Impact of stocking and exposure on outerwood acoustic properties of *Pinus radiata* in Eyrewell Forest

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Abstract

Acoustic measures based on "time of flight" tools such as the Fakopp 2D offer a non-destructive technique for assessing tree stiffness using the fundamental equation $E = \rho V^2$, where E is the stiffness, ρ is the green density and V is the acoustic velocity as measured by Fakopp. This study at Eyrewell Forest in Canterbury assessed the variation of stiffness of 27 year-old radiata pine (*Pinus radiata*) trees planted at different stockings and in two narrow contiguous strips (upwind and downwind) aligned perpendicular to the NW wind.

No significant difference was found between the outerwood acoustic velocity for the two stockings (nominally 100 and 625 stems/ha). However, a significant difference was found between the two strips for velocity and hence estimated stiffness, implying an influence of wind on the acoustic properties of outerwood.

The study indicates a broad range of outerwood stiffness with values lying between 7 and 13.5 GPa. The modest stiffness of the outerwood for the poorest trees is of particular concern when considering that the corewood will be significantly poorer. This focus on within-stand variation contrasts with much current information on wood quality of stands that typically relates to stand average values - and probably only to basic density. In revealing the range of acoustic values found within a single stand, this study draws attention to the opportunity and need to sort material within stands.

The influence of wind appears to affect a "deep perimeter" and managers may need to consider segregating such wood and marketing it separately. At the very least, the noticeable difference in acoustic velocity between the upwind and downwind needs further investigation.

Introduction

The purpose of the study was to characterise and understand the range of acoustic velocity, and hence stiffness, of standing trees in a trial at Eyrewell Forest; to test for correlations between acoustic velocity and tree height, diameter at breast height (DBH) or taper; and, in particular, to observe the influence of stocking. Only when the data had been gathered was it noted that wind appeared to have an impact on acoustic velocity and this became the topic of greatest interest. This was unexpected in that one might hypothesise that outerwood stiffness as measured at breast height will be less influenced by environmental factors in a mature stand than would be the case in a younger stand, e.g. soon after thinning (Hsu 2003). There is limited published data on the effects of wind on wood stiffness (see Telewski 1995).

Acoustic tools provide non-destructive testing methods for assessing the mechanical properties of wood. The most commonly used methods are resonance for logs and lumber, and time-of-flight for standing trees. In recent years there has been much evaluation and dicussion of the performance of resonance and time-of-flight (TOF) tools (for example Harris & Andrews 1999; Andrews 2000 & 2002; Bucur 1995 & 1996; Wang *et al.* 2000, 2001 & 2002).

If acoustic sorting of standing trees for specific end-product requirements was applied more broadly savings in material and processing costs could lead to considerable financial benefits for the industry. However in order achieve this, "field-hardened" tools will be essential.

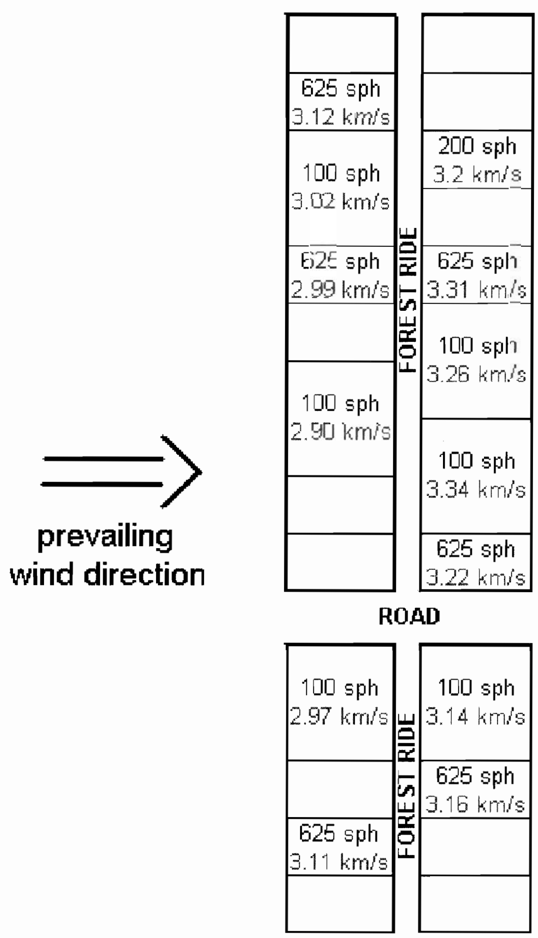
This study used one such TOF tool, Fakopp 2D (Fakopp Enterprises, Hungary), which was originally designed for detecting decay in ornamental and street trees. It consists of a control unit linked to an array of six transducers. Each transducer is attached to a long steel spike which provides the connection with the green outerwood. In turn, any one of the transducers can be used as a starter probe which is tapped with a light hammer to launch an acoustic impulse. It is able to record the travel or transit times of the wave between the starter probe and the five receiver probes.

Materials and methods

Site description

The Canterbury plains and Eyrewell Forest in particular have a history of windthrow from severe northwest (NW) winds. In consequence a narrow strip system was adopted which created a rising stepped wedge formation of age classes into the prevailing wind, the theory being that the full height of each age class is not exposed to the wind (Turner 1989). The study was conducted in a 27 year-old radiata pine stand (Cpt 32) of Eyrewell Forest on the Canterbury plains. A progeny trial (known as the GTI 850 Polycross trial) had been planted in 1975 at a stocking of 625 stems/ha. This was a single-tree plot trial (C 463) consisting of the offspring from 100 mothers (mostly 850 series) crossed with a pollen mix of 10 850 series parents. The trial had been laid out in two parallel strips aligned perpendicular to the NW wind (Fig. 1) separated by a narrow, 4 m, ride. The stand on the windward side of the trial was planted in 1987 and that to the leeward in 1997; i.e. in recent years the trees in the trial have been relatively exposed to wind from both the NW and SE directions.

Fig. 1: Map of the trial layout in CY 597 Eyrewell Forest Cpt 32, showing nominal stocking and average acoustic velocity for the assessed PSPs. The combined width of the two contiguous strips was ca. 120 m. The map further shows the 4 m wide forest ride that divides the two strips and the forest road that runs through the trial.



A final crop stocking trial (CY 597) was superimposed on the progeny trial by the Forest Research/Industry Stand Growth Modelling Cooperative, and consisted of the following treatments:

- No thinning (six replicates).
- Thinning to final crop stockings of 100, 200 and 400 stems/ha at either
  - o Age 11 (3 replicates for each stocking); or
  - o Age 14 (3 replicates for each stocking).

The trial was pruned in two lifts to a height of 4.2 m. A total of 24 PSPs (permanent sample plots) was established - one within each replicate of each treatment. The plots were circular and well clear of the stand edges.

In this study, measurements were taken on all trees in each of the six PSPs in the unthinned treatment (nominally 625 stems/ha) and the six PSPs in the treatments thinned to a nominal final crop stocking of 100 stems/ha. It was assumed that the maximum differences would occur between the extremes of stocking and therefore only these two treatments were measured. The age of thinning to final crop stocking was ignored and the data pooled.

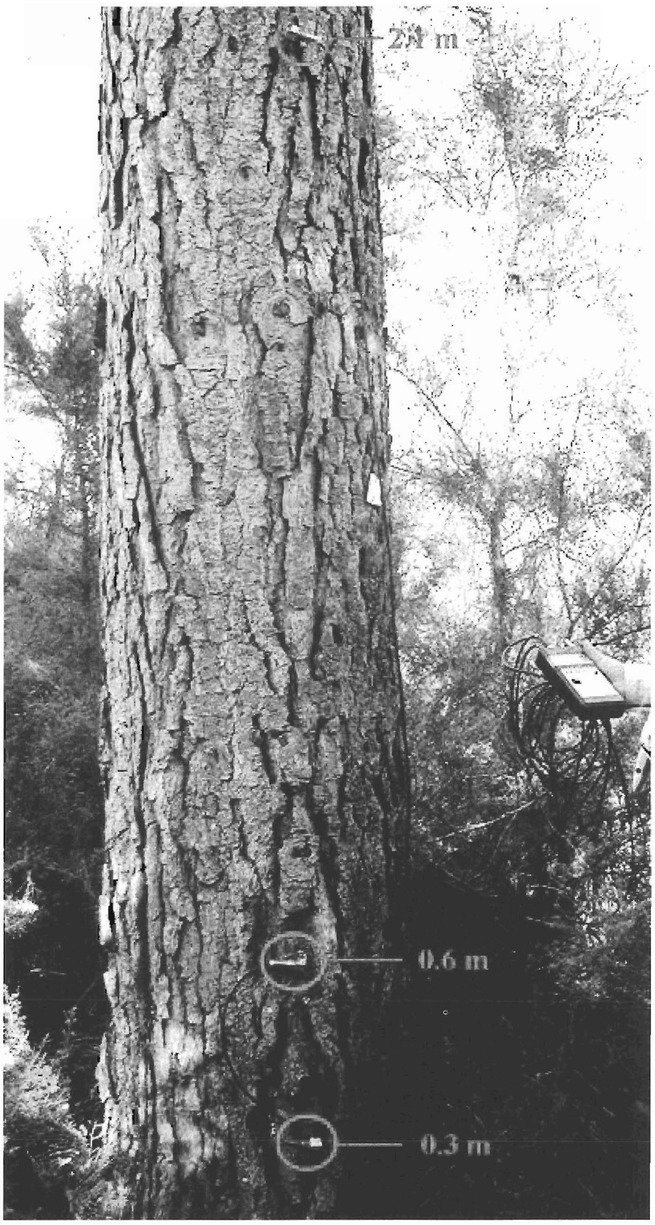
The six PSPs for each of the unthinned and 100 stems/ha treatments were distributed equally between the upwind and downwind strips. A total of 106 trees in the upwind strip and 119 trees in the downwind strip were measured (103 trees at 100 stems/ha and 122 trees in the unthinned 625 stems/ha treatment).

Measurements

Field work was undertaken between July and September 2002. The Fakopp 2D tool was used to measure acoustic velocity of outerwood in the standing trees. Only three probes were used, all aligned vertically up the stem. As the forest is exposed to prevailing NW winds, all trees were measured on the north-east facing side of the stem to avoid the possible influence of compression wood caused by tree lean. The start transducer was set about 0.3 m above ground with the two stop probes at about 0.6 m and 2.1 m above ground level (Fig. 2). All probes were placed at an angle of less than 45° from the vertical to the stem axis to ensure good measurements. The acoustic velocity in the stem [m/s] was determined from the distance (m) between the two stop probes and the travel time (Δt) of the acoustic impulse between the two stop probes ($m/\Delta t$). Because of the small variation in recorded travel time, most probably arising from the "quality" of the light hammer tap and the shape of the acoustic impulse so generated, the average of ten taps was used to estimate the travel time.

The elastic modulus (MOE) was estimated from the acoustic velocity (V) using the general equation $MOE = \rho V^2$, assuming a constant density (ρ) of 1050 kg/m^3 due to the high moisture content that one would expect to find in the

Fig. 2: Probe alignment on the tree trunk.



sappy outerwood (Andrews 2000). The quickest time-of-flight path between the two stop-probes is presumed to lie in the outerwood where the wood is stiffest. Therefore the measured acoustic velocity and the estimated dynamic stiffness (MOE) are taken to relate to the outerwood (Andrews 2002).

The following measurements were also made on each tree:

- Total height (m);
- DBH (cm); and
- Diameter at the height of each of the two stop probes (about 0.6m and 2.1m above ground level). The difference between these two diameters was divided by the distance between the two probes to derive a measure of tree taper (cm/m) for the section of tree over which velocity was measured.

Results

1. Relationship between acoustic velocity and stand attributes

Average plot stocking, DBH, height and the ratio of tree height to DBH are shown in Table 1 by stocking and strip. The average stocking of the 100 stems/ha plots at age 27 was 86 stems/ha (range 60 to 95 stems/ha) while the average stocking of the unthinned plots was 512 stems/ha (range 350 to 600 stems/ha).

An ANOVA revealed that, although differences between strips are not significant at the 5% level, the two stocking treatments have significantly different DBH ($p<0.001$), height ($p=0.001$) and height/DBH ratio ($p<0.001$). Trees in the unthinned treatment are on average thinner and shorter.

Table 1: Average plot stocking, DBH, height and ratio of height to DBH.

Treatment	Stocking (stems/ha)	DBH (cm)	H (m)	H/DBH
100 Upwind	81.7	48.6	26.5	0.55
100 downwind	90.0	48.2	28.2	0.58
Mean	85.8	48.4	27.4	0.57
625 Upwind	483.3	32.1	24.2	0.75
625 Downwind	541.7	31.4	25.0	0.80
Mean	512.5	31.8	24.6	0.78

Mean acoustic velocity across the 12 plots ranged from 2.90 up to 3.34 km/s (Fig. 1). An ANOVA looking at the relationship of velocity with stocking and strip showed that there is no significant difference in velocity between the two stockings ($p=0.33$). For both stockings there was a broad velocity distribution for individual trees, in the 100 stems/ha plots from 2.52 km/s to 3.75 km/s (mean of 3.11 km/s) and in the 625 stems/ha plots from 2.60 km/s to 3.62 km/s (mean of 3.16 km/s).

However the velocity in the two strips is significantly different ($p=0.001$). Trees growing in the upwind strip, regardless of the stocking, showed significantly lower acoustic velocities than trees in PSPs within the downwind strip (Table 2).

Table 2: Average plot velocity (km/s) by stocking and strip.

	Strip		
Stocking	Upwind	Downwind	Average
100	2.96	3.25	3.11
625	3.07	3.23	3.15
Average	3.02	3.24	3.13

2. Relationship between acoustic velocity and individual tree characteristics

The key results of the analysis are clearly shown in Figs. 3 and 4 which compare the velocity distributions by stocking and strip respectively. While the velocity distributions for the two stockings are similar (Fig. 3), they are different for the two strips (Fig. 4).

The relationship between acoustic velocity and tree characteristics (DBH, height, height/DBH, taper) was evaluated after adjusting for strip. For example, the relationship between velocity and DBH was evaluated by fitting a model of the following form to the data:

$$\text{Velocity} = a + b1 * \text{strip} + b^2 * \text{DBH}$$

where strip takes on the value 0 for trees in the upwind strip and 1 for trees in the downwind strip.

The fitted function is:

$$V = 3.114 + 0.223{*}\text{strip} - 0.0024{*}\text{DBH} \quad R^2 = 0.231, p<0.001$$
$$p<0.001 \qquad p=0.093$$

The coefficient for strip (0.223) gives the estimate of the mean difference in velocity between trees in the two strips. The coefficient for DBH is not significant at the 5% level.

There is a positive relationship between velocity and tree height. The fitted function is:

$$V = 2.780 + 0.215{*}\text{strip} + 0.0094{*}H \quad R^2 = 0.236, p<0.001$$
$$p<0.001 \qquad p=0.040$$

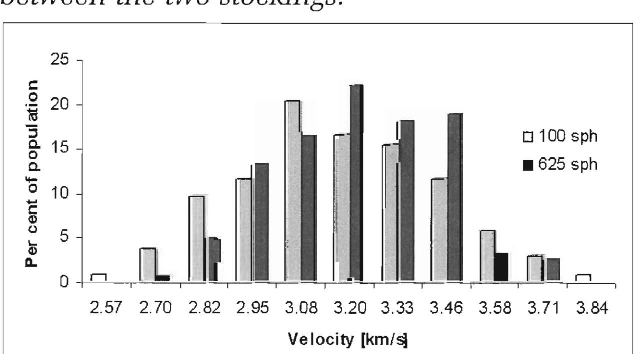
There is also a positive relationship between velocity and the ratio of tree height to DBH:

$$V = 2.819 + 0.215{*}\text{Strip} + 0.296{*}H/DBH \quad R^2 = 0.252, p<0.001$$
$$p<0.001 \qquad p=0.003$$

There is a negative relationship between velocity and taper at breast height:

$$V = 3.142 + 0.227{*}\text{Strip} - 0.0419{*}\text{taper} \quad R^2 = 0.248, p<0.001$$
$$p<0.001 \qquad p=0.005$$

Fig. 3: Velocity distribution for trees in 100 stems/ha and 625 stems/ha plots; showing no difference between the two stockings.

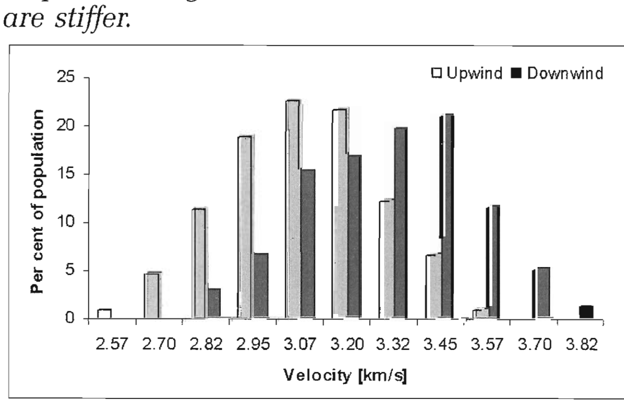


Discussion/Conclusion

The range of acoustic velocities emphasises the correspondingly large variation in the intrinsic stiffness that must be expected within any stand, even in outerwood. If one considers the broad range in acoustic velocities to be from 2.6 to 3.6 km/s, then the corresponding outerwood stiffness values would lie between 7 and 13.5 GPa. This is a very significant range of values, ranging from outerwood of marginal interest for machine stress graded framing (7 GPa) to material that would be satisfactory for the most demanding structural markets (13.5 GPa). The modest stiffness of the outerwood for the poorest trees is of even more concern when one recognises that the corewood of such trees is significantly poorer. This new knowledge contrasts with much current information on wood quality of stands that typically relates to stand average values - and probably only to basic density. In revealing the range of acoustic values found within a single stand, this study draws attention to the opportunity and need to sort material within stands.

The most intriguing observation is the difference in acoustic velocity between trees in the two parallel strips. This suggests an influence of wind on the wood properties of trees - or a combination of wind and desiccation, as the NW winds have very low humidity. This unanticipated observation opens up further avenues for research. Generally stands are presumed to be "uniform" whereas this study suggests that "edge effects" may extend much further into a stand than suspected hitherto; and these effects impact on properties of commercial value. This supposition is currently being tested by systematically sampling across some wind-prone stands. If the effects are verified, one might wish to identify and segregate logs from the "deep perimeter" and market them separately. The same could apply to trees on ridgelines.

Fig. 4: Velocity distribution for trees in the two strips; showing that trees in the downwind strip are stiffer.



It would be ironic if the Eyrewell strip/wedge system, adopted as the appropriate solution to increase wind-stability of the forest to an extreme wind event, should in consequence lower intrinsic wood quality by virtue of the enlarged edge-to-interior area ratio. While exposing the trees to wind may increase their stability to extreme wind events, the trees in the "deep perimeter" will be subject daily to mild wind-sway.

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Acknowledgements

The authors thank Carter Holt Harvey Forests for providing access to the Eyrewell Forest final crop stocking trial (CY597). The trial was established by the Forest Research/Industry Stand Growth Modelling Cooperative. Dr John Moore is also thanked for helpful suggestions for the analysis.