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INFLUENCE OF SLOPE AND CROWN BALANCE ON THE SURFACE RELEASED STRAIN AND STRESS OF *FALCATARIA FALCATA* (L.) GREUTER & R. RANKIN TREES IN AN 8-YEAR-OLD PLANTATION IN BUKIDNON, PHILIPPINES

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This study examined the impact of slope and crown balance on the Surface Released Strain (SRS) and stress in 8-year-old *Falcataria falcata* trees. The findings indicate that there is variation in SRS among the treatment groups. On average, SRS was higher in group B (<18% slope with unbalanced crown) compared to groups A (<18% slope with balanced crown), C (>18% slope with balanced crown), and D (>18% slope with unbalanced crown). However, no statistically significant difference was observed among the groups. Conversely, a notable and statistically significant difference in the average SRS between the northern and southern sides was observed in Groups B and D. Groups B and D also demonstrated elevated surface stress values on their northern side compared to their southern side. This disparity in stress distribution aligns with observations of strain distribution and may be attributed to factors such as crown balance. Our findings make a compelling case for crown balance as a factor affecting the distribution of SRS and stress in the stem of *F. falcata*. This implies that potential silvicultural interventions like pruning, thinning, or spacing could be viable approaches to tackle the challenge of high growth stress. Further experimentation to gather more data on this topic would certainly be valuable.

Keywords: *Falcataria falcata,* growth stress, released strain, Young's Modulus, crown balance, slope, anatomical properties

INTRODUCTION

The species *Falcataria falcata* (L.) Greuter & R. Rankin has become a major species for veneer and plywood production (Jimenez et al. 2015, Paquit & Rojo 2018). However, those involved in the industry have observed issues with radial splitting of harvested logs, leading to decreased value depending on the severity of the defects (Paquit et al. 2024). In 2019, the average monthly FOB price for *F. falcata* logs ranged from PHP 2,268.20–4,650.00/m^3 (FMB-DENR 2019, Alipon et al. 2021). A study by the USDA Forest Service found that, on average, 12.6% of the potential lumber tally is lost due to multiple defects (Cahill & Cegelka 1989). Considering the total volume per hectare of *F. falcata* is 30–40 m^3/ha (Krisnawati et al. 2011) and the price

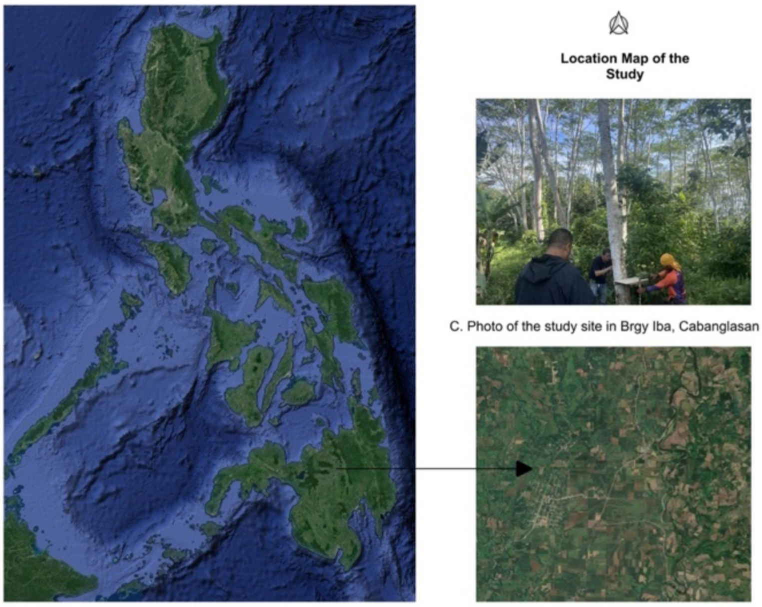

Figure 1 Location map of the study area. (A) Map of the Philippines, (B) Map of Cabanglasan, Bukidnon, and (C) Photographs of the study site in Brgy. Iba, Cabanglasan

per volume is 4,500 pesos per m^3, an estimated loss of 22,600 pesos per hectare is attributed to log defects. This is significant as it impacts the income of tree growers.

Defects in logs can be attributed to longitudinal growth stresses arising from the combined effects of increasing dead weight and maturing cell walls in growing trees (Gril et al. 2017). These growth stresses play a crucial role in maintaining a vertical orientation in standing trees. While they are a natural outcome of tree growth and present in all standing trees, elevated levels of growth stress can lead to log defects. Growth stresses in inclined or leaning stems help reorient the tree stem and crown into a more favourable position (Kubler 1988). However, reaction wood can develop in inclined stems. In angiosperms, tension wood develops on the upper side of leaning stems. Reaction wood experiences exceptional levels of longitudinal stress (Gril et al. 2017). The impact of released growth stresses becomes apparent when trees are felled and cut into logs to be processed into lumber (Matsuo-Ueda et al. 2022). Apart from growth orientation, defects are common in trees with fast growth rates and shorter rotation periods (Wahyudi et al. 2001). Fast-growing trees are typically characterized by high growth stress levels in the longitudinal direction and a significant proportion of juvenile wood (Wahyudi et al. 2001). The presence of residual stress often leads to processing defects during logging and lumbering, ultimately reducing the final yield of harvested resources (Gril et al. 2017).

Although radial cracking and lumber crooking have been observed in harvested *F. falcata* logs, there is a lack of growth stress and strain measurements for this species in the Philippines, and very few reports exist elsewhere (Paquit et al. 2024). A thorough investigation into its growth stress characteristics is essential to utilize such species effectively. The efficient utilization of plantation trees, whether for timber or veneer, is often hampered by defects arising from harvesting or processing (Wahyudi et al. 2001). This study assessed the SRS, surface growth stress, tensile and anatomical properties of *F. falcata* trees in an 8-year-old plantation, aiming to gain insights into the nature of its growth stresses. Specifically, the study evaluated the variation in growth stresses among test trees with straight stems, influenced by slope and crown balance. It also examined wood fibre and vessel properties, emphasizing the influence of slope and crown balance. By carefully examining the role of slope and crown balance in influencing growth stress levels, this study provides important information for tree breeding, silvicultural programs, and potential harvesting strategies.

Table 1 Growth characteristics of test trees

Group code	Tree No.	DBH (cm)	Total Height (m)	Slope (%)	Aspect	Crown Balance	Direction of Crown if UB
A	1	27.8	15	3		Balanced	
	2	29.6	16	5		Balanced	
	3	26.2	14	4		Balanced	
B	4	26.2	14	2		Unbalanced	S
	5	28.7	15	2		Unbalanced	S
	6	25.3	13	5		Unbalanced	S
C	7	25.3	14	23	4 SW	Balanced	
	8	25.6	13	20	4 SW	Balanced	
	9	25.3	15	23	5 SW	Balanced	
D	10	30.5	17	23	4 SW	Unbalanced	SW
	11	25.3	15	23	4 SW	Unbalanced	SW
	12	26.5	15	23	6 SW	Unbalanced	SW

MATERIALS AND METHODS

Location of the Study site

This research was carried out in a managed 8-year-old *F. falcata* plantation located in Brgy. Iba, Cabanglasan, Bukidnon (Figure 1). The plantation is positioned at 8.091166 N latitude, 125.314676 E longitude, with an average elevation of 473 meters above sea level. The area features a slope ranging from 2-35%, with its aspect facing the Southern direction. The mean annual temperature in the plantation is 30 °C (Hijmans et al. 2005). The soil pH is strongly acidic at 5.3, while soil organic carbon and organic matter content levels are 4.06% and 6.99%, respectively. N, P, and K levels are measured at 0.25%, 5.45 mg P/kg, and 0.31 meq/100g. The area is rich in understory vegetation, including a variety of trees, shrubs, and a few species of ferns.

Design of the experiment

The study employed a 2x2 factorial design comprising four groups, each with three replications. The two factors examined were % slope (factor A) and crown balance (factor B). The slope was categorized into two classes: <18% (level to undulating) and >18% (rolling to steep), and 12 test trees (six from each slope class) were selected from the stand. The slope was determined using a clinometer, and then six test trees from each slope class were also divided into two sub-classes based on tree crown balance, categorized as balanced or unbalanced crown. Each tree crown balance class consisted of three test trees. In total, four treatment groups, each consisting of 3 test trees, were used in the SRS measurements. All 12 sampled trees in this experiment had straight stems (Table 1).

Characterisation of test trees

The trees in the area were labelled with red spray paint to make them easily identifiable. After labelling, the characters, such as DBH, height, slope, and direction of crown balance, of each sample tree were carefully evaluated. The findings from the evaluations were then documented and summarised in a tabular format, as shown in Table 1.

Measurement of Surface Released Strain (SRS)

For each tree, SRS measurements were done in 8 cardinal points (Due N, 45 deg NE, Due E, 45 deg SE, Due S, 45 deg SW, Due W, and 45 NW) at diameter at breast height (DBH) (1.3 meters from the ground). A 2 x 2-inch incision was created at each cardinal point, and the bark was carefully removed to expose the secondary xylem or wood surface. Subsequently, a 10 mm electric-wire strain gauge (KFG-10-120-C1-11 L1M1R, Kyowa Co., Tokyo, Japan) was affixed to each measuring point along the longitudinal direction. These gauges were then linked to a KYOWA DBV-120A-B data logger, and the resulting readings were monitored on a computer. Following this, two grooves were made using a handsaw, each 5-10 mm deep and situated 3-5 mm from the opposite edges of the strain gauge. This step allowed for the strain release in the wood cells (Yang et al. 2005) and facilitated the final measurement. The SRS was obtained by subtracting the initial strain measurement from the final one (Kojima et al. 2009, Gilbero et al. 2019).

Wood Anatomical analysis

The small wood samples extracted from the SRS measurement points were taken to the NICER Bamboo Research Center of Central Mindanao University for anatomical analysis. To prepare the samples, thin strips of wood measuring approximately 1 × 5 mm were cut using a woodcutter. About 10 small strips were obtained from each measurement point. These strips were then soaked overnight in 1.5 ml Eppendorf tubes containing a solution of equal parts hydrogen peroxide (H_2O_2) and glacial acetic acid (CH_3COOH) to facilitate defibrillation (Alipon et al. 2021). Subsequently, the soaked samples were heated in a dry bath at 70°C for 4 hours, with intermittent checks every 30 minutes to observe the change in colour and texture. Once the samples appeared whitish or soft, they were rinsed with water to remove the chemical solution. Following this, the samples were stained with Safranin to enhance the visibility of the wood fibres during microscopic examination. Small amounts of the macerated samples were mounted on standard microscope slides (75 × 25 mm) using a micropipette and topped with a cover slip (22 × 22 mm). Afterward, 25 randomly selected intact fibres and vessel elements were measured using ImageJ software version 1.53 (Alipon et al. 2021).

Measurement of tensile strain

The specimens used for tensile testing were cut from the same positions where the SRS measurements were taken. Each specimen had dimensions of 100 × 10 × 5 mm in the longitudinal, tangential, and radial planes, which are similar to the dimensions used by Matsuo-Ueda et al. (2022). With these dimensions, the sample surface area was calculated to be 50 mm^2. The testing was conducted at the Forest and Wetland Resources Research and Development Center (FWRDEC) located in Maharlika, Bislig City, Surigao Del Sur. The specimens were maintained in a green condition before testing. A Shimadzu AGS-X (100 kN) Universal Testing Machine (UTM) was used to test the samples. Additionally, a strain gauge was affixed to each specimen to monitor the displacement or change in strain readings as the load from the UTM was applied. The strain readings were set at 1 Hz, equivalent to 1 reading per second. The strain was recorded at a load of 400 N.

Computation of Young's Modulus and surface stress

The Young's modulus was computed by taking the ratio between stress and strain values using the equation below where E are Young's Modulus, 400 N Force, surface area of the sample, and tensile strain respectively.

$$E_n = \frac{(F/A)_n}{\varepsilon_n} \qquad (1)$$

The Surface Stress values of samples were determined by multiplying the SRS data by the corresponding Young's Modulus denoted as in equations 1 and 2 with a sample computation using a sample strain value of 0.002. The procedure starts with the computation of a sample's YM (in GPa) using equation 1 below. The given data provides a strain value equal to 0.002 (a decimal form of 0.2%) obtained from a tensile stress test of a wood sample (with a cross-sectional area (A) of 50 mm^2 at a force (F) of 400 N. In Equation 3, stress (in MPa) denoted by , was computed by multiplying a sample SRS value equal to 0.002 obtained from actual field measurement by its value.

$$E_n = \frac{(F/A)_n}{\varepsilon_n} = \frac{(400N/50mm^2)}{(0.002)} = 4000N/mm^2 \times \frac{1.0\ GPa}{1000N/mm^2} = 4.0\ GPa \qquad (2)$$

$$\sigma_n = -\varepsilon_n \times E_n = -(-0.002) \times 4\ \text{GPa} \left(\frac{1000\ \text{GPa}}{1\ \text{GPa}}\right) = 8\ \text{MPa} \tag{3}$$

Data Analysis

All the necessary statistical analyses were conducted using Microsoft Excel ver. 16.94. Significant differences between the means of SRS, wood anatomical variables, and tensile strength data were examined using Analysis of Variance (ANOVA) and T-test. Post Hoc Analysis was carried out as necessary using Tukey's Honestly Significant Difference (HSD) at 95% significance level. Finally, correlation tests (Pearson's r) were conducted to assess associations among variables, particularly between growth stress, Young's Modulus, and anatomical properties.

RESULTS AND DISCUSSION

Variation in the circumferential distribution of Surface Released Strain (SRS)

The study observed variations in the circumferential distribution of SRS among different treatment groups. Specifically, the mean SRS (%) of group B (-0.109 ± 0.018) was found to be higher than that of groups A (-0.106 ± 0.009), C (-0.097 ± 0.014), and D (-0.098 ± 0.008). Despite the higher strain in group B, the analysis showed that the variations influenced by the slope (p=0.11), crown balance (p=0.78), and their interaction (p=0.90) were not statistically significant. This could be due to the large strain variation within groups. However, a significant difference in the average SRS among trees within the groups was detected when cardinal directions were grouped into two, N side and S side. It was first observed that SRS values at the N, NE, and NW in groups B & D tended to be higher than in the other directions (Figure 2). Additionally, in these groups, the values were typically lower between SE and SW compared to between NE and NW, which are the opposite directions, so further testing was performed. It is essential to note that the direction of the slope aspect is 4° SW, while the general orientation of the unbalanced crown is directed at the southern direction. Thus, there seems to be a correspondence between the slope and crown balance data with the observed strain values.

The comparison between the N side (opposite of slope and crown balance) and the S side (side of slope and crown balance) underwent a two-tailed T-test. Upon thorough examination, it was revealed that in Groups B (p=0.02) and D (p=0.04), the strain value variances between the N and S sides were highly significant (Figure 3). Conversely, this was not observed in the other treatment groups, A (p=0.84) and C (p=0.50), as none of these results were statistically significant. It is important to note that groups B (p=0.02) and D (p=0.04), have very small p values and differ significantly from the high p values of groups A (p=0.84) and C (p=0.50). These results demonstrate the intricate nature of strain development among trees and the potential impact of crown balance. Higher SRS levels on the side opposite to the heavier crown suggest that crown balance could be a contributing

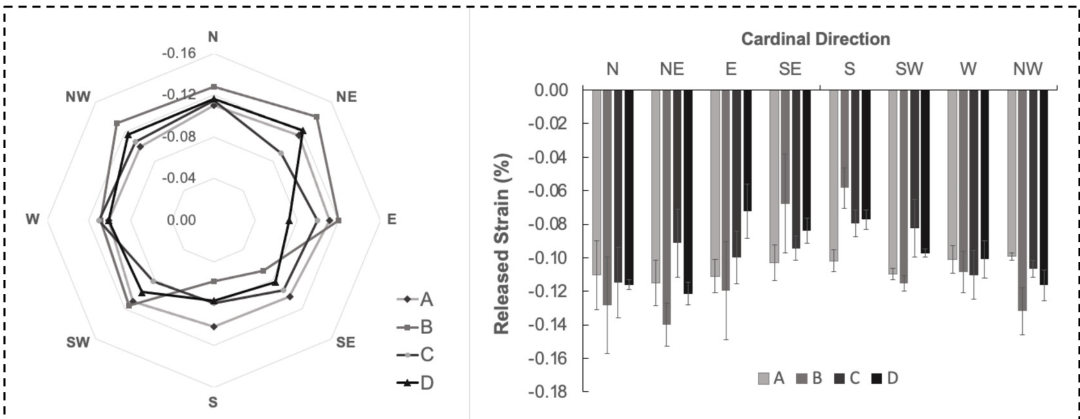

Figure 2 Circumferential distribution of surface released strain

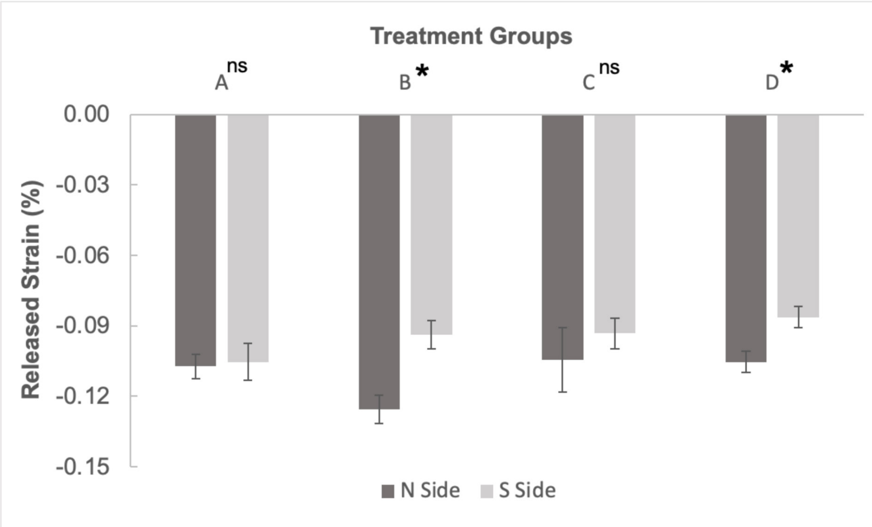

Figure 3 Variation in the average SRS between the N side vs. S side across treatment groups

factor. On the other hand, the slope alone did not seem to lead to higher strain levels. Since strain is related to stress, the higher-than-normal negative SRS indicates the presence of tensile stress at the periphery. As indicated in a previous study, one of the mechanisms through which strain develops in wood is the increase in dead weight (Gril et al. 2017). The increased static load of the larger crown on the S side may have resulted in increased tension on the N side, leading to a higher SRS value.

Previous studies have also highlighted similar findings. For instance, Jullien et al. (2013) reported that crown asymmetry led to a greater strain dissymmetry between trees. Likewise, Valencia et al. (2011) observed significantly higher longitudinal growth strain on the side with less crown dry mass in *Eucalyptus nitens*. In the current study, trees with asymmetrical crowns exhibited a greater crown mass on the south side and higher growth stress values on the north, northeast, and northwest sides. However, it is worth noting that other factors, such as wind direction and sunlight may have influenced the perceived effect of crown asymmetry. Research specifically focusing on the impact of crown asymmetry on growth stress is limited, as previous work has primarily concentrated on the ecological aspects of asymmetry, like competitive advantage (Brisson 2001, Mizunaga and Umeki 2001). Other studies on this topic have largely compared leaning and straight stems (Paquit et al. 2024), with higher strain values often recorded on the upper sides of leaning stems. Thus, this study contributes empirical evidence regarding the influence of tree crown balance on growth strain and stress.

Variation in the circumferential distribution of Surface Stress

The mean surface stress (MPa) value was higher in group B (4.74 ± 0.25 MPa) compared to groups A (4.54 ± 0.46 MPa), C (3.69 ± 0.77 MPa), and D (4.48 ± 0.63 MPa) (Figure 4). However, the differences were not statistically significant for slope (p=0.06), crown balance (p=0.08), and their interaction (p=0.27).

Similarly, T-test was done to compare the N and S sides within groups for slope and crown balance effects on surface growth stress showed that the p values for groups A, B, C & D are 0.54, 0.01, 0.15, and 0.05, respectively. This demonstrates that groups B and D exhibit significantly higher surface stress values on the N side compared to the S side (Figure 5). This phenomenon could be attributed to the influence of crown balance. Notably, as group C did not produce a significant difference, the variation in group D could be explained more by crown balance and less by slope. Considerable variations in growth stress levels were observed between the different groups studied. Previous studies by Nicholson (1971) and Nicholson (1973) on *Eucalyptus regnans* noted substantial between-tree variation. Similarly, Jullien et al. (2013) found uneven distribution of growth stress around the trunks of most European Beech trees. Malan (1988)

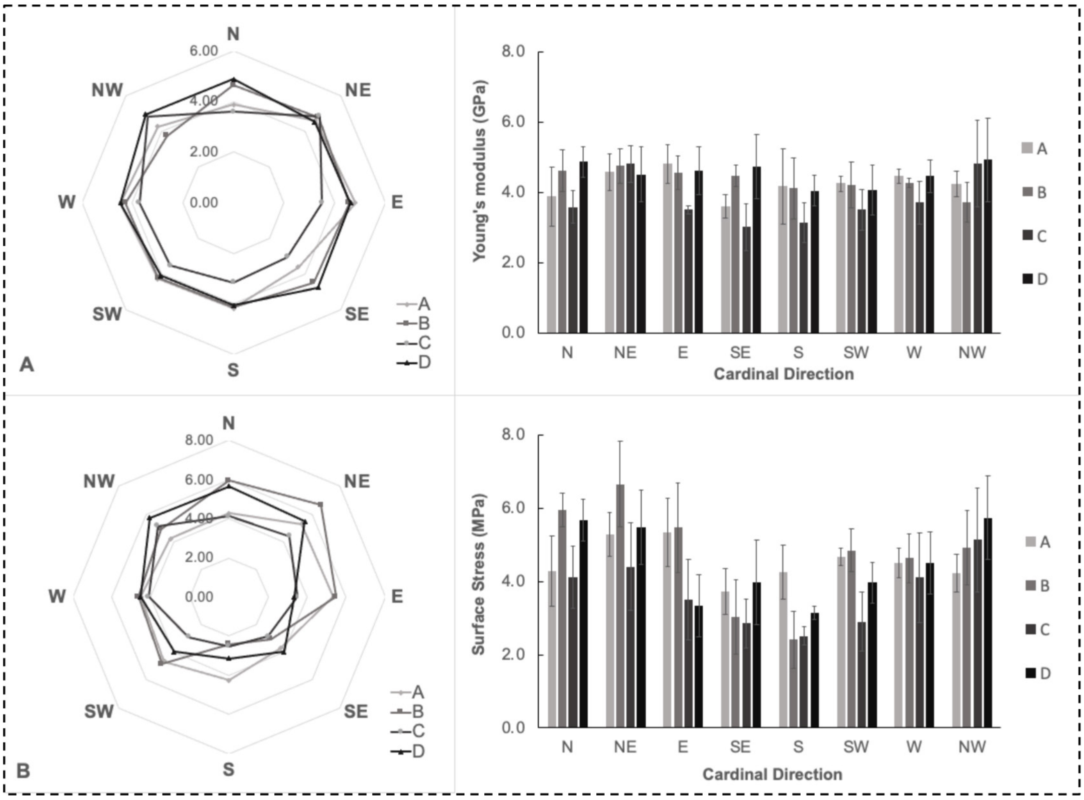

Figure 4 Variation in Young's Modulus (A) and Surface Stress (B)

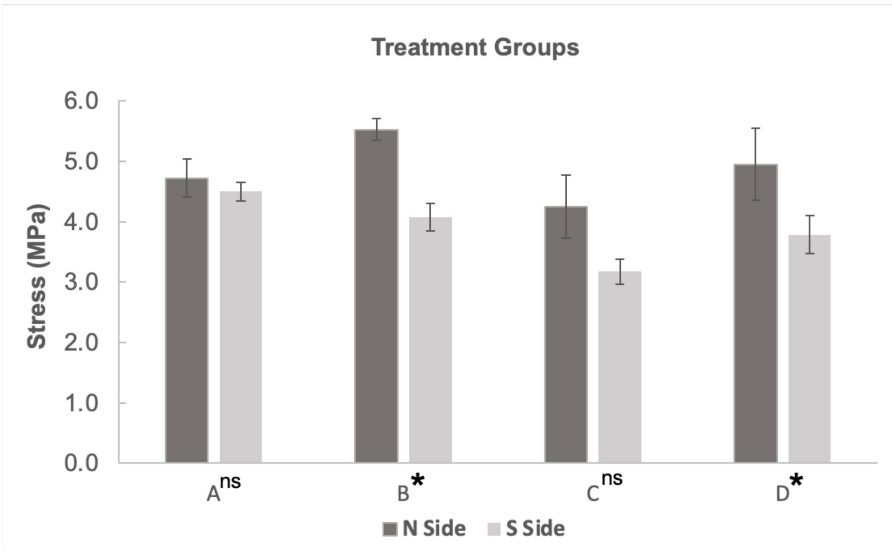

Figure 5 Variation in the average surface stress between the N side vs. S side across treatment groups

observed a similar pattern in South African-grown *Eucalyptus grandis*, where the relationship between growth stress and crown properties could not be established due to the significant deviation in growth stress levels between trees.

As mentioned earlier, groups B and D exhibited a significant difference in growth stress levels between the N (north) and S (south) directions, with higher levels of stress observed on the north side. This suggests that crown balance may have influenced the variation in stress intensity. In a study by Jullien et al. (2013), crown asymmetry was found to result in greater strain and stress dissymmetry within trees. As the dead weight increases on one side of the crown, the stem's opposite side may experience higher stress levels. Alongside cell wall maturation, an increase in dead weight is considered one of the mechanisms contributing to the development of tree growth stress (Gril et al. 2017). Jullien et al. (2013) referred to these stresses, resulting from self-weight increase, as "support stress."

Variation in the circumferential distribution of Fiber Length (FL), Fiber Diameter (FD), Fiber Cell Wall thickness (FCWT), Vessel Element Diameter (VED), and Vessel Element Length (VEL)

There were no significant differences in the average FL and FD extracted from SRS samples. Group A showed a slightly higher mean FL (Figure 6), but the difference from the other groups was negligible. The parameters slope (p=0.5), crown balance (p=0.07), and their interaction (p=0.88) did not significantly influence both parameters. The FL values in this study closely resemble those reported by Alipon et al. (2021) for near-bark samples in 7-year-old *F. falcata*. They found a mean FL of approximately 1.20 mm, which is only slightly lower than the FL of 1.23 mm observed in this study. It is important to note that although the sample trees had similar DBH, the trees in this study were slightly older. Furthermore, the wood samples were taken from SRS measuring points located at the outermost portion of the secondary xylem, which may account for the higher FL values recorded in this study. Previous related studies have also reported that FL is typically longer toward the bark due to a higher proportion of mature wood containing longer fibres (Bao et al. 2001). Conversely, the xylem exhibits shorter FL near the pith, where the juvenile wood is more prominent (Panshin & de Zeeuw 1970). Meanwhile, for FD, there was no significant difference among the treatment groups. Similarly, the variations between cardinal directions within groups were not statistically significant. The mean FD values (mm) were nearly identical among the groups, with Groups A (0.029 ± 0.0005 mm) and D (0.029 ± 0.0002 mm) slightly greater than B (0.028 ± 0.0002 mm) and C (0.028 ± 0.0002 mm). The FD values among all samples ranged from 0.017 to 0.042 mm. As shown in Figure 6, several samples exhibited a greater spread in the data, indicating high heterogeneity in FD within and between groups and among trees within groups. Since the results did not demonstrate statistically significant variation between groups, it is suggested that slope and crown balance did not affect the distribution pattern of FD. Samples extracted at the stem periphery did not appear to significantly vary as differences in FD could be readily observed from pith to bark.

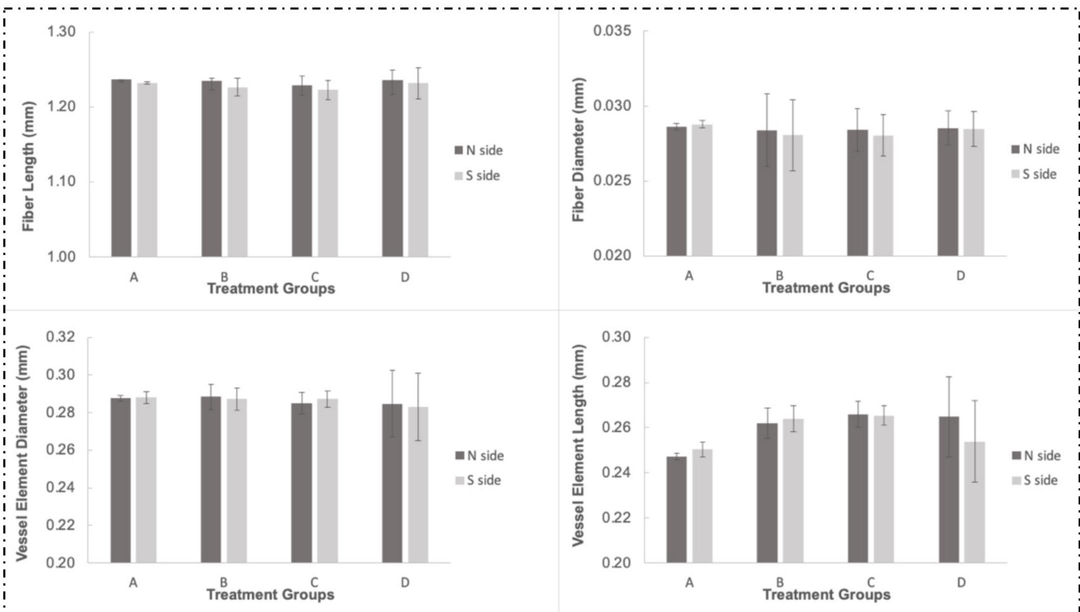

Figure 6 Variation in the averages of anatomical properties between the N side vs. S side across treatment groups

Alipon et al. (2021) reported an average FD for near-bark samples of about 0.037 mm, which is higher than the 0.029 mm observed in this study.

The mean fibre cell wall thickness (FCWT) values showed no significant variation among the treatment groups. This indicates that the slope (p=0.32), crown balance (p=0.19), and their interaction (p=0.48) did not have a significant influence on FWCT. Upon comparing the values per cardinal direction within each group, it was determined that the variation was also not statistically significant. Furthermore, the FCWT of group B (0.0033 mm) is only slightly higher than that of groups A (0.0032 mm), C (0.0031 mm), and D (0.0031 mm). Across all measured samples, FCWT values ranged from 0.0023 to 0.0049 mm.

Based on the analysis for Vessel Element Diameter (VED), it was found that the variation in the average VED was almost indistinguishable among the treatment groups, indicating no statistically significant difference in relation to slope (p=0.78), crown balance (p=0.92), and their interaction (p= 0.91). However, it is worth noting that the highest recorded average Vessel Element Length (VEL) was observed in group B at 0.289 ± 0.001 mm, while the lowest was in group D at 0.284 ± 0.001 mm. The range of VED values spanned from 0.150 to 0.361 mm. It was also observed that some samples showed a significant variation in VED while others displayed more uniform values. This resulted in greater within-tree variances, a trend observed in nearly all samples. The influence of an unbalanced crown and slope on the variations in VED was not significant in this study. A similar finding was reported by Gilbero et al. (2019) in their study on big-leaf Mahogany. As observed in other related studies, VED can vary between and within species due to age and environment. For instance, Alipon et al. (2021) discovered that 7-year-old test trees had a wider average VED than 3- and 5-year-old test trees, indicating age as a significant factor. Additionally, there was a positive correlation between DBH and VED (Gilbero et al. 2019). VEL measurements were also obtained, and across all groups, the average values showed minimal differences, suggesting that the observed variations were not statistically significant. The influence of slope (p=0.40), crown balance (p=0.67), and their interaction (p= 0.19) on the average VEL between groups was found to be non-significant. This finding concurs with Gilbero et al. (2019). Similarly, no significant disparities were observed between the groups in terms of cardinal directions.

The variation in the average of the different anatomical properties between the N and S sides in each group was also evaluated. Figure 6 presents the comparison between groups. For FD, significant variation was observed in groups B, C, and D, while A did not yield a significant result. The rest of the wood anatomical parameters did not result in statistically significant variation. As previously stated, it appears that the higher-than-usual tensile stress at the periphery of the secondary xylem on the side opposite of the heavier crown (N side) correlates with the occurrence of typically longer fibres. Additionally, empirical data suggest that slope is not a significantly contributing factor to higher tensile stress. Thus, the side of the tree opposite the slope aspect would likely develop higher than normal stress levels. While a significant variation was observed for FL, the effect of crown balance and slope to FD, FCWT, VED, and VEL seems rather negligible.

CONCLUSION

Group B demonstrated a higher mean strain than Groups A, C, and D in the study, albeit without statistical significance. Conversely, a notable and statistically significant difference in average strain between the northern and southern sides was observed in Groups B and D, which provided evidence of the influence of crown balance and slope on growth strain in *F. falcata*. Groups B and D demonstrate elevated surface stress values on their northern side in contrast to their southern side. This disparity in stress distribution aligns with observations of strain distribution and may be attributed to factors such as crown balance. Higher stress values on the side opposite the heavier crown suggest pruning could help lighten the load and lower stress levels. As observed, the slope of the plantation could promote the development of unbalanced crowns and the inclination of stems. On steep slopes, trees may grow unevenly and lean. Planting on less steep slopes can reduce stress and promote balanced growth. Additional experiments are recommended to collect data on how pruning, thinning, and other forest management techniques affect the distribution of growth stress and strain in *F. falcata*.

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