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The influence of initial and post-thinning stand density on Douglas-fir branch diameter at two sites in New Zealand

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Abstract

Background: Branches support the foliage needed for tree growth, but if the branch diameter is too large it may constitute a defect when the tree is assessed for timber quality and when the tree is processed into boards. Consequently branch diameter is an important consideration when developing a silvicultural regime.
The objectives of this study were: (a) to develop site-specific models to predict branch diameter variation with position on the stem; and (b) to use the models to evaluate the influence of initial and post-thinning stand density on branch diameter in unpruned stands of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) at two sites in New Zealand.

Methods: Branch diameters were measured using a photogrammetric technique, TreeD, on pre-selected sample trees from unpruned treatments in two silviculture experiments, one in the North Island and one in the South Island of New Zealand. The data were used to develop site-specific models to predict branch diameter along the stem. The models were then used to interpret response to a thinning at a stand age of approximately 10 years when the base of the green crown was still close to ground-level, and to make comparisons with a branch diameter limit of 40 mm.

Results: The models developed indicated that previously formed branches were influenced by the increased growing space created by thinning. At all three post-thinning stand densities (250, 500 and 750 stems ha^{-1}), the diameter of some branches on the mean tree within a stand were likely to exceed 40 mm. In unthinned treatments, the model indicated that an initial stand density of at least 1333 stems ha^{-1} would be needed to keep branch diameters on the mean tree below 40 mm along the whole stem at age 29 years.

Conclusions: This study indicates the importance of considering initial stand density, post-thinning stand density and timing of thinning when designing a silviculture regime that aims to control branch diameter.

Keywords: Douglas-fir; Branch diameter; Stand density; Thinning; Silviculture

Introduction

Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) is native to western North America where it is one of the most valuable and commercially important timber species (Miller and Knowles 1994). Outside its natural range it is an important commercial timber species in France, Germany and New Zealand (Maclaren 2009). Douglas-fir was first recorded in New Zealand in 1859, with plantations being established at various locations at the end of the 19th century/beginning of the 20th century

(Miller and Knowles 1994). Currently it is the most important exotic timber species in New Zealand after radiata pine (*Pinus radiata* D.Don.). In April 2013, planted Douglas-fir forests covered 106,500 ha compared with 1,543,600 ha of planted radiata pine (Ministry for Primary Industries (MPI) 2013).

For any tree species, the size and arrangement of branches are important for both tree growth and timber quality (e.g., Larson 1962, 1969; Megraw 1985). The distribution of branches and foliage influences the amount of light intercepted by the foliage (Whitehead et al. 1990), and consequently tree growth. However, branches result in knots within the stem that constitute a defect

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in both appearance and structural timber. There is re-
duced strength and stiffness in the vicinity of a knot,
which is considered to be due to the arrangement of fi-
bres around the knot (Phillips et al. 1981). Tustin and
Wilcox (1978) measured a 'branch index' for the 2nd log
in Douglas-fir. This index was the average diameter of
16 branches selected as follows. The largest branch was
selected from each quartile in each 4 ft. (1.22 m) section
of the 16 ft. (4.88 m) log. The position of the log was
not specified but is presumed to be between 16 ft.
(4.88 m) and 32 ft. (9.75 m). They concluded that branch
diameter effects were 2.5 times greater than wood dens-
ity effects in their influence on the variability of stiffness
of timber framing. Ledgard et al. (2005) suggested that a
desirable maximum branch diameter for unpruned
Douglas-fir stands in New Zealand is 40 mm.

The terminology used to describe the structure of a
Douglas-fir annual shoot varies. Jensen and Long (1983)
described an annual shoot as follows: 'each shoot carries
a terminal bud and a set of lateral buds from which next
year's growth will emerge. Several (0–5) of these lateral
buds occur in a tight whorl directly below the terminal
bud, these buds will be referred to as "nodals". The re-
mainder of the lateral buds are scattered along the
length of the shoot, generally more than 15 mm from
the terminal bud'. Jensen and Long (1983) referred to
these as "non-nodals". Maguire et al. (1994) use the
terms 'whorl (nodal) and interwhorl (internodal) primary
branches', and noted that whorl branches grew more rap-
idly than interwhorl branches on young plantation-grown
Douglas-fir located west of the Cascade crest in Oregon
and Washington, USA. In the current study, the word
'cluster' has been used in preference to 'whorl'.

As the largest branch on a log has the greatest influ-
ence on log grade (Weiskittel et al. 2006), a modelling
approach that predicts how branch diameter varies with
height in the stem is considered more appropriate than
a model that predicts branch index for a log. Models
have been developed to predict how Douglas-fir branch
diameter varies with depth into the tree crown (Maguire
et al. 1994, 1999; Roeh and Maguire 1997; Ishii et al.
2000; Weiskittel et al. 2007a; Hein et al. 2008a, b) for
some environments and silvicultural regimes in other
countries, but it was considered important to develop
models that are specific to New Zealand conditions (i.e.,
site and silvicultural regimes).

Decisions made during model development will affect
the model's 'domain of applicability'. Three such deci-
sions are: (1) which trees to sample; (2) which branches
to model; and (3) what section of the tree crown or stem
to consider. Tree selection criteria have included selec-
tion of trees across the DBH distribution (Maguire et al.
1994); selection of dominant and co-dominant trees
(Hein et al. 2008a; Newton et al. 2012); and avoidance of

trees with visible damage (Roeh and Maguire 1997; Hein
et al. 2008a; Newton et al. 2012). In terms of branches
modelled, nodal branches have been identified and mod-
elled (Maguire et al. 1994, 1999; Roeh and Maguire
1997; Weiskittel et al. 2007a; Hein et al. 2008a, b), whilst
Ishii et al. (2000) selected a set of maximum branches
from all live and dead branches. The definition of
'crown' varies. For example, Ishii et al. (2000) defined
crown depth as tree height minus lowest branch height.
Weiskittel et al. (2007a) defined crown base as the tree
height to the lowest live branch; whereas Maguire et al.
(1999) did not give a precise definition for crown base.
Regardless of sampling decisions, most of the models
predict that branch diameter increases from the tip of
the tree to a maximum value and then decreases again.

The objective of this study was to develop site-specific
models to predict how branch diameter varies with dis-
tance from the tip of the tree. The models developed
were then used to evaluate the influence of initial and
post-thinning stand density on branch diameter in un-
pruned Douglas-fir at two sites in New Zealand, one in
the North Island and one in the South Island. Site-
specific models were developed as there was no reason
to expect that branch diameters would be similar for
two different sites. Furthermore, an individual tree-level
model was developed rather than a stand-level model
because branch diameters on an individual log are im-
portant for determining log grade.

Methods

Site location
The two sites selected for this study were the earliest de-
signed Douglas-fir experiments established to examine the
effects of different silviculture treatments on growth and
yield. The experiments are located in Kaingaroa forest,
North Island and Ribbonwood Station, South Island. Here-
after they are referred to as Kaingaroa and Ribbonwood.
Environmental conditions for the two sites are given in
Table 1. The Kaingaroa experiment was 10.92 ha within a
116 ha block planted in 1982 at 1666 stems ha^{−1}. The Rib-
bonwood experiment, planted in 1983, consisted of four
blocks, each of about 2.5 ha and at different initial stand
densities, namely: 833, 1250, 1333 and 2000 stems ha^{−1}.

Overall experimental design
The primary aim of these experiments was to evaluate
the effects of final prune height, pruning severity at each
lift, and the number of followers[1] on the growth of
Douglas-fir. The silvicultural treatments applied reflected
the intensive level of silviculture that was considered ap-
propriate at that time for producing high quality sawlogs
(James 1990). Unpruned treatments were also included.

Thinning to different stand densities occurred in 1993
when the Kaingaroa stand was 10.9 years old[2], the

Table 1 Site and silvicultural details for the unpruned treatments at Kaingaroa Forest and Ribbonwood Station

	Kaingaroa forest	Ribbonwood station
Latitude	38.5 °S	44.4 °S
Longitude	176.6 °E	169.8 °E
Elevation (m)	450	650
Aspect	NW	Between NE and SE
Slope	3°	5° to 17° average 10°
Mean daily temperature (°C)	11.2	6.8
Annual rainfall (mm)	1255	824
Daily mean windspeed (m s^{-1})	2.2	4.3
Year trial planted	1982	1983
Seedlot	NN 79/6	CY/C/79/11
Stand age (years) when the only thinning occurred	10.9	10.1
Size of PSPs	0.2142 ha in total with measurements confined to inner 0.08 ha	0.147 ha in total with measurements confined to inner 0.08 ha
Number of PSPs from which sample trees were selected	6	15
Site index (mean top height at age 40 years) (m) for selected PSPs	39.0	30.8
	Range: 38.1 – 40.7	Range: 30.0 – 40.7

Mean daily temperature, annual rainfall, and daily mean windspeed data are from National Institute of Water and Atmospheric Sciences Ltd. (NIWA) (2012)

Ribbonwood stand was 10.1 years old, and when the base of the green crown was still close to ground level at both sites.

At the same time, Permanent Sample Plots (PSPs) (Hayes and Anderson 2007) were established in each treatment to monitor tree growth in response to the different silvicultural treatments. Their size is given in Table 1.

All PSPs have been measured 14 times between 1993 and 2012 inclusive. At each measurement, tree diameter at 1.4 m (DBH) was measured on all trees. Total height and green crown height were measured for selected trees. Green crown height is defined as the point midway between the lowest green branch and the lowest whorl where the majority of branches are green and is used to represent the base of the green crown. The data collected at each measurement were entered in the PSP database (Hayes and Andersen 2007). Within the database system, the data were analysed to estimate mean top height (the average height of the 100 largest DBH stems ha^{-1}); mean height (the height of the tree with mean DBH) and the height of individual trees. Mean crown height, which is the average green crown height for the trees measured, was also calculated. However, branch diameter is not a routine PSP measurement so a sampling scheme for branch diameter measurements needed to be developed as described later.

Selection of sample PSPs

This study examined branch diameter only in unpruned PSPs since pruning of Douglas-fir in New Zealand is now considered uneconomic.

At Kaingaroa, there were twelve unpruned PSPs, four (two in each of two replicates) at each of the post-thinning stand densities of either 250, 500, or 750 stems ha^{-1}. Six were selected for study as detailed below.

At Ribbonwood, there were four unpruned treatments for each of the initial stand densities[3], an unthinned control and three thinned treatments. There was one PSP for each of the nominal post-thinning stand densities of either 250, 500 or 750 stems ha^{-1}. For the unthinned control treatment, there were four PSPs at an initial stand density of 833 stems ha^{-1}, and five PSPs when the initial stand density was either 1333 or 2000 stems ha^{-1}. This gave a total of 23 PSPs of which 15 were selected for study as detailed below.

Where there was more than one unpruned PSP per treatment, sample trees were selected from each of two PSPs. The two PSPs selected were ones where the stand density remained close to the prescribed initial or post-thinning stand density. This approach was used to minimise variation from the prescribed treatment. At Kaingaroa, an additional selection criterion was that one PSP was selected from each replicate. At Ribbonwood, where the experiment is on a hillside, an additional selection criterion was that one

PSP was near the top and one PSP was near the bottom of the slope. Selected PSP summary data considered relevant for interpreting the branch diameter data are given for Kaingaroa in Table 2, and for Ribbonwood in Table 3 and Fig. 1.

Selection of sample trees

Twelve sample trees were selected from each treatment using the historical PSP data. All 12 trees came from a single PSP when there was only one that was unpruned. Where there was more than one unpruned PSP, six sample trees were selected from each of two PSPs (see above).

Douglas-fir has a higher incidence of stem malformation in New Zealand compared with some other countries (Ledgard et al. 2005), and large branches are often associated with stem malformation. Therefore, the decision was made to avoid trees with obvious malformations because the underlying branching pattern has been disrupted by the malformation, and consequently were not considered representative of 'normal growth'.

The following approach was then used to select trees that consistently had a small, medium or large DBH. At each re-measurement of a PSP, the minimum, mean and maximum DBH were calculated. Two boundaries were then calculated using Equations 1 and 2.

$$B_{low} = DBH_{min} + (DBH_{mean} - DBH_{min}) \times 2.0/3.0 \tag{1}$$

$$B_{high} = DBH_{max} - (DBH_{max} - DBH_{mean}) \times 2.0/3.0 \tag{2}$$

The ith tree was assumed to have a small DBH at a given stand age (re-measurement) if:

$$DBH_{min} \leq DBH_i < B_{low} \tag{3}$$

a medium DBH at a given stand age if:

$$B_{low} \leq DBH_i \leq B_{high} \tag{4}$$

or a large DBH at a given stand age if:

$$B_{high} < DBH_i \leq DBH_{max} \tag{5}$$

Where

DBH_{min} is the minimum DBH for the PSP at a given stand age

DBH_{mean} is the mean DBH for the PSP at a given stand age

DBH_{max} is the maximum DBH for the PSP at a given stand age

B_{high} and B_{low} are the two boundaries at a given stand age

Sample trees were then selected based on the following three criteria:

1. all, or if not possible, the majority of DBH measurements for a given tree fell into the same DBH class;
2. trees that had recorded stem malformation (i.e., been assigned a stem description code[4]) were avoided; and
3. sample trees were selected using a random number generator if there were more than the required number of sample trees in a DBH class.

Branch measurement

As these are long-term experiments, it was not feasible to fell trees to measure branch diameter. Branching data were collected using TreeD, a photogrammetrically based imaging methodology for capturing tree and branch dimensions from high-resolution digital images of standing trees (Brownlie et al. 2007). This methodology was selected because it provides a permanent record of the tree for future reference, and additionally avoids the health and safety risks associated with tree climbing. Data were collected in January to February 2013 when the Kaingaroa stand was 30.7-30.8 years old and the Ribbonwood stand was 29.7-29.8 years old.

Each pre-selected sample tree was located in the field and examined to determine the optimal direction to get the clearest view of the stem and branches. Generally
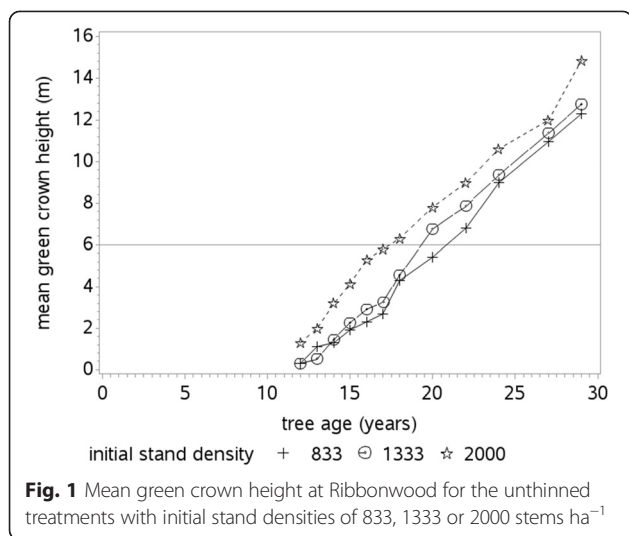
Table 2 Height, crown height and DBH data for the selected PSPs at Kaingaroa Forest

Nominal initial stand density (stems ha^{-1})	Nominal post-thinning stand density (stems ha^{-1})	Actual post-thinning stand density (stems ha^{-1})	Actual stand density (stems ha^{-1}) at age 29 years	Mean green crown height (m) at time of thinning (10.9 years)	Mean tree height (m) at time of thinning (10.9 years)	Mean green crown height (m) at age 29 years	Mean tree height (m) at age 29 years	Mean DBH (cm) at age 29 years
1666	250	250	250	0.8	10.2	10.6	26.9	46.4
1666	250	250	250	1.6	10.1	7.9	26.6	43.9
1666	500	500	500	1.2	9.9	14.6	25.2	38.3
1666	500	500	500	1.7	10.1	15.8	27.0	35.3
1666	750	738	725	1.3	10.2	14.1	28.2	30.4
1666	750	750	750	1.4	9.8	14.4	26.6	32.2

Table 3 Height, crown height, and DBH data for the selected PSPs at Ribbonwood Station

Nominal initial stand density (stems ha^{-1})	Nominal post-thinning stand density (stems ha^{-1})	Actual post-thinning stand density (stems ha^{-1})	Actual stand density (stems ha^{-1}) at age 29 years	Mean green crown height (m) at 12 years	Mean tree height (m) at time of thinning (10.1 years)	Mean green crown height (m) at age 29 years	Mean tree height (m) at age 29 years	Mean DBH (cm) at age 29 years
833	250	250	250	0.1	7.3	8.4	25.2	51.4
1333	250	250	250	0.1	7.0	6.8	24.7	46.9
2000	250	250	250	0.1	8.3	8.3	25.4	47.7
833	500	500	500	0.1	6.7	10.5	24.5	41.4
1333	500	500	500	0.1	7.3	11.6	24.9	42.5
2000	500	500	500	0.1	7.5	12.0	24.8	38.9
833	750	738	738	0.4	7.0	12.6	22.8	34.1
1333	750	750	750	0.2	8.3	12.2	24.1	34.8
2000	750	750	750	0.1	8.2	14.0	24.8	35.8
833	-	788	750	0.2	6.7	12.2	24.4	35.9
833	-	813	775	0.4	6.9	12.4	22.9	33.7
1333	-	1113	1025	0.2	6.5	12.7	23.5	30.8
1333	-	1263	1038	0.4	6.5	12.8	23.1	28.5
2000	-	1838	1688	1.4	7.4	15.5	23.0	26.4
2000	-	1950	1800	1.2	7.1	14.2	22.1	25.3

The earliest green crown measurements in this experiment were at 12 years

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Fig. 1 Mean green crown height at Ribbonwood for the unthinned treatments with initial stand densities of 833, 1333 or 2000 stems ha^{-1}

the crowns were symmetrical but in some instances crown asymmetry was apparent; for example due to sloping ground and/or gaps in the canopy. In these cases, the camera position was selected to ensure that the stem and the larger branches were clearly visible in the image. Dead branches were pruned to enable a scaling pole to hang vertically close to the stem. From the chosen sample point, two images of the stem were taken with approximately 1 m separation. The 1 m separation enables the tree image to be viewed in stereo. The horizontal distance from the camera position to the stem was measured and the lean of the stem, if any, towards or away from camera was measured (see Brownlie et al. 2007 for further details on TreeD methodology). Four variables were extracted from the images: height to base and to top of a branch cluster; diameter of the largest visible branch in the cluster; and stem diameter below the branch cluster. Whilst all branches are not visible in the image, the likelihood of a large branch being missed is minimised through the selection of an appropriate camera position.

The data extracted from the images were screened to determine if there were any 'extra-large' branches. For each tree the ratio of maximum branch diameter measured to the mean of measured branch diameters was calculated. For those trees where the ratio was greater than two, the images were re-examined to determine whether the branch with the maximum diameter was part of the regular branching pattern or whether it might have grown in response to stem damage such as a broken top. Trees considered to have stem damage were excluded from further analysis as such trees were not considered representative of 'normal growth'.

Model development

Selected PSP and TreeD data were combined to form the dataset used to develop site-specific models. Decisions were made as to which branches to include, which section of stem to include and the mathematical equations to consider.

Tree data (from PSP system)

Tree diameter, total height and green crown height were measured during routine monitoring of the overall experiments when the trees were aged 29 years. These data were retrieved from the PSP system.

Branch diameter data (from TreeD)

As it is the larger branches that will influence log quality, it was considered appropriate to develop a model that would predict the diameter of the larger branches, rather than the average branch diameter.

Initially a subset of TreeD images were examined to determine whether or not it would be feasible to identify nodal branches (larger branches), but it was concluded that any such classification would be unreliable.

To select larger branches, the stem of each tree was divided into zones of equal length based on the estimated individual tree height at age 29 years as calculated within the PSP system. Twenty zones were selected. This was a compromise between having sufficient data points for model development and minimising the likelihood of a zone not containing a nodal cluster as measured annual height data were not available for each tree. The largest branch diameter in each zone was determined. The height assigned to the branch diameter was the height of the branch or the mean height of the branches if there were two or more branches with the same diameter.

The TreeD data were collected up to 2 years later than the PSP data (see previous section) but this timing difference was considered acceptable on the basis that minimal branch diameter growth on the section of stem measured would have occurred during the intervening period. For the PSPs with post-thinning stand densities of 500 and 750 stems ha^{-1}, the majority of the measured branches were below the mean green crown height (Fig. 2), so branch diameter growth would have been negligible. For the PSPs with a post-thinning stand density of 250 stems ha^{-1}, approximately half the branches measured were above the mean green crown height (Fig. 2). Comparing the maximum height to which branches were measured using TreeD with the PSP mean height data, it was estimated that the branches measured would be 11 years of age or older, and would occur in the lower half of the green crown. The diameters of branches used for model development (Fig. 2) were generally over 40 mm. By examining figures in Weiskittel et al. (2007b), it was estimated that annual branch diameter increment was likely to have been about 1 mm per year, well within the accuracy of TreeD measurements (Brownlie et al. 2007).
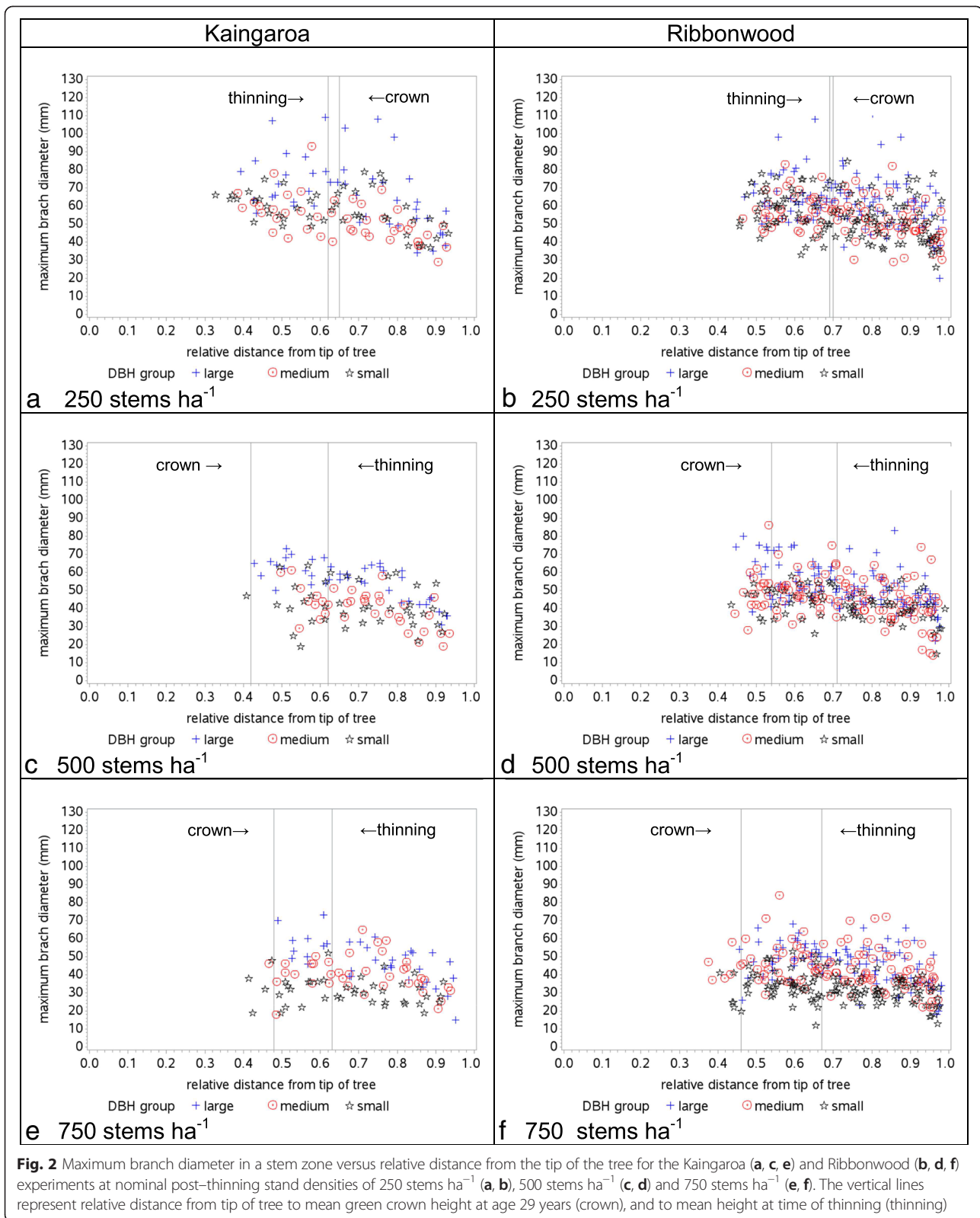
Fig. 2 Maximum branch diameter in a stem zone versus relative distance from the tip of the tree for the Kaingaroa (**a**, **c**, **e**) and Ribbonwood (**b**, **d**, **f**) experiments at nominal post–thinning stand densities of 250 stems ha^{-1} (**a**, **b**), 500 stems ha^{-1} (**c**, **d**) and 750 stems ha^{-1} (**e**, **f**). The vertical lines represent relative distance from tip of tree to mean green crown height at age 29 years (crown), and to mean height at time of thinning (thinning)

Stem section to be included in model

Two options were considered. One option was to predict branch diameter as a function of height above ground. A model developed on this basis is open to extrapolation beyond the range of heights measured. The second option was to assume branch diameter was zero at the tip

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Table 4 Model fit statistics from fitting variants of Equation 7 to the Kaingaroa dataset

Model fitted	Mean residual (mm)	Standard deviation	Range of residuals (mm)	Error mean square
1. Equation 7: individual trees	−0.050	8.49	−31.0 to 24.6	
2. Equation 7, 8, and 9: all trees	−0.040	10.61	−26.8 to 40.0	113.5
3. Equation 7 and 8: all trees	−0.025	10.63	−27.0 to 37.6	113.7

There were 364 individual observations in the dataset

of the tree and predict branch diameter as a function of relative distance from the tip of the tree using a curvilinear equation that would predict a maximum branch diameter at some point along the stem as observed in other studies (Maguire et al. 1994, 1999; Roeh and Maguire 1997; Ishii et al. 2000; Weiskittel et al. 2007a; Hein et al. 2008a, b).

Even though there were few measurements from the upper third of the stem, the second option was preferred because relative height is constrained to be between 0 and 1.

The model profile was developed for the whole stem length because dead branches below the base of the green crown also influence log and timber value.

Model selection

Model selection was an iterative process with the results from the previous iteration influencing the methodology in the next iteration. Ratkowsky (1990) proposed that models should be as simple as possible. Based on this thinking, nonlinear regression functions were examined to determine an equation that would: enable branch diameter to be predicted as a function of relative distance from the tip of the tree; provide a good fit to the data; and be logical from a biological perspective.

For the first iteration, the same methodology was applied to both sites. Functions were fitted to the data for each tree individually, and the relationship between the predicted coefficients and the independent tree-level variable, 'growing space' (Equation 6) examined.

$$S_{ij} = \sqrt{\frac{10000}{SPH_j} \times \frac{DBH_{ij}}{\overline{DBH_j}}} \qquad (6)$$

Where:

S_{ij} is the 'growing space' for tree i in plot j in m

DBH_{ij} is the current (stand age 29 years) DBH for tree i in plot j in cm

$\overline{DBH_j}$ is the current plot mean DBH (stand age 29 years) for plot j in cm

SPH_j is the current post-thinning stand density (stems ha^{-1}) for plot j

'Growing space' was selected as a 'tree-level' variable to be included in the model, as branch diameter is likely to be larger where there is a canopy gap (Maclaren

2009), suggesting that on average, branch diameter is likely to be related to the 'growing space' available to the tree.

A non-linear function which was appropriate on an individual tree basis for both sites and for which the predicted coefficients c_1 and c_2 were related to 'growing space' was:

$$BD = c_1 \times DIST_R \times e^{(-c_2 \times DIST_R)} \qquad (7)$$

Where:

BD is the branch diameter

$DIST_R$ is the relative distance from the tip of the tree (with zero being the tip of the tree and one being ground level)

c_1 and c_2 are predicted coefficients

Kaingaroa

When Equation 7 (Model 1) was fitted to each tree individually, the overall mean residual was −0.050 mm (Table 4), and 97 % of residuals were in the range ± 2 cm (Table 5). The coefficients, c_1 and c_2, increased linearly with increasing 'growing space'. In the second iteration, Model 2 (Equation 7 with c_1 and c_2, replaced by Equation 8 and 9 respectively) was then fitted to the whole dataset.

$$c_1 = b_1 + b_2 \times S \qquad (8)$$

$$c_2 = b_3 + b_4 \times S \qquad (9)$$

Where

S is the growing space for the tree in m

b_1, b_2, b_3, b_4 are the predicted coefficients

Table 5 Distribution of residuals for models fitted at individual tree level, and selected site-specific model

	Kaingaroa Model 1 (individual trees)	Kaingaroa Model 3
Number of observations	364	364
Percentage of residuals in range −1.0 to 1.0 cm	78 %	68 %
Percentage of residuals in range −2.0 to 2.0 cm	97 %	93 %

Table 6 Predicted model coefficients and approximate standard errors for most appropriate model for Kaingaroa

Coefficient	Kaingaroa – Model 3
b_1	137.9 ± 13.8
b_2	40.47 ± 2.79
c_2	2.24 ± 0.07

When Model 2 was fitted, the mean residual was −0.040 mm (Table 4). As the coefficient, b_4, was not statistically different from zero, Model 3 (Equation 7 with c_1 replaced by Equation 8) was fitted in the third iteration. For Model 3, the mean residual was −0.025 mm (Table 4).

The residuals from fitting Model 3 (Table 4) were not correlated with predicted values, relative distance from the tip of the tree, individual tree 'growing space', or nominal post-thinning stand density. Consequently Model 3 was selected as the site-specific model for Kaingaroa. This model predicted 68 % of branch diameters to ≤ 1 cm, and 93 % of residuals to ≤2 cm (Table 5). The predicted coefficients are shown in Table 6.

Ribbonwood

When Equation 7 was fitted to each tree individually the overall mean residual was −0.019 mm (Table 7), and 98 % of residuals were in the range ± 2 cm (Table 8). The coefficient, c_1, increased linearly with increasing 'growing space', but c_2 was not correlated with 'growing space', nominal initial stand density, nominal post-thinning stand density, or the difference between nominal initial and post-thinning stand densities. For the second iteration, Model 3 (Equation 7 with c_1 replaced by Equation 8) was then fitted to the whole dataset. The residuals from fitting this model were correlated with initial, and nominal change in stand density due to the thinning. For the third iteration Model 4 (Equation 7 with c_1 replaced by Equation 8 and c_2 replaced by Equation 10) was then fitted to the whole dataset.

$$c_2 = a_3 + a_4 \times \left(SPH_{init} - SPH_{fin}\right) \qquad (10)$$

Where:
SPH_{init} is the nominal initial stand density (stems ha^{-1})

SPH_{fin} is the nominal post-thinning stand density (stems ha^{-1}) in the case of thinned PSPs or the stand density at age 29 year for unthinned PSPs (See Table 3) a_3, a_4 are model coefficients.

Using Model 4, the residuals were not correlated with predicted values, relative distance from the tip of the tree, 'growing space', initial stand density, nominal post-thinning stand density or change in stand density as defined above. Consequently, Model 4 was selected as the site-specific model for Ribbonwood. This model predicted 73 % of branch diameters to ≤ 1 cm, and 96 % of residuals to ≤2 cm (Table 8). The predicted coefficients are shown in Table 9.

Results and discussion

The maximum height to which it was practical to measure branch diameter from the TreeD images was 17.7 m at Kaingaroa, and 15.4 m at Ribbonwood. As these heights are less than 20 m, branches are anticipated to have been measured to within ±1 cm (Brownlie et al. 2007). That few branch diameters were measured on the upper third of the stem (Fig. 2) is not considered critical in terms of model development, as most of the stand value comes from the lower part of the stem. For example, when radiata pine is grown for structural timber without pruning, 80 % of the stand value falls within the first 19 m of tree height (New Zealand Forest Owners Association 2013).

None of the sample trees selected at Kaingaroa were excluded from the dataset due to 'extra-large' branches. At Ribbonwood, there were 12 trees that were excluded from the data set as they were considered to have incidences of stem damage. One or two trees were affected in each of nine different treatments. There were two other trees with an 'extra-large' branch, but these were left in the data set as it was not obvious that the branches resulted from stem damage.

There was a large variation in measured branch diameter at a given relative distance from the tip of the tree at a given nominal post-thinning stand density even with trees with obvious stem damage excluded (Fig. 2). While branch diameter tended to be larger for the trees from the large DBH group, and smaller for trees from the small DBH group, there was a degree of overlap between the three DBH groups. Visually, branch diameter was

Table 7 Model fit statistics from fitting variants of Equation 7 to the Ribbonwood dataset

Model fitted	Mean residual	Standard deviation	Range of residuals	Error mean square
1. Equation 7: individual trees	−0.019	7.44	−22.5 to 44.4	
3. Equation 7, and 8: all trees	−0.016	10.26	−32.8 to 76.7	105.3
4. Equation 7, 8 and 10: all trees	−0.013	9.96	−32.4 to 75.5	99.5

Note: there were 1286 data points in the Ribbonwood dataset

Table 8 Distribution of residuals for models fitted at individual tree level, and selected site-specific model

	Ribbonwood Model 1 (individual trees)	Ribbonwood Model 4
Number of observations	1286	1286
Percentage of residuals in range −1.0 to 1.0 cm	83 %	73 %
Percentage of residuals in range −2.0 to 2.0 cm	98 %	96 %

similar for trees with a similar growing space at the two sites (Fig. 3). Of interest is the difference in branch form. At Kaingaroa, branches generally grew upwards, whereas at Ribbonwood branches often curved downwards. The exact reason for this difference is not known but there are several factors that may contribute. These include: different seedlots (Table 1); the fact that more cones are produced at Ribbonwood adding more weight to branches (C. Low, Scion, pers. comm.); and /or that Ribbonwood often receives snow in winter, whereas snow is a rare event in Kaingaroa. The site-specific models also indicated that branch diameters are similar at the two sites (compare Fig. 4a with Fig. 4b), but with slightly larger branch diameters at the base of the stem at Ribbonwood.

At Kaingaroa, all PSPs were planted at the same initial stand density and the only thinning occurred when the green crown height was still close to ground level (Table 2). Therefore, current 'growing space' was sufficient to explain the difference in branch diameter profile between individual trees. The predicted branch diameter profile for a tree of average DBH at various stand densities using Model 3 (Table 6) are shown in Fig. 4a. The profile for a stand density of 1666 stems ha^{-1} represents an unthinned stand. The fact that the predicted branch diameter profile for a tree of average DBH in a stand decreases with increasing post-thinning stand density (i.e., 250 >, 500 > 750 stems ha^{-1}) (Fig. 4a) and are all higher than that for the initial stand density of 1666 stems ha^{-1} indicates that branches at the base of the tree have been influenced by the severity of the thinning. This result is logical given that the green crown height was close to ground level (Table 2) when the thinning occurred.

Table 9 Predicted model coefficients and approximate standard errors for most appropriate model for Ribbonwood

Coefficient	Ribbonwood – Model 4
b_1	67.96 ± 6.23
b_2	45.38 ± 1.87
a_3	1.85 ± 0.04
a_4	0.00015 ± 0.00002

Fig. 3 TreeD image for two trees with a similar 'growing space'. Left image, tree from Kaingaroa with a 'growing space' of 4.4 m. Right image, tree from Ribbonwood with a 'growing space' of 4.5 m

At Ribbonwood, where PSPs were planted at a range of initial stand densities, current 'growing space' was not sufficient to explain the difference in branch diameter profile between individual trees. It was necessary to include an additional term in the model to account for the difference between initial and current stand density. The predicted branch diameter profile for a tree of average DBH in a stand with an initial density of 1666 stems ha^{-1} and post-thinning stand densities of 250, 500, 750 and 1666 stem ha^{-1} using Model 4 (Table 9) is shown in Fig. 4b. The predicted profiles for a stand at the post-thinning stand densities of 250, 500 and 750 stems ha^{-1} are higher than the profile for an unthinned stand at 1666 stems ha^{-1}, which indicates that branches at the base of the tree have been influenced by the severity of the thinning. This result is logical given that the green crown height was close to ground level at the time of thinning (Table 3). Even though the green crown height was close to ground level at the time of thinning, initial stand density has influenced the branch diameter profile in the lower two-thirds of the stem (Fig. 5a-c), but not in the upper part of the stem. The upper part of the crown would have been formed at the post-thinning stand
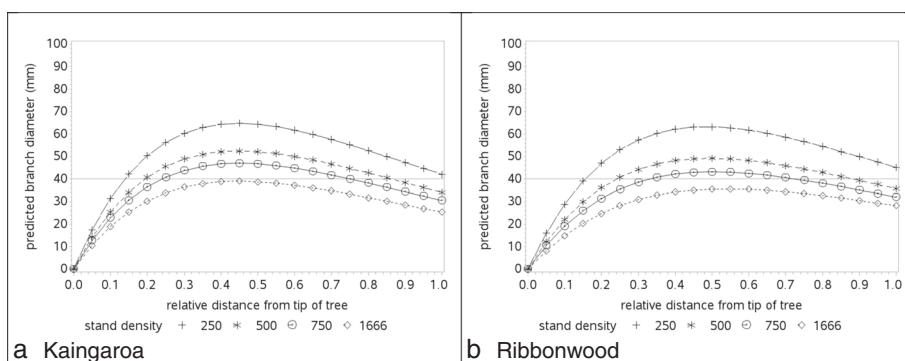
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Fig. 4 The predicted crown profile for a tree of average DBH in a stand at Kaingaroa (**a**) where the initial stand density was 1666 stems ha^{-1} and the stand density after any thinning was 250, 500, 750 or 1666 stems ha^{-1}. For Ribbonwood (**b**), an initial stand density was 1666 stems ha^{-1} was used for comparative purposes and the stand density after any thinning was 250, 500, 750 or 1666 stems ha^{-1}

density, but considering the position of mean tree height at the time of thinning (Fig. 2b, d, f), it appears that the initial stand density may have had an impact on branch diameter development for branches formed after thinning.

For a tree of average DBH, some branches are predicted to be larger than the 40 mm maximum suggested by Ledgard et al. (2005) at all three post-thinning stand densities, namely 250, 500 and 750 stems ha^{-1} at both Kaingaroa (Fig. 4a) and Ribbonwood (Fig. 5a-c). Larger branch diameters were predicted at lower post-thinning stand densities. This suggests that post-thinning stand density of at least 750 stems ha^{-1} would be desirable to reduce the occurrence of branches with a diameter larger than 40 mm.

The predicted branch profiles, at a stand age of 29 years, for a tree of average DBH in unthinned stands with different initial stand densities (Fig. 5d) indicate that an initial stand density of at least 1333 stems ha^{-1} would be necessary to ensure branches in the lower stem are below 40 mm.

If carrying out a single thinning operation, a method for controlling branch diameter in the lower stem would
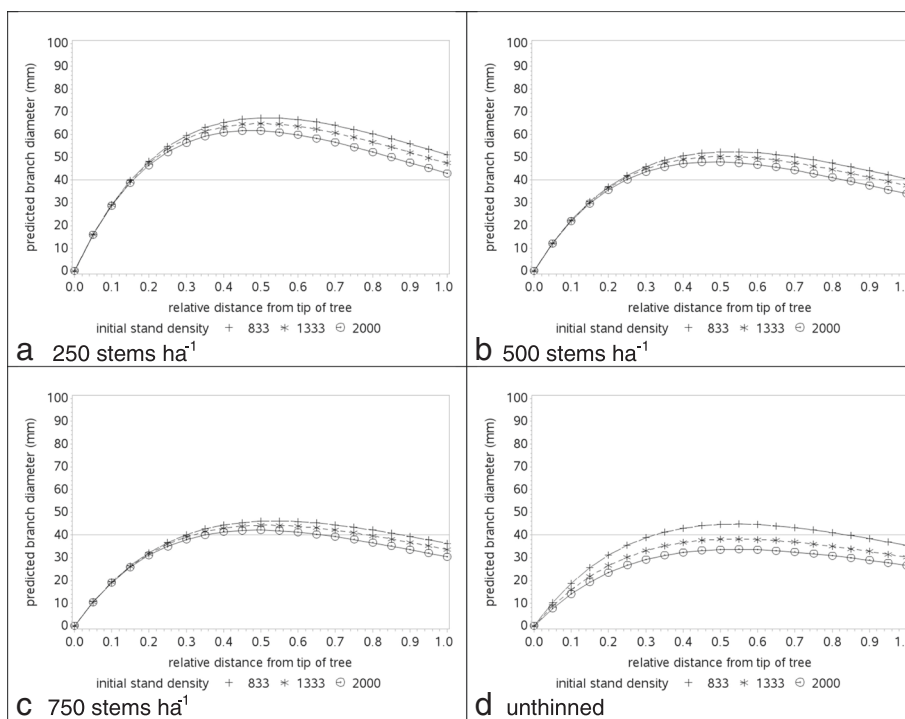

Fig. 5 The predicted crown profiles for a tree of average DBH in a Ribbonwood stand with an initial stand density of 833, 1333 or 2000 stems ha^{-1} and a nominal post-thinning stand density of 250 stems ha^{-1} (**a**), 500 stems ha^{-1} (**b**), 750 stems ha^{-1} (**c**) and unthinned (**d**)

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be to delay the operation to an age where branches in the lower crown would be unlikely to take advantage of the increase in 'growing space'. For the unthinned treatments at Ribbonwood, the variation in green crown height with age depends on the initial stand density (Fig. 1). If the lowest log was cut from between stump height and 6 m, then thinning would need to be delayed until a stand age of approximately 17 years, 19 years or 21 years when the initial stand density was 2000, 1333, or 833 stems ha^{-1} respectively. This would ensure that the green crown height was at the top of the log at the time of thinning (Fig. 1).

Neither the timing nor severity of thinning should be based on predictions of branch diameter alone. Deciding on such variables will need to be a compromise between tree growth and branch growth as well as minimising the risk of wind damage since stem damage leads to larger than expected branches. A different approach to that taken in this study would be appropriate if one wished to predict stand value and/or create links to sawing simulators.

Conclusions
The TreeD methodology proved useful for collecting branch diameter data. The data collected from two different sites in New Zealand indicate that both initial and post-thinning stand density influence branch diameter for Douglas-fir. Branch diameters at the base of the tree were affected by the thinning, which occurred between 10 and 11 years of age. At post-thinning stand densities of less than or equal to 750 stems ha^{-1}, some branches on a tree of average DBH will be greater than 40 mm.

Endnotes
[1]A follower is a tree that is not pruned as severely as the 'crop' trees and is usually removed prior to stand maturity.

[2]In New Zealand forestry, a stand age of zero is assigned at the time of planting.

[3]For this study, the block at 1250 stems ha^{-1} was ignored as 1250 stems ha^{-1} is similar to 1333 stems ha^{-1}.

[4]Tree features such as a broken top may be noted using a stem description code.

Authors' contributions
SK initiated the study, selected the experiments to use and reviewed the paper. RB collected and analysed the TreeD images and reviewed the paper. JG selected the sample trees, analysed the data and wrote the paper. All authors read and approved the final manuscript.

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