# Report 7: A comparison of radial wood property variation in Pinus radiata between three different IML PD-400 'Resi' instruments and increment cores analysed by SilviScan.

Interim Report

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## Contents



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### Abstract

Mature age *P. radiata* trees were sampled across nine sites in northern New South Wales that were expected to exhibit significant variation in productivity and wood quality, as determined from site quality and inventory metrics. Twenty trees per site were harvested and of these two 13mm diameter, pith-to-bark increment cores were extracted from three trees per site from eight of the nine sites. The same trees were also sampled using three different IML PD400 (Resi) instruments.

Radial mean properties of wood basic density derived from Resi traces were found to correlate strongly with the mean density data derived from SilviScan analyses. Resi-derived basic density of 20mm radial segments were strongly correlated with SilviScan measures of basic density averaged at similar intervals. Resi-predicted MoE tended to over-predict juvenile and under-predict mature wood SilviScan values.

## Introduction

Over the past few decades the SilviScan technology (Robert Evans 1994, 2008; R. Evans et al. 1995) has repeatedly demonstrated its capability for generating accurate measures of a wide range of physical wood properties (Wang 2021) in samples taken from standing trees. These provide strong correlations with the commercial products sourced from logs (McKinley et al. 2003). Basic density, microfibril angle (MfA) and dynamic stiffness (MoE), along with a range of cell dimensional properties (e.g. radial and tangential fibre diameter, fibre wall thickness and fibre coarseness) can rapidly be determined at high radial resolution, with a sampling interval of 25 *u*m (MfA and MoE at 0.2 - 5 mm minimum sampling interval).

The IML PD-series power drill (Resi) is increasingly being accepted as a tool for commercial pre-harvest assessment of stand-average wood quality in Australia. Its rapid, low cost measurement capability, combined with its accuracy and precision for estimating wood density, and its consequent prediction of log stiffness (MoE) has been demonstrated in a range of industry and Forest and Wood Products Australia (FWPA) funded studies (Downes, Drew, and Lee 2019; Bailleres et al. 2019; Downes et al. 2016; Gendvilas et al. 2021). Its application to tree breeding has also been demonstrated in multiple studies over recent years (Nickolas et al. 2020; Fundova, Funda, and Wu 2019).

To date, the commercial use of the Resi has focussed primarily on estimating the average density of the stem at the point of sampling (Downes et al. 2018), with limited attempts to explore the accuracy of the radial assessments at the annual ring or radial segment level (Gendvilas et al. 2020). The commercial objective has been to provide a reliable measure of the wood quality within a forest that is non-destructive and potentially deployable during a standard forest inventory program, from which the value of the sawn timber product from that stand can be inferred with a commercially-useful level of precision.

Radial variation in wood properties is an important component of the overall log quality. Given that SilvScan represents an accepted standard in wood property assessment, the objective of this study was to compare the basic density estimates generated from Resi traces with those generated by SilviScan, where both Resi and Silviscan data has been derived from effectively the same sampling point in then stem. Resi and SilviScan data were obtained from 22 trees sampled across eight different, mature age radiata pine sites in the northern NSW Oberon region. As well as mean density estimates, the radial variation of density, as well as estimates of MoE were examined.

## Methods

As part of a larger study (Downes, Drew, and Lee 2019), 180 trees were sampled across 9 sites in the Oberon region of northern New South Wales in March 2019 (Table 1, Figure 1). The sites were selected to represent as broad a range of growth and wood properties as possible within the constraints of available close-to-harvest age plantations in the region and current harvesting operations.

Twenty trees per site were sampled and felled for sawn timber processing to assess the accuracy and precision of pre-harvest measurements based on traces taken using the IML Resi. Two different Resi instruments were used on all nine sites and an additional instrument on 6 of the 9 sites. Two Resi traces were taken per instrument at breast height from each tree, orthogonal to each other, resulting in up to 6 Resi traces per tree. Traces were collected with a forward speed of 200 $cm.min^{-1}$ and 2500 RPM. A 13mm diameter by 50 mm long outerwood core was sampled close to the sampling location of the first Resi trace, to use in calibrating the Resi instruments for basic density estimation. A wooden dowel was inserted into the resultant hole and the tree number recorded on it to assist in identifying the buttlog in the logyard (Figure 2).

### SilviScan sampling

From three trees at each site, selected to cover the range in breast height diameter, a 13 mm diameter full radius core was taken for SilviScan analyses (Figure 2). SilviScan and outerwood cores were sampled close to the location sampling point of the first of the pair of Resi traces sampled from each tree (Figure 3).

Table 1: Site data for SilviScan and Resi analysis

| Site | Annual Rainfall (mm) | Elevation (mASL) | Plant Year | Initial Stocking (sph) | Thinning year | Thinned stocking (sph) | Previous Land Use | Residual Stocking (sph) | No.Trees | Latitude | Longitude |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 952 | 1189 | 1991 | 1122 | NA | NA | Forest | 1122 | 20 | -33.42 | 149.86 |
| 2 | 927 | 1221 | 1988 | 1288 | NA | NA | Forest | 1007 | 20 | -33.72 | 149.91 |
| 3 | 832 | 1066 | 1986 | 1080 | 2001 | 600 | Pasture | 419 | 21 | -33.63 | 149.87 |
| 4 | 823 | 669 | 1987 | 1100 | NA | NA | Pasture | 452 | 20 | -33.82 | 149.19 |
| 5 | 849 | 964 | 1991 | 1100 | NA | NA | Pasture | 1073 | 20 | -33.56 | 149.74 |
| 6 | 906 | 929 | 1986 | 815 | NA | NA | Forest | 815 | 22 | -33.32 | 148.96 |
| 7 | 949 | 1042 | 1987 | 1100 | 1992 | 600 | Pasture | 486 | 21 | -33.38 | 148.97 |
| 8 | 952 | 1204 | 1990 | 1100 | 2004/2011 | 800 | Forest | 294 | 20 | -34.02 | 149.82 |
| 9 | 763 | 768 | 1985 | 1100 | NA | NA | Pasture | 549 | 20 | -34.02 | 149.52 |

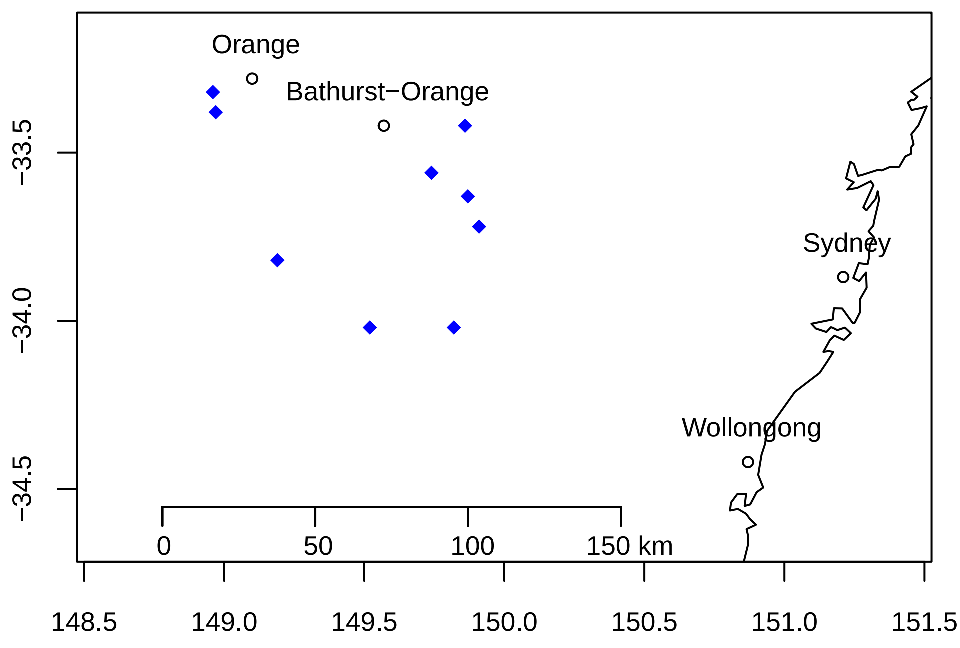


Figure 1: Locations of the sample sites


Figure 2: Twenty trees were selected as sawlogs. Plugs were inserted in the outerwoood core sampling hole to assist in identifying individual butt logs in the log yard, and on three trees per site full radius cores were taken for SilviScan analyses.

Given the potential for wood properties to vary significantly within a relatively short distance within stems, it is important to sample as close to the same portion of the stem with both the Resi and SilviScan core to obtain optimal comparisons. The slight curvature in the red line in Figure 3 illustrates a potential for the Resi needle to follow a slightly curved trajectory through the tree, as it interacts with the slope of grain and rotation direction of the needle. In most trees the trajectory is quite straight if the Resi instrument is level and the stem is perpendicular. Extreme curvature can be generated if the Resi instrument is angled significantly up or down (i.e. more than 5 degrees). However, in many trees the pith is not in the exact centre and so a perfectly cross-sectional trace through the geometric centre may miss the pith by centimetres.

Of the 24 SilviScan cores sampled, 22 full radius cores were sent to FP Innovations in Vancouver, Canada (https://web.fpinnovations.ca/) for SilviScan analysis. SilviScan data was returned as radial, pith-to-bark profiles of density, cell diameter (radial and tangential) and wall thickness at a 25 $u$m radial sampling interval. Radial profiles of microfibril angle (MfA) and dynamic modulus of elasticity (MoE) were also measured at a 2mm radial sampling interval. Annual ring means generated using automated ring detection algorithms were also provided. However, these were found to be to inaccurate in most radii (see Figure 5b).

Resi resistance traces were converted to density traces after calibrating the relationship for each instrument (Downes et al. 2018) using web-based software (https://forestquality.shinyapps.io/FWPA-4/). Mean predicted density and stiffness (MoE) metrics were obtained, along with annual ring boundary positions on the traces to generate measures of annual ring mean density and ring width. The web platform cited above has the capability to read the radial profiles of wood properties generated by SilviScan in which annual ring boundaries were manually positioned, to generate annual ring mean properties comparable as much as possible to those generated by Resi.

SilviScan density is air-dry density, not basic density, determined at a moisture content of ~7-8%, derived from the sample conditioning and measurement at a constant 20°C and 40% relative humidity. In the analyses reported here, the values were multiplied by 0.78, to approximate basic density. This value was identified as minimising the bias between the mean SilviScan density and the mean Resi density values.

An important issue in comparing Resi and SilviScan (SS) data was the way the SilviScan data were presented. Because the SilviScan analysis included the image analysis of fibre properties, the radial profiles were corrected as if the core had been taken directly towards the pith. This is illustrated in Figure 3 as the differences between the yellow line indicating the actual trajectory of the SilviScan core (SS) and the white

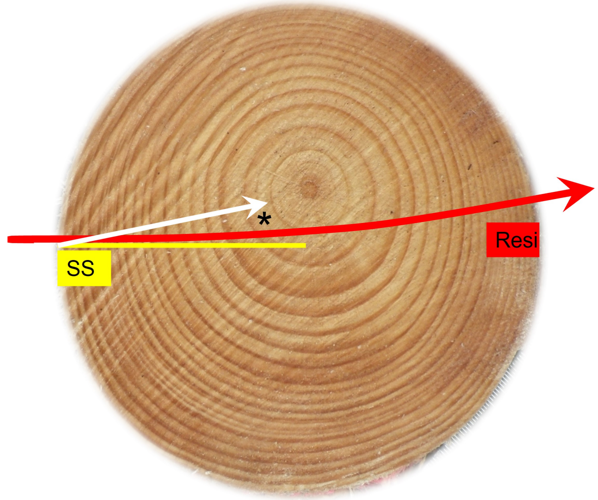


Figure 3: Disc cross section illustrating the effect on radial length and annual ring count on SilviScan profiles and Resi traces. The white arrow indicates the direct bark-to-pith trajectory obtained from the SilviScan analyses.

arrow indicating the corrected trajectory of the data generated. The automated image processing employed by Silviscan, requires the orientation of the rays to be known (Robert Evans 1994). Typically the vascular rays in wood are aligned radially, running from pith to bark (Figure 4) which gives a ray angle of zero degrees at the bark. If the sample misses the pith, the ray angle will progressively increase towards 90 degrees (red arrows) as it passes the pith. From this change in direction, the position of the pith can be estimated and the radial profiles corrected accordingly. This, however, causes issues for comparing between SilviScan and Resi values, especially if either of them misses the pith by a substantial distance (as illustrated in Figure 3.

In Figure 5a, the annual rings were clear, and corresponded well between the Resi trace and SilviScan profiles. In many samples however, (e.g. Figure 5b) annual ring positions could not be accurately identified. Likewise the lower resolution of the Resi traces also made accurate annual ring detection impossible in many traces. As the main focus of this study was to compare radial wood property variation between SilviScan and Resi traces, only a 6 to 8 of the samples were able to be meaningfully compared using annual ring values.

Consequently, the focus of the analyses presented here was on comparisons undertaken using all samples by generating the means of 20mm intervals starting from the cambium. A similar approach had been adopted and reported in Gendvilas et al. (2020) in *Eucalyptus nitens* comparing the radial variation in basic density with that of wood blocks of 20mm radial thickness. The mean ray angle of the SilviScan segment was used to identify segments where the comparison with Resi segments was most likely to be too affected by sampling and analysis related issues. Segments with a mean SilviScan ray angle greater than 20 degrees were excluded from comparisons.

### Data analyses

All analyses and reporting was done in R (R. C. Team 2019) using RMarkdown (Allaire et al. 2020) within the RStudio environment (Rs. Team 2020).

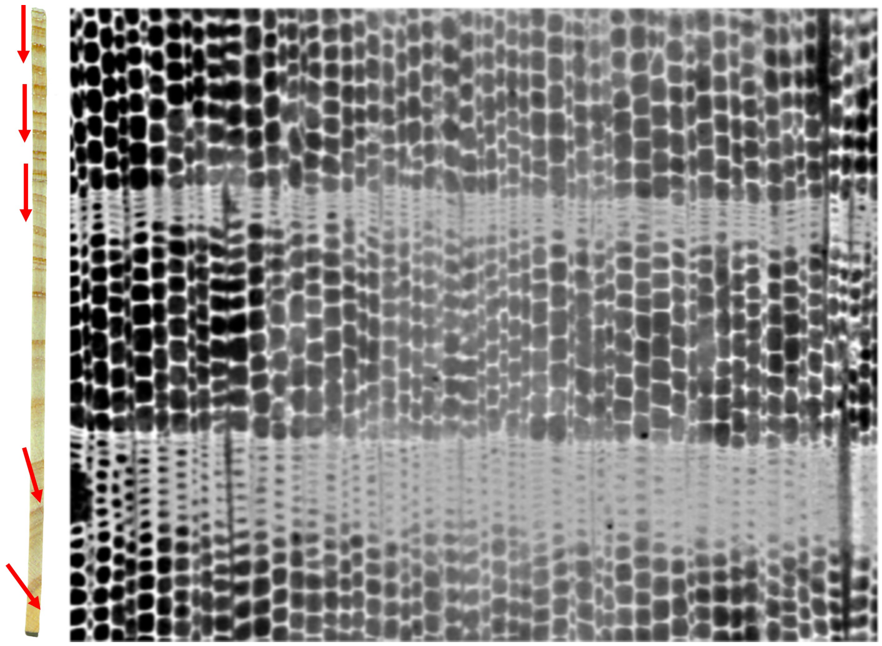

Figure 4: A typical surface image used by SilviScan to determine fibre dimensions on the right hand side. On the left is a SilviScan bark-to-pith strip prepared from the increment core that was missing the pith. The red arrows illustrate the orientation of the rays (and the direction of the pith), that are vertically aligned in the microscope image used by SilviScan. The right hand image from top to bottom represents 1 mm of radial distance.

## Results and Discussion

### Calibrating the Resi density estimates

From the stem position from which the first Resi trace was collected, a 50mm long, 13 mm diameter outerwood core was sampled in each of 20 trees per site, to develop a calibration relationship between Resi values (% amplitude) and basic density. To simplify the calibration process, protocols have been developed relating the mean resistance values of the outer 50 mm of wood from the entry side of the trace with the corresponding Resi values for those samples. The web processing platform (https://forestquality.shinyapps.io/FWPA-4/) facilitates defining the relationship between the relative Resi amplitude values (0-100%) and core basic density. In the relative scale of the Resi values, zero is defined by the resistance experienced within the instrument prior to the needle entering the wood. Maximum resistance is defined as 100% of the torque of both motors minus a safety factor. Previous work has shown that this relationship, at the core mean level is linear (Downes et al. 2018).

Resi values for the outer 50 mm underbark were calculated for the three Resi instruments used in the study and the regression coefficients for the relationship with core basic density determined for each (Figure 6). The fitted regressions were defined using standardised major axis (SMA) regression within the "lmodel2" package (https://cran.r-project.org/package=lmodel2). These coefficients were used in subsequent analyses comparing Resi-predicted basic density with SilviScan-derived density.

### Comparison of Resi and SilviScan radius mean values

The length of the disc radius determined from the length of the SilviScan profile and the pith-to-bark length of the Resi trace were strongly correlated ($r^2 = 0.86$) for all three Resi instruments (Figure 7a,c,e). The radius obtained from the length of the SilviScan profile tended to be shorter than that of the Resi data owing

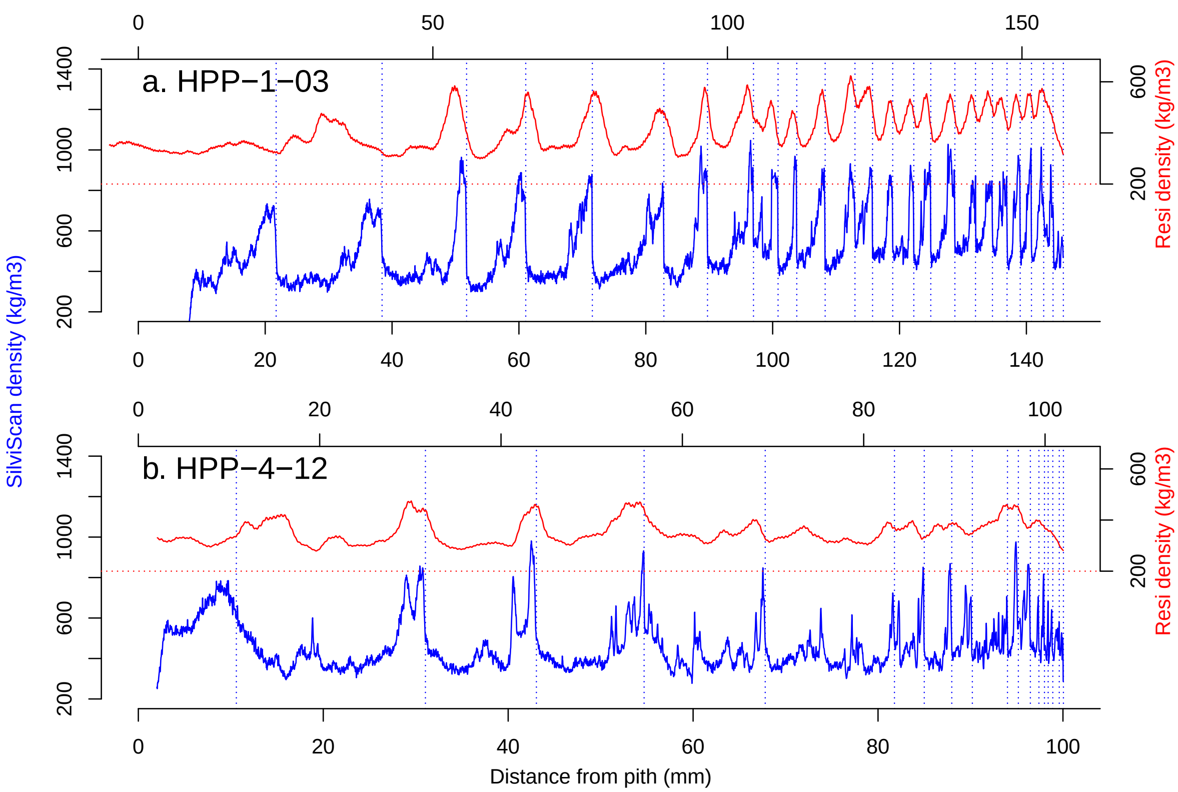


Figure 5: Narrow and false ring structures made accurate annual ring detection impossible in many samples, especially in the lower resolution Resi (upper red) traces compared to the SilviScan (lower blue) profiles. Blue vertical lines indicate annual ring positions allocated in SilviScan profiles

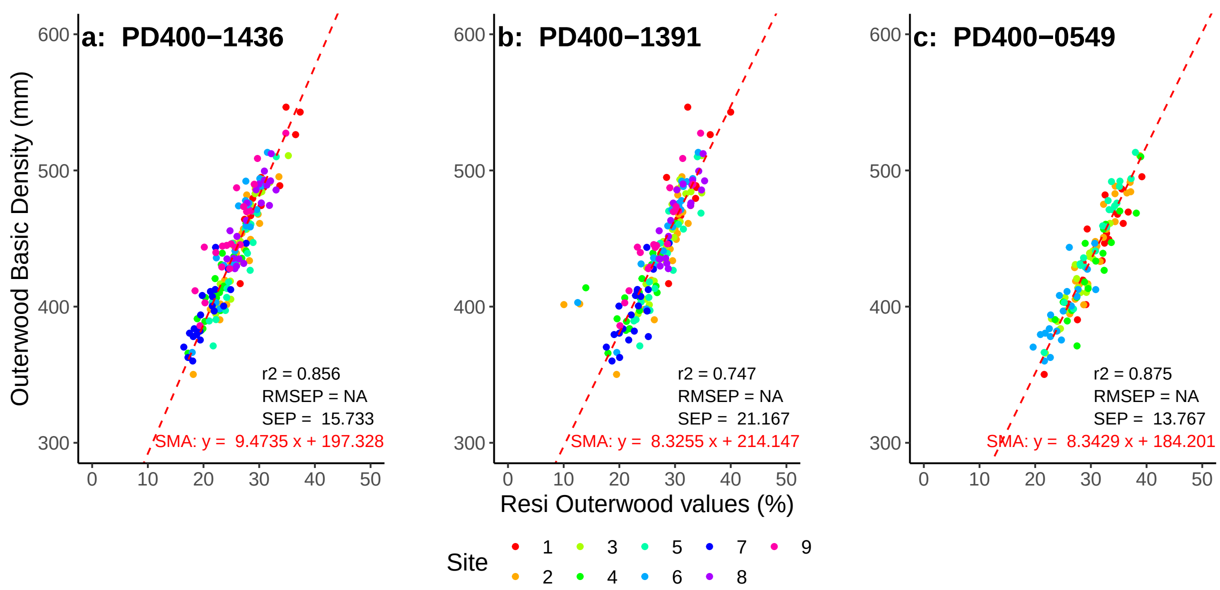


Figure 6: The correlation between outerwood core basic density and outerwood Resi values from twenty trees from each of nine plots, was strong for each of the Resi instruments defined by serial number. Each instrument exhibited a slightly different linear regression relationship. The standard error of prediction (SEP) was based on the relationship between the fitted density values derived from the Resi data using the standardised major axis (SMA) regression equation defined on the plot, and the actual outerwood density values.

to the ray angle correction in the SilviScan data described above. The mean density of the SilviScan profile and Resi trace were also strongly correlated for all three Resi instruments with $r^2$ values of 66%, 59% and 51% respectively Figure 7b,d,f).

### Comparing 20mm segment means

As a result of the pith-to-bark alignment adjustments made to SilviScan profiles, ring widths determined from SilviScan profiles are more accurate than those obtained from Resi to the degree to which the Resi trace misses the pith. The effect is more marked in the wider, more curved rings of the juvenile core (e.g. asterisk in Figure 3), and minimal in the narrower mature wood rings.

In order to compare annual ring means it is necessary to ensure that the annual ring data represents the same growth year in both the SilviScan data and the Resi data. This requires that annual ring boundaries be clearly resolved and accurately allocated to the year of growth they represent. This is most reliable in the SilviScan data resulting from the higher resolution (25 *u*m sampling interval), combined with the pith-to-bark adjustment of the traces and the ability to adjust the x-ray densitometry such that the x-ray path alignment is parallel to growth ring boundaries (R. Evans et al. 1995). However, even in the SilviScan data from some samples, ring widths were sufficiently narrow or indistinct to make this impossible to do with certainty (e.g. Figure 5b).

In many samples the alignment of ring boundaries was a problem in the early juvenile rings. In many Resi traces (e.g. Figure 5b) the coarser resolution of the data made it impossible to clearly resolve narrow annual ring boundaries in the mature wood. Consequently meaningful comparisons between annual ring means could not be made on a sufficient number of samples where rings could be confidently identified and cross-matched between the Resi and SilviScan data sets.

The precision and accuracy of the estimated mean density of a whole sample (outerwood core, bark-to-bark core) has been established (Downes et al. 2016, 2018). The main purpose of this study was to determine the extent to which the Resi-predicted basic density of radial intervals can be shown to be accurate. The predicted mean basic density of 20mm radial segments were calculated from each of the Resi and SilviScan data starting from the bark and working towards the pith. To reduce the sampling error effect of misalignment between the SilviScan and Resi data, only the segments from the first 120 mm from the bark (first 6 segments) were considered, as the sample depth at higher segment numbers, combined with the "close-to-pith" alignment issues, made comparisons unreliable.

The Resi values explained 70% to 80% of the variance in the SilviScan values (Figure 8), sixteen outliers were removed where the variance between the Resi and SilviScan means exceeded 80 $kg.m^{-3}$, arising predominantly from segments close to the pith (i.e. segment six represents segments 100 to 120 mm from the cambium). The explained variance increased several percent using 25 mm segments as the net effect of misalignment between the Resi and SilviScan data reduced.

The Resi-predicted density values were subtracted from the SilviScan values to calculate the difference. The first segment tended to exhibit a lower density value in the Resi data (Figure 8b). Previous work (Gendvilas et al. 2020), using 20 mm segments of *E. nitens*, reported a similar tendency for the Resi-derived basic density of the first segment from the bark end to be slightly under-estimated relative to the other segments.

### Baseline correction of Resi traces

A noted feature of the Resi trace is the presence of resistance on the needle after it exits the tree on the opposite side. This is attributable in large part to friction on the 1.5 mm diameter needle shaft resulting from drill chips accumulating from the cutting edge. Most recent publications (Downes, Drew, and Lee 2019; Downes et al. 2018; Fundova, Funda, and Wu 2018) employ a linear baseline correction which assumes the linear accumulation of friction from the beginning of the trace to the point of exit. The measurement of the magnitude of the resistance can be calculated and corrected after the needle exits the stem or log. However, given the shape of the cutting head of the needle and the radial variation in wood anatomy, chemistry,

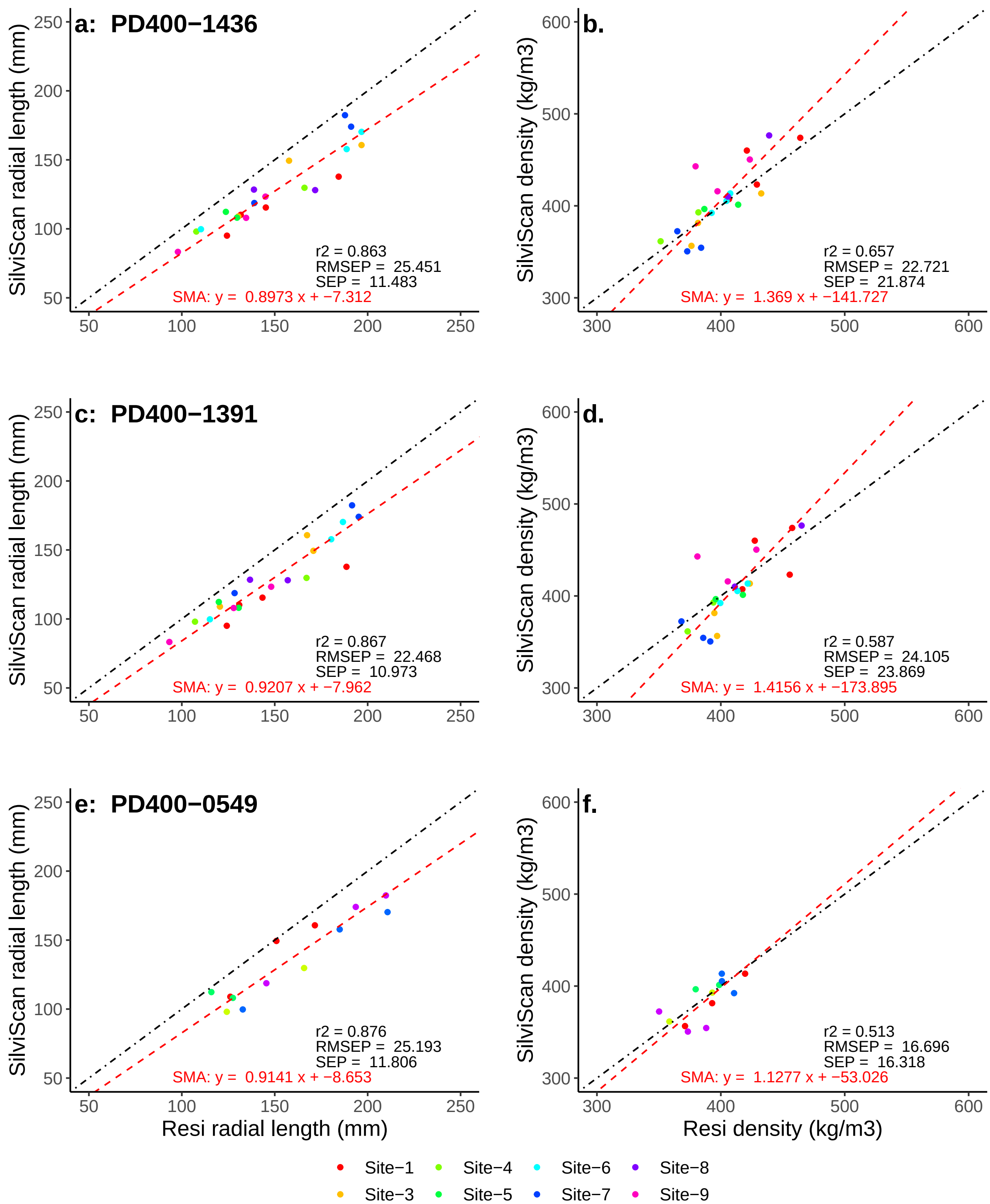


Figure 7: SilviScan sample length (a,c,e) and basic density (b,d,f) was strongly correlated with the pith-to-bark length and density determined from the Resi trace. Along with the variance explained, the root mean standard error of prediction indicates the accuracy of the predicted values comapred to the actual values. SEP indicates the precision (ranking) by removing the effect of bias between the actual and predicted values.

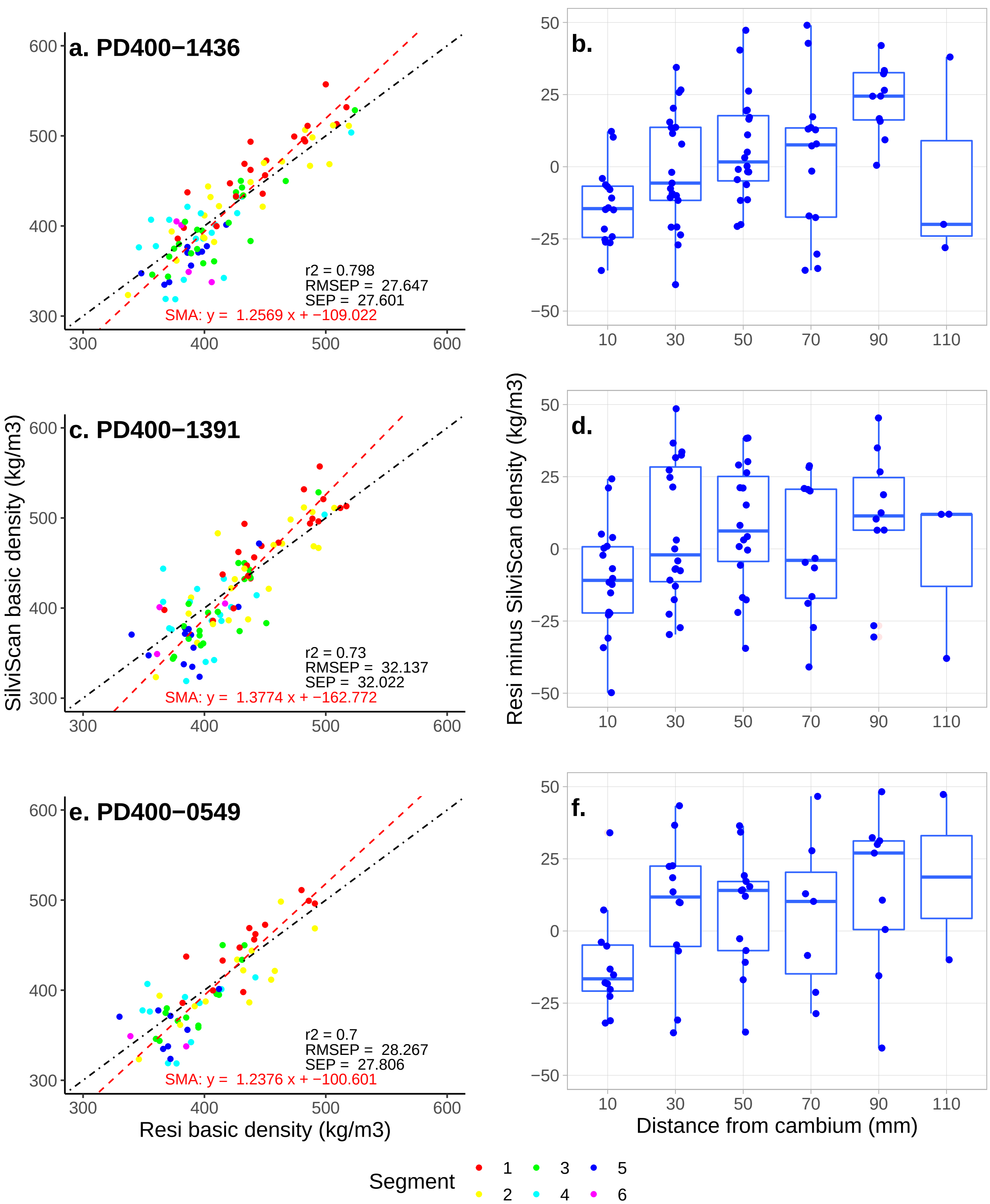


Figure 8: (a,c.e) The mean Resi-predicted density of 20 mm segments was compared to the SilviScan density values for each Resi instrument. (b,d,f) The effect of distance from the cambium on the difference between SilviScan and Resi mean basic density.

basic density and growth stresses within the tree, it is unlikely that the baseline correction is strictly linear. Previous work (Gendvilas et al. 2020) had also identified that the first 28-30 mm of the Resi trace tended to under estimate the basic density if a linear baseline correction was employed. Thus the under-prediction of the first segment (Figure 8b) and the possible tendency for subsequent values to be over-predicted is important to quantify and in some applications, correct for.

An additional aspect for investigation is the effect of bark thickness on the non-linear corrections. Gendvilas et al. (2020) used discs with bark removed, thus the Resi traces started in wood immediately beneath the cambium. The Resi traces collected here were on standing trees so that bark effects may be a contributing factor. The radial pattern of the density differences for this study were examined when bark thickness was added to the segment data (Figure 9a) and a logarithmic model fitted to the relationship as defined below.

$$BasicDensityAdjustment = -75.913 + 19.447 * ln("distance - from - entry") \quad (1)$$

Adjusting the Resi-derived basic density data using equation (1) slightly increased the variance explained to 78% and reduced the mean difference between the SilviScan and Resi values to close to zero. Segment data from all three Resi instruments was combined in this analysis.

### Comparisons with other wood properties

SilviScan has the ability to measure a range of wood properties directly (e.g. density, radial and tangential cell diameter, and microfibril angle (MfA)) and indirectly (e.g. dynamic MoE, fibre wall thickness, fibre coarseness and specific surface area). Resi measures turning resistance expressed as basic density, although effort has been made to develop models that process the Resi trace to predict MoE and acoustic wave velocity (AWV) (Downes and Lausberg 2016).

Resi-predicted MoE ("Density" model) explained up to 64% of the variance in SilviScan dynamic MoE (Figure 10a-c) at the mean sample level. These predictions gave higher $R^2$ and lower SEP values than using Resi predicted core basic density alone (Figure 10d-f).

At the segment mean level Resi predicted basic density explained 60% of the variance in SS Moe whereas Resi predicted MoE explained only 33% of the SilviScan values (Figure 11a &b). The relationship in the latter varied markedly from the 1:1 line with Resi predictions over-estimating the SilviScan dynamic MoE at low MoE values and under-predicting at higher values

Using the Resi mean density data corrected using the above equation, segment means explained 55% percent of the variance in MfA (Figure 11b) and 68% of the variance in fibre wall thickness (data not shown). In the relationship with MfA, it was evident that in segments most likely to be within the juvenile core (4, 5, and 6) where MfA was high, there was little relationship with basic density, suggesting the relationship overall was largely driven by covariance with the radial trend. This was supported by plotting the difference in the segment mean MoE predictions from Resi and SilviScan (Figure 11d), where high MfA showed little relationship with the difference.

Over recent years efforts have been made to develop Resi trace processing algorithms to predict average log MoE as determined using the following relationship (Downes, Drew, and Lee 2019; Downes and Lausberg 2016).

$$LogMoE = AWV^2 * LogGreenDensity \quad (2)$$

Mean segment MoE was determined from Resi traces using the different AWV prediction models available in the web portal and compared with SilviScan MoE and MfA values. Three models were tested ("Density," "NZSWI" and "Mature") which represent multiple regression relationships that use different variables extracted from each Resi trace, in an effort to capture additional variance to explain log MoE other than from using basic density alone. These models are described in Downes, Drew, and Lee (2019) with respect to how they perform in predicting that actual mean board MoE of sawmill output.

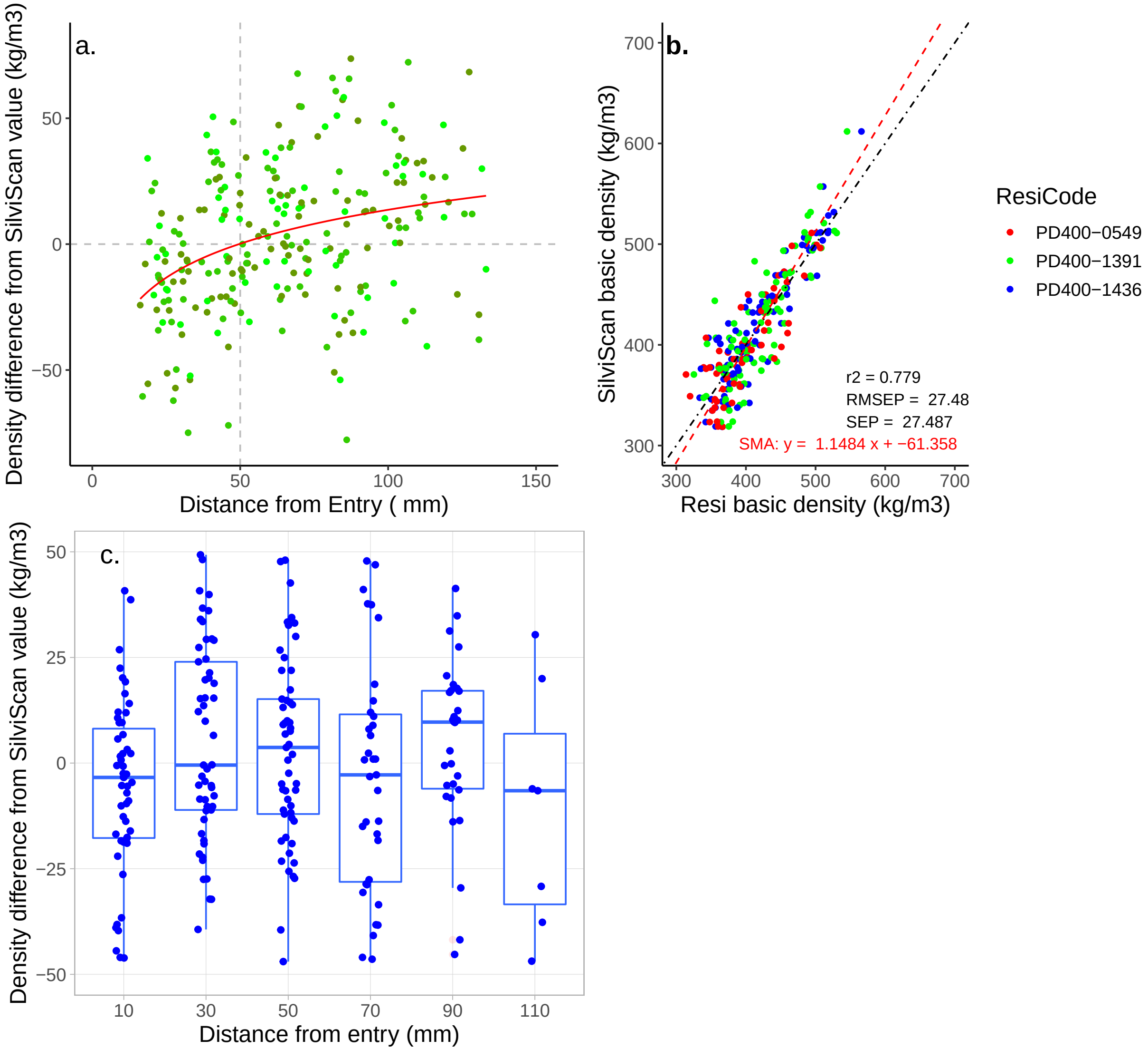


Figure 9: (a) (b) mean corrected Resi-predicted density of 20 mm segments compared to the SilviScan density values (c)

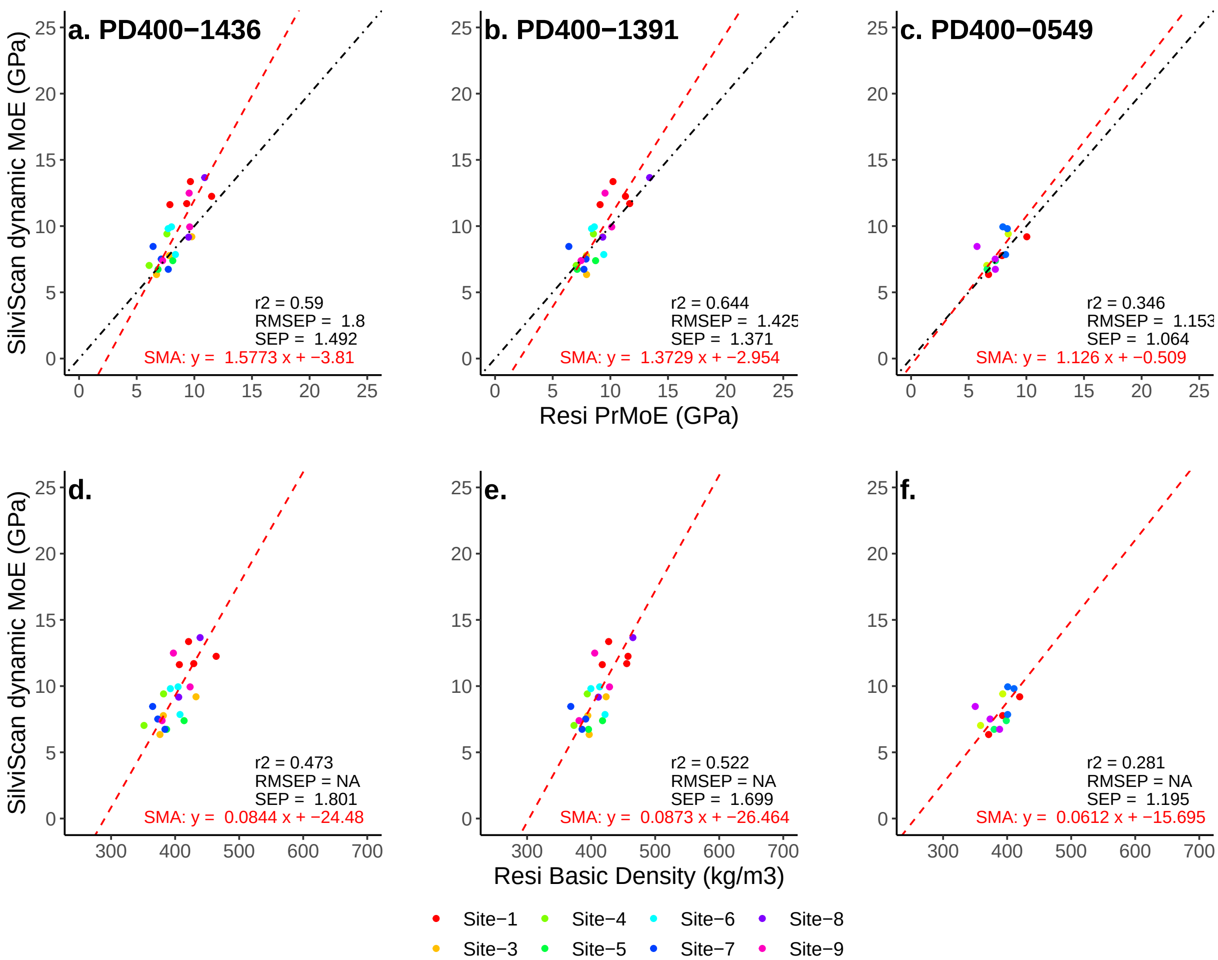


Figure 10: Comparison of radial mean SilviScan dynamic MoE and (a-c) Resi-predicted MoE and (d-f) Resi basic density for each Resi instrument. In the latter, the SEP values are based on predicted MoE values using the SMA regression defined in each plot, hence RMSEP is the same as SEP.

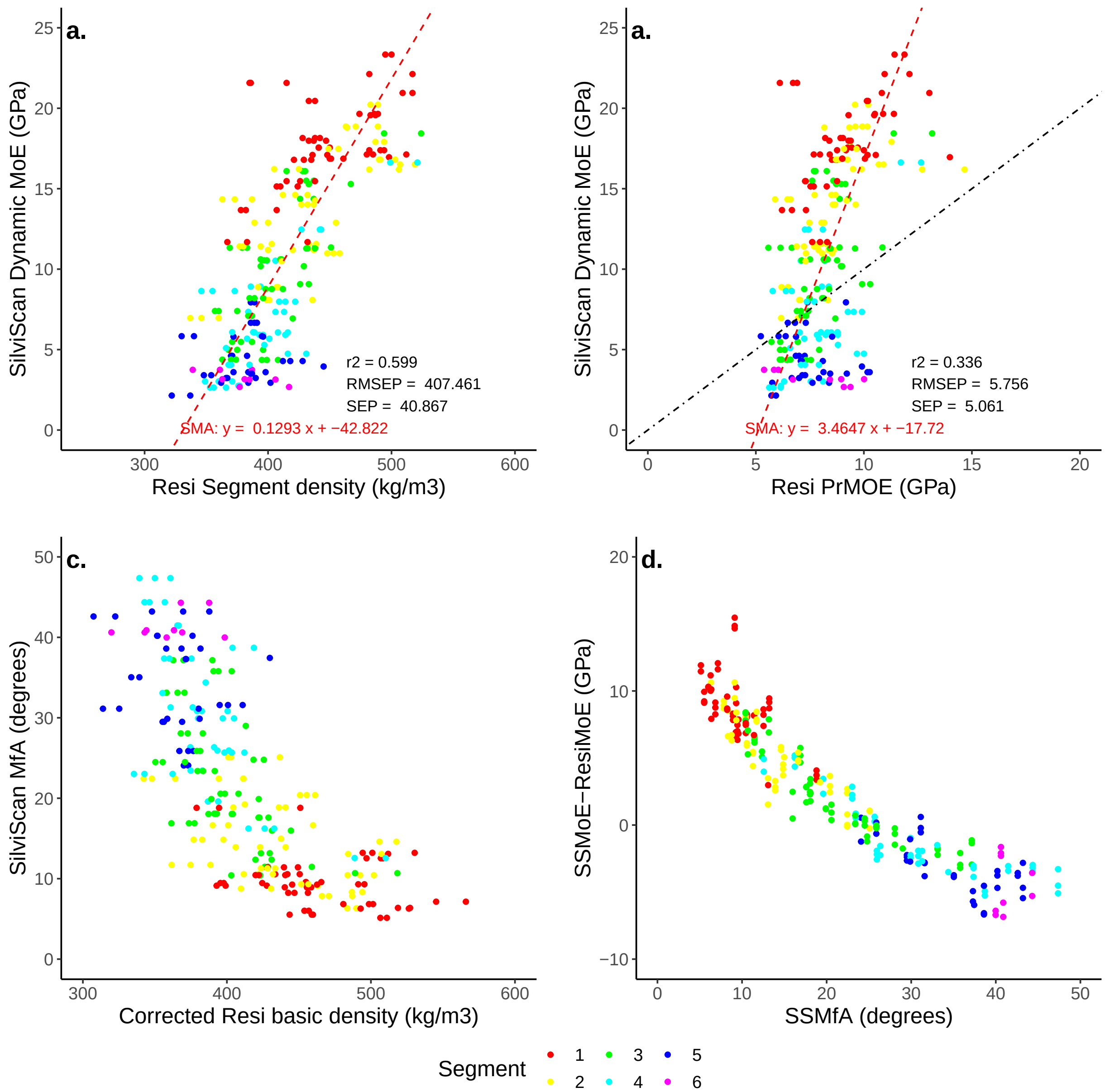


Figure 11: Relationships between Resi predicted values and other SilviScan measured propertiesat the 20mm segment mean level. Resi predicted MoE vs (a) SilviScan dynamic MoE and (b) SilviScan MfA. Corrected Resi basic density and (c) the microfibril angle, and (d) SilvbiScan MFA and the difference between the Resi and SilviScan MoE values.

Each of the models explain similar amounts of variance, with the model derived using predicted basic density alone generating the strongest relationship. The obvious question is why is the slope so markedly different from the 1:1 line (Figure 11a)?

The Resi-derived MoE values were made using regressions developed from from actual log MoE data generated from 4 to 6 m logs. Log MoE is an average of the whole log and includes the effects of knots, slope of grain, moisture content, heartwood proportion and other sources of potential variance unable to be accounted for from the Resi data obtained from clearwood at a single point in the log. Typically Resi data was derived from a single trace, taken at one point in the stem close to the large end, and from one aspect. Thus the Resi data represents a small sample of the wood properties of the whole log.

To generate the MoE segment means from the Resi trace, the average MoE value of the log is first predicted. This value is then apportioned to the whole trace radius such that the mean of the area-weighted trace is equal to the predicted MoE value. The net effect is that this tends to over-estimate the MoE of the core wood and under-estimate the outer mature wood in the harvest age trees.

In contrast SilviScan dynamic MoE is calculated from the combination of x-ray density determined by x-ray absorption (and sample volume and mass) and x-ray diffraction using a variable related to MfA but also includes the proportion of orientated microfibrils in the fibre wall, which can vary markedly (Robert Evans 2008) within and between trees. These two variables are combined in a model developed against actual dynamic MoE values determined acoustically in short clears or small samples free of defect. The SilviScan measure of MoE is directly of the sample being analysed. Consequently there are fewer sources of unexplained variance using actual MoE values that are higher, being unaffected by factors such as knots and variable moisture content within the log. Silviscan-derived MoE is able to account for the MoE directly attributable to cellulose microfibrils (MfA). Resi can only do this via the collinearity with basic density, and the relationship shown in Figure 11b indicates density is largely unrelated to MfA at the segment level in the juvenile core.

## Conclusions

- Radial estimates of basic density derived from calibrated Resi traces are reasonably accurate representations of the true variation.

- Estimated basic density values derived from annual means or segment means can be used to describe the within-tree pattern of wood density variance at that sampling resolution.

- Resi estimates of MoE tend to underestimate the SilviScan dynamic MoE values in mature wood, and further work is needed to determine whether the Resi estimates can be better modelled by applying a correction based on the SilviScan relationship. This can then be tested in independent data sets to determine the extent to which it improves the predictions of board stiffness variation.

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