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Relationships between leaf area, growth, tree health attributes, and LiDAR

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Client Report No. 12713

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EXECUTIVE SUMMARY

Objective
The objectives of this report were to assess the usefulness of crown transparency and needle retention as indicators of leaf area and growth; and to test whether these crown attributes can be assessed remotely using LiDAR, and to relate these attributes with measures of productivity.

Key Results
Crown health attributes were assessed in 9-year-old stands in Puruki Forest, where leaf area and tree growth were directly measured, and crown transparency, and needle retention assessed by experienced observers. At Puruki, crown transparency and needle retention (NR) were strongly correlated with each other, with NR explaining 65% of the variation in total crown transparency and 68% of the variation in upper crown transparency. Crown transparency also depended to some extent on the number of branch cluster per m of stem length.

The three methods used to estimate LAI in 9-year-old radiata pine plots at Puruki all performed well. Two LiDAR metrics, p50fp and %veg were jointly outstanding as estimators of LAI, explaining 95% of the variation. In addition, NR and upper crown transparency explained 85% and 79%, respectively, of the variation in LAI, provided that stocking was concurrently taken into account.

Relationships between the four crown variables LAI, Upper crown transparency, NR, and LiDAR with tree volume were all remarkably strong, considering that the crown variables were the result of one-off assessments. While the results from Puruki Forest clearly demonstrate that growth depends on LAI, and other attributes that influence leaf area, evidence for tree health effects on growth were less clear in the Nelson/Marlborough pilot study. Nationally, stem volume depends on tree age, silviculture, site fertility, and climate, so unless these factors are adequately taken into account, they can be expected to obscure relationships between health attributes and stem volume.

Application of Results
Crown transparency and NR influence tree growth, primarily through their effect on leaf area, or crown health. Two LiDAR metrics (p50fp and %veg) were also responsive to spatial variation in leaf area, crown transparency, and NR. However, the LiDAR height metric is also related to tree height, through its sensitivity to the height that the leaf area is displayed.

Further Work
LiDAR points will penetrate deeper into the crown, and the point cloud mean height will therefore be lower down, in unhealthy stands compared with healthy stands. The effect of changes in tree health scores over time on LiDAR relationships with stem volume therefore remains uncertain, and warrants further research, if there is interest in predicting stem volume and growth rate from LiDAR information.

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Information for Scion abstracting:

Contract number	MS 2
Client Report No.	12713
Products investigated	LiDAR
Wood species worked on	Pinus radiata
Other materials used	
Location	Puruki, Nelson and Marlborough

INTRODUCTION

Forest condition monitoring provides a basis for assessing whether there are changes in tree health and by implication growth rate over time. Annual stem volume increment and dry matter production per ha are determined by the leaf area index (Beets and Whitehead 1996). Stands with a high leaf area index will accumulate more biomass and total volume per ha than stands with a low leaf area, other things being equal. However, stands differ in age, silviculture, and site productivity. The effect of stand age and silviculture on stem total volume can largely be predicted using models. However, less predictable factors influence site productivity, which is determined by climate, topography, soil fertility, and various weather related events that influence survival, growth, and tree health.

A number of crown attributes are being considered to assess forest condition in New Zealand using a network of Forest Condition Monitoring plots (Bulman 2008). Of these attributes, crown transparency, which can be envisaged as a visual assessment of the leaf area, is considered to be the most important and is used to estimate forest health condition (ICP 2007). Leaf area can be low, and the crowns therefore appear thin (high transparency) for a number of reasons. For example, needle shedding owing to fungal diseases can result in fewer needle age classes being retained, or alternatively the tree may be deficient in one or more nutrients. While still healthy, uninodal trees with few branch cluster present per unit of stem length, have a lower leaf area than multimodal trees, and will therefore have a more transparent appearance. A crown transparency score integrates all these effects, regardless of cause.

Other attributes can be assessed in order to tease out which factors are influencing leaf area. For example, off-colour foliage, when coupled with its location, appearance, and retention in the crown, signify specific conditions (eg nitrogen deficiency, magnesium deficiency (UMCY), Dothistroma needle blight, Cyclaneusma needle-cast). While these other attributes are very useful, visual symptoms vary depending on the season of the year, and crown assessments of specific disorders are therefore unlikely to be optimal for identifying all factors that influence crown health.

Another attribute that can be assessed is needle retention (NR). This is a count of the number of needle age classes retained within the lower crown, where there is the potential for at least three needle age classes to be present. It is well known that Cyclaneusma results in the casting of needles. Typically the older needle age classes are most affected, so NR is low in the centre of the crown. Defoliation can be so severe that in some cases all needle age classes from the centre to the perimeter of the crown are cast, and only buds may still be live. Genetic differences in susceptibility to Cyclaneusma needle-cast are large, so NR scores can vary markedly between neighbouring trees. A different pattern occurs for Dothistroma needle blight. Needles are not cast, but become blighted with red bands and die while still attached to the twig. Neighbouring trees are often similarly affected, which is characteristic of infection by Dothistroma, even though trees vary in susceptibility. Needle retention in the upper crown is also used to score magnesium deficiency in large trees (often called UMCY) because magnesium deficiency symptoms (yellow-tipped needles that give a hallow appearance to the shoot, with affected shoots located symmetrically in the upper crown) are hard to assess from the ground in large trees. Needle retention and transparency scores provide useful health information at any time of the year.

Recently, it has been shown that leaf area is related to LiDAR metrics, although this technology is at a relatively early stage in its development. Suitably dense LiDAR data, when graphed in three dimensions, have the appearance of clouds of points that define individual tree crowns within a stand. Leaf area, needle retention, and LiDAR data were acquired in plots located at Puruki forest for LUCAS (New Zealand Land Use and Carbon Analysis System) to better understand LiDAR data. To make use of the Puruki data, crown transparency and needle retention assessments were undertaken in the plots at Puruki during part of milestone 1 of this Forest Condition

Monitoring study

The objectives of this report are to:

1. Examine the usefulness of crown transparency and needle retention in relation to leaf area and growth rate; and

2. Test the potential to assess these attributes remotely using LiDAR.

MATERIALS AND METHODS

Definitions

Crown transparency

This index of foliage projected area is based on a transparency (Transp) score of individual tree crowns relative to standard photographs. It was obtained by viewing a tree crown from an oblique angle, and allocating a score relative to reference photos. Separate assessments were made for the upper half of the crown, and for the entire crown to account for suppression effects in the lower part of the crown. Crowns are expected to have low transparency (indicating low needle loss) if the foliage is dense and largely obscures the stem, and medium to high transparency (and therefore needle loss) if the crown is thin (Fig. 1).

Fig 1 – Low transparency tree with dense foliage that obscures the stem compared with a medium to high transparency tree with a relatively thin crown.

Needle retention

Needle retention is a count of number of needle age classes evident in the lower third of the green crown. Needle retention is expected to be 3 or more years in healthy radiata pin7e trees. Where needle retention is less than 3 years, premature needle loss is likely to have occurred. Note that the crown length (specifically, the number of years of height growth from top to crown base) determines the maximum needle age class count that is possible.

Proportion of crown affected

The proportion (projected area) of coloured foliage to total foliage (crown viewed obliquely) provides an estimate of disease severity. Foliage infected with Dothistroma is red/brown, peaking in September, while foliage infected with Cyclaneusma is yellow, visible in September/October. Both needle diseases are easy to diagnose during appropriate times of the year and do not require specialist knowledge, once observers are trained.

Leaf area index

The total leaf area of trees in a plot is normal expressed on a plot horizontal surface area basis, and it is then referred to as the leaf area index, LAI. An LAI of 10, for example, indicates that there are 10ha of needle surface area per ha of ground surface area.

LiDAR

Light **D**etection **A**nd **R**anging refers to an active laser-scanning technology that allows accurate 3-D measurement of forest vegetation and the ground surface based on laser pulse return times.

P50fp

P50fp is one of many LiDAR height metrics. It refers to the height above ground corresponding with the 50^{th} percentile of the point cloud above a base height, which was set at 0.5m in this study.

%veg

%veg is the percentage of first returns above a base height – it is an estimate of canopy cover.

Puruki Trials

This forest is located at the southern end of the Paeroa Range mid-way between Rotorua and Taupo, where a pasture site was converted to radiata pine in 1973 (Beets and Brownlie 1987), and the forest subsequently harvested and replanted with radiata pine in 1997, at which time a number of trials were established there (Beets et al., 2003). The terrain is moderately steep to steep, with elevation ranging from 530 – 650.m, and pumice soil originating from the Taupo eruption centre (Beets and Brownlie 1987). Crown health and tree growth were assessed in three trials established in Puruki Forest (Beets et al. 2004).

Trial FR443/5 is comprised of 20 plots planted with four seedlots (GF0, GF7, GF30, High Wood Density), with each plot containing seedling origin material from a single seedlot. Plots were installed on either high or low radiation sites at two elevations in a randomised block design with six replicate plots per seedlot (except GF0, with material available for only 2 plots, which were installed on low radiation aspects). The plots were nominally 30 x 30 m square, although some plots were rectangular in shape to ensure all trees in the plot were on planted on a similar aspect face. Crop trees (approx. 380 trees/ha) were pruned to a nominal height of 6 m, with followers still present.

Trial FR443/1 is comprised of six 50 x 50 m plots each established with fascicle cuttings developed from seed collected from two GF7 stands at Nelson and Puruki (both 1st rotation), and were established as one contiguous block. The plots were stocked at approximately 1600 trees/ha, and subsequently thinned to approximately 1000 trees/ha, after which all trees were pruned to a nominal height of 6 m.

Trial FR443/2 is comprised of ten 50 x 50 m plots, with each plot containing a mixture of GF30 and GF7 material, planted in alternating rows, at a stocking of 600 trees/ha. Crop trees (approx. 380 trees/ha) were pruned to a nominal height of 6 m, with followers still present.

The location of each plot at Puruki was accurately known, which ensured the LiDAR metrics applied to the plot trees.

Puruki trial data available for analysis

The three trials were assessed in August 2006, when diameter at breast height (DBH) of all plot trees, and tree total height, green crown height, prune height, and NR of all height trees were measured. For trials FR443/5 and FR443/2, nominally every 3rd tree in the plot, while in

FR443/1 one tree per row (23 trees/plot) was selected as a height tree. The number of branch clusters (or whorls) within the live crown of height trees was also counted. Concurrently, LiDAR data was acquired for 36 plots (all three trials), and leaf area index was measured in 10 plots in trial FR443/5. Plots with leaf area measurement were purposefully selected to cover a wide range in canopy thinness.

To test LiDAR relationships with LAI, trees selected for biomass and leaf area measurement needed to be representative, in terms of crown transparency, of all the trees in the plot. Sample trees were therefore selected on a stratified random basis, taking into account NR and whorl count/m of crown length, both of which determine crown transparency. After the LiDAR data were acquired (16th and 17th August 2006) sample trees were felled from 21st August - 8th September 2006, and leaf area measured by 2 m height zone. Leaf area was determined following methods given in Beets and Lane (1987), and LAI calculated by height zone for each plot using the basal area ratio method (Madgwick 1981). Relationships between LiDAR, LAI, and tree growth were intended to focus on the upper part of the canopy, to avoid possible confounding with understory vegetation. Therefore, cumulative leaf area index was calculated, starting at the top of the crown down to a specified height above ground. For example TOPD_6 is the cumulative LAI from top of canopy down to 6m above ground, and TOPD_8 is cumulative LAI from top of canopy to 8m above ground. The nominal prune height was 6 m, so for TOPD_6, TOPD_8 the cumulative LAI's are above the maximum prune height. However, cumulative LAI's from TOPD_4 and below were within the partially pruned part of the canopy where understorey shrubs also occurred, and were therefore excluded from this analysis. Mean top height and stem total volume inside bark was estimated for each plot at stand age 9 years.

Forest Condition Monitoring study (MS 1)

Crown transparency and needle retention of height trees assessed in 2006 were reassessed in 2007 (December 2007/ February 2008) for all 20 plots in trial FR443/5. Transparency of the upper 50% of the crown and also of the whole crown were assessed by a single experienced observer, Lindsay Bulman, to allow objective testing of relationships between crown transparency and other attributes. NR assessed predominantly by one experienced observer, Steve Pearce. Plot means of growth, and tree health attributes were calculated for statistical analysis (Table 1).

Statistical analysis

Relationships between various crown health attributes (transparency in upper 50% and total crown, NR) were examined using GLM procedures of SAS (Windows Version 9, SAS Institute Inc., Cary, NC, USA). Relationships between growth, leaf area, and crown health attributes were then explored. For illustrative purposes, the coefficients of the relationships are sometimes given to show the sign and magnitude of the coefficients. Inclusion of these parameters does not imply that the relationships can be generally applied elsewhere.

Table 1. Plot summary data for 9 year old trial (FR443/5) at Puruki Forest. NR and transparency were assessed in Dec 2007/Feb 2008

	Mean	Min.	Max.
MTH (m)	12.9	11.0	16.0
BA (m2/ha)	31.5	20.4	48.9
LAI from tree top to 6m ht	10.4	5.4	18.5
NR (2007/08)	1.4	0.5	2.0
Transp (upper 50%) %	28.0	20.0	38.5
Trees/ha	809	622	977
Brch clusters/m of crown	1.59	1.31	1.79

RESULTS

Puruki trial results

The two transparency scores (upper 50% and total crown) were closely related to each other, but transparency was less in the upper crown where foliage density was consistently higher. Crown total transparency explained 84% of the variation in upper crown transparency:

Transp (upper 50%) = 0.101 + 0.670 x Transp (total crown)

The plot mean NR score based on the 20 FR443/5 plots assessed in 2006 averaged 2.04 age classes per tree, with a mean of 2.2 at high and 1.9 at low radiation sites. The plot mean NR score decreased to an average of 1.36 age classes per tree in 2007/08. NR in 2007/08 was significantly related to NR in 2006. Solar radiation level explained additional variation in the 2007/08 plot means, when the least squares mean NR were 1.6 and 1.1 at high and low radiation sites, respectively, after taking account of the 2006 scores.

Transparency of the total crown in 2007 decreased as NR in 2007 (R2 = 65%) increased, although the relationship was not strong using the 2006 NR scores (R2 = 39%), presumably because the relative health of plots trees changed between years. We expected transparency and NR to be related because trees which do not retain needles have noticeably thinner and therefore more transparent crowns compared with trees that retain older needle age classes. The correlation between transparency and NR in 2007 was slightly stronger using the upper crown transparency scores (R2 = 68%), therefore the upper crown transparency data were of interest in relation to LAI and LiDAR.

It should be noted that, on a plot mean basis, transparency decreased as the number of branch clusters recorded per m of green crown length increased, with the R^2 increasing from 68% (using NR alone) to 80% when both NR and the number of branch clusters/m were included in the analysis. In other words, plots with more branch clusters per m of green crown had significantly lower crown transparencies than plots with more widely spaced branch clusters:

Transp (upper 50%) = 66.76 - 14.15 x Clusters/m – 11.88 x NR in 2007/08

Relationships with LAI

Transparency

The logarithm of leaf area index (TOPD_6) decreased as transparency in the upper crown increased (Prob. > F = 0.0053) and increased as stocking increased (Prob. > F = 0.0129), with an R^2 = 76%. The results obtained using TOPD_8 were similar to when using TOPD_6, with the transparency (Prob. > F = 0.0513) and stocking (Prob. > F = 0.0019) based relationship having an R^2 = 79%. Leaf area was expected to be less in plots where trees have transparent crowns. Stocking was included in the model, because transparency focuses on individual tree crowns, while LAI includes the gaps between tree crowns. The transparency based function based on the 10 plots with leaf area measurements is:

Log (LAI – for TOPD_8) = -0.688 - 0.014 x Transp (upper 50%) + 0.0021 x SPH

NR

The results for NR were similar to those obtained for transparency, although the logarithm of LAI for TOPD_8 was marginally more strongly related to NR in 2007 (Prob. > F = 0.0143) and stocking (Prob. > F = 0.0005), with an R^2 = 85%. This suggests that NR is broadly comparable to crown transparency as an indicator of leaf area. Using the LAI from the top of the canopy down to 6 m height, TOPD_6, where NR (Prob. > F = 0.0006) and stocking (Prob. > F = 0.0009), explaining 87% of the variation, was only slightly better than using TOPD_8.

LiDAR metrics

The logarithm of leaf area index (TOPD_8) was strongly positively related to the two LiDAR metrics, p50fp (Prob. > F < 0.0001) and %veg (Prob. > F = 0.0003), with an overall R^2 = 95%. The R^2 = 89% using TOPD_6m. The p50fp metric, which is the height above which 50% of the returns originated, was higher in plots with larger LAIs, and was statistically significant when fitted on its own but more so when fitted jointly with %veg. The %veg metric was not significant on its own.

Relationships between crown health attributes and LiDAR metrics
Crown transparency was strongly negatively related to p50fp (Prob. > F = 0.0198) and positively related to %veg (Prob. > F = 0.0021), with an R^2 = 55%. These LiDAR metrics were also strongly related to NR in 2007. NR was positively related to p50fp (Prob. > F = 0.0202) and negatively related to the %veg (Prob. > F = 0.0056), with an R^2 = 50%. Clearly, these two LiDAR variables, which were both related to LAI, are related to crown transparency and NR through their correlations with LAI.

Relationships with stem volume

LAI
Stem total volume under bark per ha was strongly positively related to plot LAI (TOPD_6m) (Prob. > F < 0.0001), with an R^2 = 94%. Using LAI of TOPD_8 gave a similar R^2 = 91%. LAI was expected to be strongly related to the increment in stem volume (Beets and Whitehead 1996), however, in trail FR 443/5 plots were all of the same age and had the same silvicultural history, and therefore total stem volume is also well correlated with LAI. This relationship will change with stand age and silviculture.

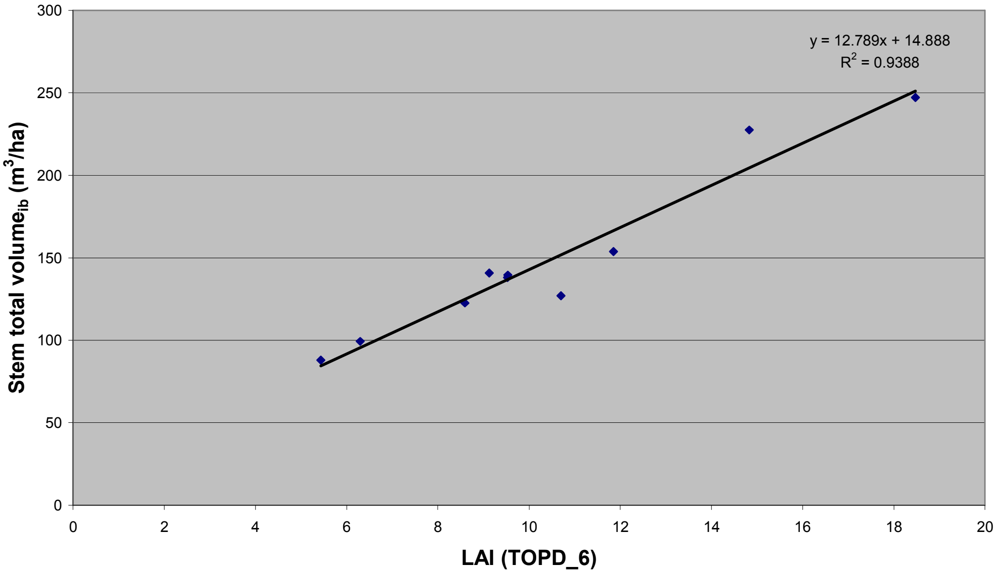

Fig.2. Relationship between stem total volume and leaf area index in 9 year old trees of trial FR443/5 at Puruki

Transparency
The logarithm of stem total volume under bark was also strongly positively related to stocking (Prob. > F < 0.0018), and transparency (Prob. > F = 0.0130), with an R^2 = 50%. The overall model is:

Log (Volume) = 1.792 + 0.0008 x SPH - 0.011 x Transp (upper 50%)

The transparency coefficient is negative, which indicates that less stem volume occurs in plots with more transparent crowns. Total transparency (Prob. > F = 0.1045) and stocking (Prob. > F = 0.0048) explained only 38% of the variation in stem volume, with stocking having a statistically significant effect.

NR
Not surprisingly, the logarithm of stem total volume under bark was also strongly positively related to stocking (Prob. > F < 0.0001), and NR (Prob. > F = 0.0016), with an R^2 = 66%. The overall model is:

Log (Volume) = 1.278 + 0.0007 x SPH + 0.151 x NR

The NR coefficient is positive, which indicates that more stem volume occurs in plots with high needle retention.

LiDAR metrics
Using 20 plots of FR443/5, the logarithm of stem total volume under bark was strongly and positively related to p50fp (Prob. > F < 0.0001) and also positively related to %veg (Prob. > F = 0.0044), with an R^2 = 87%.

Log (Volume) = 1.220 + 0.0039 x %veg + 0.0975 x p50fp

These two LiDAR metrics (p50fp, %veg) were selected for analysis because, of the various metrics tested, they were both strongly related to LAI and mean top height.

Across all 36 plots at Puruki (representing a range in stocking) the logarithm of stem total volume under bark was strongly and positively related to p50fp (Prob. > F < 0.0001) and also positively related to %veg (Prob. > F = 0.0002), although the variation explained by these two LiDAR metrics decreased using all three trials, with the R^2 = 70%.

Log (Volume) = 0.825 + 0.0080 x %veg + 0.0991 x p50fp

Adding stocking improved the overall fit, with the overall R^2 increasing to 79%. The two LiDAR metrics (p50fp, %veg) do not appear to be adequate on there own to represent the effect of stocking differences on stem volume.

The plots at Puruki were 9 years old when the LiDAR data were acquired, nevertheless these two LiDAR metrics can be expected to be more generally related (i.e. at different stand ages and SI) to total stem volume through volumes relationship with tree height and LAI. Nevertheless, it is to the LAI of these plots that the LiDAR height metric (p50fp) is likely responding to. As trees grow in height, the mean height of the canopy (leaf area) above the ground surface will increase.

Nelson/Marlborough Pilot project

Forest health was assessed at sites located on a 4 km grid in the Nelson/Marlborough region in pilot study for LUCAS (Moore *et al*., 2005). Assessments included crown transparency, needle retention, and the proportion of crown area affected by a particular condition, which applies specifically to Dothistroma needle blight and Cyclaneusma needle-cast severity. At each sample site, a cluster of four 0.04 ha circular plots was installed. The centre of plot 1 was located at the 4 km grid intersection point, with the centres of plots 2, 3, and 4 located 35 m horizontally from the centre of plot 1 on bearings of 0, 120 and 240°, respectively (Figure 3). The DBH of each standing tree on a plot was measured and its bearing and horizontal distance from the plot centre recorded. A subsample of up to 16 trees spanning the range of DBH values was selected for measurement of total height, green crown height and pruned height. There were some issues in this pilot study regarding the accuracy of plot locations based on GPS measurements.

Forest health assessment

Estimates of tree health were made in September/October 2004 on trees selected across the diameter range for height measurement. For each selected tree, crown transparency was estimated by comparing the crowns of individual trees to a series of photographs of spruce across the range in transparency (provided by Lindsay Bulman). A count of the number of needle age classes present in the lower 1/3rd of the green crown was also made. The proportion of crown area affected by either Dothistroma needle blight or Cyclaneusma needle-cast was assessed.

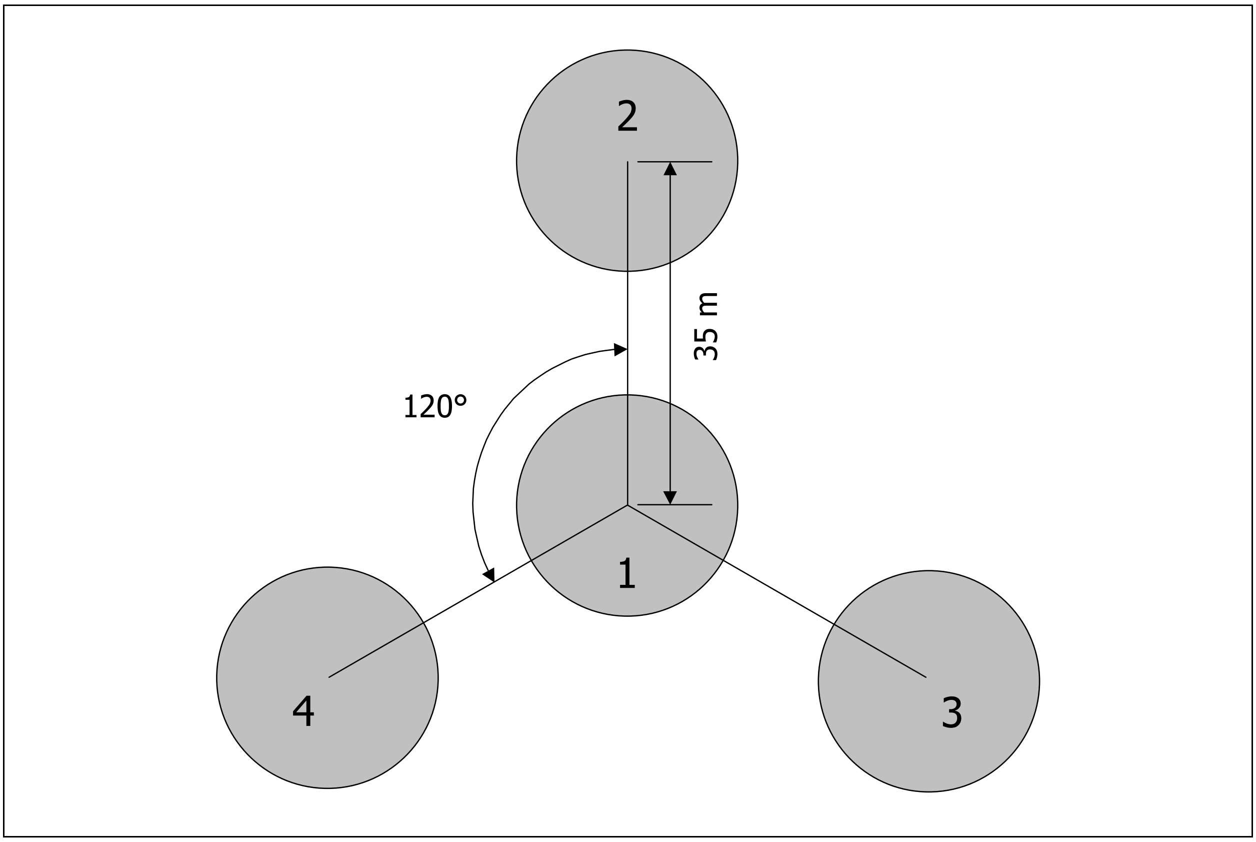

Fig 3. Layout of the cluster of four 0.04-ha plots.

Forest health results

Stand health varied widely among sites within the pilot region. The mean needle retention score ranged between 1-3 years. Dothistroma needle blight ranged between 0 – 55% on a plot mean basis, while Cyclaneusma needle-cast ranged between 0-20%.

Mean needle retention NR (Fig 4), Dothistroma needle blight (Fig 5) and Cyclaneusma needle-cast (Fig. 6) scores generally improved from west to east within the region. An analysis of the individual tree data showed that tree health scores accounted for a significant proportion of the variation in tree diameter within sites. For example, the effect of NR on DBH, which was tested while accounting for the effect of other site factors (represented by Cluster in the analysis) was highly significant, with Cluster and NR jointly accounting for 72% of the variation in tree DBH across the region. The F-value for Cluster was 132, with Prob. > F <0.0001. For needle retention the F-value was 62, with Prob. > F <0.0001.

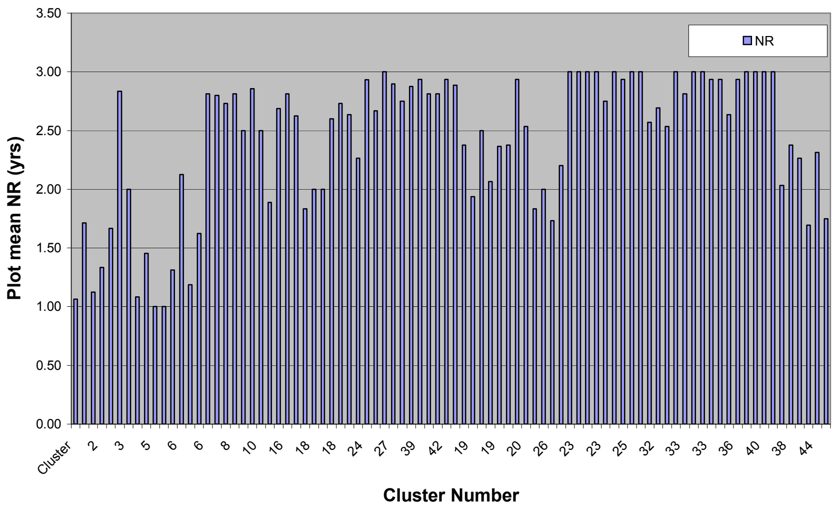

Fig 4. Plot mean needle retention score in the Nelson/Marlborough region, with plots ordered from West to East.

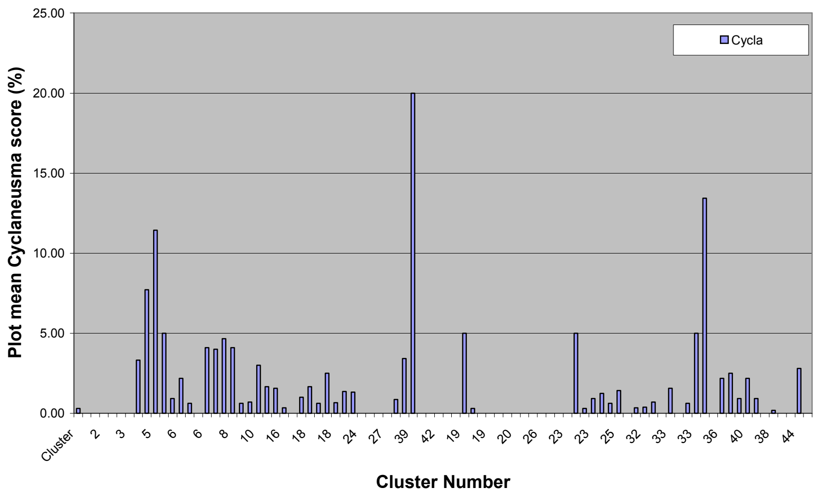

Fig 5. Plot mean score of the percentage of crown affected by Cyclaneusma needle-cast.

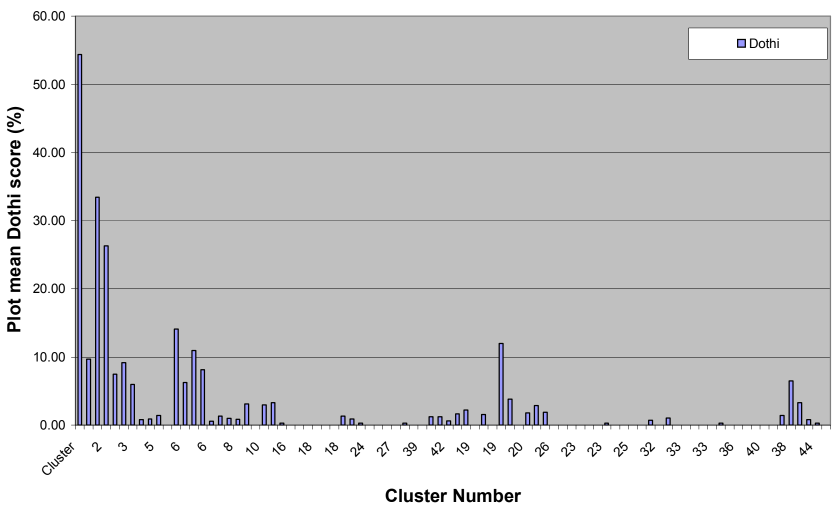

Fig. 6 Plot mean score of the percentage of crown affected by Dothistroma needle blight

The two transparency scores (upper 50% and total crown) were closely related to each other, and transparency was less in the upper crown, as found at Puruki. Crown total transparency explained 64% of the variation in upper crown transparency, which is a lower R^2 than found at Puruki:

Transp (upper 50%) = -0.09 + 0.296 x Transp (total crown)

Transparency of the upper crown decreased as NR (R^2 = 25%) increased, although the relationship was weaker than that observed at Puruki.

Relationship of health related attributes with LiDAR metrics

Using the 74 plots in Nelson/Marlborough, NR was negatively related to p50fp (Prob. > F = 0.0125) and positively related to %veg (Prob > F = 0.0002), with an R^2 = 22%. The relationship was weaker than at Puruki, and furthermore the sign of the parameters are opposite to those found at Puruki. Neither of the two crown transparency scores (upper 50% or total crown) were related to LiDAR metrics. It can be inferred that in these 74 plots in Nelson/Marlborough neither transparency nor NR are closely related to LAI, with the latter presumably varying in relation to site and management factors other than tree health.

LiDAR metrics for estimating volume

Across all 74 plots the logarithm of stem total volume under bark was strongly and positively related to p50fp (Prob. > F < 0.0001) and also positively related to %veg (Prob. > F = 0.0004), with an R2 = 73%. These particular LiDAR metrics were selected for this analysis because they were both related to LAI at Puruki.

Log (Volume) = 1.016 + 0.0074 x %Veg + 0.0858 x p50fp

Adding stand age improved the relationship, although stocking was not significant, with the overall R^2 = 74%. The same two LiDAR metrics (p50fp, %veg) were related to stem total volume, even though the stands in the pilot study differing in age, SI, stocking, and productivity from those at Puruki.

DISCUSSION

Once conversant with the Forest Health assessment methodology, the field crews generally had little difficulty making the necessary measurements and observations. The one exception was the Crown Transparency assessment at Nelson/Marlborough, which was poorly explained in the methods and difficult to apply with any degree of consistency. Transparency and NR at Puruki were moderately strongly related to LiDAR metrics with R^2 values of 0.55 and 0.50, respectively. No such relationship was found at Nelson/Marlborough, and NR was only weakly related to LiDAR metrics there. The first result was expected given the inadequate training period for transparency assessment. Regular training and use of the field assessment guide currently under development by Lindsay Bulman (pers.comm.) will overcome this limitation.

The three methods used to estimate LAI performed well, with LiDAR an outstanding predictor of LAI, explaining 0.95 of the variation among plots at Puruki. There were also strong relationships between upper crown transparency and NR with LAI, having R^2 values of 0.79 and 0.85, respectively, when stocking was taken into account. The procedure followed at Puruki to select sample trees for leaf area measurement was particularly rigorous, and explains why LAI relationships with LiDAR and tree health attributes were strong.

The relationships between the four crown variables LAI, Transparency, NR, and LiDAR with tree volume were also strong, considering that the crown variables were the result of one-off assessments. It is best practice to relate an average crown value from data collected over a number of consecutive years when establishing relationships with growth, particularly on sites prone to high annual variation in crown health and needle retention.

Following on from the reservations associated with using one-off estimates of crown health, a question that remains uncertain is what would happen to LiDAR height metrics in situations where a healthy stand becomes unhealthy later on in life and the leaf area decreases? Likewise, leaf area generally decreases as site fertility decreases. It might then be anticipated that the LiDAR points will tend to penetrate deeper into the tree crown and the point cloud mean height will therefore be lower down within the crown, compared with healthy stands or stands on more fertile sites.

For assessments of specific disorders, the time of year is critical for assessing the proportion of crown affected. Timing is less important for NR and transparency, although transparency and NR assessments should be undertaken as close to the same time of year as is practical.

CONCLUSIONS

To examine trends over time:

1. The order in which plots are remeasured is important. A particular plot should be remeasured at the same time of the year as far as practicable.
2. Needle retention and transparency should be assessed in winter or early spring, when tree growth is normally measured.
3. Cyclaneusma needle-cast symptoms are typically visible during late spring. Regions prone to Cyclaneusma should be scored at that time, assessing the proportion of crown affected. If plots have to be measured in winter, Cyclaneusma can not be scored directly, but its impact on health and growth inferred from other evidence
4. The proportion of crown affected by *Dothistroma* can be scored at any time during the winter/spring plot remeasurement period.

In a one-off assessment undertaken in 9-year-old stands at Puruki, crown transparency and NR were strongly related to leaf area index and LiDAR metrics. However, the particular LiDAR metrics involved were also strongly associated with stem volume, both at Puruki and

Nelson/Marlborough, which indicates that factors other than tree health are also involved, including for example stocking and stand age.

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