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SURFACE RELEASED STRAIN (SRS) AND WOOD ANATOMY OF YOUNG *FALCATARIA FALCATA* TREES PLANTED IN AGUSAN DEL NORTE, PHILIPPINES

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This study was conducted to assess the variation in surface released strain (SRS), fiber length (FL) and diameter (FD), and vessel length (VL) and diameter (VD) of 3-6-year-old leaning and straight *Falcataria falcata* (L) Greuter & R. Rankin trees. This pioneering study on *F. falcata* growth strain in the Philippines aimed to determine the influence of growth orientation on SRS and wood anatomy, which affect mechanical properties and defect formation. Surface released strain varied significantly, with the highest SRS values recorded on the east, upper side of the lean in leaning trees. Meanwhile, FL and FD at the four cardinal points (north, south, east, and west) were not significantly different on leaning and straight trees. For leaning trees, VL from the west side of the tree stem was significantly lower ($p = 0.009$) than that in the other three cardinal directions. Mean FL (± standard deviation) was significantly higher in leaning trees (1.103 ± 0.007, $p = 0.012$) than in straight trees (0.989 ± 0.012 mm). The mean FD of straight trees was significantly higher than that of leaning trees (0.029 ± 0.0006 mm and 0.020 ± 0.0002 mm, respectively, $p = 0.0004$). The length of vessels measured from the north, south, east, and west sides of straight trees were not significantly different ($p = 0.399$). There was no significant difference in VD measured in the four cardinal directions of leaning and straight trees. Correlation analysis revealed a weak positive correlation between SRS and all anatomical properties except VD.

Keywords: Surface Released Strain, leaning stem, straight stem, cardinal direction fiber length, fiber diameter, vessel length, vessel diameter

INTRODUCTION

The global consumption of roundwood is likely to increase by about 10% to 2.2 billion cubic meters by 2030 (Brown et al. 2020). As tight regulations cut supply from natural forests, producers now focus more on forest plantations to meet domestic and global demand. In the Philippines, the most significant area under tree plantations is in Mindanao, the southernmost part of the country. Mindanao is considered a forerunner in the country's industrial tree plantation development (Paler et al. 1998). The Caraga region of Mindanao alone contributed 60% of the country's wood production in 2011, and 67% of the national log production was from *Falcataria falcata* (DENR-FMB 2021). Growers prefer *F. falcata* because of its short rotation period and available market (Paquit & Rojo 2018). It is an economically important plantation species mainly utilized for veneer and plywood (Uriarte & Piñol 1996). However, even with the proliferation of plantations, the current log production rate of *F. falcata* plantations in the country, which is about 632,574 m^3 or 0.006 m^3 per capita (DENR-FMB 2019), is still meager compared to the world's average production rate of 0.5 m^3 per capita. Hence, there is a need to increase the supply of wood produced from *F. falcata* in the country.

Compounding the supply problem are defects, e.g., radial cracks and lumber crooking, that depreciate the value of *F. falcata* logs. A study conducted by the USDA Forest Service showed that, on average, 12.6% of the potential lumber tally is lost due to multiple defects (Cahill & Cegelka 1989). Considering that the total volume per hectare of *F. falcata* is 30–40 m^3/ha (Krisnawati et al. 2011) and the price per volume is 4500 Philippine pesos (PhP) (US80) per m^3, an estimated 22,600 PhP ha^{-1} is lost due to wood defects. These defects can be attributed to longitudinal growth stresses resulting from dead weight increase and cell wall maturation in the growing trees. Exceptional levels of longitudinal stress are reached in reaction wood in the form of compression in gymnosperms or higher-than-usual tension in angiosperms (Gril et al. 2017). Growth stresses are not visible but can be measured and are called growth strain (GS) (Yang et al. 2005). When trees are felled and cut into logs and subsequently processed into lumber, the results of growth stress release become evident (Matsuo-ueda et al. 2022).

To understand the growth stress phenomenon in *F. falcata*, trees with different growth orientations, e.g., leaning and straight, were assessed. The variation in the anatomical characteristics of fibers and vessels in these trees was also analyzed. The findings in this study revealed new insights into the variation in fiber and vessel anatomy of leaning and straight trees, as well as concerning different cardinal directions. Moreover, new empirical evidence of variation in the pattern of growth stress within trees and between growth orientations is presented.

MATERIALS AND METHODS

Study area and sample tree selection

This study was conducted in a young *F. falcata* plantation in Buenavista, Agusan del Norte. The trees were between three to six years old. Representative trees with straight and leaning growth orientations were randomly sampled (Figure 1A). As presented in Table 1, six trees were sampled in this study. The largest Diameter at Breast Height (DBH) recorded was in L3 (34 cm), whereas the smallest DBH was recorded in S2 (24 cm). Leaning trees had a mean DBH of 31.3 cm greater than straight trees (28.0 cm). The average lean angle for leaning trees was 17 ± 6.5 degrees; the highest was recorded in L1. Two leaning trees (L2, L3) also face the NW direction.

Measurement of Surface Released Strain (SRS)

The longitudinal SRS of the surface growth stresses of the trees were measured at four cardinal points (north, south, east, and west) at 1.3 m from ground level. An electric wire strain gauge (KFG-10-120-C1-11L3M3R, Kyowa Electronic Instruments Co., Tokyo) with a gauge length of 10 mm was glued longitudinally to the secondary xylem surface and connected to a data logger (DBV-120A-B data logger, Kyowa Electronic Instruments Co., Tokyo) and the initial strain was measured (Figure 1B). A groove 5–10 mm deep was then made using a handsaw, 3–5 mm from the edge of the strain gauge, to release the surface stress (Yang et al. 2005). The final strain was then measured, and

Table 1 Growth characteristics of *F. falcata* trees sampled from a 3–6-year-old plantation in Buenavista, Agusan del Norte

Growth Orientation	DBH (cm)	Height (m)	Lean angle (°)	Lean direction (°)
Leaning 1	32	20	24	243
Leaning 2	28	20	16	276
Leaning 3	34	22	11	310
Straight 1	32	18	0	0
Straight 2	24	20	0	0
Straight 3	28	20	0	0

SRS was computed by subtracting the initial measurement from the final measurement. The values measured at the four cardinal points were averaged for each tree sampled (Kojima et al. 2009, Gilbero et al. 2019).

Wood anatomical analysis

Following the grove created for each tree at each cardinal direction, four rectangular wood samples measuring ca. 1 mm × 20 mm were extracted, labeled, and stored in individual plastic bags for anatomical analysis at the laboratory (Gilbero et al. 2019). Two sets of samples were prepared for anatomical analysis, one each from the straight and leaning trees. Using a woodcutter, ten strips of wood measuring ca. 1 mm × 5 mm were cut from the surface of the wood samples corresponding to the four cardinal directions. The strips were then placed in 1.5 ml Eppendorf tubes (Figure 1C) filled with hydrogen peroxide (H_2O_2) and glacial acetic acid (CH_3COOH) in a 1:1 ratio. The soaked samples were placed in a dry bath at 70 °C for 4 hours. Samples were checked every 30 minutes to monitor the progress of the defibrillation. After defibrillation, the samples were rinsed with distilled water to remove excess reagent and stained with safranin red dye. The specimens were mounted on glass slides and examined under a pre-calibrated light microscope (microscope model, e.g., Optika B-353 LD2, Optika, Italy). Image J software (version 1.51K) was used to measure the following parameters: fiber length (FL) and diameter (FD) and vessel length (VL) and diameter (VD) (Figure 1d).

Statistical analysis

Statistical analyses were performed in Microsoft Excel. Significant differences in mean values of SRS and wood anatomical variables were analyzed using Analysis of Variance (ANOVA). Tukey's test was then used for post hoc analysis. Correlation analysis was also performed to determine associations among variables.

RESULTS AND DISCUSSION

Variation in Surface Released Strain (SRS)

The mean SRS values tended to be higher for leaning (-0.214 ± 0.03) than for straight trees (-0.149 ± 0.04) (Figure 2a), but this difference was not significant (p = 0.34). The variation in SRS across cardinal directions was significant for leaning trees (p = 0.00005, Figure 2b) but not for straight trees (p = 0.47). The wood cells at the surface of hardwood tree stems are generally

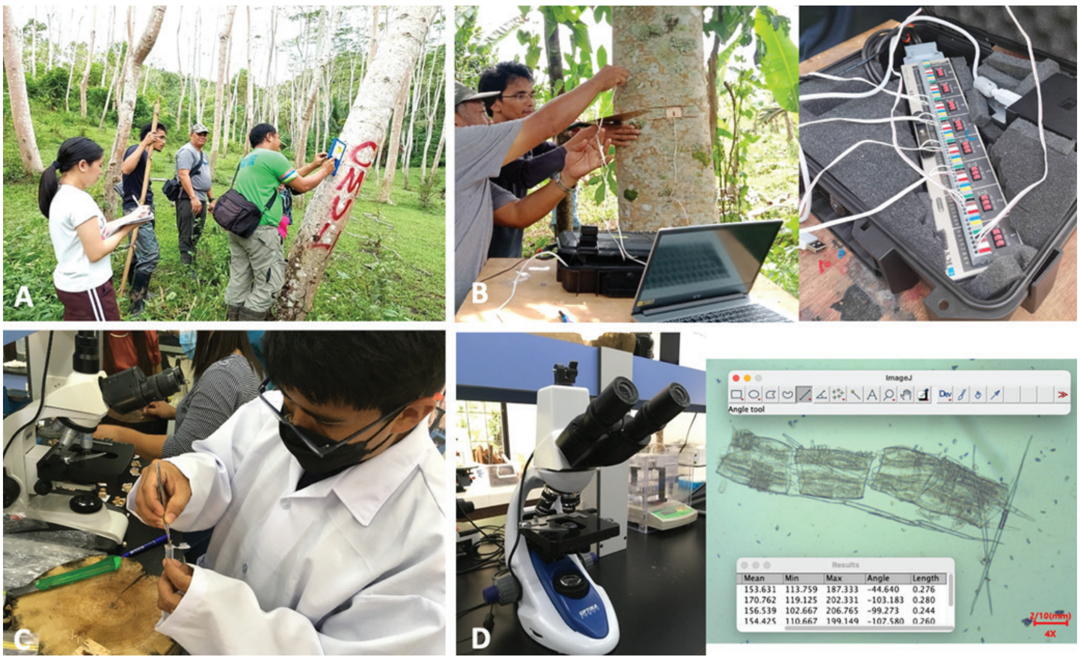

Figure 1 Sampling and analysis procedure: (A) selection of sample trees, (B) collection of SRS data, (C) sample preparation, (D) microscopic analysis using Image J software

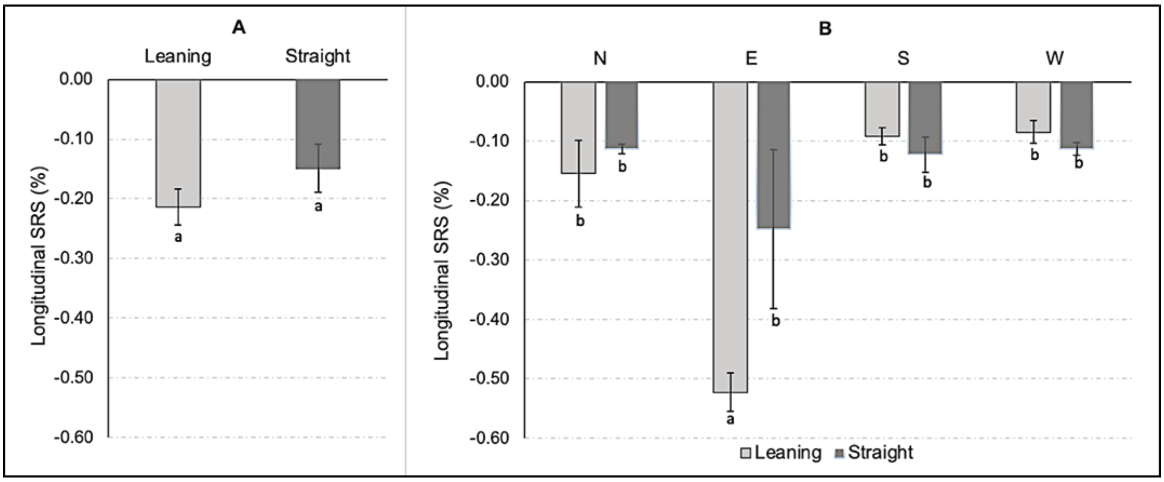

Figure 2 Variation in SRS between leaning and straight trees (A). Variation in Longitudinal SRS between cardinal directions in leaning and straight trees (B). Means with the same letters are not statistically different

held in tension, while wood cells inside the trunk are typically under varying degrees of compression (Yang et al. 2005). Hence, the observed negative strain values indicate tensile stress at the stem surface of *F. falcata*.

The mean SRS values for leaning trees varied by cardinal point, ranging from -0.085% on one side to -0.503% on the east side, which was the upper side of the lean for these west-ward leaning trees (Table 1). The higher strain values on the upper, east-facing side of the trees in our study likely indicate tension wood formation. Tension wood tends to form on the upper side of leaning hardwood stems (Yang et al. 2005), and angiosperms experience higher-than-usual tension in reaction wood due to elevated stress levels (Gril et al. 2017). The increased growth stress in leaning trunks contributes to restoring verticality (Yoshida et al. 2000, Jullien et al. 2012).

Interestingly, the east side also yielded the highest mean SRS value indicative of possible tension wood formation for straight trees instead of showing closely comparable tension levels across the four cardinal points. A closer examination revealed that while two of the sampled straight trees had balanced crowns, the third had an unbalanced crown directed at 230 degrees azimuth. The increased static load of the crown being more significant on the west side of that straight tree may have caused increased tension and tension in wood formation on the east side, resulting in a higher SRS value. Crown asymmetry has been reported to result in larger stress dissymmetry between trees (Jullien et al. 2012). Valencia et al. (2011) also found significantly higher longitudinal growth strain on the side with lesser crown dry mass in *Eucalyptus nitens*. Trees with asymmetrical crowns had greater crown mass on the NE side and higher growth stress values on the NW and SW sides. However, other factors like wind direction could have confounded the study's perceived effect of crown asymmetry. Tree growth stress resulting from the combined impact of dead weight increase and cell wall maturation in growing trees fulfills biomechanical functions by enhancing the strength of growing stems and controlling their growth orientation (Gril et al. 2017). Direct studies of the effect of crown asymmetry on growth stress are uncommon as previous work has focused on ecological aspects of asymmetry, such as competitive advantage (Brisson 2001, Mizunaga & Umeki 2001). Further studies are needed to establish the relationship between crown asymmetry and growth stress, including the possible influence of slope and aspect.

Variations in fiber length and diameter

Leaning trees had a mean FL of 1.103 ± 0.007 mm, significantly more than straight trees (0.989 ± 0.012 mm, p = 0.012; Figure 3a). FL did not vary significantly within leaning trees, but it was not the case with leaning versus straight trees. The main reason for this was that the mean FL values in the upper side of the lean were higher in leaning than in straight trees. The average FL in straight trees did not reach 1 mm.

There was also no significant difference (p = 0.733) in the mean FL of samples with respect to cardinal direction. The highest mean FL values were obtained from the south and east sides (Figure 3b). The lean direction ranged from 243 to 310 degrees (NW to SW) or an average of 276 degrees in leaning trees. This might explain the occurrence of greater FL on the east side of leaning trees, with higher tension due to lean. It is well established that FL can be higher in tension wood tissue (Jourez et al. 2001). Elongated wood fibers under tensile stress exhibit contraction upon stress release by cutting, but growth stress cannot be eliminated simply by removing all mechanical actions, including cutting (Grit et al. 2017). Growth stress is progressively applied over the life span of a tree, and because of the viscoelastic behavior of wood cell walls, stress would be reduced but not return to zero (Gril et al. 2017). Despite this, our results must be interpreted cautiously since they did not include any assessment or measurement of the reaction wood. Like leaning trees, there was no significant difference (p = 0.406) in mean FL for straight trees. However, a higher average was recorded from east-facing samples (Figure 3b). These findings suggest that FL did not vary significantly in young *F. falcata* regardless of growth orientation. Different species can have similar FL values (Kojima et al. 2009). Meanwhile, there was a significant difference (p = 0.0004) in the mean FD of leaning and straight trees (0.020 mm and 0.029 mm, respectively, Figure 3c). Fiber diameter was larger in samples taken from the east side of both leaning and straight trees (0.0202 mm and 0.033 mm, respectively) but not significantly different (p = 0.893 and p = 0.203, respectively).

Variations in vessel length and diameter

Vessel length did not vary significantly (p = 0.199) between leaning and straight trees (Figure 4A). The same result was observed for VD (p = 0.30). For VL in leaning trees, a significant difference (p = 0.009) was shown with respect to cardinal direction. VL was significantly higher in the south, north, and east sides than in the west-facing samples (Figure 4b). The south side recorded the highest VL of 0.278 ± 0.017 mm. The vessel length on the upper side of the lean, where tension wood is likely to occur, was generally higher. In a related study by Jourez et al. (2001), vessel elements were reportedly longer by 2.6% in tension wood than in opposite wood. In contrast, VL in straight trees did not vary significantly (p = 0.399) with respect to cardinal direction. For VD, there was no significant difference (p = 0.30) with respect to the cardinal direction for

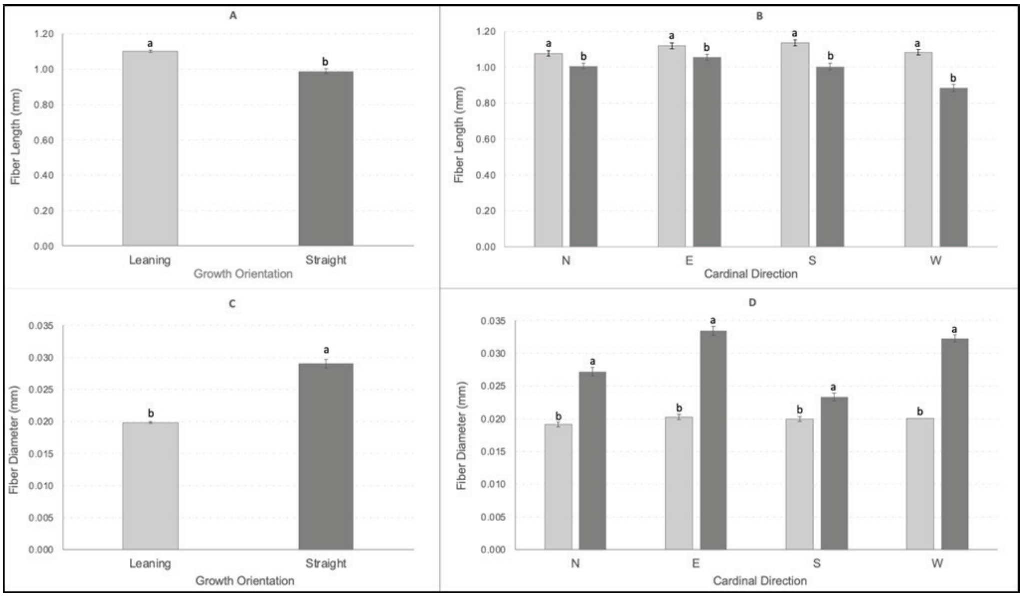

Figure 3 Mean values of fiber length (A) from the surface of leaning and straight tree stems, and (B) in relation to cardinal direction; and mean fiber diameter of wood sampled from (C) leaning and straight trees, and (D) in relation to cardinal direction. Different letters above each bar indicate significant differences (p < 0.05) in N, S, E and W measurements by tree category

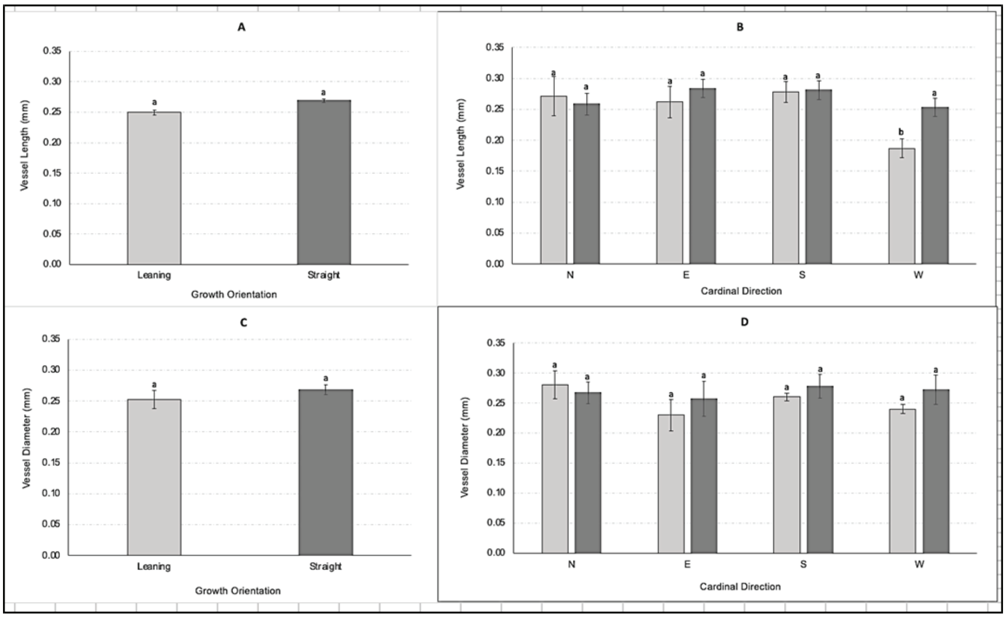

Figure 4 Variation in mean vessel length between Leaning and straight trees (A) and between cardinal directions (B). Variation in mean vessel diameter between Leaning and straight trees (C) and between cardinal directions (D)

both leaning and straight trees. However, the differences among means of VD in leaning trees were greater than that of straight trees. Jourez *et al.* (2001) likewise reported that VD was 3.7% larger in tension wood in their study.

Relationship between SRS and anatomical properties

The FL and FD in leaning and straight trees showed a weak positive correlation (Figure 5a). The correlation between FL and FD was slightly higher in leaning trees (r = 0.45) than in straight trees (r = 0.43). This implies that in *F. falcata*, samples with longer fibers also tended to have wider diameters. On the other hand, VL and VD had a weak positive correlation for both leaning (r = 0.14) and straight (r = 0.15) trees (Figure 5b). Gilbero et al. (2019) similarly found a positive correlation between FL and FD in *Swietenia macrophylla* sampled from one site but reported a negative correlation between FL and FD at a second site. Thus, FL and FD may not always correlate positively. Factors like genetics and growing conditions may impact FL and FD (Yang et al. 2001). Areas with better growing conditions promote longer but thinner fibers (Gilbero et al. 2019).

Meanwhile, longitudinal SRS in leaning trees had weak positive correlations with FL, FD, and VL (r = 0.11, 0.09 and 0.21 respectively, Figure 6) and was negatively correlated with VD (r = -0.29). For straight trees, longitudinal SRS had positive correlations with FL and FD (r = 0.34 and 0.42, respectively), a negative correlation with VD (r = -0.29), and no correlation with VL (r = -0.039, Figure 7). Gilbero et al. (2019) also reported weak positive correlations of longitudinal SRS with FL, FD and VL for 8-year-old *S. macrophylla* trees grown in Butuan and Cagayan de Oro. Generally, wood fibers exposed to higher stress will have larger lengths and diameters. This phenomenon could be explained by the viscoelastic behavior of the wood cell wall and the duration it was exposed to stress. According to Gril et al. (2017), stress is progressively applied in the stem, and the release of the wood cell wall from stress by cutting does not result in its total return to its original dimension. The higher stress results in greater contraction, as evidenced by higher SRS. However, the long duration of stress exposure and the viscoelastic property of the wood cell wall tend to slow down the contraction, and it may take some time for the fibers to shorten fully.

CONCLUSION

The Surface Released Strain (SRS) did not show significant variation between leaning

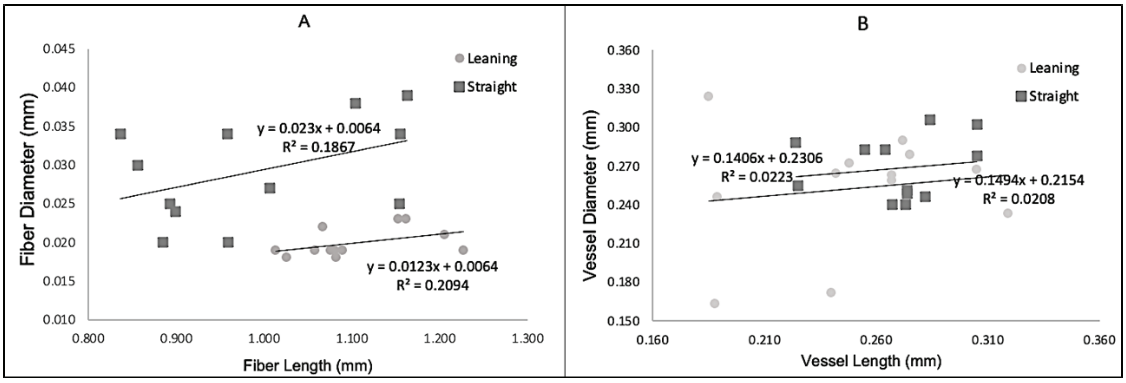

Figure 5 Correlations between FL and FD in leaning and straight trees (A). Relationship between VL and VD in leaning and straight trees (B).

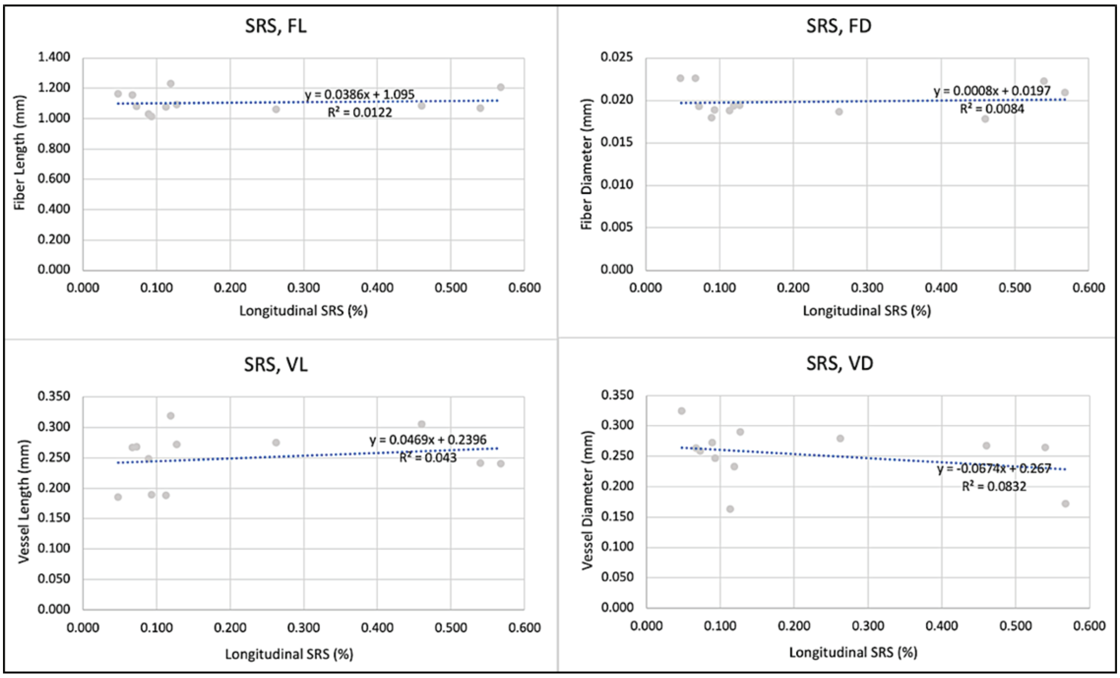

Figure 6 Correlations between longitudinal SRS and anatomical properties of wood sampled from stems of leaning *F. falcata* trees

and straight trees. However, within the leaning trees, a significant variation was observed, with the highest SRS recorded on the east, upper side of the lean. Fiber length (FL) across the four cardinal directions was not significantly different in both leaning and straight trees, and the same was found for fiber diameter (FD). However, FL was noted to be significantly higher in leaning trees ($p = 0.012$) compared to straight trees. Conversely, FD was significantly higher in straight trees ($p = 0.0004$) than in leaning trees. Furthermore, vessel length (VL) in straight trees did not significantly vary across the cardinal directions ($p = 0.399$). For vessel diameter (VD), there was no significant difference across cardinal directions in both leaning and straight trees. Correlation analysis revealed a weakly positive correlation between SRS and all anatomical properties measured except for VD.

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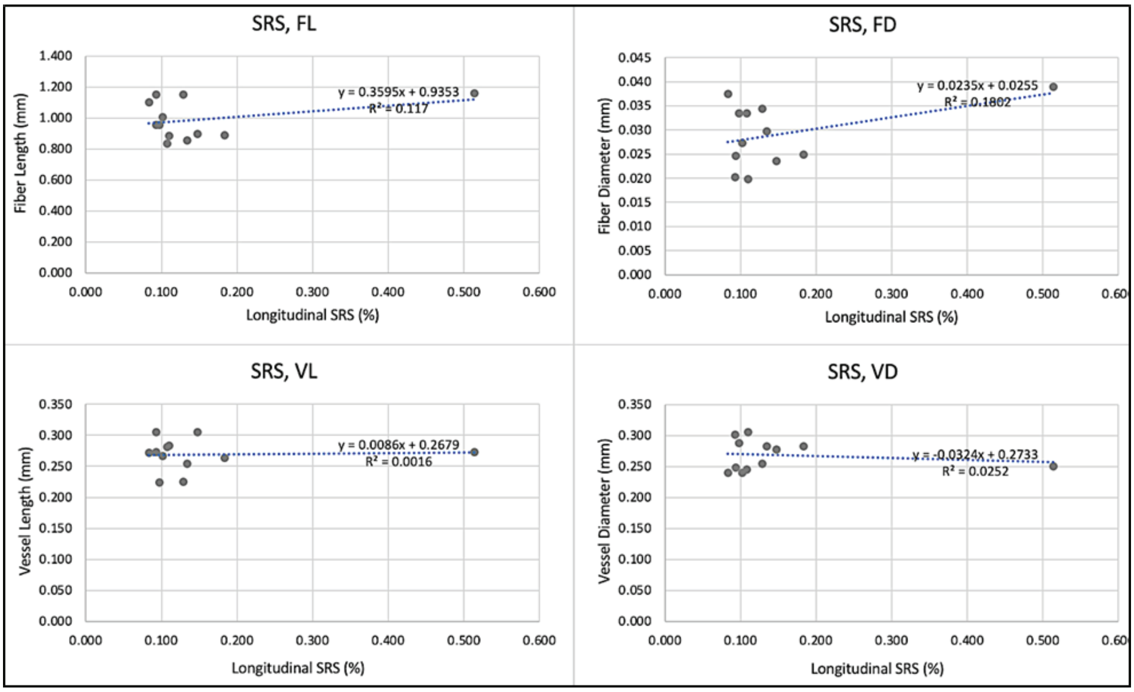

Figure 7 Correlations between longitudinal SRS and anatomical properties of wood sampled from stems of straight *F. falcata* trees

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