

## The effects of gap size in a group selection silvicultural system on the growth response of young, planted Douglas-fir: a sector plot analysis

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The growth response of planted 7- and 11-year-old Douglas-fir was measured in a series of 11 group selection harvest gaps ranging in size from 0.05 to 1.1 ha repeated on two study sites. The sites are part of the Silviculture Treatments for Ecosystem Management in the Sayward experiment on central-eastern Vancouver Island, British Columbia, Canada. In each gap, trees were measured in four 9° sector plots oriented in orthogonal cardinal directions from a central vertex. A non-linear two-parameter model was used to examine relationships between per tree and unit area measures and gap size. Despite high levels of growth variability, there was a general, consistent asymptotic growth response to increasing gap size. The minimum gap size required for adequate Douglas-fir sapling height growth was between 0.24 and 0.33 ha and the gap diameter divided by surrounding residual tree dominant height ( $D_{gap}/H_{gap}$ ) at the two sites was 1.5 and 2.2. The site with the smaller minimum gap size had taller surrounding residual trees and thus lower light levels, but had higher relative soil moisture and nutrients and was a younger age at the time of sampling. The largest gap size sampled in this study was relatively small (1.1 ha) and greater growth responses are likely in gaps larger than this. The results of this study suggest that gap sizes below a minimum will not create conditions to ensure adequate growth of Douglas-fir regeneration in group selection systems. In addition, only one group selection pass is examined here: under full implementation several group selection passes are envisaged leading to further changes in the gap-level environment throughout. Further work is needed to confirm the localized relationships found here including: greater replication across a range of site quality, sampling of larger gap sizes and examination of older ages of both regeneration and surround trees.

### Introduction

In parts of the Pacific north-west, there is interest in examining the use of a variety of silvicultural systems as alternatives to traditional clearcutting to meet broad social, environmental and ecological objectives (e.g. Clayoquot Scientific Panel, 1995; Franklin *et al.*, 1997; Lindenmayer and Franklin, 2002; Curtis *et al.*, 2004; Peterson and Anderson, 2009; Gustafsson *et al.*, 2012). Group selection silvicultural systems (GSS) (Troup, 1966; Matthews, 1989) are one alternative. Group selection systems may be used to manage the establishment, growth and final harvest of small gaps or openings on short intervals to develop a mosaic of at least three or more age classes throughout the stand (British Columbia Ministry of Forests, 2003). Although generally considered to be more difficult to implement and maintain than even-aged silvicultural systems like clearcutting, the diversity of vertical and horizontal structure that is created results in a range of stand conditions, wildlife habitat and visual

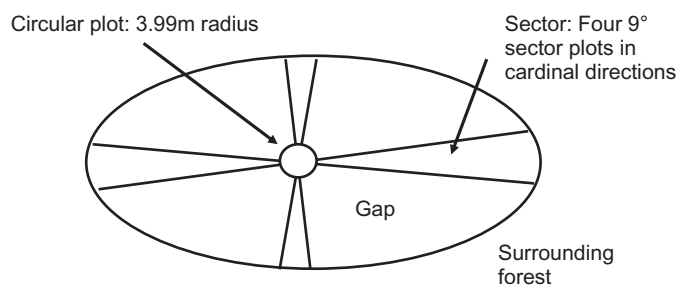
appearances, which significantly benefit multiple non-timber values (Curtis *et al.*, 2004). However, the growth of regenerating trees within the gap is complicated by the presence and continued growth of the residual trees at the gap edges. The growth and development of individual trees that regenerate adjacent to residual stands of trees can be affected by lower levels of light (Carter and Klinka, 1992; Wright *et al.*, 1998; Coates and Burton, 1999; Lieffers *et al.*, 1999), soil moisture, temperature and nutrients (Drever and Lertzman, 2001; Spittlehouse *et al.*, 2004; Voicu and Comeau, 2006; Walters *et al.*, 2006). As a result of the complexity in growing conditions, the long-term consequence to future timber yields of silvicultural systems that create smaller openings and result in greater residual tree edge is not well understood compared with even-aged silvicultural systems.

In mature Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco.) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) forests, GSS mimics gap disturbances caused by wind or tree disease that are important natural processes in the dynamics of these

forests (Spies *et al.* 1990). Pioneering early work by Isaac (Isaac, 1943, p. 69; Isaac, 1956) suggested that in old-growth Douglas-fir stands, at least a 0.4-ha (1 acre) opening was required to ensure adequate early natural regeneration establishment and growth (see also Curtis *et al.*, 2004, p. 4). Spies *et al.* (1990) suggested gap sizes for regeneration. In mature Douglas-fir/western hemlock forests of 0.075–0.1 ha, York *et al.* (2003, 2004, 2007) in California examined a variety of species growing in gaps ranging in size from 0.1 to 1 ha and found that 3- to 7-year height growth of planted Douglas-fir did not appear to greatly increase from a gap size over 0.6 ha. Malcolm *et al.* (2001) postulated that a ratio of gap diameter divided by surrounding residual tree dominant height ( $D_{gap}/H_{gap}$ ) where  $D_{gap}$  is diameter of the gap and  $H_{gap}$  is the height of the surround, of between 1 and 2 was sufficient to allow adequate natural regeneration establishment and growth of Douglas-fir and other species in the UK. Huff (2008) examined Douglas-fir trees growing in a variety of gap sizes in Oregon and found a minimum  $D_{gap}/H_{gap}$  ratio of ~1.5 or above was needed for survival and growth of 15- to 16-year-old trees and that growth was greater in nearby clearcuts. Given the range of recommended gap sizes for Douglas-fir regeneration and growth, further work is needed to better quantify the minimum gap size needed for adequate early Douglas-fir establishment and growth.

Recently, a number of large-scale alternative silvicultural system experiments have been established in the US Pacific northwest and southern British Columbia with objectives that include examining Douglas-fir seedling growth in GSS treatments: the College of Forestry Integrated Research Project (CFIRP) (Ketchum and Tappeiner, 2005; Maguire *et al.*, 2006; Lam and Maguire, 2011), the Demonstration of Ecosystem Management Options (DEMO) experiment (Peterson and Anderson, 2009), the Silvicultural Options for Young-growth Douglas-fir Forests (also called the Capitol Forest Study) (Curtis *et al.*, 2004) and the Silviculture Treatments for Ecosystem Management in the Sayward study (STEMS) (de Montigny, 2004; de Montigny and Nigh, 2009). In each of these experiments, a series of systematically located fixed area sample plots have been established across the treatment unit to be used as a permanent plot network for growth and yield measurements. This system is well suited to sampling even-aged or two-aged tree distributions such as dispersed retention or shelterwood, clearcut and uncut even-aged forests. For silvicultural systems that leave less uniform residual tree spatial patterns such as GSS (Matthews, 1989), patch cuts (Curtis *et al.*, 2004) and variable retention (Mitchell and Beese, 2002), a higher proportion of seedlings grow under the influence of the residual stand with corresponding microsite variability across the gap.

In consideration of the variability across the gap, we used sector sampling (Iles and Smith, 2006; Smith and Iles, 2012), which are sector-shaped fixed-angle plots with rays emanating to the gap border from a vertex that is located in the approximate centre of a GSS opening (a schematic sector plot is shown in Figure 1). Sector sampling has some advantages over systematically located circular fixed area plots to sample alternative silvicultural systems experimental units. Namely, sector plots can be used to sample trees along a resource gradient and do not have boundary overlap sampling bias issues. In addition, sector sampling selects trees in proportion to their occurrence in the population whereas fixed area transects of strip plots do not (Smith and Iles, 2012).



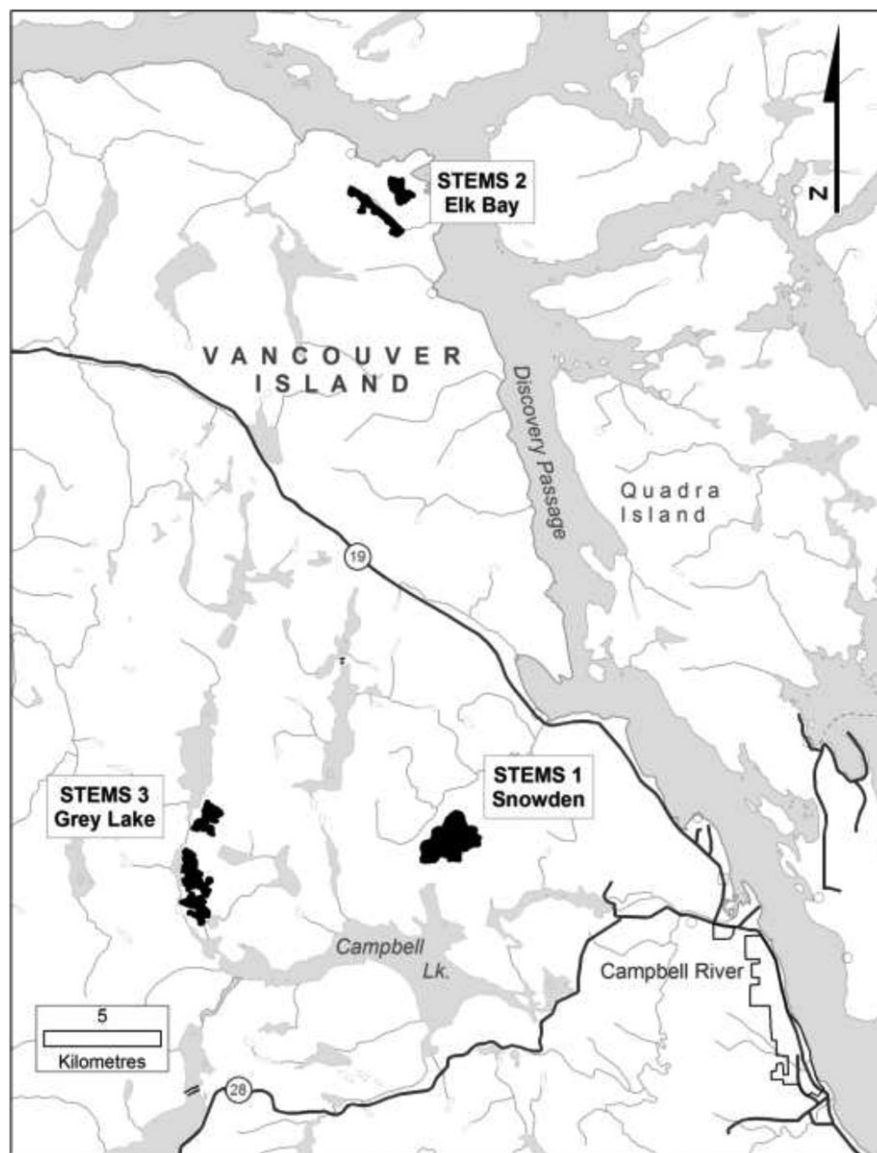
**Figure 1** Schematic layout of the sector plots established in cardinal directions in each of 11 gaps at each of 2 sites (STEMS 1 and 2) ranging in size from 0.05 to 1.1 ha.

The objective of this study was to examine the growth response of young, planted Douglas-fir across various size openings in the GSS treatments at the STEMS experiment.

## Study area

STEMS is a long-term experiment that examines a variety of silvicultural systems including clearcut with reserves, GSS and modified patch cut (MPC) (de Montigny, 2004; de Montigny and Nigh, 2009). The GSS and MPC treatments were intended to maintain partial forest cover over at least two conventional rotations (80 years in this case) in order to reduce the amount of area in the highly visible, freshly harvested condition. The expectation over time was that the treatment units would become an uneven-aged mosaic of even-aged Douglas-fir. This condition could be desirable in forests located at the urban interface or where a mix of habitat conditions is needed to enhance wildlife. The harvest openings (gaps) range in size from 0.01 to 0.5 ha in the GSS treatment and from 0.5 to 2 ha in the MPC treatment. The number of openings harvested in any one harvest cycle depends on the size of the treatment area, the total size of the openings harvested and the harvest return interval, so that the entire area will be harvested within one conventional rotation.

The STEMS experiment is located on Vancouver Island near Campbell River, BC, Canada (Figure 2) and there are three replications: STEMS 1 is located in the Snowden Demonstration Forest, ~20 km north-west of Campbell River, STEMS 2 is located near Elk Bay ~40 km north of Campbell River and STEMS 3 is located near Gray Lake ~32 km west of Campbell River. For this study, only STEMS 1 and 2 were sampled because STEMS 3 had only recently been established. The experimental areas are in the Very Dry Maritime Coastal Western Hemlock Biogeoclimatic Subzone (CWHxm) (Green and Klinka, 1994) characterized by warm and dry summers, moist and mild winters with relatively little snowfall, and long growing seasons with water deficits on zonal sites; forests in zonal sites are dominated by Douglas-fir accompanied by western hemlock and minor amounts of western redcedar (*Thuja plicata* (Donn ex D. Don in Lamb.)). The experimental areas are located in different variants of the CWHxm: STEMS 1 is located in the western very dry variant (xm1) at 231 m elevation, where mean annual temperature and precipitation are 9.3°C and 1510 cm, respectively; STEMS 2 is located at 327 m elevation in the eastern very dry variant (xm2) where mean annual temperature and precipitation are 8.4°C



**Figure 2** Location of the three replications of the STEMS experiment near Campbell River, BC Canada.

and 2086 cm, respectively (STEMS 1: latitude 50.0708, longitude 125.4291; STEMS 2: latitude 50.3144, longitude 125.4948 (decimal degrees)). The xm2 is generally cooler and moister than the xm1.

At STEMS 1, soils are mainly ferro-humic podzols with a moder humus form and a sandy-loam structure, a coarse fragment content of ~40 per cent and average soil depth from 50 to 80 cm (de Montigny, 2004). At STEMS 2, soils are ferro-humic podzols with a mor-moder humus form and a loamy structure, a coarse fragment content of 25–35 per cent, and an average soil depth of 60 cm (de Montigny and Nigh, 2009). The site series of the STEMS 1 GSS and MPC treatment units are predominantly O1 HwFd – Kindbergia (Green and Klinka, 1994) characterized by a very-poor to medium relative soil nutrient regime (RSNR) and a slightly dry to fresh relative soil moisture regime (RSMR). The site series of the STEMS 2 GSS and MPC treatment units are predominantly O5 Cw – Swordfern (Green and Klinka, 1994),

characterized by a rich to very-rich RSNR and a slightly dry to fresh RSMR. It is important to note that although both STEMS 1 and 2 are classified as having slightly dry to fresh RSMR, the classification is based on slope position and surface and ground-water flow and not actual moisture.

STEMS 1 treatment units, logged in 2001 consisted predominantly of 55- to 62-year-old Douglas-fir, with some western hemlock and western redcedar. In the GSS treatment unit, 11 gaps were harvested with the following sizes: 0.06 (2), 0.13, 0.14, 0.19, 0.22, 0.29, 0.30, 0.41, 0.52 and 0.80 ha. The harvested areas at STEMS 1 were planted with 1200 stems per ha (SPH) Douglas-fir in spring 2002. STEMS 2, logged in 2005, consisted predominantly of 78- to 104-year-old western hemlock, the remainder being Douglas-fir with some western redcedar, grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.) and red alder (*Alnus rubra* Bong.). In the GSS treatment unit, 11 gaps were harvested with the following sizes: 0.05, 0.06, 0.1 (2), 0.21, 0.22,

0.23, 0.36, 0.50, 0.56 and 1.10 ha. The harvested areas at STEMS 2 were planted with 686 SPH Douglas-fir and 327 SPH western redcedar (planted in wetter microsites) in spring 2006. The harvested areas in the MPC treatment at STEMS 2 were planted with 625 SPH of Douglas-fir and 278 SPH 412 western redcedar (planted in wetter microsites) in spring 2006. The treatment unit mean dominant height of the surrounding residual trees was ~29.3 and 37.5 m for STEMS 1 and 2, respectively; and mean relative density (RD) (Curtis, 1982) was ~9 and 12 at STEMS 1 and 2, respectively (de Montigny, 2004; de Montigny and Nigh, 2009).

## Methods

Sector plots were established in the approximate centre of 11 openings at each site in spring 2012 when planted trees were 11 and 7 years old from seed at STEMS 1 and 2, respectively. At each site, 10 plots were established in the GSS treatment unit across a range of gap sizes (0.05–0.5 ha) and 1 plot was established in the MPC to sample larger openings close to 1 ha.

The sector plots were established as four systematic, 9° sectors arranged in cardinal directions as described by Iles and Smith (2006) but with the addition of a 3.99-m radius plot near the centre point. The central circular plot was intended to sample more trees at the sector plot vertex. All trees greater than or equal to 1.3 m in height were assigned to a circular or sector plot although the trees in the central plot were not noted as to a particular sector plot. Variables measured or calculated included height (HT, cm), diameter at 1.3 m (DBH, cm), height-to-live crown (HLC, cm), live-crown ratio (LCR) = (HT – HLC)/HT, stem height-to-diameter ratio (HT : DBH ratio), basal area per ha (BAHA, m<sup>2</sup> ha<sup>-1</sup>), stems per ha (SPH) quadratic mean diameter (Dq, cm) and distance along the sector plot central ray to the surround crown edge (further details can be found in Brundke, 2013). Note that HT : DBH was modelled as (400-HT : DBH) to transform the data from reverse 'J' shaped to the asymptotic form shown by the other variables. Surrounding stand tree statistics were derived from an analysis of original fixed area, systematically located post-treatment average plot statistics established throughout all STEMS treatments (Curtis et al., 2004; de Montigny, 2004; de Montigny and Nigh, 2009).

To calculate mean tree measures (e.g. HT, DBH, Dq, LCR and HT : DBH ratio), the trees were averaged into the four 9° sector (Smith and Iles, 2012). When compiling data for a given sector plot the inner 3.99 m radius circular plot trees did not need to be expanded, i.e. they had an expansion factor of 1. This was because all trees in the circular plot were measured. The outer sector plot trees were similarly expanded by weighting with an expansion factor (EF) of 40 (i.e. 360°/9°) as, on average, only 1/40th of the trees outside the circular plot was measured:

$$\bar{y} = \frac{\bar{y}_c n_c + \bar{y}_s n_s (EF)}{n_c + n_s (EF)}$$

where  $\bar{y}$  is the mean tree measure,  $\bar{y}_c$  is the mean tree value in the central plot,  $\bar{y}_s$  is the mean tree value in the sector plot outside the central plot,  $n_c$  is the number of trees in the central plot,  $n_s$  is the number of trees in the sector plot outside the central plot and EF is the expansion factor for the sector plot, 40 if based on one sector (i.e. the N, S, E or W sectors) or 10 if averaging all four sectors at once. It should be noted that the contribution of the circular plot was very small, ~2 per cent of the trees or area in total. Thus the two tree samples, central plots and sector plots were combined as in the above formula (and for SPH and BAHA below).

For stems per hectare, the number of trees in the sector plot was expanded to the complete sector plot and divided by the estimated area of the sector plot:

$$SPH = \frac{n_c + n_s (EF)}{\pi r^2 / 10\,000}$$

where SPH is stems ha<sup>-1</sup> and  $r$  is the length of the sector central ray radius,  $m$ , which varies for each sector. EF is the expansion factor for the sector plot, 40 if based on one sector or 10 if summing all four sectors at once.

For basal area per hectare, the total basal area of trees in the sector plot was divided by the estimated area of the sector plot:

$$BAHA = \frac{\sum_{i=1}^{n_c} ba_i + \sum_{j=1}^{n_s} ba_j (EF)}{\pi r^2 / 10\,000}$$

where BAHA is basal area per hectare (m<sup>2</sup> ha<sup>-1</sup>),  $ba_i$  is tree basal area (m<sup>2</sup>) for the  $i^{\text{th}}$  tree if in the central circle or the  $j^{\text{th}}$  tree if in the sector plot outside the central plot. EF is the expansion factor for the sector plot, 40 if based on one sector or 10 if summing all four sectors at once.

For sector samples based on a ratio-of-means approach such as SPH or BAHA, the variance estimate may be biased (Cochran, 1977, p. 153; Smith et al., 2008). However, a systematic sample located in the centre of a regular polygon (using the four orthogonal sectors) has been shown to yield asymptotically unbiased estimates (Smith et al., 2008). Thus, standard formulas for calculating approximate standard errors across plots in a given strata may be used assuming approximate independence between sector samples. Strictly speaking, sector plot sample selection should be based on a random angle or random point (Smith et al., 2008). The approach used here was selected to examine cardinal bearings but should not greatly affect results when generalized to predominantly N, S, E or W directions.

Species composition was based on summed basal area for the entire gap (all four cardinal sectors). Although the trees are young, basing the calculations on basal area helped weight composition for tree size rather than simple tree counts (only trees over 1.3 m tall were measured).

A two-parameter monomolecular model (Draper and Smith, 1981, p. 506; Fekedulegn et al., 1999) was used (equation 1) to model mean sector plot HT, DBH, LCR, HT : DBH ratio, BAHA and SPH vs gap size. Other model forms including logistic and Chapman-Richards (Fekedulegn et al., 1999) were examined but offered similar fits or additional complexity with no apparent advantage:

$$y_{ij} = a_1(1 - e^{-a_2 X_{ij}}) + \varepsilon_{ij} \quad (1)$$

where  $y$  is the variable of interest,  $X$  is actual gap size in hectares,  $a_1$  and  $a_2$  are asymptote and shape parameters to be estimated for the  $i^{\text{th}}$  installation ( $i = 1, \dots, 11$ ) (e.g. gap) and  $j^{\text{th}}$  transect ( $j = 1, \dots, 4$ ), (e.g. N, S, E and W sectors), and  $\varepsilon_{ij}$  is model error.

Models were fitted using generalized non-linear least-squares via the `gnls()` function in the `nlme` package of R (R Core Team, 2014). The residual error was modelled as a block diagonal with unstructured correlation among the four sectors within each gap. In addition, each cardinal direction was given its own variance to yield the most general covariance structure (Pinheiro and Bates, 2000). The sensitivity of  $a_1$  to transect bearing was explored using indicator variables for tree data in each of the sectors. To this end, 'dummy' binary variables (0 or 1) representing the cardinal directions were tested for significant difference ( $P < 0.05$ ) using a  $t$  test separately for STEMS 1 and 2.

## Results

Ten years after harvest at STEMS 1, regeneration consisted of predominantly planted Douglas-fir (95 per cent by basal area)

that was 11 years old from seed, with a small amount of red alder and white pine (*Pinus monticola*, Douglas ex D. Don.) (4 and 1 per cent, respectively) (only regenerating trees that were greater than or equal to 1.3 m in height were measured). Regeneration density averaged 1319 total SPH ( $\pm 209$  SD) of which planted Douglas-fir comprised 999 SPH ( $\pm 158$  SD) with an average height of 412 cm ( $\pm 94$  SD).

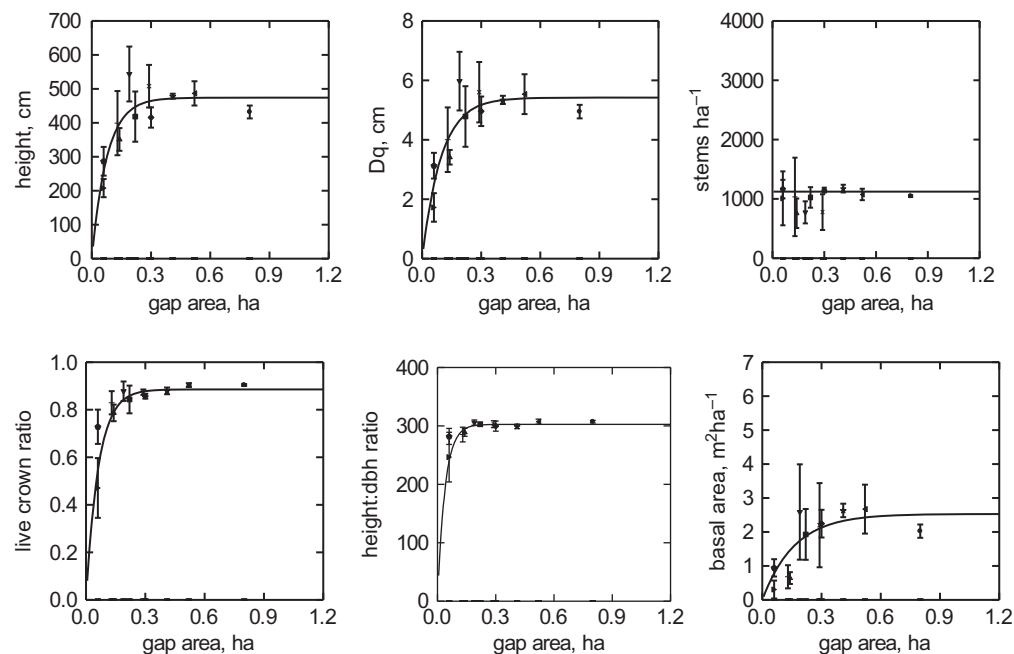
Six years after harvest at STEMS 2, regeneration consisted of predominantly planted Douglas-fir (75 per cent by basal area) that were 7 years old from seed, planted western redcedar (4 per cent) and naturally regenerated western hemlock (21 per cent). Regeneration density averaged 3384 total stems ( $\pm 3362$  SD) of which planted Douglas-fir comprised only 381 SPH ( $\pm 250$  SD) which is well below the density at the time of planting (records show that 686 sph Douglas-fir were planted) and indicates either mortality since planting and/or that half of the planted trees had not reach the measurement height of greater than or equal to 1.3 m. Despite the greater density of natural regeneration at STEMS 2, the height of the planted Douglas-fir exceeded the height of the planted western redcedar and natural regeneration. Average height of planted Douglas-fir was 222 cm ( $\pm 59$  SD), planted redcedar was 177 cm ( $\pm 33$  SD) and western hemlock naturals were 154 cm ( $\pm 18$  SD).

Figures 3 and 4 show model fits to HT, Dq, HT : DBH ratio, LCR, BAHA and SPH vs actual gap size at STEMS 1 and 2. As gap size increased the modelled relationship appeared to level off. Table 1 shows the point at which 99 per cent of the asymptote is reached; this ranged from 0.13 to 0.69 ha across all variables at both STEMS 1 and STEMS 2 (excluding SPH (STEMS 1) and BAHA (STEMS 2) which were not significant or did not approach an asymptote, respectively).

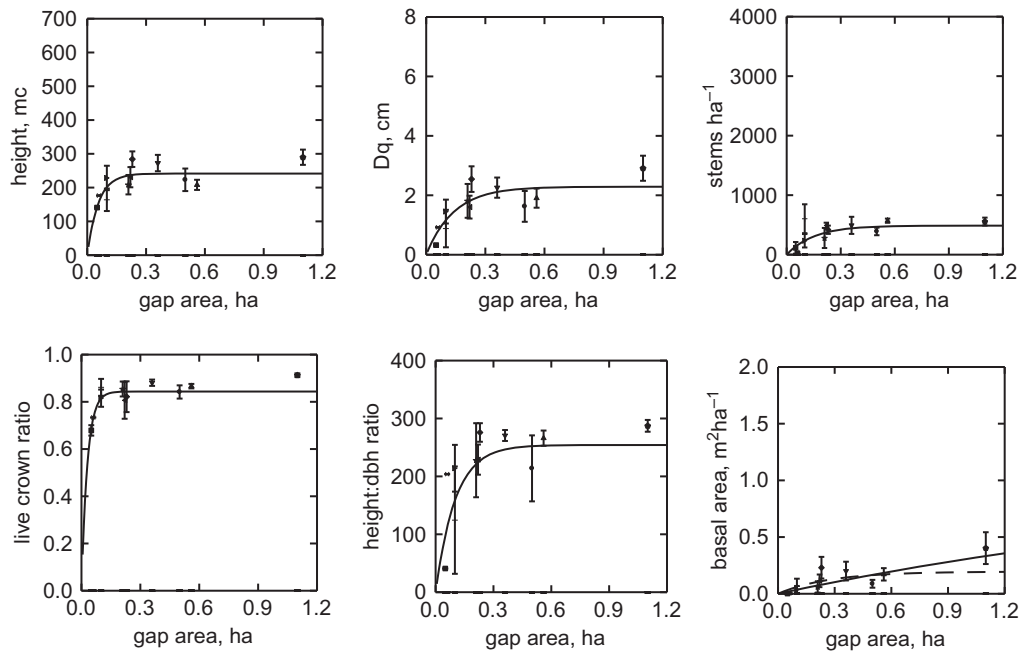
Table 1 shows statistics for equation (1) fitted to variables for both STEMS 1 and STEMS 2; namely mean sector plot HT, DBH, LCR, HT : DBH ratio, BAHA, SPH and Dq vs gap size. Fit statistics averaged 38 per cent for relative mean squared error (RMSE/mean) or an  $R^2$  of 33 per cent and these statistics suggest considerable response variability. However, plots of residual variance (Figure 5) suggest a reasonably homogenous variance given the small sample size. Normal probability plots indicated that the residuals were approximately normally distributed. The modelled proportional relationship (equation (1), Table 1) between maximum height growth and gap size at STEMS 1 and STEMS 2 is shown in Figure 6. STEMS 2, the moister, richer site achieved maximum height at a smaller gap size than STEMS 1. The block diagonal plus direction error structure model resulted in smaller parameter standard (Table 1).

## Discussion

Gap size was found to impact all mean tree measures at both STEMS 1 (Figure 3) and STEMS 2 (Figure 4) except for SPH at STEMS 1 and BAHA for STEMS 2 if the largest gap data are used. Survival was not examined. The data suggest an asymptotic relationship between young planted Douglas-fir mean tree and unit area growth measures and GSS gap size at both sites. In particular, the mean tree values of HT and Dq showed a distinct, though highly variable, monotonic relationship to gap size. Ninety-nine per cent of the asymptote (an upper level) for height growth occurred at gap sizes of 0.24–0.33 ha at STEMS 1 and 2, respectively, and 0.46–0.54 ha for diameter growth. The asymptote was approached very steeply; for example, Figure 6 shows that HT at STEMS 1 is 55 per cent of the maximum (or  $a_1$ )



**Figure 3** STEMS 1 planted Douglas-fir mean tree height, quadratic mean diameter, LCR, 400-height : dbh ratio, basal area per hectare and stems per hectare vs gap size. Error bars represent one standard error of each predicted value. \*Note that height : dbh ratio is modelled as 400-height : dbh ratio, this was to use equation (1) without modification.



**Figure 4** STEMS 2 planted Douglas-fir mean tree height, quadratic mean diameter, LCR, 400-height : dbh ratio, basal area per hectare and stems per hectare vs gap size. Error bars represent one standard error of each predicted value shown. \*Note that height : dbh ratio is modelled as 400-height : dbh ratio, this was to use equation (1) without modification. The solid line for BAHA is from a fit of gnls equation (1) using the variance weighting but not the block-diagonal correlation structure. The dashed line for BAHA is from a full gnls fit of equation (1) but not using the largest gap (1.1 ha) data. This shows that BAHA approaches an asymptote if the largest gap is not used in the equation fitting.

**Table 1** Estimated model parameters and statistics for planted Douglas-fir regeneration using equation (1) at STEMS 1 and STEMS 2

Area	Dependent variable	Gap size for 99% max (ha)	$a_1$ (SE)	$a_2$ (SE)	SD	Mean	$R^2$	$n$
STEMS 1	HT, cm	0.33	474.033 (21.351)	13.022 (2.374)	94.44	411.57	45%	44
STEMS 1	DBH, cm	0.46	5.195 (0.320)	9.323 (1.964)	1.25	4.14	43%	44
STEMS 1	LCR	0.27	0.886 (0.029)	15.847 (2.361)	0.10	0.81	50%	44
STEMS 1	HT : DBH ratio	0.17	302.605 (4.376)	26.078 (2.459)	28.16	293.40	14%	44
STEMS 1	BA, $m^2 ha^{-1}$	0.69	2.530 (0.395)	6.143 (2.502)	1.19	1.72	29%	44
STEMS 1	Stem $ha^{-1}$	–	1122.373 (50.103)	ns	501.49	998.56	0%	44
STEMS 1	Dq, cm	0.41	5.419 (0.313)	10.296 (2.060)	1.20	4.49	46%	44
STEMS 2	HT, cm	0.24	241.483 (13.608)	17.797 (4.411)	49.89	221.96	35%	43
STEMS 2	DBH, cm	0.54	2.054 (0.236)	7.831 (2.734)	0.72	1.55	37%	43
STEMS 2	LCR	0.13	0.844 (0.012)	33.390 (3.415)	0.06	0.82	45%	43
STEMS 2	HT : DBH ratio	0.44	254.193 (29.466)	9.723 (3.739)	83.60	208.44	42%	43
STEMS 2	BA, $m^2 ha^{-1}$	–	0.195 (0.0463)	3.681 (1.690)	0.12	0.13	16%	43
STEMS 2	Stem $ha^{-1}$	0.64	488.000 (64.248)	6.577 (2.422)	217.45	390.18	16%	43
STEMS 2	Dq, cm	0.59	2.288 (0.255)	7.122 (2.314)	0.72	1.68	43%	43

Gap size for 99% max (ha) = gap size (ha) at 99% of the asymptote (see Figure 6).

SE = standard error, SD = standard deviation,  $R^2$  = coefficient of determination.

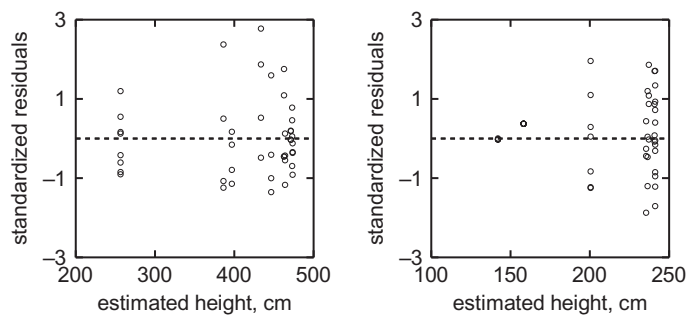
All parameters significant  $P < 0.05$ , unless noted (ns).

at the smallest gap size of 0.06 ha and increases to ~86, 93 and 99 per cent of maximum at gap sizes of 0.15, 0.2 and 0.4 ha, respectively.

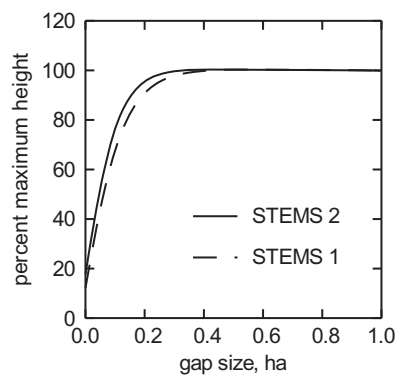
For BAHA, there appeared to be an increasing, though still asymptotic relationship over the range of gap sizes. BAHA for STEMS 1 peaked at 0.69 ha (Figure 3, Table 1). At STEMS 2, the

higher BAHA in the largest gap may have lead to equation (1) failing to converge. Dropping the largest gap data from the analysis suggested an asymptotic relationship for STEMS 2 BAHA (Figure 4).

Others have found asymptotic relationships between tree growth measures (height and diameter) and gap size for a



**Figure 5** Standardized residuals vs predicted average height for STEMS 1 (left) and STEMS 2 (right): see Table 1 and equation (1).



**Figure 6** Relationship between modelled proportional maximum height growth with increasing gap size for STEMS 1 and STEMS 2 (using equation (1), Table 1 parameters).

given site. Coates (2000) examined 5-year growth of different coniferous species across a range of gap sizes up to 0.5 ha in Northern British Columbia, Canada where the average surround residual tree height was ~30 m and found that shade intolerant species examined approached the asymptote more slowly than shade-tolerant species but growth was greater in the open. Malcolm *et al.* (2001) postulated an asymptotic relationship between growth measures (height and diameter) for a variety of tree species, including Douglas-fir, growing in the UK.

At STEMS 1, planted Douglas-fir density decreased from 1200 SPH at the time of planting to ~1000 SPH and this was constant or level across gap sizes (i.e. the equation (1) model shape parameter  $a_2$  was not significantly different from 0); this implied that relative survival of planted Douglas-fir at STEMS 1 was not affected by gap size. At STEMS 2, planted Douglas-fir density was affected by gap size, decreasing sharply from ~480 SPH in the larger gaps, to well below this in gaps smaller than 0.3 ha (Figure 4). This may be because the planted trees at STEMS 2 were only 7 years from seed, or that not all trees had reached the minimum sample height of 1.3 m especially in the smaller gaps, or that survival was lower at STEMS 2.

At both STEMS 1 and 2, the LCR of planted Douglas-fir was notably reduced in smaller gaps while the HT : DBH slenderness ratio was greater in smaller gaps (Figures 3 and 4). The higher HT : DBH ratio may have resulted because more photosynthates were allocated to height rather than diameter growth under

shade (Smith, 1982). The absorption of light by residual trees surrounding the gaps may reduce the red-to-far-red ratio, leading to greater stem elongation and slower diameter growth, especially in shade intolerant trees such as Douglas-fir (Smith, 1982; Malcolm *et al.*, 2001).

STEMS 2 had a higher proportion of naturally regenerated western hemlock (17 per cent) compared with STEMS 1 (effectively 0 per cent). The greater component of western hemlock natural regeneration at STEMS 2 was expected, due to the higher proportion of residual western hemlock surrounding the gaps (de Montigny and Nigh, 2009) and the generally prolific seed production of western hemlock (Fowells, 1965). Brundke (2013) found the mean density of naturally regenerated hemlock at STEMS 1 ranged from 25 SPH to 454 SPH in GSS gaps and at STEMS 2 from 81 to 5519 SPH; there was no significant relationship between gap sizes and naturally regenerated western hemlock density at either site. The absence of a relationship between natural western hemlock regeneration density and gap size was found by Spies *et al.* (1990) who suggested that western hemlock has a low gap size threshold for establishment if any, and that factors other than light, such as presence of suitable organic seedbeds and belowground competition, may be the primary controls of seedling germination and survival. Despite the greater density of naturally regenerated western hemlock at STEMS 2, the height of the planted Douglas-fir at STEMS 2 of 222 cm ( $\pm 59$  SD) exceeded the height of the natural western hemlock regeneration of 154 cm ( $\pm 18$  SD) indicating that 6 years after planting, the Douglas-fir was out-competing western hemlock height growth at STEMS 2. This is important for Douglas-fir because growth in height is the most critical factor in competition (Smith *et al.*, 1997).

Modelled height growth (Table 1 and Figure 6) showed that the gap size requirements needed to achieve 99 per cent of the maximum height growth were smaller at STEMS 2 (0.24 ha) than at STEMS 1 (0.33 ha). This might reflect that there was less light available at STEMS 1 due to differences in residual surrounding tree height. To examine this, we scaled gap diameter (Dgap) to the average height of dominant trees (Hgap) at each site (29.3 and 37.5 m at STEMS 1 and 2, respectively) and found the Dgap/Hgap ratio for each gap varied from 0.9 to 3.4 and 0.7 to 3.2 at STEMS 1 and 2, respectively (we had only one average Hgap for each site which limited the usefulness of the analysis). The minimum gap sizes of 0.33 and 0.24 ha at STEMS 1 and 2, respectively, were equivalent to a Dgap/Hgap ratio of 2.2 and 1.5; therefore despite the taller residual trees at STEMS 2, the minimum gap size at STEMS 1 was larger. Aspect could affect light levels as well, but STEMS 2 gaps were located on 20 per cent slopes with a N to NE aspect where there was presumably less light availability than at STEMS 1 where gaps were located on shallower slopes with a somewhat more variable SW to W aspect.

Lower light levels at STEMS 2 were confirmed by Fielder (2013) who examined 5-year individual tree planted Douglas-fir growth and microclimate along a north-south (N-S) transect in a 0.45-ha GSS gap with a 300° aspect at STEMS 1 and a 0.43-ha GSS gap with a 25° aspect at STEMS 2 (the actual openings were not part of this study). The maximum transmittance of above-canopy photosynthetically active radiation at tree height on a N-S transect mid-way between the east/west edges was 80 and 60 per cent at STEMS 1 and 2, respectively; transmittance was lower in the STEMS 2 gap from the south edge to all

equivalent positions to the north edge by between 30 and 40 per cent (Fielder, 2013). Consequently, the smaller gap size needed to achieve a given proportional height growth found at STEMS 2 vs STEMS 1 was not due to greater light availability at STEMS 2.

Light is not the only factor affecting gap dynamics (Spittlehouse *et al.*, 2004; Voicu and Comeau, 2006; Walters *et al.*, 2006). STEMS 1 was characterized by a very-poor to medium RSNR and a slightly dry to fresh RSMR, while STEMS 2 was characterized by a rich to very-rich RSNR and a slightly dry to fresh RSMR. Drever and Lertzman (2001) estimated that the proportion of Douglas-fir height growth variability explained by light availability increased as soil nutrient and moisture increased, i.e., from dry, poor to fresh, rich sites. Sacks (2004) found that relative growth rates of first year seedlings of 13 species of European trees and shrubs were higher under both 3 and 30 per cent light irradiance when given ever-moist soil compared with droughty soils; the shade and drought tolerances varied independently indicating the potential for extensive species niche differentiation in combinations of irradiance and water supply. Fielder (2013) examined soil moisture characteristics and found that the soil moisture deficit period was much lower at the STEMS 2 than at the STEMS 1 gap; this was due to the more northerly, coastal location of STEMS 2 where cumulative rainfall over 5 measurement years was 45 per cent greater than at STEMS 1 (Soil moisture deficit period is the fraction of growing-season days where soil water potential exceeded the threshold of plant stress.). Fielder (2013) found that planted Douglas-fir mean stem volume increment over the first 5 years in the GSS gap increased to a maximum of 300 cm<sup>3</sup> and 600–800 cm<sup>3</sup> per 5 years (STEMS 1 and 2, respectively) at 20–30 m from the S edge at maximum transmittance then levelled off to 100 and 500 cm<sup>3</sup> (STEMS 1 and 2, respectively) at 5 m from the N edge, where it began to decline. The reduction in growth was correlated with greater soil moisture deficits at the north edge presumably because of higher radiative heating compared with the south edge; soil moisture deficits at the north edge were much higher at STEMS 1 than at STEMS 2. Fielder concluded that GSS gaps smaller than 0.5 ha may not provide adequate light for less shade-tolerant species such as Douglas-fir, but that greater moisture availability can help compensate for lower light levels. The influence of greater soil moisture and/or nutrients on the minimum gap size required for sapling height growth may explain why STEMS 2, the moister, richer site but with lower light levels had smaller minimum gap size requirements than STEMS 1.

The smaller gap size needed to achieve the same relative height at STEMS 2 than at STEMS 1 (Figure 6) may also have been due to the effects of different age of assessment at the two sites. The sector sampling study reported here was undertaken as a preliminary research investigation, and to measure STEMS 1 and 2 at the same age would have required a 4-year wait. A common age of assessment for future measurements would help reduce experimental noise. This age of assessment should occur when the mean height of the planted trees is well past the minimum sapling height of 1.3 m, perhaps at the time when free-growing assessments are done, typically when mean height is 3–4 m.

There appeared to be no differences in growth response between sectors with different bearings (N, S, E or W) based on

an indicator variable analysis for all variables. Apparent data variability for these young trees masked any discernible trend.

There are several limitations to this study. The objective of this study was to examine the growth response of young, planted Douglas-fir across gaps in the GSS treatments at the STEMS experiment that varied from 0.05 to 0.5 ha and we sampled slightly larger openings of 0.8 and 1.10 ha from the patch-cut treatment at STEMS 1 and 2, respectively, and not larger openings or the clearcut treatments. For these young trees, growth response to gap size appears to be asymptotic although a full range of sites was not examined; growth is expected to be highest in clearcuts but clearcut data were not available for this study. The asymptotic level suggests a minimum size for adequate tree establishment and early growth under GSS silvicultural system. York *et al.* (2007) found that 7-year height growth of planted Douglas-fir did not appear to greatly benefit from a gap size over 0.6 ha, but Fielder (2013) found no suggested light saturation with response of planted Douglas-fir across a 0.5-ha gap; therefore, future studies should include much larger gap sizes to better reflect what is maximum growth across a greater range of opening sizes.

In general, the growth data were highly variable suggesting that alternate hypotheses might be supported. However, there are few studies examining the impacts of gap size on young Douglas-fir establishment and growth and the general results for this dataset appear to support an asymptotic relationship. It is important to stress that such additional studies are needed to further test the findings shown here.

The central 3.99 m radius plot was established to increase sample trees close to the gap centre where the sector plot becomes very narrow. However, this plot altered each tree's sample inclusion probability, making estimation unnecessarily challenging for such a small contribution to statistics (~2 per cent on an area or tree basis on average). In future studies, a centre plot could be added as an independent sample but the full sector should be measured.

## Conclusions

Seven- and eleven-year-old planted Douglas-fir were measured in a series of 11 small group selection openings ranging from 0.05 to 1.1 ha at two sites on central-eastern Vancouver Island, British Columbia, Canada. In each gap, trees were measured in four sector plots oriented in orthogonal cardinal directions (i.e. N, S, E and W sectors) from a central vertex to examine mean tree and mean unit area growth responses per gap. There was an evident asymptotic relationship for mean tree plot measures (HT, Dq, CR and HT : DBH ratio) and gap size and most peaked between ~0.3 and 0.7 ha and then levelled off as gap size increased further. The findings by Isaac (1943) that Douglas-fir requires at least a one acre opening (0.4 ha) for adequate regeneration and early growth is supported. Per unit area measures, BAHA and SPH also showed increasing values with plot size except for SPH at STEMS 1 which showed no relationship. Density of Douglas-fir saplings at STEMS 2 was found to be lower than the density at the time of planting, which may indicate that the 7-year-old trees had not reached the minimum sample height or that survival was not as high as at STEMS 1. However, despite the greater density of naturally regenerated western hemlock at



STEMS 2, the 7-year height of the planted Douglas-fir exceeded the height of the natural western hemlock regeneration indicating that planted Douglas-fir had retained a competitive height advantage at this time. The minimum gap size required for adequate Douglas-fir sapling height growth was between ~0.24 and 0.33 ha and Dgap/Hgap was different at the two sites (1.5 at STEMS 2 for a 0.24-ha gap and 2.2 at STEMS 1 for a 0.33-ha gap). STEMS 2 with the smaller Dgap/Hgap had taller surrounding trees and lower light levels but higher relative soil moisture and nutrients and was a younger age at the time of sampling.

There was no apparent difference between the four cardinal sector orientations and mean tree or unit area measures. As a caveat, there was significant data variability for these young trees; in addition no clearcut data were used in the comparisons and most samples were for gaps below 0.6 ha. The largest gap size sampled in this study was relatively small (1.1 ha) and greater growth responses are likely in gaps larger than this. The results of this study suggest that gap sizes below a minimum will not create conditions to ensure adequate growth of Douglas-fir regeneration in group selection systems. Further work is needed to confirm the localized relationships found here including: greater replication across a range of site quality, sampling of larger gap sizes and examination of older ages of both regeneration and surround trees. In addition, only one group selection pass is examined here: under full implementation several group selection passes are envisaged leading to further changes in the gap-level environment throughout.

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None declared.

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