Non-destructive wood evaluation: Operationalising a Resistograph in the South Island of New Zealand

A dissertation submitted in partial fulfilment for the requirements of a Bachelor of Forestry Science with Honours

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Abstract

In New Zealand, some sawmills are requesting logs above a stiffness grade, prompting forest managers to integrate stiffness-related data into their resource inventories. The IML PD400 resistograph provides a rapid and non-destructive means of sampling trees for density with studies demonstrating a high correlation between site-average estimates of basic density and site-average stiffness of board outturn at a sawmill.

OneFortyOne New Zealand has purchased a resistograph with the intention of using the estimates of basic density that it provides to segregate their stands for stiffness. This study investigated the sampling intensity necessary to achieve a probable limit of error (PLE) of 10-15 % for stand-level basic density estimates to help OneFortyOne operationalise the tool. High-intensity sampling was carried out across 15 stands that covered a range of environmental conditions. Simulations of the PLE equation were run in R with the sampling intensity systematically reduced to assess the influence on PLE.

Results suggested that sampling programs for stand-level estimates of basic density can be carried out at a very low sampling intensity. With only 10 total measurements across two sample plots, a PLE of less than 12.5% was achieved across the range of stands assessed. Increasing the sampling intensity to 30 total measurements across 15 plots returned a PLE of 2.5-5%. However, beyond this point, further increases to sampling intensity yielded diminishing returns.

Decisions relating to sampling intensity should be an operational call that takes into account the findings of this study alongside manager experience and knowledge of wood variability across a forest estate. Further research should be conducted to confirm the relationship between site-average estimates of basic density and site-average stiffness of board outturn. The IML PD400 and the processing software is a rapidly evolving space that will likely continue to be adopted as wood product customers demand higher quality logs.

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Contents

1. Introduction

1.1. Background

Forest inventory is used throughout New Zealand plantation forestry to better understand forest assets. A pre-harvest inventory generally provides an estimate of the recoverable volume by log grade, within a given margin of error, for a forest stand. This information is used for estate valuation, or operational and strategic planning such as harvest scheduling. Carrying out forest inventory is necessary as there are high levels of variability both within and between stands due to factors such as site conditions, silvicultural practices, and tree stock genetics. This variability can result in significant disparities in log volumes, log quality, and therefore financial returns between stands (Carson et al., 2014). Given the value of this information, inventories are a fundamental tool for effective forest management.

1.2. Purpose

At present, some forest management companies are facing increasing demands from their customers for higher quality structural sawlogs. These logs are used to make structural timber and engineered wood products, such as laminated veneer lumber. For these structural products, the most important wood quality characteristics are stiffness, strength, dimensional stability, and durability (Carson et al., 2014). Having an understanding of these internal wood quality characteristics in a forest prior to harvest can change the way a forest estate is managed. This might be through improved harvest scheduling to better meet customer requirements. For example, a forest management company could have supply agreements with a customer that requires logs above a certain stiffness grade. If the company knew that one of their stands was growing on average higher quality logs relative to another stand, they may choose to harvest the higher quality stand first to meet those supply agreements.

These internal wood quality characteristics are challenging to measure accurately and efficiently, particularly as part of a forest inventory where the trees are still standing and must not be damaged. Therefore, large scale sampling for these traits can be difficult, time consuming, and expensive. Several non-destructive evaluation (NDE) tools have been developed over the past 30 years for in-field sampling of standing trees for these internal wood quality characteristics. To gain an understanding of the current technology available, three of these methods have been reviewed in Section 1.3.

1.3. Technology Review

Acoustics

Acoustic devices are widely recognised by forest management and wood processing companies as a means of predicting wood stiffness. These devices function under the principle that the speed of sound waves in wood is influenced by the mechanical properties of wood such as stiffness (Toulmin & Raymond, 2007). Several tools such as the FAKOPP, IML Hammer, and TreeTap have been developed as non-destructive methods of sampling trees for wood stiffness. These devices are known as time-of-flight tools as they measure the time it takes for an induced acoustic stress wave to travel between two probes that are separated by a known distance in a tree (Figure 1). From this information an acoustic wave velocity (AWV) can be calculated, and an estimate of stiffness derived. Resonance devices such as HM200 are an alternative and more accurate acoustic measurement approach to predicting stiffness. These devices obtain an average value for the whole tree section whereas time of flight tools only measure the outermost rings where the wood is most stiff. However, resonance devices are destructive as they require the tree to be cut down to take a measurement (Dickson et al., 2004).

Time of flight tools have demonstrated having a significant positive relationship between AWV and wood stiffness. For example, using a TreeSonic tool Mora et al. (2009) found a strong relationship between the devices estimates of tree stiffness and actual board stiffness values through machine stress grading, though there was a bias and overestimation with these estimates, as found in other studies (Chauhan & Walker, 2006; Grabianowski et al., 2006; Mahon Jr et al., 2009). To properly correct for this, the data must be processed in a certain way and there must also be a reference method; this requires estimates of moisture content and green density (Moreno et al., 2011). However, Moreno et al. (2011) suggests that the strength of the relationships do not need to be as strong if the aim is to segregate logs based on stiffness, particularly at a stand-level. This idea has been demonstrated by Matheson et al. (2002) who, when using a Fakopp device, found a correlation between average board stiffness and estimates of AWV in standing radiata pine trees, indicating that the tool could be used to segregate logs by stiffness. This study also highlighted the potential value in segregation, which was substantial, particularly for a wood processing company.

At present time of flight tools are generally used as part of trials and for experiments and breeding programmes (Apiolaza, 2009; Matheson et al., 2008). They are less useful for routine inventories due to their lower sampling rate of approximately 50 samples per day (Schimleck et al., 2019).

Figure 1. A time-of-flight tool being used to measure acoustic wave velocity in a standing tree (Photo credit: Xiping Wang).

Pilodyn

Used for measuring wood properties, the Pilodyn is a portable device that has a rapid sampling rate. The tool works by striking a spring-loaded pin into the stem of the tree and measuring the extent by which that pin penetrates under a known force (Cown, 1978). The depth of penetration is negatively correlated with wood specific gravity, as demonstrated by Micko et al. (1982) in a study investigating Pilodyn measurements on white spruce trees. The devices measurements are therefore correlated with density, a relationship that several studies have found to be strong. For example, Cown (1978) found Pilodyn readings to have a strong relationship with density in radiata pine. Similarly, Chen et al. (2015) found a strong relationship of Pilodyn measurements and density in Norway Spruce. Several other studies have confirmed this relationship (Taylor, 1981; Wu et al., 2010).

Despite being a rapid, and relatively accurate means of estimating tree density, the efficacy of the Pilodyn for large scale sampling can be restricted. To achieve a reliable measurement, a portion of bark should be removed so that the pin can strike the wood directly (Figure 2). On larger, or thicker barked trees, usage of the tool is often slower, though this will depend on the species and genetics. Additionally, the Pilodyn only penetrates up to a maximum of 20mm deep meaning that the results are only representative of the outermost rings and not the mean density of the entire stem (Cown, 1978). Furthermore, the tool is currently unable to store measurements digitally meaning that values would have to be written down or manually input onto a separate device. Based on a review of a number of studies, Schimleck et al. (2019) suggests that approximately 800 younger trees can be sampled per day and 150 per day on older and thicker barked trees.

Figure 2. Pilodyn in use. Note the removal of bark (photo credit: Shan Gao)

Resistograph

The resistograph was first developed over 30 years ago as a means of identifying decay in trees and poles. During this period, studies indicated that measurements were strongly correlated with wood density (Rinn et al., 1996). The device works by driving a drilling needle into a tree under a constant feed speed and rotation rate (RPM) while measuring the change in resistance to turning (torque) every 0.1 mm. Measurements provide a radial trace that represents a density profile in the tree under the principle that drilling resistance is directly related to wood density.

Figure 3. IML PD400 resistograph in use.

In recent years, this technology has been improved to provide more reliable measurements and higher correlations between estimates and actual values, leading to a more widespread adoption of the device for assessing density. As of 2023, the IML PD400 is the most recent resistograph model (Figure 3). This device has largely been adopted in Australia and New Zealand as an operational means of assessing basic density. At a site-average level, Downes et al. (2016) has demonstrated resistograph estimates of density explaining over 80% of the variance in actual density. At a tree level, previous studies have indicated a weaker positive correlation between resistograph density estimates and actual tree density (Gwaze & Stevenson, 2008; Isik & Li, 2003). More recently, Downes et al. (2020) has suggested that their current work (unpublished data) is indicating that resistograph density typically explains between 65-88% of the variance in actual tree density at an individual tree level.

An online data processing software for the resistograph has been a topic of research and development in recent years. Alongside processing each measurement, the software provides an estimate of modulus of elasticity (MOE) and AWV through various predictive algorithms. MOE is a property that represents the stiffness or rigidity of an object. Using this software, Downes et al. (2020) have demonstrated that site-mean level estimates of density and MOE are strongly correlated with site-mean actual values of log and board MOE, showing that the tool can be used to identify one stand as being higher stiffness than another (Figure 4). It must be emphasised that this correlation is only at a site-average level, and the relationship between actual MOE and resistograph estimates of MOE will quickly weaken if assessing on a plot or individual tree level. Through this software, the resistograph can also provide estimates of AWV, ring count, and diameter, among several other variables. See appendix (a) for full list of variables predicted by resistograph software.

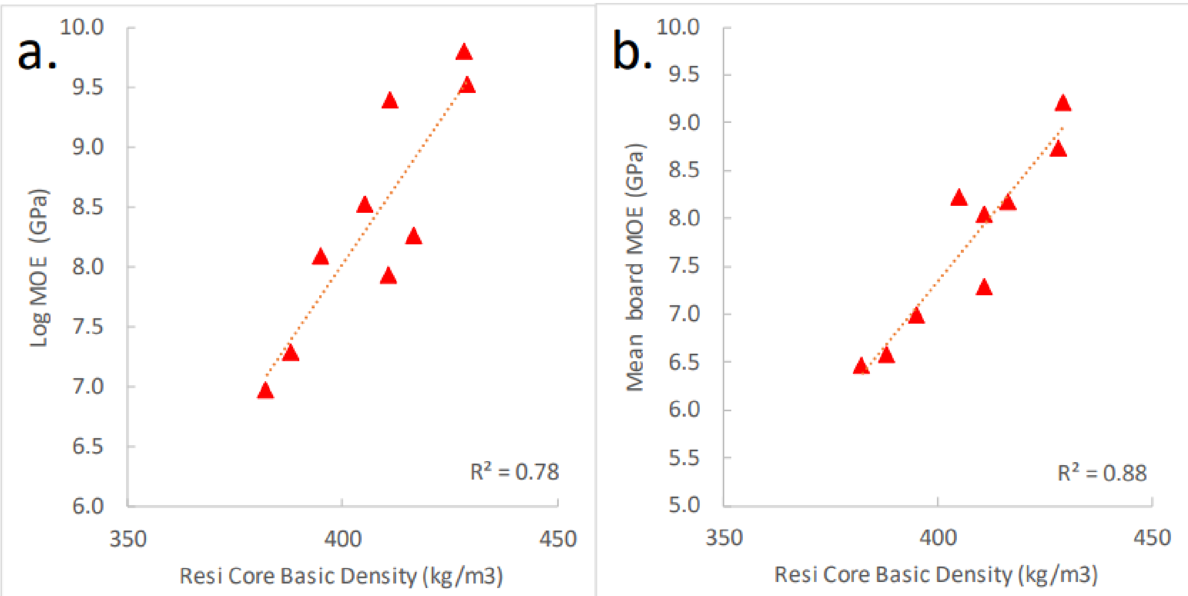

Figure 4. Relationship between resistograph estimates of basic density and log MOE (a) and mean board MOE (b). Note. From "Validated Softwood Stiffness Predictions Using IML-Resistograph and eCambium," by G. Downes, D. Drew, and D. Lee, 2020.

The resistograph has a high sample rate of 300 – 400 trees per day (under ideal circumstances) and has been suggested to be a more rapid and lower cost option to alternative wood density measuring devices (Schimleck et al., 2019). Studies such as Fundova et al. (2019) and Fundova et al. (2020) also found that the resistograph was an efficient and effective device relative to other NDE devices, in this case as an approach for the selection of trees for stiffness in breeding programs.

1.4. Analysis for OneFortyOne

OneFortyOne New Zealand, a forest management company based in the Nelson/Marlborough region, would like to integrate wood stiffness and density into their harvest scheduling. This initiative comes from the recent demands from one of their local customers who would now like to receive logs above a certain stiffness threshold.

At present, OneFortyOne has limited knowledge of the wood quality across their estate. They know that some forests tend to grow higher quality trees; however, within those forests, they have no method of determining if an unharvested stand is growing higher quality logs compared to another. If OneFortyOne can gain an understanding of the internal wood quality characteristics within their stands ahead of harvest, they hope to better meet the demands of their customers and extract the most value out of their wood resource.

OneFortyOne has purchased a resistograph with the intention to take samples as part of a pre-harvest inventory and segregate their stands for site-average stiffness based on the resistograph site-average density. A challenge in forest sampling is finding the right compromise between gaining sufficient data to accurately assess the mean and the variability of a specific property, and managing the cost of sampling efforts and subsequent analysis (Downes et al., 1997). OneFortyOne first needs to come up with a sampling method, part of which involves determining the sampling intensity that they should use the resistograph at, which is the primary focus of this research. OneFortyOne are also interested in investigating if there are any trends between the resistograph estimates of density and site characteristics, this is the secondary "bonus" element of this research.

1.5. Research Questions

- What is the minimum number of sample trees necessary to achieve a probable limit of error of 10-15% for site-average density estimates?
- Are there any indications of trends between resistograph estimates of density and MOE and site factors?

2. Methodology

2.1. Site Selection

Across the OneFortyOne estate 15 stands between age 24 and 28 were selected (Table 1). These stands each had a pre-harvest inventory carried out recently meaning that sample plots were already set up, and tree/plot information was available. In selecting these stands, a range of environmental conditions were covered and used in an attempt to maximise the range in expected site mean wood quality. Five different blocks were chosen with three stands selected to represent each block.

Table 1. Elevation, Rainfall, Regime, and Number of Trees Sampled Across the 15 Stands Selected for this Study. Each Block is Represented by Three Stands.

Block name	Elevation (m)	Rainfall (mm)	Regime	No. trees sampled
Inwoods	648	1627	Structural	60
	782	1450	Structural	60
	592	1386	Structural	66
Smiths	319	1625	Structural	68
	301	1375	Structural	60
	326	1375	Structural	62
Norris	296	1125	Clearwood	72
	449	1125	Clearwood	69
	442	1125	Clearwood	66
Western Boundary	606	1375	Untended	145
	554	1375	Structural	70
	580	1375	Structural	150
Berryman’s	303	1125	Structural	73
	299	1125	Structural	65
	328	1434	Structural	67
Range	**296 - 782**	**1125 - 1627**		**60 - 145**

2.2. Sampling Method

2.2.1. Pre-Harvest Inventory

Each stand had a pre-harvest inventory carried out by a contractor within the last five years, using the following general procedure. Each plot was established by marking a plot centre and then determining which trees fall within the plot according to a radius scaled to achieve a plot size of between 0.02–0.06 hectares. The plot coordinates were recorded, and site characteristics such as slope were noted. Each tree was measured for diameter at breast height (DBH) with 2-5 trees measured for height. Height trees had to be of normal form, and reasonably vertical. Cruising information for sweep, branching and defects was taken for all trees in the plot unless they were dead, or windblown and flat on the ground. Each tree was given a number that was marked with spray paint. A stocking was calculated from the number of trees within the plot area.

The following site attributes were then obtained for each plot using geographical information systems:

- Mean annual rainfall.
- Elevation.
- Aspect.
- Soil type.
- Stand age.

2.2.2. Resistograph Sampling

<u>Identification and Sampling Intensity</u>

Sampling of the first 12 stands was carried out between January and February of 2023. The remaining 3 stands were sampled in July of 2023. Having arrived at a stand, Avenza maps was used to navigate between sample plots; these plots were the same as those used in recent pre-harvest inventories. Each plot was already numbered and this value, alongside the tree number and stand ID was put into an ID field on the resistograph. It was important to update this field with each tree that was sampled as the results would later be analysed against the tree results of the pre-harvest inventory. Between 60-150 samples were taken at each stand; this was determined as being a high sampling intensity based on OneFortyOne's current aim of sampling 20-30 height trees per stand when carrying out resource inventory. Initially, between 2-10 trees were measured per plot; this differed in response to the number of plots per stand as the goal was to achieve 60 samples total. Upon a review of the data, the second series of stands were measured at a minimum of 10 trees per plot to examine between-plot variability. A total of 18 days of field work was carried out with most stands taking 1 day to complete.

Positioning

When measuring each tree, it was important to line the resistograph up with the centre of the tree so that the needle went through the core wood and ideally the pith. Each sample was taken at a height of 1.4m on the stem. A 50cm range (± 25 cm) was allowed for movement of the entry position so that any branches, knots, or other defects could be avoided as these can cause unusual readings on the resistograph that do not represent the mean characteristics of the stem. The length of the tool was positioned perpendicular to the vertical direction of the stem (Figure 5). To ensure this, the operator had a second person acting as a spotter, advising them of their positioning on the tree. Where trees were located on a hill, measurements were taken perpendicular to the direction of the slope to ensure that sampling was consistent.

Figure 5. Positioning of IML PD400 Resistograph on tree. Left showing the instrument at 90-degree angle. Right showing tool aimed for centre of stem and away from knots.

<u>Taking the measurement</u>

Having established a satisfactory position on the tree, drilling would be initiated, and a trace would be taken. The device was set at a feed speed of 200 cm/min and an rpm of 2500. These values were suggested by the manufacturer as being a good trade-off between sampling speed and battery life when sampling radiata pine. The feed speed and rpm can be adjusted in response to the sampling speed, or the type of tree being sampled, e.g., higher rpm and lower feed speed for a denser tree.

In trees less than 40 cm in diameter the needle extends out the other side of the tree. The user has the option to retract the needle upon exit, however, for each trace it was left to extend at least an additional 2 cm. This was done to ensure that any needle drag could be measured and corrected for in the web app software, improving the accuracy of measurements. The software assumes a linear accumulation of friction from the point where the needle enters the tree through to the point where it exits. This relationship is unlikely to be perfectly linear however it provides a good approximation (Downes et al., 2022).

Each trace was checked immediately after measurement and if the trace looked unusual, it would be deleted straight away and remeasured. An unsatisfactory trace might have an irregular spike in amplitude or no clear pith position (Figure 6). Every 5-10 trees the nose cap of the tool was taken off and cleared of debris. This was an important step as the needle can pull in debris as it retracts which can affect the telescopic system. It was also important to keep track of the total number of traces that each needle has taken as, with time, the needle becomes blunt, affecting the accuracy of the measurement. The needle was replaced once during this study after 1000 traces had been taken. The needle was also inspected periodically throughout the day to make sure it wasn't bent.

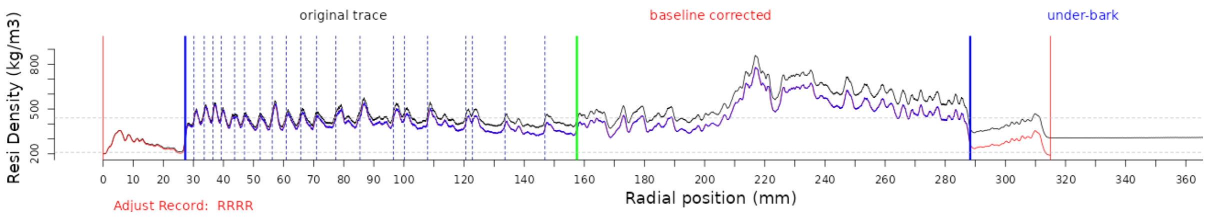

Figure 6. Unsatisfactory trace.

2.3. Calibration

Resistographs can be calibrated to improve the accuracy of measurements. The rationale for calibration comes from a study that found that there is bias between resistograph instruments (Downes et al., 2020). The study compared three different devices (of the exact same model) and found that, while the correlation between actual basic density and resistograph estimates of density were strong, there were clear differences between the slope and intercepts of each regression equation. Unique slopes and intercepts (to each machine) can be input to the processing software to calibrate a device.

The instrument used in this study was calibrated as part of the sampling work. Across two of the stands, 64 outerwood core samples were taken using a hand corer; these were 50mm long and 5mm in diameter. These core samples were measured for basic density using the maximum moisture content method (Smith, 1954). The actual basic density values were plotted against the resistograph estimates of basic density to form a regression with the slope and intercept of this regression being used as inputs in the web application to calibrate the machine.

2.4. Data Analysis

2.4.1. Web Application

Traces were uploaded to a web application (Forest Quality Pty Ltd, 2023) where they are processed to provide estimates of internal wood properties such as density, AWV and MOE. The web application automatically assigns pith and annual ring positions upon the upload of a trace; however, there is the option for a user to manually allocate these positions. Manual pith and year ring allocation was carried out for this analysis. Below is a general explanation of how density, AWV and MOE are estimated in the software. A more in-depth explanation can be found in Downes et al. (2020).

- **Density:** Resistograph torque values are first standardised to a common range to account for different sampling conditions (feed speed and rpm). A baseline linear correction is then applied to account for needle drag. Lastly, the torque values are converted to basic density with a simple linear equation that uses the calibration rSlope and rIntercept coefficients.

- **Predicted AWV:** A number of predictive equations are used to estimate AWV, each draw from several of the resistograph trace variables in an attempt to explain independent variance in AWV. It should be noted that values are not expected to be accurate or precise, particularly for a single measurement. The idea is that these values may help to explain variance in MOE on a site-average level. These algorithms are a large focus in development at present.
- **Predicted MOE:** To predict MOE, estimated density and AWV values are used in equation 1. Similar to resistograph predicted AWV, improving predicted MOE is also a focus for the developers of the web application software.

$$MOE = PredictedAWV^2 * CoreDensity * 2$$

Equation 1. Modulus of elasticity equation used in web app software.

The web application also provides the option to select a model for the prediction of AWV. For this analysis the “density” model was used. This model is sensitive to changes in pith and year ring position.

2.4.2. Probable Limit of Error

In New Zealand plantation forestry, the precision of an estimate, e.g., total recoverable volume, is often expressed by the probable limit of error (PLE). This provides a range in which an estimate may fall within a given level of confidence, which is typically 95%. For example, if the mean total recoverable volume of a stand is 700 cubic meters per hectare, and the PLE is 10%, 95 times out of 100 we would expect the true population mean value to be within 630–770 cubic meters per hectare. The PLE will be dependent on the natural variation within each stand, alongside the sampling intensity (e.g., number of plots).

$$PLE = \frac{Students\ t * Standard\ Error}{Sample\ Mean} * 100$$

Equation 2. Probable limit of error

Forest managers will have a level of error that they deem acceptable for their sample estimates. Therefore, to save costs when carrying out an inventory, sampling intensity will often be scaled to meet this maximum level of error. The PLE equation (Equation 2) was used for this analysis to determine an operational sampling intensity for OneFortyOne to implement when using the resistograph. Samples were input to this equation and then analysed under a Monte Carlo simulation (Section 2.4.3).

2.4.3. Data Analysis – Sampling Intensity

To determine the operational sampling intensity a Monte Carlo simulation was built in R (R Core Team, 2023) using the dplyr and ggplot2 packages for data management and plotting (Wickham, 2016; Wickham et al., 2023). A Monte Carlo simulation works by running a model a number of times, each with a randomly selected sample from a dataset. This will provide the range of possible outcomes and the probability that each outcome will occur (Knoke et al., 2021).

For this analysis a model was designed to run the PLE equation (Equation 2) to obtain a value of PLE for each stand. The model also allows a user to specify a series of different sampling combinations (e.g., 30 plots of 2 trees, 20 plots of 3 trees etc) and different total sample sizes to gain a sense of how sampling strategies may effect stand PLE. For this analysis, 100 iterations of each plot and tree combination were run to establish a large distribution of possible outcomes. The mean value of these iterations were used in graphing the results. The sample size began at 60 trees and was progressively lowered to 10 trees for each stand. The plot and tree combinations under each total sample size can be found in appendix (b). This method provides a sense of the optimal sampling intensity, as well as a degree of confidence in how truly representative each sample size is.

2.4.4. Data Analysis - Trend Analysis

The effect of forest management practises and environmental factors on basic density was modelled using linear mixed-effects regression. This type of model allows for the incorporation of both random and fixed effects. Plot mean values were calculated for each of the response and predictor variables. In separate models resistograph estimates of basic density and MOE were treated as response variables with elevation, rainfall, soil type, aspect, slenderness, regime, and slope treated as predictor variables. Stand was used as a random effect variable to account for the differences between stands, thus enhancing the estimates of the fixed effects of the predictor variables. Models were built in R using the lme4 package (Bates et al., 2015).

2.5. Limitations and Assumptions

One limitation of this study was in the calibration of the device. As noted in section 2.3, this device was calibrated using 64 core samples across 2 different sites. This is a small range and does not calibrate the tool for the full expected range seen in the estate. Core samples should have been taken across more sites to improve the calibration. This limitation should not affect the primary goal of determining a sampling intensity as the within-stand variability is still being captured.

A second limitation was that samples were taken at different times of the year, meaning the measurements were potentially influenced by different environmental conditions of alternate seasons. Research by Walach et al. (2015) suggests that this could be an issue due to wood moisture content having a significant effect on the results of non-destructive sampling. A study by Lin et al. (2003) found this to be the case, with results showing that drilling resistance values decrease with decreasing moisture content. However, these results oppose the results of a study by Chan et al. (2012) who found that while wood moisture content will influence resistograph drilling resistance, the effects are small and statistically insignificant. The study suggested that only extreme differences such as a drought would have the potential to significantly impact the moisture content in the wood. During the summer period when the first set of samples were taken there was a particularly high amount of rainfall (75 mm), exceeding that of the amount in July (33.6 mm) when the second set of samples were taken (Tasman District Council, 2023). Therefore, the effect of seasonal differences is unlikely to have any impact on the results of this study.

A third limitation is the limited amount of research and literature validating the ability of the resistograph to predict site-average stiffness based on density. While the results of the study by Downes et al. (2020) show promise, it is the only study available when this report is being written. Additionally, the study builds a regression model based on just 9 site-average estimates of density, whereas a minimum of 15 would be preferable. Therefore, the results of this research are built on the assumption that the tool is capable of providing density data that can be used to identify site-average differences in stiffness.

3. Results and Discussion

3.1. Sampling Intensity

The results show that as the total number of measurements increases, the precision associated with a stand level estimate of basic density increases. This same trend continues with an increase in the number of plots sampled per stand (Figure 7). Each of these trends are to be expected; this is because a lower sample number results in a higher student's t-value and, in calculating PLE, the t-value is multiplied by the standard error. Therefore, a lower sample number should yield a higher PLE. As demonstrated in Figure 8, Student's t-value increases substantially once the number of samples falls below 15. This trend is reflected in the results of this study where PLE tends to increase more quickly when there are less than 15 sample plots.

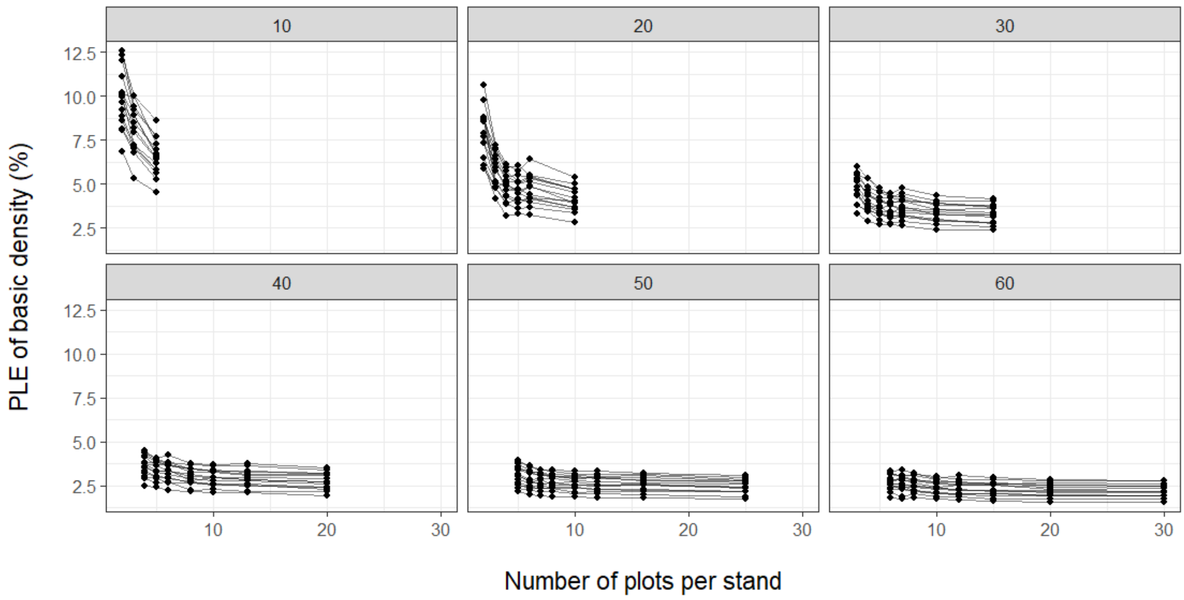

Figure 7. Effect of sampling intensity on PLE of stand level estimates of basic density. Each point represents a PLE value (reflected on Y axis). Each box represents a different total number of measurements (number in grey)

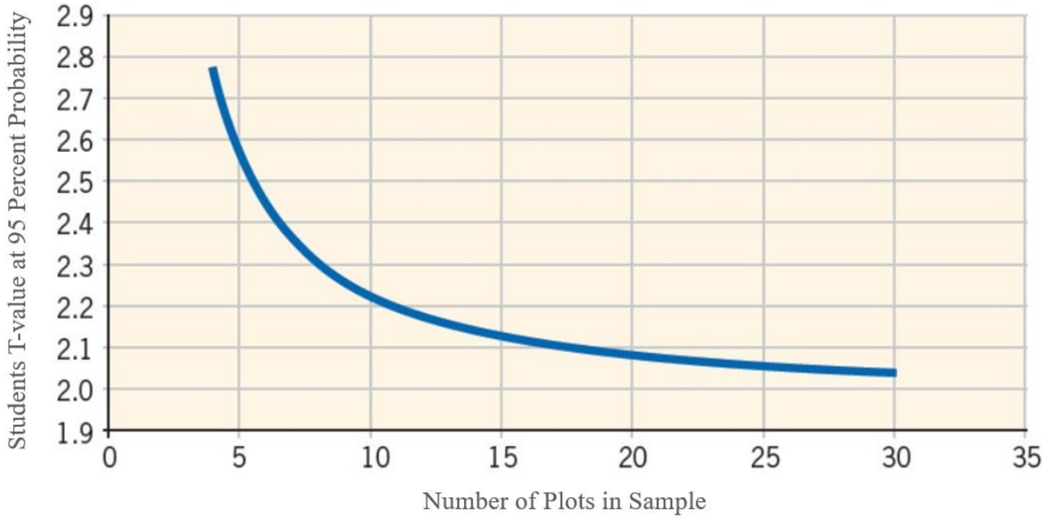

Figure 8. Students T-value at 95% Probability vs Number of Plots. Note. From “The Science or Art of Forest Inventory” by A. Bell, August 2016, New Zealand Tree Grower

Interestingly, the PLE for basic density is quite low, even at a low sampling intensity of fewer than 10 samples (high t-value). This suggests that the within-stand variability for density is very low. The sampling intensity where a PLE of 10% was achieved for basic density would result in a much greater PLE when sampling for total recoverable volume (derived from height and diameter). To investigate why these differences exist, a coefficient of variation was calculated for the basic density, height, and DBH variables in the dataset. This value illustrates the extent of the variability that each variable demonstrates for each stand.

Table 2. Coefficient of variation of DBH, height, and resistograph estimates of basic density for each stand measured in this project.

		Coefficient of variation (%)	
Stand ID	**DBH**	**Height**	**Basic density**
751-106-23	8.3	4.2	5.3
751-172-3	9.8	3.3	5.5
751-172-6	12.6	5.1	3.8
751-182-1	11.0	3.9	6.7
751-191-10	20.1	7.0	6.1
751-191-9	18.2	4.4	5.9
751-194-8	6.1	3.9	2.9
751-201-1	10.8	5.6	3.5
751-201-3	12.2	14.0	5.6
751-202-1	7.0	2.9	3.4
751-45-4	10.3	2.4	3.7
751-55-16	11.9	3.9	5.3
751-70-14	14.5	4.4	6.3
751-70-15	13.1	5.5	5.1
751-89-12	10.1	4.2	7.0
Mean	**11.7**	**5.0**	**5.1**

On average, the coefficient of variation for DBH was more than twice that of height and density. (Table 2). This is important to understand as the number of samples required to accurately assess each different attribute will be influenced by this variability. An attribute that has higher variability will require higher sample numbers than a less variable attribute.

This makes sense as the more variation an attribute has, the less likely an individual sample is to accurately reflect the true mean value (Downes et al., 1997). Given that density is less variable than DBH, fewer samples are needed within each stand to achieve the same PLE when calculating total recoverable volume, as suggested by Figure 7.

These trends could be explained by the type of factors that influence tree density. Studies show that environmental factors such as soil nutrition and mean annual temperature account for the largest variation in tree density (Beets et al., 2007; Palmer et al., 2013). Growth rate, which can be associated with silvicultural treatments, has also been negatively correlated with density, though this relationship is weaker (Cown, 1973). Each of these factors that influence wood density are more affected by differences between sites, as opposed to within sites. In comparison, while diameter growth (DBH) is also influenced by these factors, it is further influenced by factors such as competition, which can vary substantially within a stand. This has been suggested by Lasserre et al. (2009) where it was found that stocking (essentially competition) significantly influences tree diameter, but not height or density.

3.2. Trend Analysis

3.2.1. Density Model

A matrix of scatter plots and correlations was created to explore if there were any trends in the data (Figure 9). The matrix suggests that plot average density estimates could be positively correlated with plot average stem slenderness. Regime also appears to impact density, with the highest density trees falling under the untended regime. Unexpectedly, there was no indication of a relationship between elevation and density. A trend was expected here as previous studies found that temperature, a variable that decreases with elevation, has a positive correlation with density (Beets et al., 2007). The lack of relationship found in this study could be attributed to the relatively small range in elevation (230–850 m) between stands.

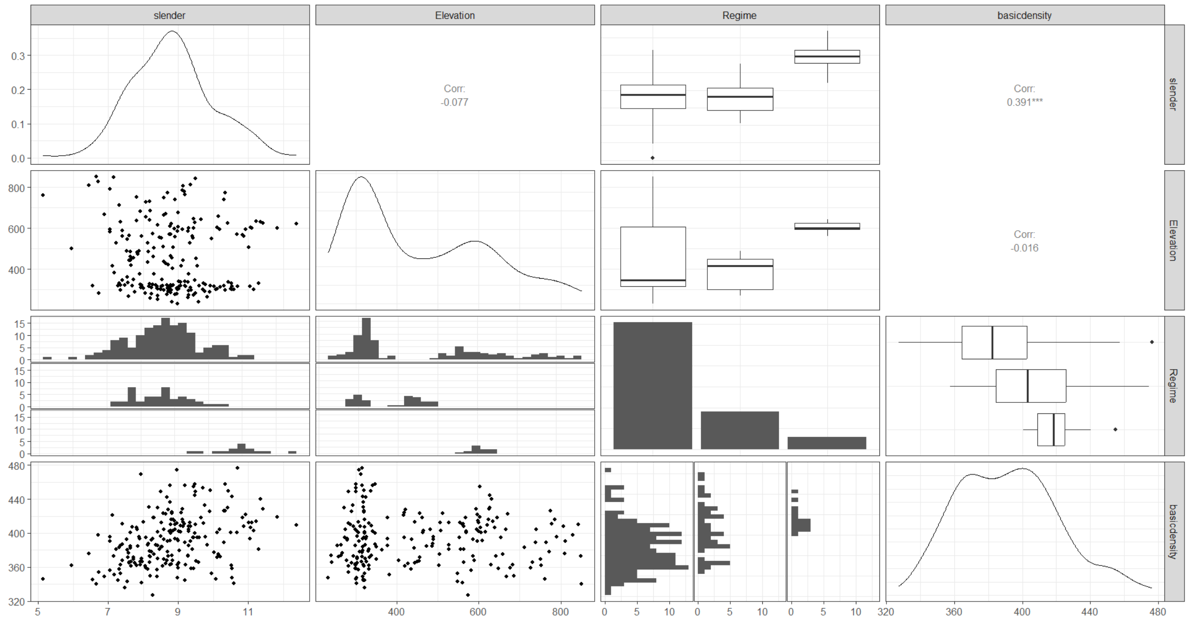

Figure 9. Matrix of scatter plots and correlations for tree slenderness, elevation, regime, and basic density.

The slender and regime variables were investigated further to determine the significance of their effects on density. It was found that the effect of the slender variable was highly significant with a p value of <0.001. The idea that slenderness has an effect on tree density has been suggested by Groot and Cortini (2017). However, this result could be due to a stocking effect as an increase in slenderness has been associated with higher stockings (Waghorn et al., 2007; Warren et al., 2009), and higher stockings associated with increased density (Beets et al., 2007; Watt et al., 2011). Conversely, Lasserre et al. (2009), reported that, while stocking affected MOE, there was no significant effect on tree density. Regime was found to be insignificant as a predictor however it was close to the significance threshold with a P value of 0.054. As previously noted, some studies have found that stocking may have an effect on density. Each of the three regimes assessed had a different stocking which may be the reason for these results almost being significant.

Interestingly, the slenderness in the untended regime was negatively correlated with density, unlike the structural and clearwood regimes (Figure 10). Beyond potential differences in genetics or environmental conditions between stands, there is no clear reason for why this trend was observed. A full model containing aspect, geological information, slope, and rainfall was also built, however the effects of these variables on tree density were negligible.

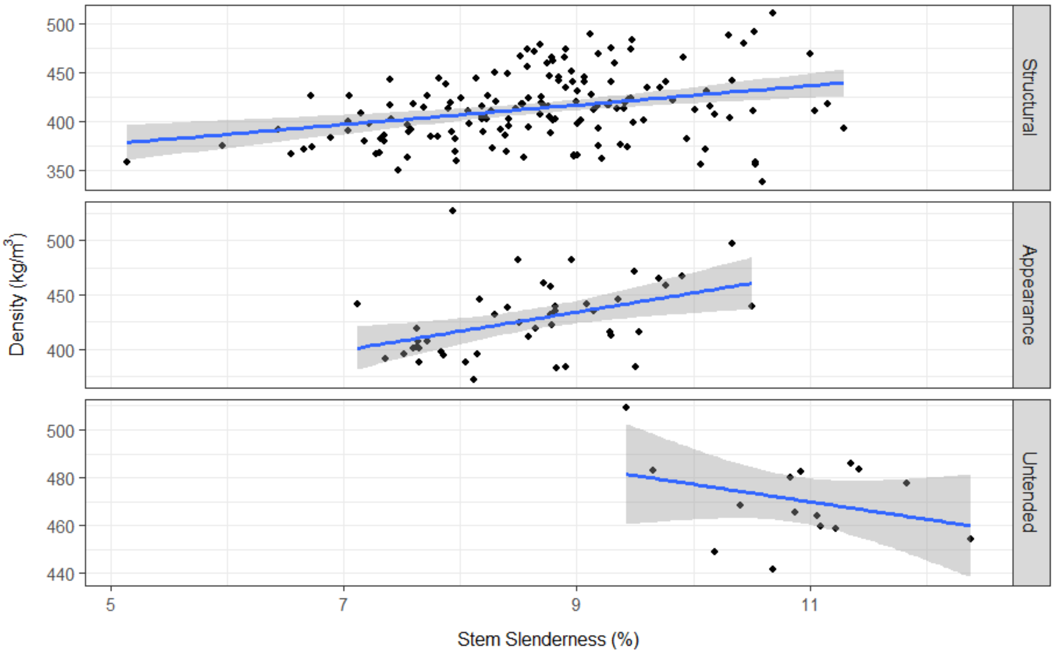

Figure 10. Regression between stem slenderness (%) and basic density (Kg/m^3) by regime.

3.2.2. Modulus of Elasticity Model

A second matrix was created to explore the effects of the same variables on the resistograph estimates of MOE, to see if the trends were the same as that for density. As expected, these results were similar to that of density, with stem slenderness and regime being the only variables indicating a trend with MOE (Figure 11). This was expected as the estimates of MOE are predominantly influenced by density variation, as previously noted, and explained by Downes et al. (2020).

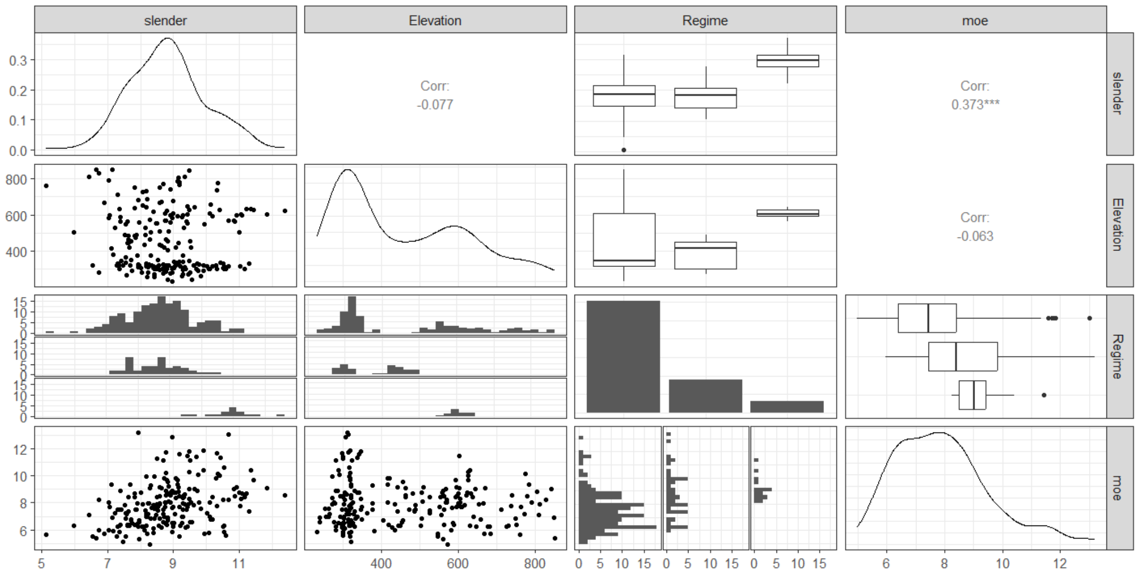

Figure 11. Matrix of scatter plots and correlations for tree slenderness, elevation, regime, and MOE

Despite the similar trends to basic density, a second model was built to investigate the significance of the environment and management effects on MOE. Interestingly, regime was now significant with a p value of 0.039, despite being a marginally insignificant predictor in the density model. This would make sense if this study was utilising a tool that was better suited to predict MOE as each regime has a different stocking, and stocking has been well documented as being a predictor of MOE. However, in the case of this analysis with the resistograph, much of the variation in MOE is expected to be explained by variation in density meaning that estimates should be similar, as previously noted. This means that we would expect regime to likely remain an insignificant predictor. The increase in the significance of regime as a predictor suggests that the tool is picking up the up some of the variation in MOE that is not otherwise explained by variation in density, which is something that the processing software does try to achieve. Visually, similar trends are observed to that of the density model (Figure 12).

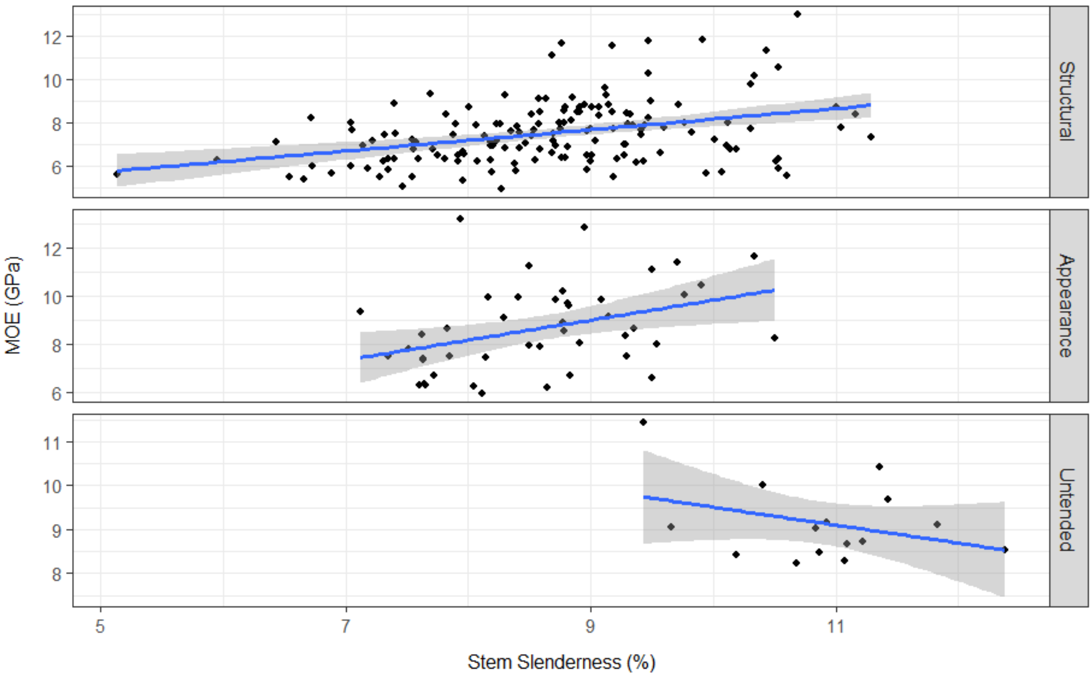

Figure 12. Regression between stem slenderness (%) and MOE (GPa) by regime.

It should be noted that the overarching study was not designed for the purpose of assessing the trends between these variables. Because the data was available, it was analysed to see if there were any interesting trends, and this was purely a bonus to the main objective of this study. The results of the trend analysis section should be considered with that in mind.

3.3. General Observations

The resistograph was found to be straightforward to use with measurements being rapid, and easy to take. The devices interface was user-friendly and the process of changing settings and inputting unique IDs was simple. The tool was robust and high quality as it had a solid feel, a bright screen, and a battery that easily lasted all day. However, the device was relatively heavy which made navigating a hillside more difficult, particularly over broken terrain or in stands that have had large amounts of windthrow. In these environments the sampling rate decreased significantly. It was also found that having a second person acting as a spotter was beneficial when sampling. This person would ensure that the tool was aligned perpendicular to the vertical direction of the tree and away from any knots on the other side of the tree that the operator may have missed. The device does have a built-in level however this was found to be ineffective, particularily when trees were on a lean. The operators positioning was frequently corrected by the spotter in this experiment, though the extent by which this enhanced the accuracy of measurements has not been quantified.

4. Implications

The findings of this study have numerous implications, both for forest managers and wood processors alike. At its core, the study has delivered valuable information for OneFortyOne as the results are useful for developing processes and in facilitating informed decision making and strategic planning. In a broader sense, the resistograph tool and in particular, the processing software are a rapidly developing technology that is beginning to be adopted by forest management companies across New Zealand and Australia. The adoption of NDE technologies will likely continue to increase as wood product customers request higher quality logs. As this adoption increases, the findings of this study will become more relevant and could influence the way that forest management companies decide to carry out sampling in the future.

The results of this study have also raised additional questions to be explored. The study warrants further research into validating the relationship between site-average estimates of basic density and the MOE of the outturn of boards at a sawmill. This research has been carried out in Australia but a sister-study in New Zealand would be valuable. Furthermore, while the research indicates that the device can be used to segregate stands for stiffness, there is a distinct lack of literature that demonstrates the tool being applied operationally for this purpose.

As OneFortyOne begins to operationalise this tool there is the opportunity to document and record the extent of any value gain that they may achieve.

5. Recommendations

5.1. Operational Sampling Intensity

The decisions relating to sampling intensities will be an operational call and should be based on managers experience, their knowledge of variability between each stand, and the results of this study. This study indicates that sampling intensity does not need to be high when using a resistograph to predict stand average basic density. With just 10 measurements that were spread across 2 different sample plots all 15 stands in this study returned a basic density PLE below 12.5%. It is recommended that OneFortyOne consider their end goal when choosing their sampling intensity. While the company aims for a PLE of 10-15% for their estimates of total recoverable volume, a lower level of error would perhaps be advantageous when segregating to meet customer supply agreements based on density.

If sampling efforts were aimed for 30 trees per stand this would only require sampling 2 trees per plot across a minimum number of 15 plots. The results of this study have demonstrated that this sampling intensity should return a very low PLE of between 2.5 - 5% for a range of stands. 30 trees has been suggested as this provides a very low PLE and, beyond this point, increasing the sampling intensity provides diminishing returns. Given the rapid sampling rate of this tool, perhaps this slightly higher, yet still reasonable, sampling intensity should be applied.

There is further value to having a greater number of measurements in that OneFortyOne can build up a database of information that could be used for a variety of purposes. For example, the tool provides a number of different estimates on different tree properties. With time, a large database can be created and used to better understand the plantation estate and the management practices that have and could be applied.

5.2. Validation Study

A further recommendation is for OneFortyOne to carry out a validation study that links the estimates of density to the output of boards at their sawmill. A project doing this has been carried out in Australia by Downes et al. (2020) however OneFortyOne should do this for their own estate. This would help to confirm that OneFortyOne can reliably use this tool in the way that they intend to. A mill validation study would build on the results of this study by determining the effect of how decreasing the PLE influences the strength of the relationship between site-average density and site-average board stiffness at the mill.

If OneFortyOne were to carry out this study, an approach similar to Downes et al. (2020) would be appropriate. In this study, 9 different sites were sampled with site-average resistograph density and MOE estimates analysed against site-average log and board MOE values from a sawmill. For their own study, OneFortyOne should sample at least 15 different sites covering the range in wood quality that they expect across their estate. This study should be carried out at the Kaituna sawmill (owned by OneFortyOne) with logs being processed through the mill in site groups with enough time between for board output to be identified to the site level. Similar to the previous study, OneFortyOne should test how well the resistograph estimate of MOE compares to resistograph estimate of density for predicting MOE. OneFortyOne should also test the extent by which decreasing PLE increases the strength of the relationship between these resistograph estimates and the mill output, to help consolidate a sampling strategy plan.

6. Conclusion

In general, the within stand variability of density is low, meaning that sampling programs for density can be carried out at relatively low sampling intensities. A PLE of between 10 - 15 % can be achieved with as little as 10 total measurements that are spread across 2 different sample plots. As the total number of samples increases, the PLE for density decreases. Similarly, as the number of sample plots increases, the PLE for density decreases. This rate by which PLE decreases with an increase in measurements is rapid up until the point of 30 samples, beyond this point decreases in PLE are marginal. A PLE of between 2.5 - 5% can be achieved with approximately 30 samples across 15 different plots. This sampling intensity is suggested as being a good trade-off between sampling efforts and quality of data, should forestry companies find extra value in having a lower PLE.

OneFortyOne are yet to begin using this device for their goal of harvest scheduling. While research carried out in Australia indicates that the tool could be used for this purpose, the operational value for a forest management company has yet to be proven. The relationship between site-average density estimates and site-average MOE of board outturn should also be confirmed in OneFortyOne’s plantation estate. This confirmation would allow for an investigation into the benefit of having a more precise estimate of density for the end goal of harvest scheduling for stiffness. Further research is warranted to build on the findings of this study and contribute to determining operational sampling strategies for this device.

The resistograph and in particular, the processing software are rapidly evolving technologies that are the subject of current research and development. At present, the tool is showing some predictive capability for wood qualities beyond density. As this technology evolves, the predictive capabilities of the resistograph and its processing software are expected to continue to improve.

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8. Appendix

a. List of values that the resistograph can estimate.

- Diameter over bark.
- Diameter under bark.
- Bark thickness.
- Outerwood density.
- Core basic density.
- Acoustic wave velocity.
- Modulus of elasticity.
- Exit radius.
- Decay.
- Disc area.
- Ring count.

b. Sampling combinations

Combination	Number of trees	Number of plots	Total number of measurements
1	2	30	60
2	3	20	60
3	4	15	60
4	5	12	60
5	6	10	60
6	7	8	56
7	8	7	56
8	9	6	54
9	2	25	50
10	3	16	48
11	4	12	48
12	5	10	50
13	6	8	48
14	7	7	49
15	8	6	48
16	9	5	45
17	2	20	40
18	3	13	39
19	4	10	40
20	5	8	40
21	6	6	36
22	7	5	35
23	8	5	40
24	9	4	36
25	2	15	30
26	3	10	30
27	4	7	28
28	5	6	30
29	6	5	30
30	7	4	28
31	8	3	24
32	9	3	27
33	2	10	20
34	3	6	18
35	4	5	20
36	5	4	20
37	6	3	18
38	7	2	14
39	2	5	10
40	3	3	9
41	4	2	8
42	5	2	10