ACOUSTIC TESTING TO ENHANCE WESTERN FOREST VALUES AND MEET CUSTOMER WOOD QUALITY NEEDS

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ABSTRACT

Nondestructive testing (NDT) of wood products, such as lumber and veneer, for stiffness and strength evaluation has been proven and commercialized for many years. The NDT concept has been extended and commercialized in the Director HM-200™ tool for testing logs in advance of processing so manufacturers can make more informed log purchases and better match logs to customer needs for product stiffness and strength. Further extension of the NDT concept to standing timber is a logical progression and a new commercial tool, the Director ST-300™, has just been developed for this application. This paper describes operating principles of both tools and presents examples of their use with various species. The potential effects of wood density, moisture content, temperature, and age on results from these tools are also discussed.

Keywords: Nondestructive testing, tree quality, log quality, modulus of elasticity, stiffness

INTRODUCTION:

While a large body of research has been focused on understanding and improving the productivity of Western forests, improving value must also consider quality. As harvest age decreases and use of intensive silviculture increases, quality of stands, logs, and products is becoming more variable. However, application of intensive silviculture throughout the life-cycle of a stand also presents an opportunity to measure, manage and control quality as well as tree size and volume.

Product markets readily segregate into applications where aesthetic appearance features, such as grain, color and knottiness, predominate in defining quality and applications where mechanical properties, such as stiffness and strength used by architects and engineers in designing structures, predominate in defining quality. In the US, about 52% of the solid-sawn lumber consumed is used in new residential and nonresidential construction and another 30% is used for repair and remodel of existing structures (Eastin 2004). Much of the veneer production is also used in products where stiffness and strength are critical quality characteristics. The dependence of Western forests on markets

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for softwood structural products is illustrated by the state of Washington where 92% of the harvest is softwoods, of which 71% is sawlogs for lumber and 17% is peeler logs for veneer (Smith et al 2001).

Traditionally, quality of softwood trees, logs and products has been assessed by human visual observation of surface characteristics, such as knots, splits, and rings per inch, and assignment to one of several possible grades based on simple, broad allowable ranges for the characteristics. Although these grades may be sufficient where appearance is the primary consideration, the adequacy of visual grades for applications involving stiffness and strength is questionable since no measure of these properties is actually obtained. Indeed, a concern over reliability and the broad, conservative design values associated with visual grades for structural applications led to the development of machine-stress-rating (MSR) technology for lumber that was commercialized since the 1960's. MSR technology non-destructively measures the stiffness of lumber and uses a pre-established relationship between stiffness and bending strength to define a set of strength-based grades. This provides a more refined and flexible approach than visual grading for identifying and sorting lumber into stress grades used in products such as glulam beams and engineered trusses. With the development and rapid growth of new engineered wood products such as laminated veneer lumber (LVL), I-beams and I-joists, there has been a parallel growth in non-destructive testing (NDT) for the stiffness and strength of lumber and veneer used as components of these products. In addition, concerns with design values of structural lumber graded with visual methods is creating momentum for verification testing of visually graded structural materials.

These trends have renewed interest of mills in non-destructive methods. Mills seeking to capture a price premium (Spelter 1996) by producing non-destructively tested lumber and veneer, find that it is very expensive to process logs or purchase timber stands that have low yield of product with stiffness and strength levels desired by their customers. Consequently, researchers have developed technology for applying NDT to measure stiffness of logs to improve sorting and matching with desired levels of lumber or veneer stiffness (Wang et al. 2002, 2004a). This research has led to successful introduction of the Director HM-200™, a log stiffness testing tool described later in this paper. A logical and desirable extension is to apply the NDT technique to measure stiffness of wood in standing trees (Wang et al. 2001, 2003), thereby providing timber sellers and purchasers with a means for improved harvest scheduling and timber marketing based on the potential yield of stress-graded products that can be obtained from trees within a stand. A new tool, the Director ST-300™, has been developed for evaluating wood stiffness in standing trees and is also described in this paper.

BASICS OF NDT ASSESSMENT OF STIFFNESS

Stiffness of a piece of lumber, or a log, can be measured by placing it in a suitable static bending test apparatus, recording the deflection as load is applied, and calculating the modulus of elasticity (MOE or E), a measure of stiffness or resistance to deflection. Although this "static bending" MOE can be measured without testing the piece to failure, it is slow and involves expensive equipment that is not very portable. Consequently researchers have been exploring the use of the "dynamic" MOE, which is well correlated with the static MOE. Dynamic MOE is obtained by measuring the velocity of an acoustic wave through the material and is expressed by the following formula

$$E_d = \frac{r}{g} V^2 \qquad (1)$$

where

E_d	dynamic modulus of elasticity (lb/in^2 (Pa))
r	density of the material (lb/ft^3 (kg/m^3))
g	acceleration due to gravity (386 in/s^2 (9.8 m/ s^2))
V	velocity of the wave through the material (ft/s (m/s))

Recognizing that g is a constant and applying any conversions between units, the constant k can be introduced and the equation becomes

$$E_d = k\, r V^2 \qquad (2)$$

In practice, the density of many materials is relatively constant hence the velocity of the acoustic wave can be used as a direct indicator of the dynamic MOE, a measure of the material's stiffness.

ASSESSING STIFFNESS OF LOGS WITH THE DIRECTOR HM-200™

Operating the Director HM-200™

Figures 1 and 2 show use of the Director HM-200™ for evaluating logs. The user first enters the log length or selects the length from a pre-loaded list and then presses the Director HM-200™ against the log. A sensor head signals that it has contact and a hammer blow is struck. The sensor picks up the acoustic wave signal as it passes back and forth along the length of the log at a rate of a few hundred passes per second. Software in the Director HM-200™ processes the signal and displays the velocity in either feet or meters per second depending on whether the unit has been set for metric or imperial units. The same velocity will be displayed regardless of which end of the log is chosen or where on the end the sensor head is placed and the hammer blow is struck. This is because the Director HM-200™ software obtains the weighted average velocity for the log from its analysis of the whole wave signals received. The user can program the Director HM-200™ to recognize up to 3 grade categories based on the displayed velocity. These are signaled to the operator by a color code in the display and by a unique sound signal. The operator can then suitably color spray or otherwise mark the log for subsequent sorting.

Velocity, Stiffness of Product Within Log, and Economic Benefit

Figure 3 illustrates the correlation between the acoustic velocity (km/s) of green radiata pine (lower curve) and Southern pine (upper curve) logs and static bending MOE of the dry boards sawn from the logs. Each data point represents a log batch. A high correlation (R^2=0.98) was observed for both species. Figure 4 illustrates the relationship between acoustic velocity for log batches (10 percentile groups from log sample) for Southern pine and the average ultrasound propagation time (UPT) of veneer from the logs. Ultrasound propagation time is the elapsed time for ultrasound to travel between fixed roller wheel points on a Metriguard™ veneer tester. Although a linear regression seems adequate to represent the relationship, a power regression model was found to best fit the trend, with a coefficient of determination (R^2) value of 0.99.

Figure 5 shows the increasing yield of structural grades of lumber with increasing acoustic velocity of logs processed as measured with the Director HM-200™ at two New Zealand radiata pine sawmills. Assuming a price differential of NZ\$200/m^3 on lumber, an increase of 0.1 km/s in logs sorted with the HM 200 produces a gain in structural lumber yield of about 5%. This translates into a gain of about NZ\$6/m^3 on log volume or about NZ\$1.8 million for a mill processing 300,000 m^3 of logs per year. A similar analysis for veneer for LVL production in the US resulted in a gain of about US\$16/m^3 on log volume (about \$80-\$100/MBF Scribner log scale).

Variation With Log Position and Age

As trees grow in height, they produce new cambium along the shoot. This young cambium forms growth rings with low wood density and a large microfibril angle which together result in wood of low stiffness and strength. As the cambium ages, it eventually produces denser, lower microfibril angle wood which then is stiffer and stronger. Thus a tree typically has a core of “juvenile” wood, depending on species from about 7 to 20 or more rings wide, that becomes surrounded by later rings of “mature” wood. More rings, hence more mature wood, occur in the butt log of a tree whereas the top log has few rings and has not yet undergone the transition to mature wood formation. Therefore, one can expect that stiffness and acoustic velocity would decrease as the percentage of juvenile wood increases from the butt log to top log position in a tree. With the exception of the butt log, this pattern is borne out as shown in Figure 6 for Douglas-fir and Ponderosa pine logs (Wang et al. 2004b). It appears that the butt log does not follow the expected pattern. Researchers have found that the lower bole has mature wood with lower density and higher microfibril angles leading to lower stiffness (Megraw et al. 1999).

Since logs in the upper stem of a tree have both fewer rings and a higher percentage of low stiffness juvenile wood, one would expect low acoustic velocity in these low age logs. This is also borne out and leads to a generally rising trend of average acoustic velocity of logs from a stand with stand age (Figure 7). Figure 8 shows 21 radiata pine stands in order of increasing average log acoustic velocity as measured by the Director HM-200™. Each stand is shown with the mean point as well as 2 standard deviations. The result indicates much greater variability within rather than between stands. This shows the obvious advantage of the Director HM-200™; some younger stands contain logs with much greater velocities than logs in older stands; the Director HM-200™ provides a more reliable means for identifying and sorting the better stiffness logs regardless of their age or other misleading appearance features. Although sorting logs with the Director HM-200™ at a landing or log yard provides obvious advantages, it would be desirable to have counterpart technology for standing trees to help find the best stands.

ASSESSING STIFFNESS OF STANDING TREES WITH THE DIRECTOR ST-300™

Operating the Director ST-300™

Figure 9 shows the components and set-up of the Director ST-300™. Transmitter and receiver probes are driven through the bark into the outerwood of the lower stem. They are vertically aligned along the stem approximately 1.3 meters apart and it does not matter which probe is the higher and which is the lower unit. A laser guided ultrasound rangefinder measures the exact distance between the probes. An acoustic wave is imparted into the tree stem through the transmitter probe by a hammer blow. The receiver probe picks up the acoustic signal passing through the tree and determines the time-of-flight of the acoustic wave. The distance and time are sent by wireless communication to a PDA which calculates the acoustic velocity and also allows the user to enter other tree and stand data. Unlike the Director HM-200™ which obtains the weighted average velocity by analyzing whole wave signals transmitted between the ends of a log, the Director ST-300™ measures time-of-flight for a single pulse wave to pass through the outer wood of the tree from transmitter probe to receiver probe. Given this difference in how velocity is measured and the fact that the Director ST-300™ only measures velocity along a short distance along what will become the base of the butt log from the tree, the most obvious and immediate question is the relationship between velocities obtained with the Director ST-300™ and the Director HM-200™. Figure 10 shows excellent relationship between acoustic velocity measured in trees and acoustic velocity measured in logs (Wang et al. 2004b).

Figure 11 shows tests in radiata pine of the effect of misaligning the probes i.e. keeping the receiver probe at X and moving the source probe further and further out of alignment. Since time-of-flight is measured through the outerwood between the probes, Figure 11 also shows that moving the probes to different locations around the circumference of the stem will produce different velocities (YE vs XA). Finally, Figure 11 shows the effect of lengthening the distance between the probes; including a knot whorl with associated deviant grain lowers the velocity and stiffness prediction. Results shown in Figure 11 imply that correlations between Director ST-300™ and Director HM-200™ velocities will be improved as one acquires and averages more samples around the stem circumference with the Director ST-300™. The issue of whether or not one should acquire more samples within each tree or sample more trees within the stand of interest depends on the objective of the assessment project.

Experience with the Director ST-300™ in Douglas-fir

A test of the Director ST-300™ was conducted in September 2004 in an unthinned and a thinned plot in the Stand Management Cooperative's (SMC) Type II Installation 803, Beeville Loop, located near Shelton, WA. This thinning trial was placed in a stand that was planted with 2-0 Douglas-fir seedlings in 1955 on King's (King 1966) site class II (122 feet). In 1987, the SMC established five plots, a control that had 320 trees per acre and would receive no future treatments and four plots of similar initial stocking that would undergo thinning regimes. A crew of three measured 63 trees in the unthinned control (plot 2) and 50 trees in a plot that was thinned in 1987 from a Curtis relative density (Curtis 1982) of 55 to a relative density of 35 (plot 1). At the time of test, breast height age was 43, stand age was 49 and age from seed was 51. Time to locate and walk between trees, set up the test, and measure dbh averaged 1 minute per tree.

Figure 12 presents the cumulative mean and standard error for each plot as more trees were measured; by the time 35 trees were sampled, the difference between the plots became apparent. The thinned plot, with faster growing and larger diameter trees, has higher average acoustic velocity hence would be expected to produce greater yield of products with higher stiffness. We speculate that this site may experience water stress in summer hence the unthinned stand, with more competing trees, may stop growing earlier thereby truncating formation of dense latewood. The reduced production of latewood would result in lower overall wood density which would translate into slower velocity and lower stiffness. This is atypical of what would be expected on sites where moisture is not limiting. In a wood quality study conducted on Western wood species, Wang examined the effects of thinning treatments on both stress wave velocity and wood stiffness of young-growth western hemlock and Sitka spruce. The results revealed that highest stress wave velocity and stiffness are mostly found in unthinned control stands whereas the lowest values were found in stands received heavy and medium thinning (Wang et al. 2001). This indicated that lower density stands exhibited a trend toward decreased stress wave velocity and decreased stiffness.

Figure 13 shows weak negative trends of velocity with tree diameter in each plot. The unthinned plot trend is lower than the thinned plot although the trends converge for the larger diameter, presumably dominant crown class, trees. Figure 14 shows similarly weak relationships between velocity and rings per inch[5] for trees on the plots. RPI is often viewed by mills and others as a good indicator of strength and stiffness and often prefer “slower growing” trees and logs. Does sorting by acoustic velocity improve on sorting by RPI? Trees averaging 6 RPI or greater had an average V^2 (see Equation 1), a direct measure of MOE, of 16.66 km^2/s^2 whereas the mean V^2 of all of the trees in both plots was 18.09 km^2/s^2, a gain of 2.3%. Note that roughly half of the trees with less than 6 RPI have V^2 greater than 18.09 km^2/s^2 and many trees with more than 6 RPI have V^2 less than 18.09 km^2/s^2. Using the preceding economic analysis data, this 2.3% gain from acoustic sorting would translate to about $8/m³ ($40-48/MBF Scribner).

OPERATIONAL CONSIDERATIONS

At a given time of year in a given stand, one can assume that the density, ? in Equation (1), which is simply weight divided by volume, is reasonably constant and that temperature change effect would be minimal. Although for many materials density is constant, it is variable for wood hence there may be seasonal and other effects to consider. In the case of fresh, wet “green” wood, density can be calculated as follows:

$$r = r_{H_2 0} SG_g (1 + MC_{od}) \qquad (3)$$

Where r = density (lb/ft³ (kg/m³))
$r_{H_2 0}$ = density of water (62.4 lb/ft³ (1000 kg/m³))
SG_g = wood basic density[6] (also referred to as specific gravity or relative density)
MC_{od} = wood moisture content (oven-dry basis, in decimal form)

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[5] RPI = breast height age divided by stem radius (diameter at breast height / 2)

[6] Based on oven dry weight and green volume

The basic density of wood varies by species and has a systematic pattern of change from pith to bark and base to top of trees that is associated with the formation processes of juvenile and mature wood. These patterns are part of the explanation of why acoustic velocity changes with log position within a tree (Figure 6) and why acoustic velocity is correlated with log age (Figure 7).

It should be apparent from the equation (3) that density increases as wood moisture content increases; this is simply a result of the fact that water in wood cells weighs much more than air space when water is absent. Consequently, one can expect lower velocities in wet wood as compared to dry wood. In living trees and freshly-cut logs, lumber, and veneer, wood moisture content often varies between sapwood and heartwood. For example, moisture content for softwood species ranges from 98 to 249% for sapwood and from 31 to 121% for heartwood (Forest Products Laboratory 1999). The moisture content of a log whose velocity is being measured by the Director HM-200™ is a weighted average of sapwood and heartwood moisture contents. The moisture content of the outerwood of a tree whose velocity is being measured with the Director ST-300™ will be that of sapwood. Fortunately, it has been found that when moisture content is above 40%, there is little effect on acoustic velocity (Ross et al. 2004). However, for logs from species with low heartwood moisture contents, for dead timber, and for logs that may have undergone some drying since harvest, an adjustment for the effect of moisture content may be needed. Continuous monitoring of moisture content of a sample of logs will be useful to gain an understanding of the moisture content effect and make appropriate adjustments, if necessary. Figure 15 illustrates the typical directions that changes in moisture content and basic density have on deviation of samples from an established trend line.

In addition to the effects of basic density and moisture content, large seasonal temperature changes may also require to make an appropriate adjustment on acoustic measures. Figure 16 illustrates the effects of seasonal changes in temperature and moisture content on acoustic velocity of radiata pine. In-depth research is still needed to further explore the influence of seasonal weather change on acoustic measurements on trees and logs.

CONCLUSIONS

Nondestructive testing of logs for stiffness with the Director HM-200™ offers a new reliable and flexible approach for sorting and matching logs to manufacturer and customer demands for stiffness and strength of products they contain. It may also provide a new means by which landowners and loggers can grade and market logs.

The nondestructive testing concept has been extended to standing trees with Director ST-300™ which provides an indicator of stiffness over an approximate 1.3 m distance in the lower stem; lower portion of the butt log. This will provide a new means for assessing mature stands for marketing, for harvest planning and scheduling, and has the potential for assisting in planning silvicultural operations in immature stands.

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Figure 1. The Director HM-200™

Figure 2. Operating Principle of the Director HM-200™

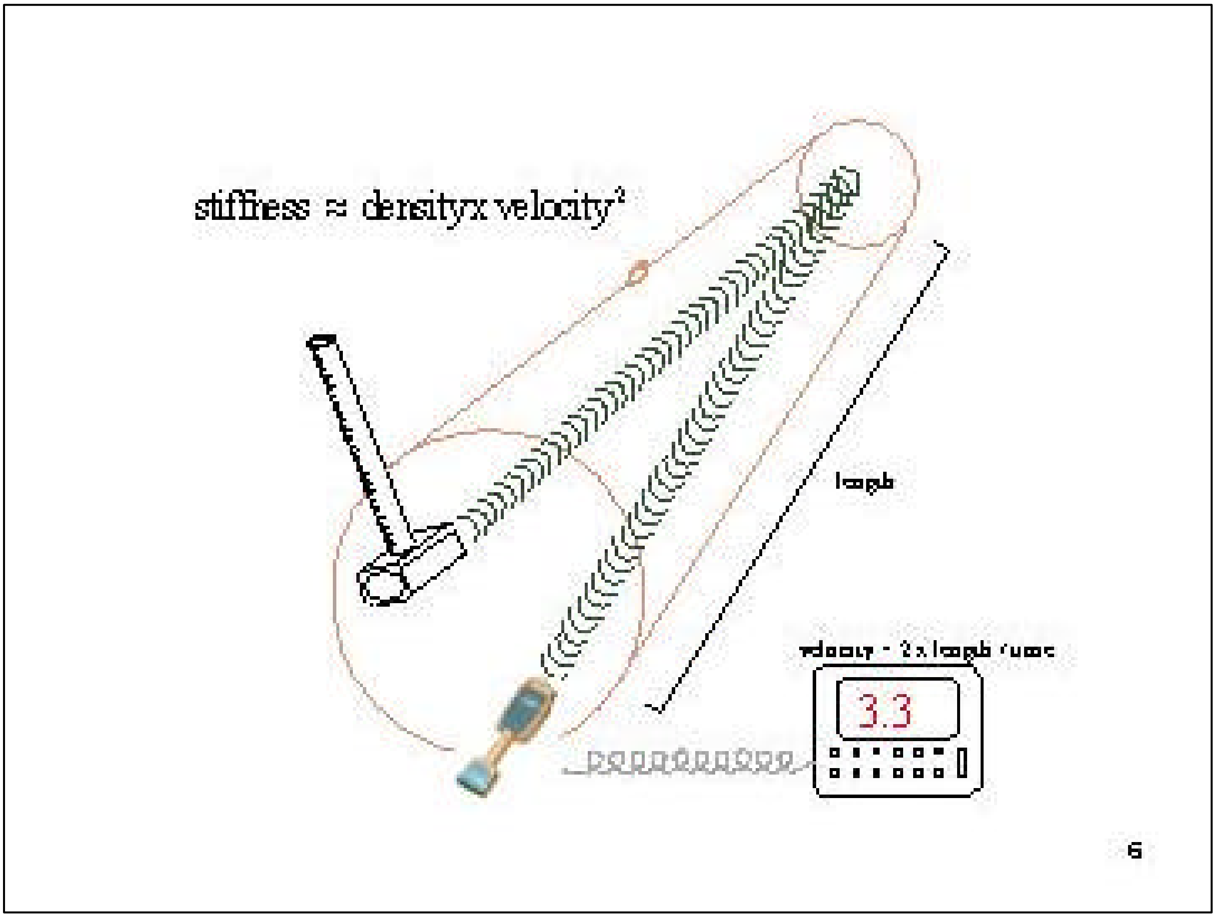


Figure 3. MOE (Pa) of dry lumber from a log vs Director HM-200™ velocity of the log (km/sec) for Southern pine (upper curve) and radiata pine (lower curve)

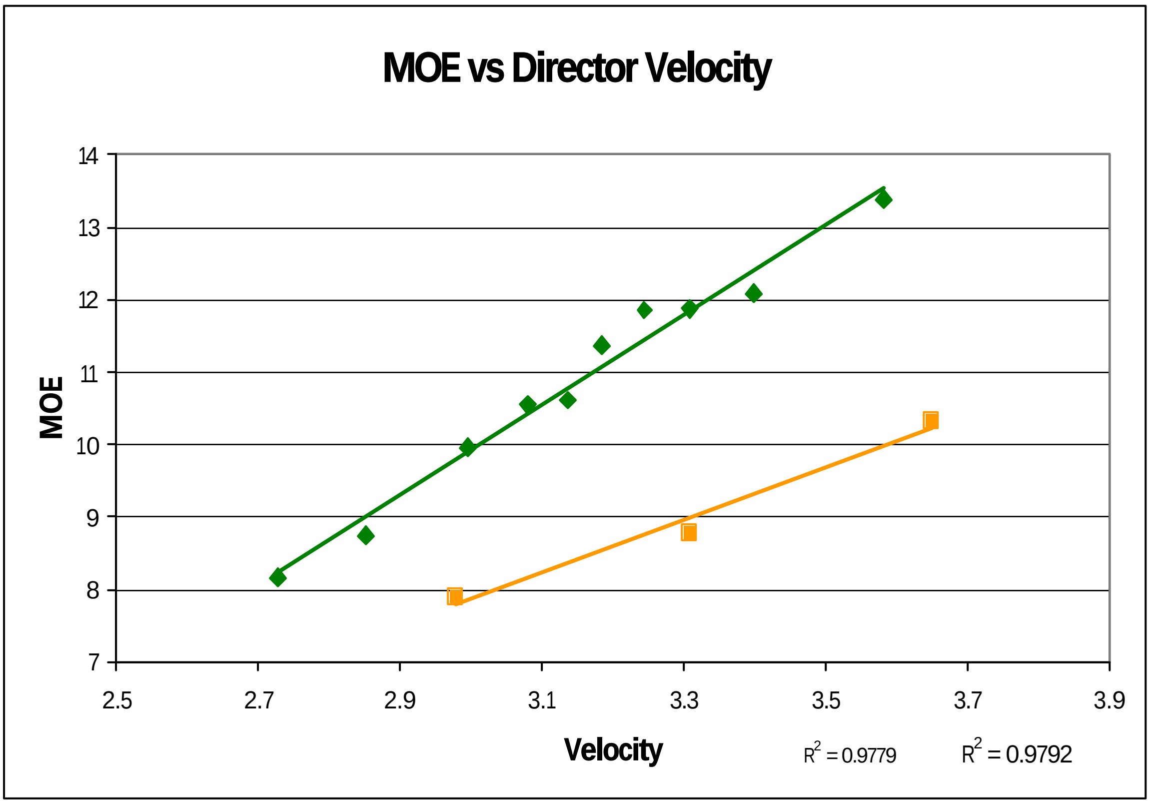


Figure 4. Ultrasound propagation time (UPT) of veneer from a log vs Director HM-200™ velocity of the log (km/sec) 10 percentile log batches from a Southern pine trial

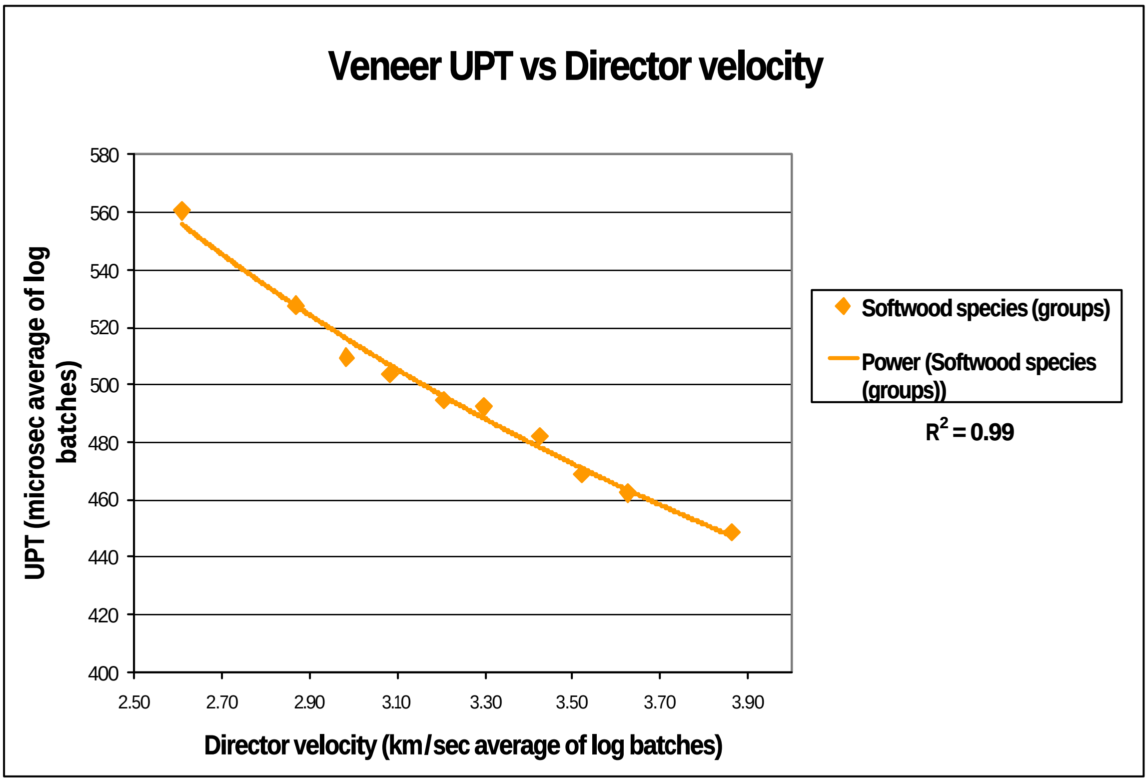


Figure 5. Yield of structural lumber grades vs Director HM-200™ log velocity (km/sec) for two New Zealand radiata pine sawmills

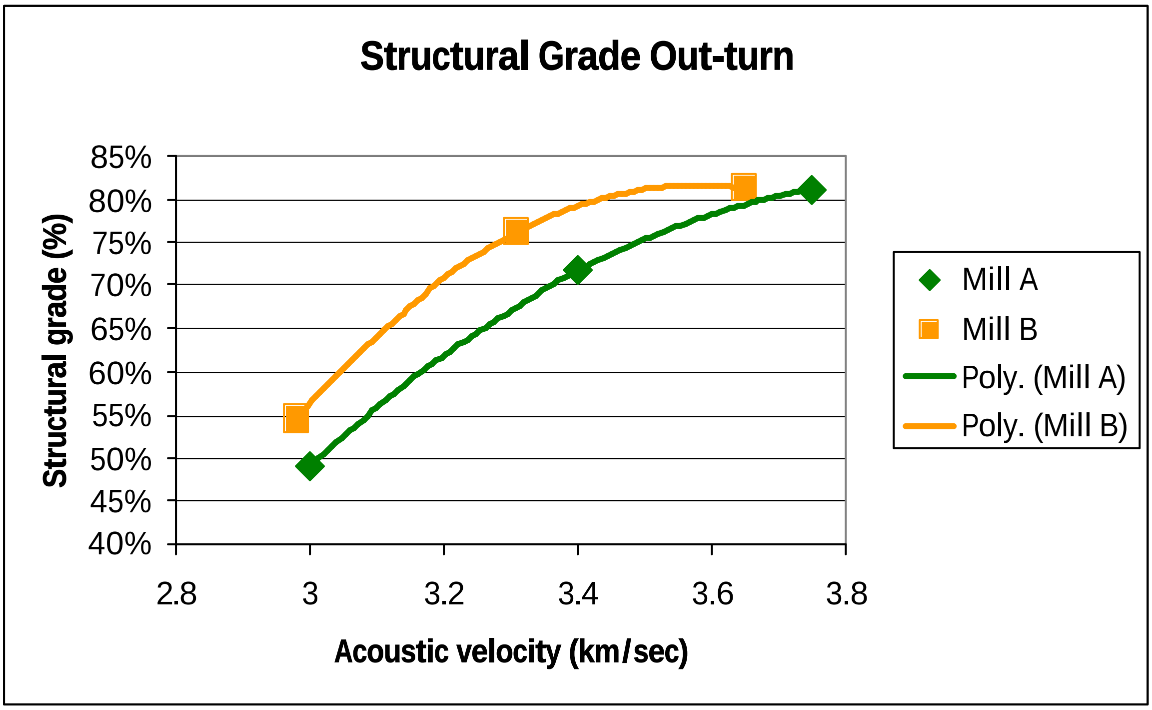


Figure 6. Acoustic velocity of logs in relation to log position in a tree stem

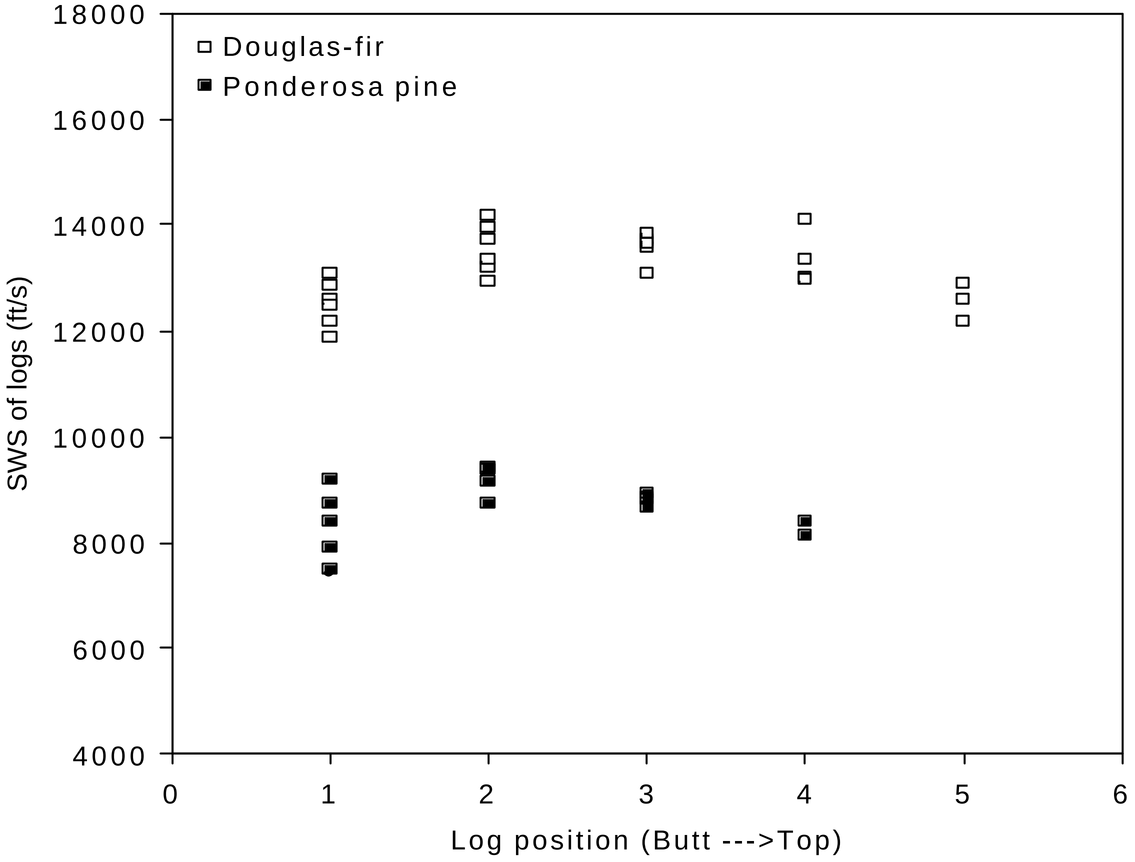
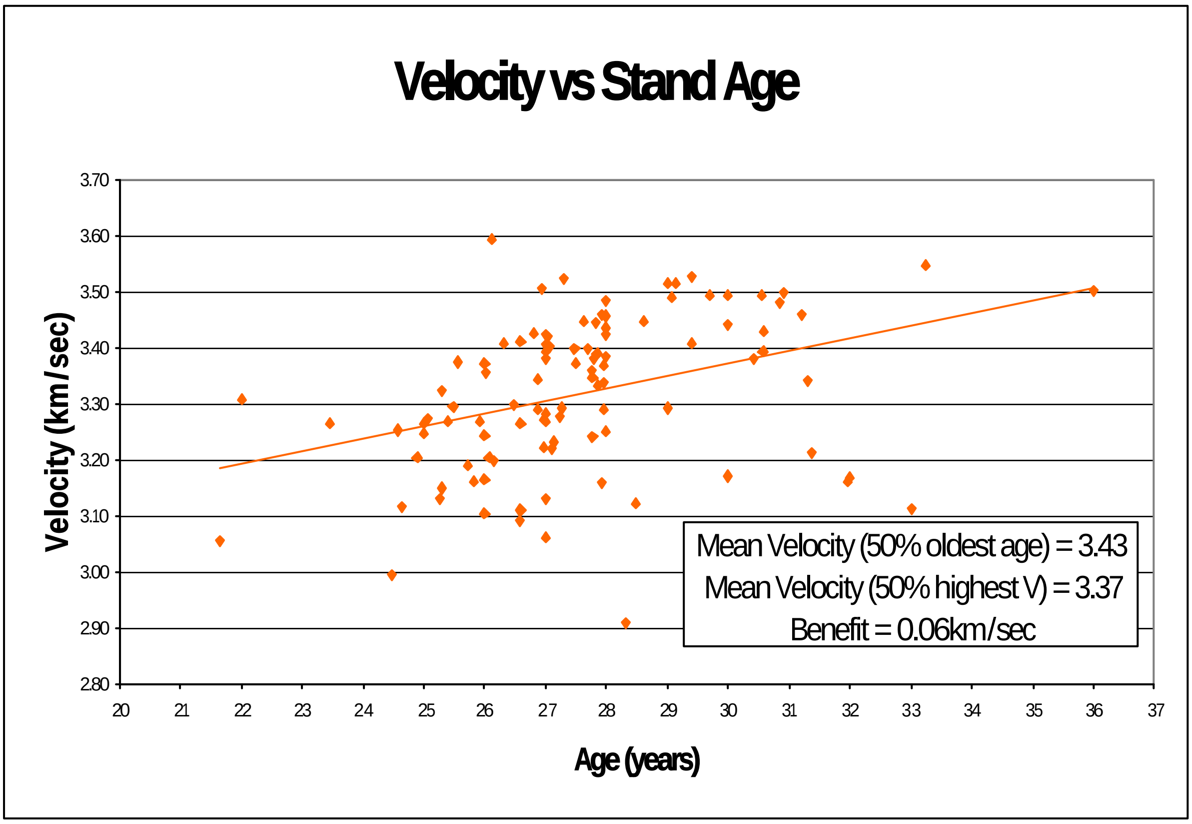
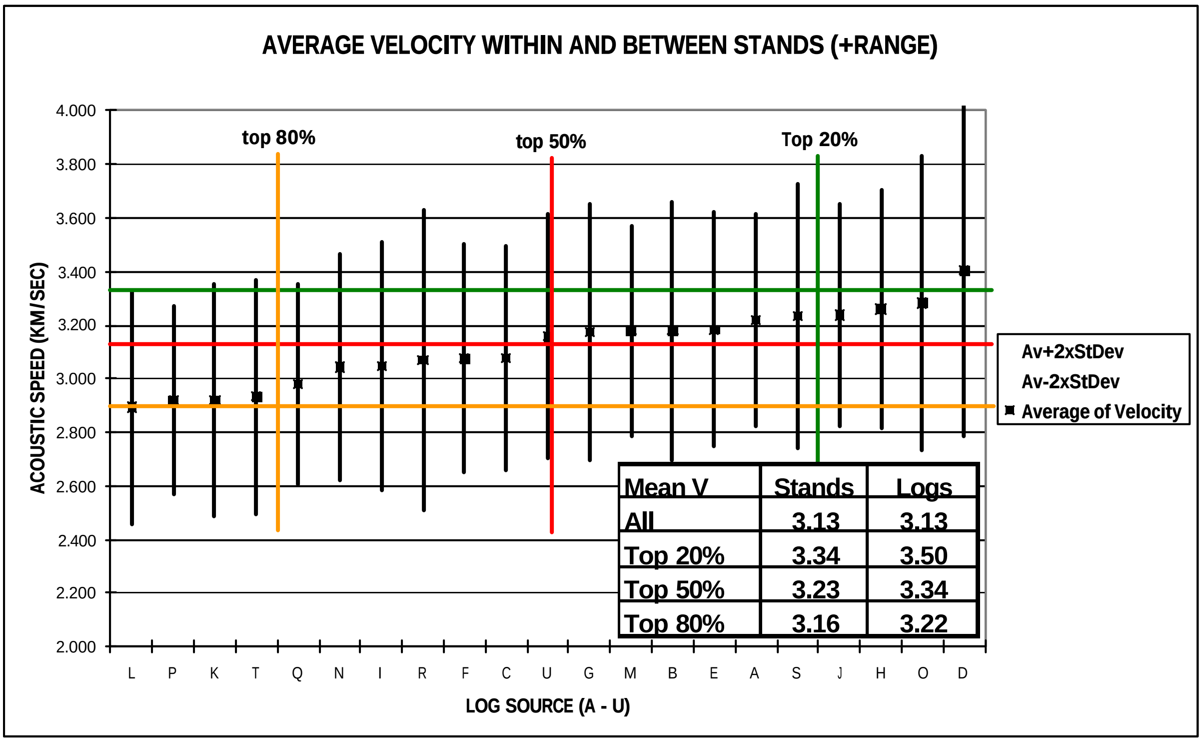


Figure 7. Director HM-200™ velocity (km/s) vs average log age in New Zealand radiata pine stands



Mean Velocity (50% oldest age) = 3.43
Mean Velocity (50% highest V) = 3.37
Benefit = 0.06km/sec

Figure 8. Mean and variation of Director HM-200™ velocity (km/s) for logs from New Zealand radiata pine stands



Mean V	Stands	Logs
All	3.13	3.13
Top 20%	3.34	3.50
Top 50%	3.23	3.34
Top 80%	3.16	3.22

Figure 9. The Director ST-300™

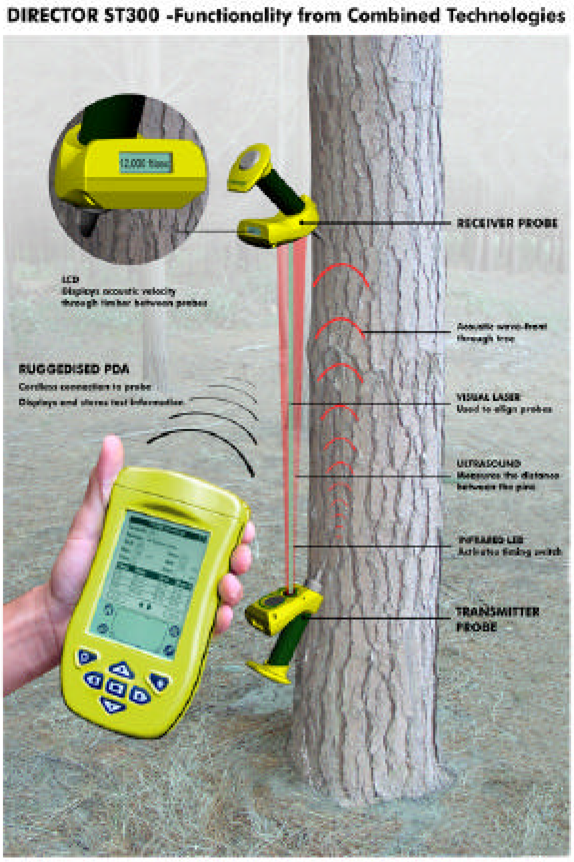


Figure 10. Relationship between measurement of acoustic speed of logs with the Director HM- 200™ and measurement of acoustic speed of parent trees with the Director ST-300™

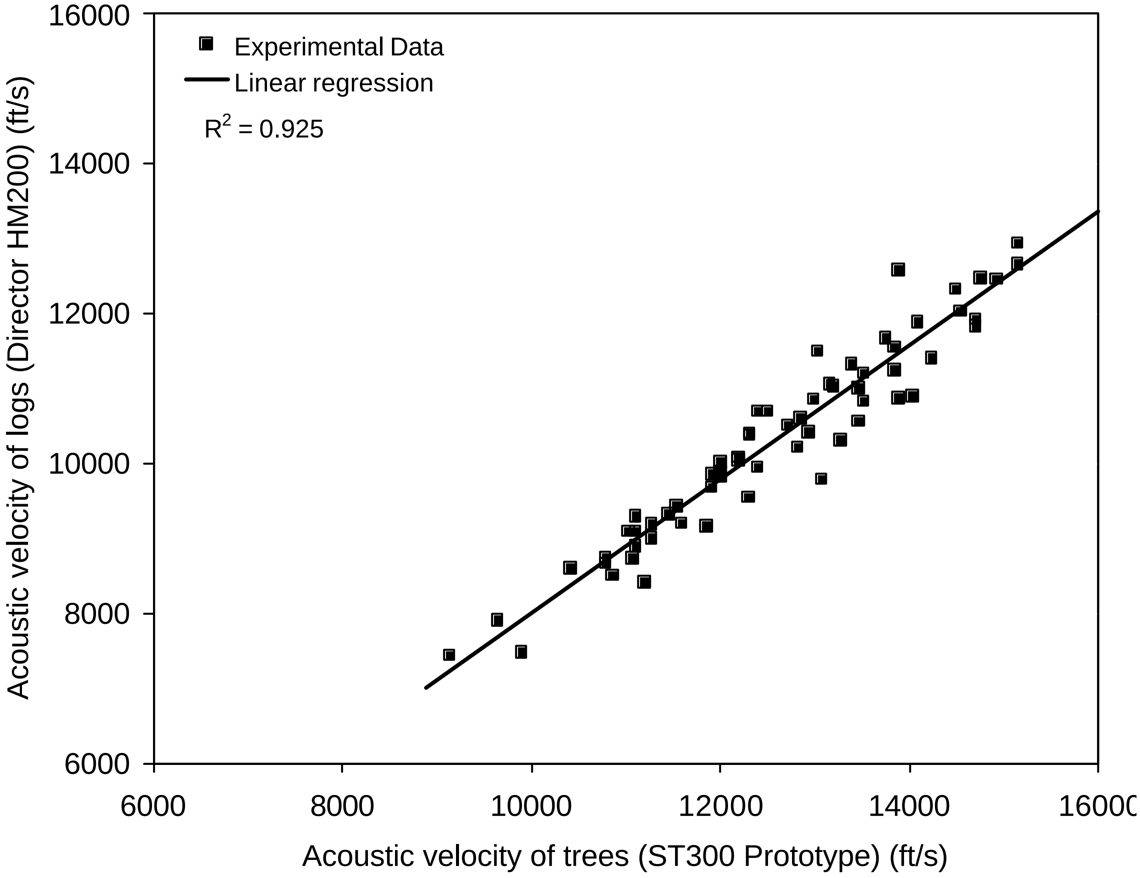
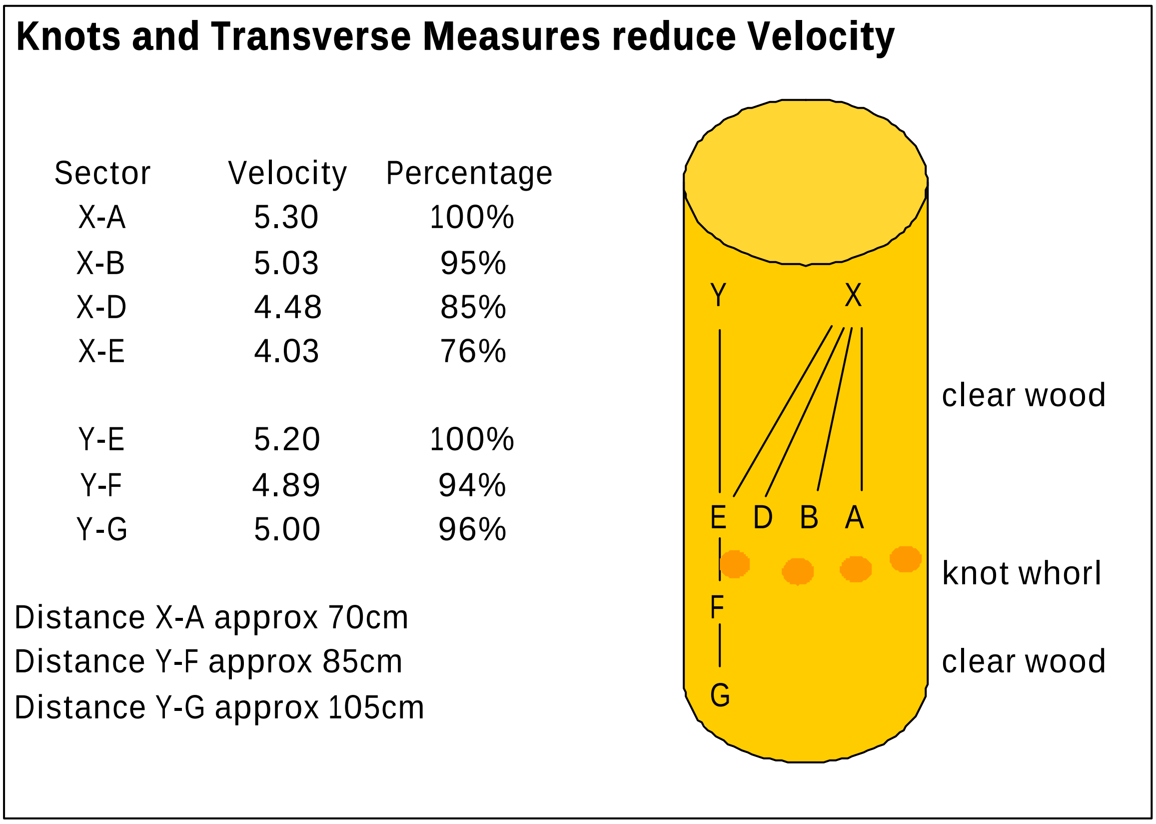


Figure 11. Effect of Director ST-300™ probe location and displacement on velocity in radiata pine



Knots and Transverse Measures reduce Velocity

Sector	Velocity	Percentage
X-A	5.30	100%
X-B	5.03	95%
X-D	4.48	85%
X-E	4.03	76%
Y-E	5.20	100%
Y-F	4.89	94%
Y-G	5.00	96%

Distance X-A approx 70cm
Distance Y-F approx 85cm
Distance Y-G approx 105cm

Figure 12. Beeville Loop Douglas-fir: effect of increasing sample size on mean and standard error of Director ST-300™ acoustic velocity

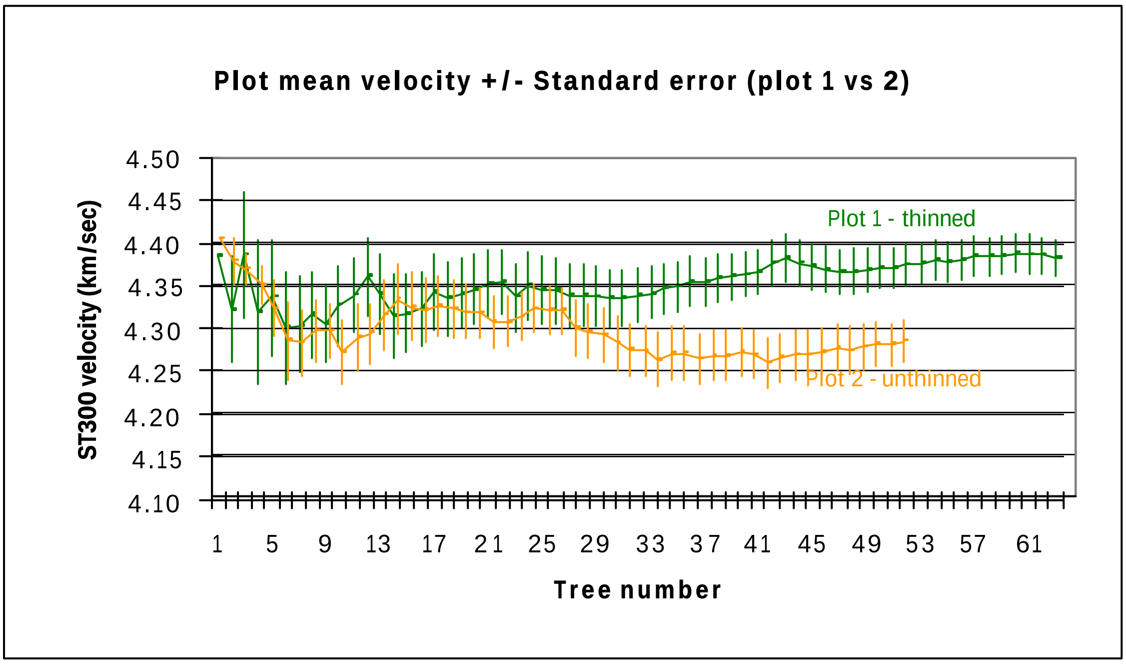


Figure 13. Beeville Loop Douglas-fir: effect of DBH of tree on Director ST-300™ velocity.

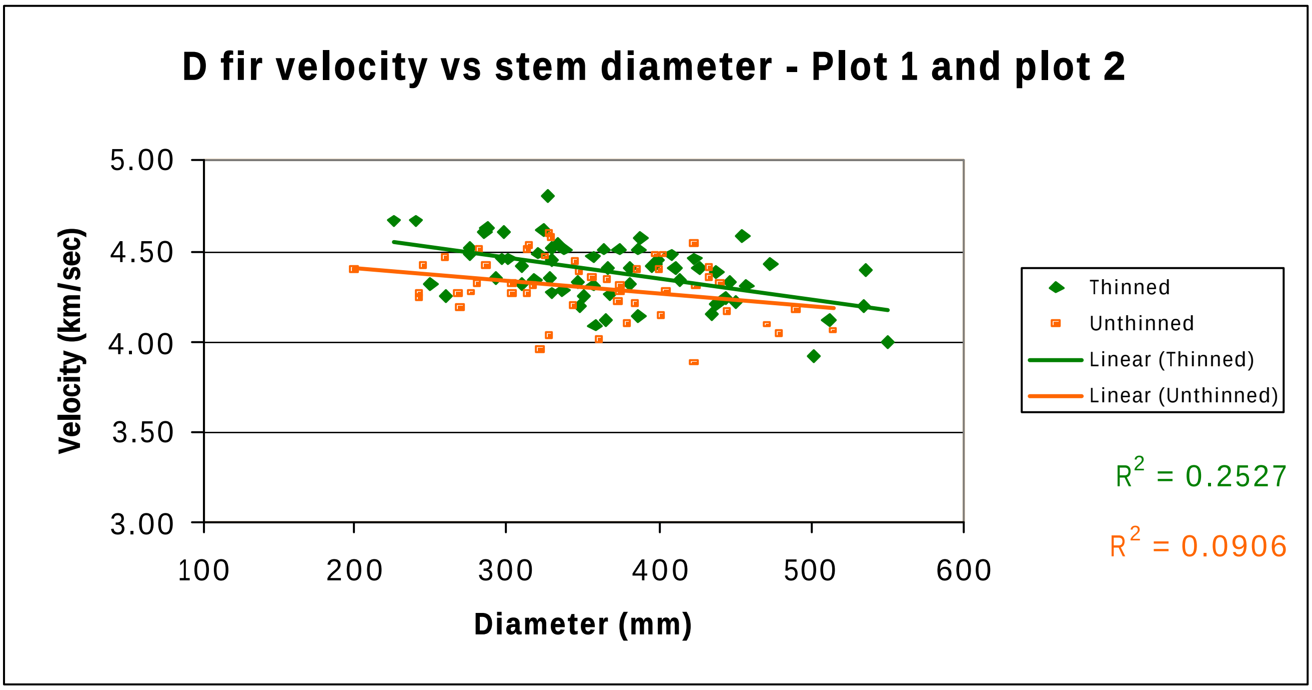


Figure 14. Beeville Loop Douglas-fir: effect of rings/inch on Director ST-300™ velocity

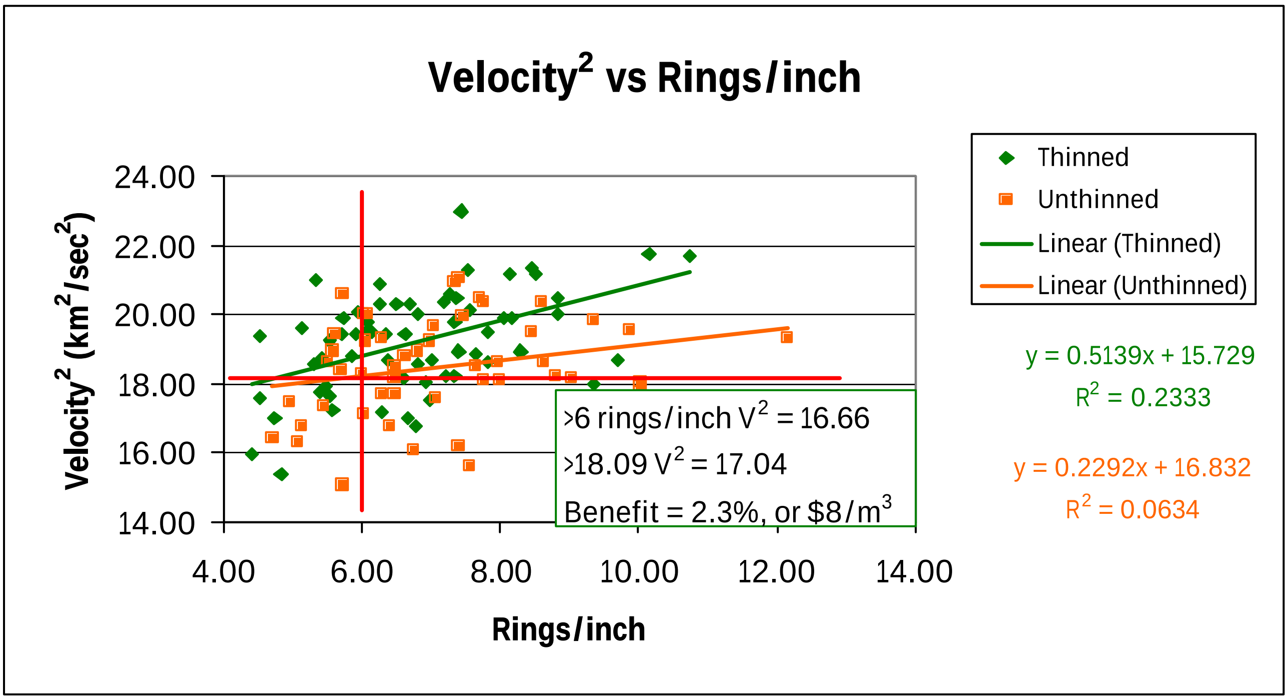


Figure 15. Direction of change in velocity associated with changes in wood basic density and moisture content in radiata pine

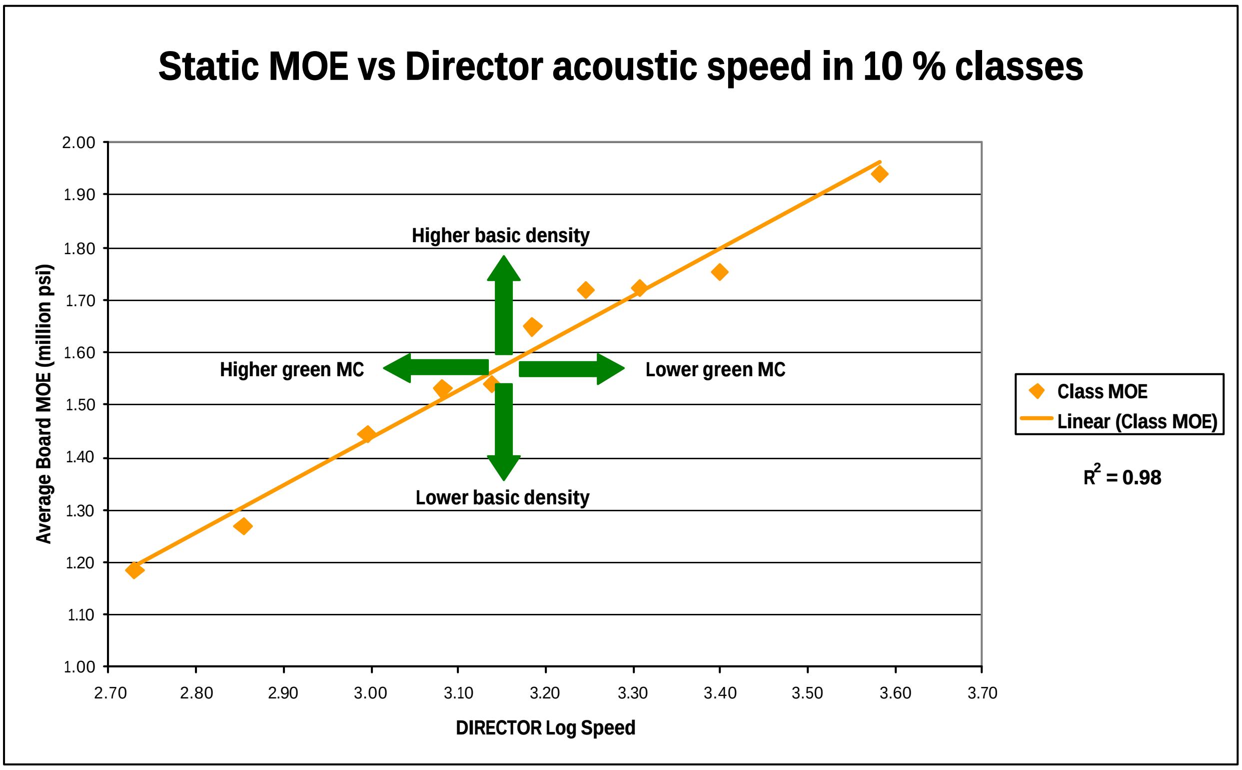


Figure 16. Effect of seasonal change in temperature and moisture content on velocity in radiata pine