gaps – does the type of gap matter? An assessment with lidar time series

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Abstract

Large canopy gaps in old-growth forests, formed as a result of tree fall events over time, could be composed of regeneration in various stages of growth different from that of single mortality events. Though important to understand forest dynamics such complex processes are rarely monitored due to limited techniques. Applying object-based techniques on a series of three lidar datasets acquired over nine years in boreal forests, we characterised gap events into old gaps, gap expansions and new random gaps. Combining broad species class from high resolution images, and individually locating gap saplings on the lidar surface, specieswise height growth across gradients of height was estimated. The results indicate distinct height growth patterns of both hardwood and softwood gap saplings in different gap events. The methods can potentially be extended to develop accurate juvenile growth patterns.

Keywords: height-growth, multi-temporal lidar, gap dynamics, advanced regeneration

1. Introduction

Canopy gaps created by the fall of one or more overstory trees are important for regeneration dynamics in old-growth forests (Pickett and White 1995). The availability of increased site resources enhances the height growth rates of all species within canopy gaps. Research in various forest systems showed that sapling height growth is a function of gap characteristics, such as gap size (Kneeshaw and Bergeron 1998). Due to the vulnerability of gap edge trees to mortality, some larger canopy gaps could be a result of tree fall events over successive periods of time (Runkle and Yetter 1987, Foster and Reiners 1986). As a consequence, such large gaps in an old-growth forest could be composed of regeneration in different stages of growth whereas gaps formed from a single mortality event should have a single regeneration cohort. Hence it is important to characterise the type of gap events to forecast growth patterns of the regeneration. However, gap formation (expansion vs a single event) is rarely investigated due to the difficulty in collecting data and the limited techniques available for monitoring canopy gaps over time. Moreover, measurement of a canopy gap, gap dynamic characteristics like gap expansions and closure and reliable measurement of height-growth in the field is complex. Conventional remote sensing based methods have been criticized for inadequately identifying gaps (Koukoulas and Blackburn 2004) while assessment of vegetation height is prone to error in closed canopies (St-Onge *et al.* 2004).

In recent decades lidar has emerged as a powerful tool in remote sensing to accurately measure canopy height and vertical structure (Lefsky *et al.* 2002). Owing to its high density and accuracy, the potential to detect tree fall and growth estimation using multi-temporal discrete small-foot print lidar data sets was also shown in a few recent studies (Hopkinson *et al.* 2008, Yu et al. 2006, Naesset and Gobakken 2005, St-Onge and Vepakomma 2004). Using tree matching techniques on high density lidar, Yu *et al.* (2006) showed a good correspondence with field measurements. Lidar was effective in observing significant growth at plot and stand levels (Naesset and Gobakken 2005) and in detecting annual conifer growth (Hopkinson *et al.* 2008). St-Onge and Vepakomma (2004) compared and confirmed acceptable results of dissimilar density lidar data for expected forest height growth. Vepakomma et al. (2008a) validated the feasibility of using medium density small-foot print lidar to map several gap dynamic characteristics like canopy gap opening and closure of sizes ranging from 5 m^2 to 9.8 ha. Nonetheless, no studies have yet been conducted to characterise height growth patterns of vegetation in canopy gaps using lidar.

Assuming lidar accuracy and potential to estimate changes in forest growth with similar and dissimilar densities from earlier studies, we characterise the height growth patterns of gap saplings growing following different gap events by analysing a time series of lidar data. Using a validated method to locate individual trees/ sapling tops and identify their species class (hardwood or softwood), we quantified the height growth rates of saplings over four years in canopy gaps. By delineating the canopy gaps and identifying the nature of gap events as old existing gaps, new gap expansions and new random gaps, we investigated whether the height growth patterns vary between them.

2. Methods

2.1 Study area

The study site is within the conservation zone of the Teaching and Research Forest of Lake Duparquet (TRFLD, 79°22'W, 48°30'N), in the Province of Quebec, Canada. This area is characterized by small hills that vary in elevation between 227 m and 335 m. The mixed vegetation of this part of forest is composed of common boreal species, dominated by balsam fir (*Abies balsamea L.* [Mill.]), paper birch (*Betula papyrifera* [Marsh.]), and trembling aspen (*Populus tremuloides* [Michx]). The stand level age structure found at this site results from a fire driven disturbance regime (1760-1919), and a recent infestation of a defoliating insect (1970-1987) called the spruce budworm (*Choristoneura fumiferana* [Clem]). Most stands are mature or over mature reaching heights of up to 25 m. The climate is cold temperate with an average annual temperature of 0.8° C with annual precipitation of 857 mm The frost free period lasts for nearly 64 days, while the length of the growing season is on average 160 days (Environment Canada 1993).

2.2 Lidar data

A time series of lidar data in three time steps was collected on June 28th 1998, August 14 to 16 2003, and July15th, 2007. The 1998 survey was carried out using an Optech ALTM1020 flown at 700 m above ground level (AGL) operating at a pulse frequency of 5 kHz. with two passes for the first returns and one pass for the last returns, resulting in 0.3 and 0.03 hits/m^2 respectively. The 2003 survey was done with Optech's ALTM2050 lidar flown at 1,000 m AGL, with 50 kHz and 50% overlap between adjacent swaths resulting in 3 and 0.19 hits/ m^2. The 2007 survey was conducted using ALTM 3100 flown at 700 m AGL with 67 kHz and over 50% overlap between adjacent swaths resulting in 10 hits/ m^2 for the first returns. All returns were classified by the provider as ground and non ground and were assumed correct for the study.

Accuracy assessment of lidar derived canopy heights for 1998 and 2003 was carried out in two different studies with 36 (1998) and 77 (2003) field measured trees ranging in height from 5.6 m – 33.1 m that yielded an r^2 of 0.88 and 0.86 with an RMSE of 1.8 m and 1.85 m respectively (Véga and St-Onge 2008, Coops et al. 2004). It is to be noted that at the time of this study, the accuracy assessment of the 2008 data using field measurements was not performed. However, visual and statistical comparisons of the 2007 CHM with high resolution images from the 2007 and 2003 lidar data sets showed a good match.

2.3 Lidar surface and gap characterisation

The three datasets were co-registered for temporal comparisons using the methods suggested by Vepakomma et al. (2008a). The Digital terrain model (DTM) was generated by combining the last returns in 1998 and 2003. The time series of canopy height distributions or canopy height models (CHMs) were generated using an optimised grid resolution (0.25 m) and an interpolation algorithm (a combination of local maxima and an inverse distance method) for accurate and reliable delineation of gap geometry. Defining a gap as an opening in the canopy caused by the fall of a single or a group of trees of a certain height (greater than 5 m, determined in the field), a highly accurate ground validated algorithm on the lidar CHMs was used to explicitly map canopy gaps for each of the years. Mapped gaps are individual objects of contiguous binary grid cells determined by a gap indicator function (Eq. 1). The comparison of 29 gaps measured in the field along 980 m of transect length with lidar delineated gaps showed a good matching of 96.5% overall accuracy.

$$G_i(x,y) = \begin{Bmatrix} 1 & if \ \ CHM_i(x,y) < a \\ 0 & otherwise \end{Bmatrix} \qquad (1)$$

where $a = 5$ m in this study, CHMi(x,y) is the lidar height of the canopy surface in the ith year, (x, y) is a cell that does not belong to any open-ended system.

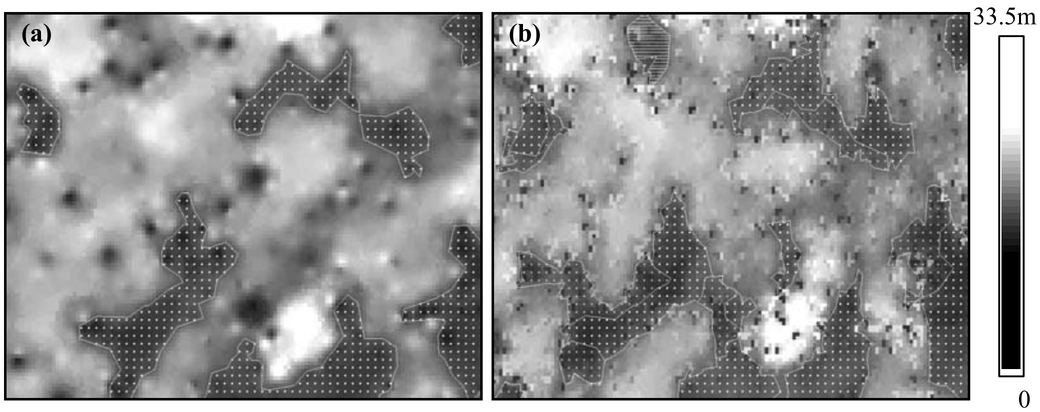

Figure 1: An example of automatically delineated canopy gaps. (a) Gaps in 1998 (dotted objects) overlaid on CHM_{1998} (b) Old gaps (dots), new gap expansions (crosses) and new random gaps (lines) that appeared between 1998 – 2003 overlaid on CHM_{2003}.

Gap objects were delineated on 1998 and 2003 lidar surfaces. We define old gaps as those gaps that are open in 1998 and 2003 while gaps that opened between 1998 and 2003 are new gaps. New gaps that share the edge of an existing gap in 1998 are gap expansions, otherwise they are considered new random gaps. Areas where the difference in vegetation height between 1998 and 2007 within a gap is greater than 5 m, i.e. the smallest difference that is considered to be too high for vertical growth, and contiguous with the gap edge, are classified as lateral growth of adjacent vegetation. Separating laterally growing gaps from regenerating areas reduces ambiguity in height growth patterns of regeneration. We performed various combinatorics on the delineated gap objects of 1998 and 2003 to define the nature of the gap events, namely, old gaps, new gap expansions and new random gaps. An example of automatically delineated canopy gap events is shown in Fig. 1.

2.4 Species class delineation

Orthorectified high resolution multi-spectral Vexcel UltraCamD image data acquired five weeks prior to the 2007 lidar data was used to classify the vegetation of the study area into broad species classes, namely, hardwood (HW) and softwood (SW). Canopy height derived from the lidar data was integrated with the spectral signatures of the image data to automatically extract individual image objects using eCognition v. 3.0. The overall accuracy of the image classification based on a comparison matrix with 25 hardwood and softwood field identified trees, and 15 open grown, non-forest locations is 91.5%.

2.5. Identifying Maximum Tree Height Locations and Extraction of Growth Statistics

Height growth statistics for individual saplings were estimated based on raw lidar returns from 2003 and 2007 extracted after identification of sapling tops on the CHM_{2007}. A local maxima filter with a circular non-overlapping (moving) window was applied to the CHM_{2007} to derive a layer of sapling apices, *LMAX (x,y)*. Local maxima filtering is a common technique first adopted to identify trees in high resolution optical imagery and successfully extended to lidar surfaces (Popescu and Wynne, 2004). We selected a search radius of 5 pixels (1.25 m) equal to the average crown radius of 30 visually interpreted sapling crowns of varying maximum heights (3-5 m). A local maximum within a search window that matches the height on the CHM i.e. $LMAX(x,y) = CHM_{2007}(x,y)$, is assumed to be the maximum height (*TMAX(x,y),* hereafter *TMAX*) of the sapling crown. This method applied on CHM_{2003} was previously validated with 940 trees and saplings identified using manual photogrammetric methods on Ultra Cam D images of 2007 elsewhere in the study area (Vepakomma *et al*., 2008b). An example of identified sapling tops is seen in Fig. 2.

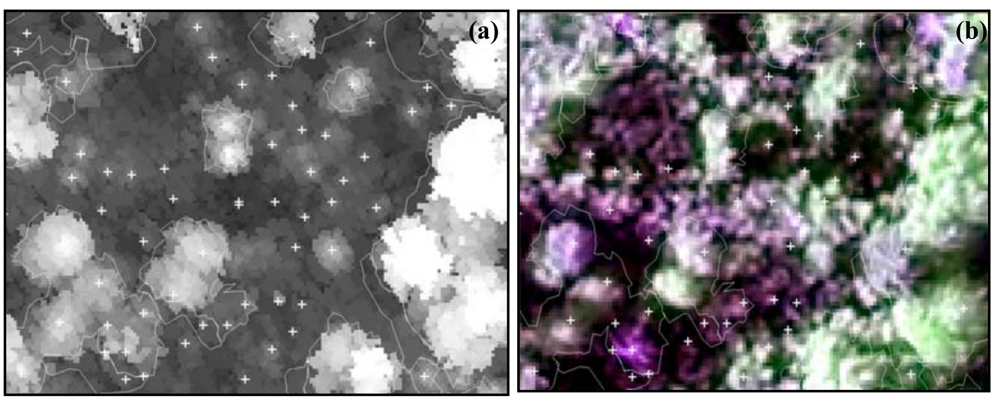

Figure 2: Identification of sapling tops (crosses) along with gap edges (solid line) shown on (a) the CHM_{2007} (b) UltraCam D Image of 2007. CHM brightness is proportional to the canopy height

Lidar raw point clouds of the vegetation (first returns) of 2003 and 2007 were extracted within a buffer zone of 0.5 m radius around each sapling top of *TMAX*. In order to make the lidar datasets of varying densities comparable, the lidar sampling point densities within these buffers were matched by randomly selecting n_i sample points for both years such that

$$n_i = \min\,(n_i^{2003}, n_i^{2007}) \qquad (2)$$

where n_i^{2003} and n_i^{2007} are the number of first returns within the i^{th} buffer zone in 2003 and 2007 respectively. All buffer zones were further constrained to have a minimum point density of 3 hits /m^2 and a lidar determined height not less than 2 m of the zonal maxima to minimise possible errors due to insufficient representation of canopy apices and lidar penetration into the foliage.

Sapling height growth was calculated as the differences in height of the sample maximum

(MAXGTH) and sample average (AVGGTH) of the 2003 and 2007 first returns. Reference average (AVG03) and maximum (MAX03) sapling height for each buffer zone are the sample average and sample maximum of the difference in the height of the 2003 lidar first returns and their respective ground elevation extracted from the DEM. Growth rates in terms of average growth per unit height (AGTH), i.e. (AVGGTH / AVG03), and maximum growth per unit height (MGTH), i.e. (MAXGTH / MAX03) were used to assess growth. It is to be noted that MGTH and AGTH computed here are the rates of growth over the four growing seasons and being proportional growth they are unit free measures. Thus a MGTH value of 0.2 signifies a 20% maximum growth increase from its 2003 maximum reference height.

2.6. Height growth patterns of regeneration in canopy gaps

To understand if height growth patterns differ based on the nature of the gap events, we considered three windows with varying gap fraction (percentage of gap area) that constituted a total size of 26 ha. Since hardwood and softwood trees have different architecture and respond differently to available resources, we assessed AGTH and MGTH based on species class across gradients of sapling height and also between the gap events using:
(1) exploratory statistics
(2) scatterplots and
(3) non-parametric regression estimation of MGTH given the initial height of the sapling.

To investigate whether distinction of the type of gap events is important for understanding growth patterns of regenerating saplings in gaps, we compare the statistics and models generated separately by pooling the sapling data.

3. Results

3.1. Canopy gap characteristics and sapling height

Delineation of canopy gap events indicates that about 16.8% of the study area is in canopy gaps during 1998 – 2003 of which 13.1% is composed of old gaps that opened before 1998 (Table-1). During the period 1998 - 2003, gaps are seen to be expanding at a higher rate and more

Table 1: Gap characteristics in the study area

Statistic	*Old gaps*	*Expansion**	*Random**	*Pooled*
# Gaps	420	617	80	483
Total area in gaps (m2)	34028.7	8667.5	861.38	43557.58
% area in gaps	13.1	3.3	0.3	16.8
Minimum gap size (m2)	5.01	5.02	5.26	5.01
Maximum gap size (m2)	2988.7	288.9	87.3	6024.5
Mean gap size (m2)	80.9	149.8	28.7	104.9
# of saplings identified	388	52	12	452
Avg. sapling height (m)	3.28	3.06	2.1	3.23
Mean MGTH (AGTH)	0.4 (0.7)	1.23 (0.76)	1.14 (0.6)	0.76 (0.6)

* Both expansions and random are new gaps that opened between 1998-2003

frequently than the formation of random gaps. Average gap size of gap expansion is almost twice the average size of old gaps and seven times the average size of new random gaps. However, average gap size of pooled data is the largest at 6024.5 m^2.

In all, 452 gap saplings with a height ranging between 0.5 – 5.0 m were automatically identified in the 26 ha study area, of which 85% belong to the old gaps (Table-1). On average, the saplings in new gap expansions are fast growing compared to those in new random and old gaps. In all cases, the correlation between average and maximum sapling height generated by the two lidar datasets (2003, 2007) is very high at over 0.97 suggesting that growth between the two periods can be measured using multi-temporal lidar data.

3.3. Height growth patterns in canopy gaps

The average and maximum height of saplings in old gaps are higher than in new gaps (Table 2). The range of sapling height in old gaps is greater than that of saplings in new gaps. Except for saplings in old gaps, the maximum growth rates are higher than average growth rates. However, the height growth of HW and SW saplings within old and new gaps and between gap events is highly significant (Kruskal-Wallis ANOVA by ranks and Median tests, $p \approx 0$). SW saplings are taller than HWs in all the gap events (Table -2). The results indicate that HW saplings in old gaps and gap expansions are growing at a faster rate than SWs, but the contrary is noted in new random gaps. Though maximum MGTH is noted for HW saplings in old gaps, HWs are growing only slightly faster than SWs. On the other hand, HWs are growing at twice the rate of SWs in new gap expansions. Scatter plots and predictive models (Figs. 3 and 4) indicate that the height growth of saplings in all gap events is considerably different.

Table 2: Summary of growth statistics during 2003 – 2007 in various gap types

A. Hardwood sapling (s# Saplings in Old gaps : 138; new gap expansions: 23; new random gaps : 6)

	Old gaps			***New gap expansions***			***New random gaps***			***Pooled***		
Variable	***Min***	***Max***	***Mean***	***Min***	***Max***	***Mean***	***Min***	***Max***	***Mean***	***Min***	***Max***	***Mean***
AVG03	0.42	6.53	3.25	0.30	4.34	2.34	0.82	2.94	1.43	0.30	6.53	3.06
MAX03	0.42	6.65	3.39	0.30	4.85	2.42	0.82	2.94	1.43	0.30	6.65	3.19
AVGGTH	0.10	4.8	0.90	0.01	5.45	1.26	0.01	2.02	0.50	0.12	19.60	1.25
MAXGTH	0.02	4.7	1.31	0.09	4.76	1.67	0.60	3.53	0.97	0.10	19.60	1.83
AGTH	0.10	4.8	0.40	0.02	2.72	1.15	0.50	2.13	0.62	0.01	5.45	0.61
MGTH	0.00	4.7	0.52	0.02	3.78	1.23	0.20	3.73	1.01	0.02	4.79	0.79

B. Softwood saplings: (# Saplings in Old gaps : 250; new gap expansions: 29; new random gaps : 6)

	Old gaps			***New gap expansions***			***New random gaps***			***Pooled***		
Variable	***Min***	***Max***	***Mean***	***Min***	***Max***	***Mean***	***Min***	***Max***	***Mean***	***Min***	***Max***	***Mean***
AVG03	0.41	6.31	3.49	0.98	6.06	2.71	0.76	5.09	2.68	0.06	6.31	3.39
MAX03	0.41	7.19	3.71	0.98	6.99	2.84	0.76	5.78	2.79	0.06	7.19	3.60
AVGGTH	0.01	4.86	0.66	0.10	2.78	0.83	0.19	2.42	1.14	0.10	4.86	0.69
MAXGTH	0.00	4.74	1.08	0.08	4.63	1.33	0.67	4.49	2.46	0.00	5.00	1.12
AGTH	0.10	3.10	0.25	0.01	1.74	0.46	0.04	1.27	0.58	0.01	7.06	0.31
MGTH	0.00	3.78	0.36	0.02	2.01	0.61	0.14	4.47	1.26	0.00	3.78	0.58

4. Discussion

The ability of lidar to reliably estimate gap disturbance regimes is well known (St-Onge and Vepakomma, 2004, Koukoulas and Blackburn 2004, Vepakomma *et al*., 2008a). Estimated gap sizes and gap fraction in this study falls within the reported range of characteristics of boreal forests found in earlier studies (McCarthy, 2001, Vepakomma *et al*., 2008a). Gap expansion is a prominent feature in a number of forest ecosystems (Runkle, 1998, Worall *et al*., 2005). Though less frequent in hardwood forests, similar to our observations here trees bordering an old gap are more vulnerable to mortality compared to interior canopy trees in wind fall prone *Picea-Abies* forests of New Hampshire (Worall *et al*., 2005).

The Identification of saplings in old gaps was more successful than in new gaps. Owing to the longer period of opening, the range of sapling height in old gaps is wider than that in new gaps. A higher average height of 3.3.9 m in older gaps also enabled its easy identification on the lidar surface (Table-1). Identification of saplings within new random gaps was difficult due to their small sizes and to the lateral growth of adjacent vegetation.

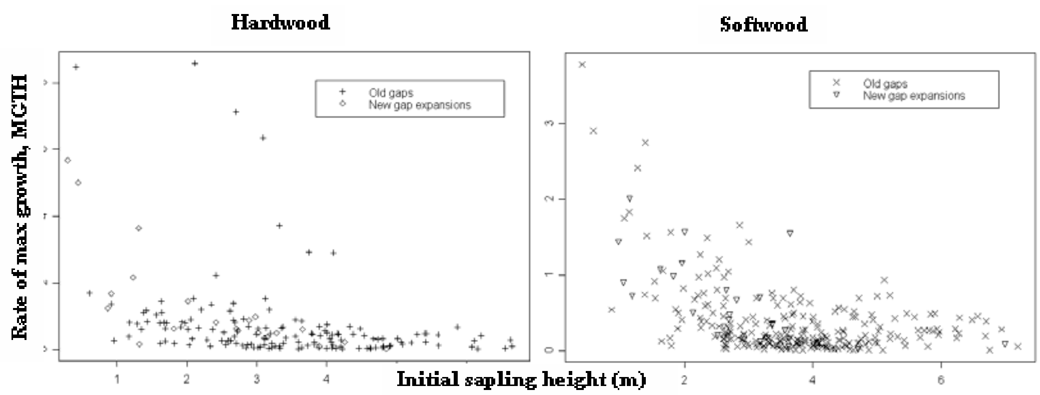

Figure 3:Scatterplot of the rate of maximum growth per unit height during 2003 – 2007 in old gaps and gap expansions.

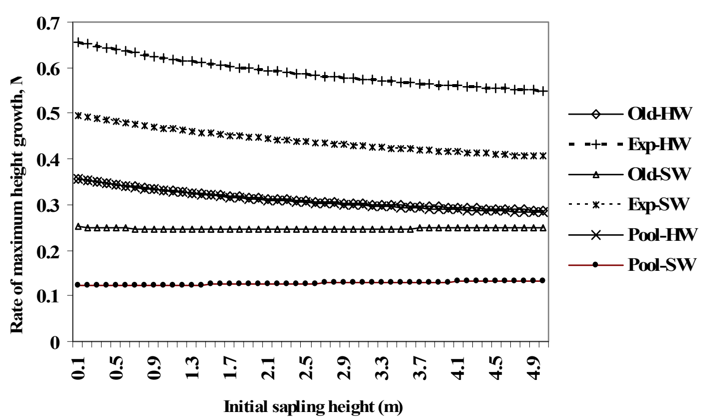

Figure 4 Estimated non-parametric regressions of the rate of maximum growth per unit during 2003 – 2007 height in old gaps and gap expansions (*Old stands for old gaps; Exp for new gap expansions, Pool for pooled dataset*)

Previous research in boreal forests has suggested that large gaps favour intolerant hardwoods while shade tolerant softwoods successfully regenerate in small gaps (Kneeshaw & Bergeron, 1998). The HWs in this forest are all shade intolerant and SWs are all shade-tolerant. The present analyses support this evidence as HWs grow faster in old gaps whose average gap size is larger than new gaps (Tables -1 and 2). SWs are growing faster in new random gaps that are smaller in size. The resources within gaps, especially light, increases with gap expansion, which primarily benefits the HW saplings growing in old gaps adjacent to the new gap openings. The HWs growing in the study area are shade intolerant (Kneeshaw *et al* 2006) and require high light levels to successfully recruit. The dominant conifers on the other hand are shade tolerant and they have been found to be successful in smaller gaps and in the shadier southern portions of gaps due to their requirement for higher moisture (McLaren and Janke, 1996).

The present results clearly indicate distinct growth patterns of saplings in different gap events. This suggests the need to characterise the type of gap events to forecast growth patterns of the regeneration. The use of time series of lidar data for documenting the height- growth differences of advanced regeneration in the canopy gaps spanning full range of height gradients is particularly relevant given the complexity of field based methods. This establishes multi-temporal lidar as an excellent tool to characterise gap dynamics, and thus provides insight into boreal forest dynamics. With rigorous field verification for height of regeneration, these methods can be extended to develop accurate height growth models for juvenile vegetation in a non-destructive way.

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