

# **Driving Dynamic Ecosystems in the Bunya Mountains:**

## **A Comparative Analysis**

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## **Abstract**

This study investigates the influence of biotic and abiotic drivers on tree and seedling dynamics across the diverse ecosystems of the Bunya Mountains, Queensland, including araucarian microphyll rainforests, dry rainforests, dry sclerophyll forests, notophyll vine forests, and montane grasslands. Tree density, basal area, and volume were measured to evaluate variations between ecosystems, while abiotic factors such as litter depth, light availability, and relative humidity were analysed to assess their impact on seedling establishment. The results revealed significant differences in tree density and basal area across ecosystems, highlighting the role of environmental constraints and competition in shaping forest structure. Seedling densities were higher in wet habitats, where moisture and moderated light conditions were more favorable for growth. Key abiotic factors, particularly soil water, light availability, and humidity, were found to play important roles in seedling establishment, emphasizing the importance of microenvironmental conditions. These findings offer valuable insights into how both biotic and abiotic factors interact to shape plant communities and provide a foundation for understanding ecosystem responses to climate change, informing future conservation strategies.

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## 1.0 Introduction

Understanding the biotic and abiotic drivers of plant communities is central to ecology. Various paradigms have been established to describe and predict these drivers' complex nature. One well-accepted concept is that inter- and intraspecific competition organises plant community structures through facilitative and competitive mechanisms, often acting together (Callaway & Walker, 1997). In addition to species interactions, environmental drivers, particularly climate, are crucial large-scale controls on the distribution of organisms and community structures (Treurnicht et al., 2016). Quantifying these factors at different spatiotemporal scales can enhance our understanding of how ecosystems respond to large-scale threats, such as invasive species and climate change.

Plant species interactions have been extensively studied. Gersani et al. (2001) examined intraspecific competition in soybean plants, showing how energy allocations to root biomass in homogeneous soil led to a "tragedy of the commons," where resource overuse decreased reproductive yield. Wijesinghe et al. (2005), focusing on interspecific competition in heterogeneous soil, found significant prioritisation of root biomass, although species richness and diversity were weakly linked to soil heterogeneity. These studies revealed correlations between local factors, such as soil nutrients and competition, prompting further research into plant community complexity. More recently, Treurnicht et al. (2016) explored abiotic drivers on a broader scale, analysing the effects of climatic conditions and fire regimes on pyrophytic shrub demographics. They discovered a trade-off between survival and reproduction and clear links between recruitment and climate, but mixed evidence for environmental factors driving interspecific differentiation. These findings highlighted the role of abiotic factors in plant demographics and the impact of climate change.

Ecological research has increasingly focused on regions sensitive to climate change (Treurnicht et al., 2016; Trivedi et al., 2008), such as Queensland's Bunya Mountains. This national park is home to more than 30 ancient and threatened species and features distinct plant assemblages—araucaria rainforests, dry rainforests, dry sclerophyll forests, notophyll vine forests, and montane grasslands—that respond uniquely to environmental stimuli (Department of Environment, Science and Innovation, 2023). These markedly different ecosystems have led ecologists to make important developments in conservation and ecological theory (Butler et al., 2006; Fensham & Fairfax, 2006; MacDermott et al., 2017). The articles published by these ecologists, particularly by Butler and MacDermott et al., have applied an in-depth focus on bottom-up drivers and plant competition; however, gaps remain in understanding the distribution of plant traits and proliferation between ecosystems within the context of environmental drivers.

While prior research in the mountains has focused on nutrient dynamics, disturbances, and competition, there is limited exploration of how the combination of biotic and abiotic factors affect tree density, basal area, and volume across the ecosystems and habitats in the Bunya Mountains. Examining these factors will clarify how different conditions shape forest structure. Additionally, the influence of abiotic factors such as light availability, soil moisture, and litter depth on seedling density has been explored by ecologists (Comita et al., 2009; Mensah et al., 2020); however, there remains limited evidence on how co-occurring biotic and abiotic factors contribute to seedling establishment at local scales. By addressing these gaps, this research aims to link large-scale environmental drivers with local biotic processes through observations within the Bunya Mountains, providing evidence for how these ecosystems, and ecosystems alike, may respond to growing environmental pressures and inform conservation efforts.

## **2.0 Methodologies**

### **2.1 Study Site and Data Collection**

Data was collected within the managed regions of the Bunya Mountains. For each ecosystem, measurements for light conditions, soil properties, and vegetation were taken within a 6 m x 5 m transect, further divided by four randomly placed 1 m<sup>2</sup> standard quadrats. The dimensions for the transects were measured using an 8 m measuring tape, with the boundaries signified by coloured corner posts and the quadrat boundaries indicated by a plastic frame.

### **2.2 Quantitative Analysis**

The following vegetational and abiotic data were tested for significant differences between ecosystems and habitats: tree and seedling population density, tree basal area and tree volume. The ambient temperature, wind speed, relative humidity, light lux, leaf litter depth, soil pH, and soil moisture were tested for pairwise correlations and relationships to seedling density. The vegetation data were primarily tested using one-way analysis of variance (ANOVA) tests and the abiotic factors were tested for a significant contribution to ecological trends *via* a principal component analysis (PCA) and PERMANOVA test. The analyses then provided a determination of ecological differences which gave suitable evidence for the established research questions.

#### ***2.2.1 Vegetation Sampling***

Trees inside the transect and larger than 4 cm were recorded, and all seedlings were counted from inside each quadrat. The height of the tree was calculated by first using the Suunto PM-5/360 PC Clinometer to measure the angle of elevation from the user's eye to the crown of the tree and an 8 m measuring tape to measure the distance from the tree to the user. Using these

values, the Pythagoras theorem was then applied to these values to calculate the height of the tree. The DBH was then measured using a 2-metre fiberglass diameter tape. The basal area and volume of each tree were then calculated using the following equations:

$$BA = \frac{\pi \times DBH^2}{40000}$$

Where BA is the basal area (m<sup>2</sup>), and DBH is the diameter at breast height (cm).

$$V = 0.42 \times BA \times H$$

Where V is the tree volume (m<sup>3</sup>), and H is the height of the tree (m).

### ***2.2.2 Vegetation Analysis – Trees***

Averages of tree population density, basal area, and volume were all tested for a significant difference across ecosystems and habitats using a one-way ANOVA test. If the relationship was found to be significant ( $p < 0.05$ ), the Tukey Honest Significant Difference (Tukey HSD) test was used to identify which groups were significantly different from one another. These tests were conducted in the context of both ecosystems and habitats (dry and wet) to determine if the response variables could be explained in broader contexts.

The effects of ecosystems and habitats on tree density were tested for normality, linearity, homoscedasticity and independence. If these conditions were not met, non-parametric tests (i.e., the Kruskal-Wallis test and Wilcoxon signed-ranked test) were used to assess these relationships without parametric assumptions and the existence of significant pairwise comparisons.

### ***2.2.3 Vegetation Analysis – Seedlings***

Seedling population densities were tested for a significant in means in the same way the tree populations were tested, using a one-way ANOVA, followed by the appropriate post-hoc and/or non-parametric tests.

### ***2.2.4 Abiotic Sampling***

Ambient temperature, relative humidity, light lux, and wind speed were recorded using the Lutron Multifunction 4 in 1 Thermometer – LM-8000A. Averages of soil pH, litter depth, and soil moisture were recorded within each quadrat, using the Inoculo Soil pH test kit, a ruler, and the Acclima TDR Digital Soil Moisture Sensor Reader kit – IC-RD1200.

### ***2.2.5 Abiotic Analysis***

All abiotic factors were initially considered in pairs using Pearson's correlations, then were analysed through a PCA to simplify any highly correlated data and test for variables that contributed most significantly to grouped principal components. Furthermore, a PERMANOVA test was used to determine whether significant differences existed between ecosystems.

## **3.0 Results**

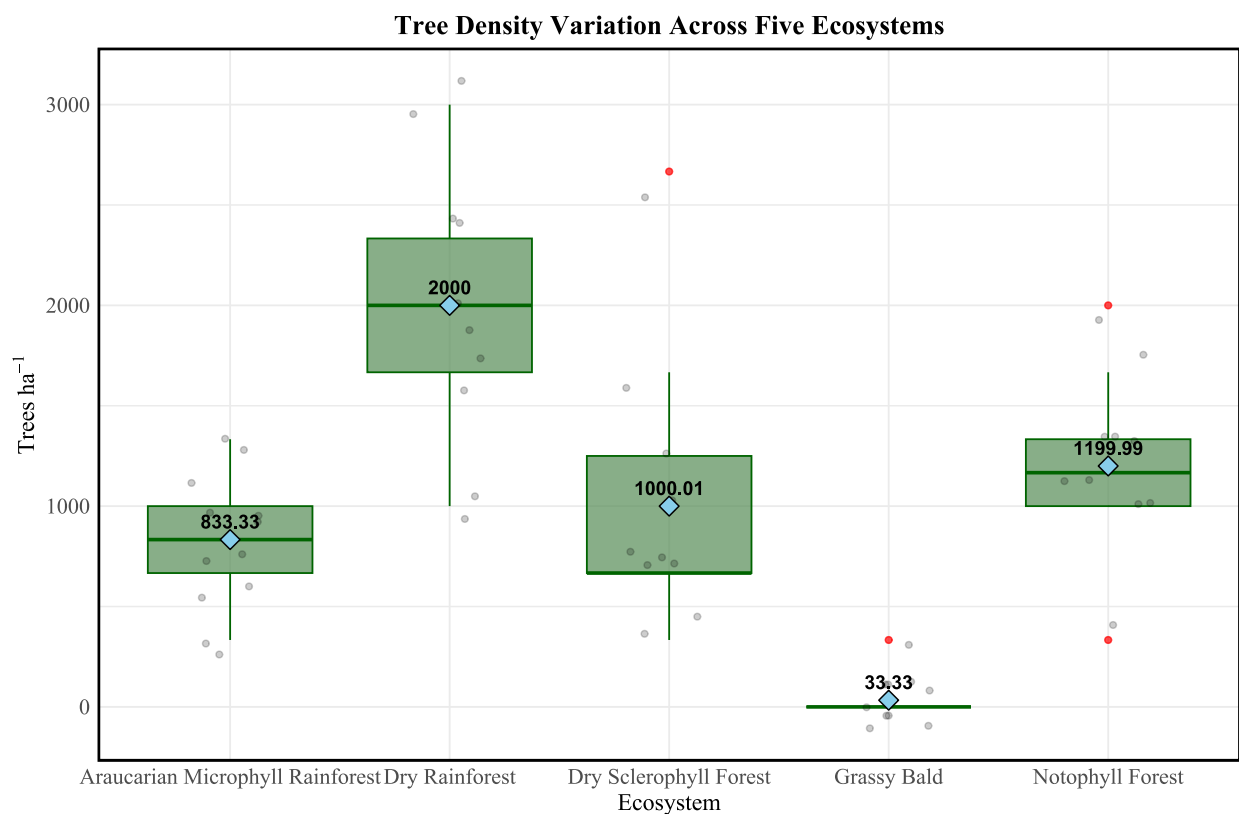
### **3.1 Tree Density**

#### ***3.1.1 Ecosystems***

The effect of ecosystems on the variance of average tree density shown in Figure 1 was significant ( $DF = 4$ ,  $F = 19.25$ ,  $p < 0.05$ ). The dry rainforest presented the highest average (2000 trees  $ha^{-1}$ ), while the araucarian microphyll rainforest, dry sclerophyll rainforest, and notophyll forest were observed to be far lower (833.3, 1000, and 1200 trees  $ha^{-1}$  respectively). From this, a Tukey HSD Test for multiple comparisons (Table 1) highlighted, unsurprisingly, that the grassy bald was significantly different from all other ecosystems; however, the following notable differences were revealed:



- Tree density in the notophyll forest was significantly lower than in the dry rainforest (mean difference = -800.01, 95% CI [-1447.8, -152.2],  $p < 0.05$ )
- Dry rainforest tree density was significantly higher than araucarian microphyll rainforest (mean difference = 1166.7, 95% CI [546.5, 1786.8],  $p < 0.05$ )
- Tree density in the dry sclerophyll forest was significantly lower than the dry rainforest (mean difference = -1000, 95% CI [-1647.8, -352.2],  $p < 0.05$ ).



**Figure 1.** Boxplot showing the distribution of tree density (Trees ha<sup>-1</sup>) across five different ecosystems. Outliers are indicated by red points outside the whiskers and the means are indicated by a blue diamond. Ecosystem categories include Araucarian Microphyll Rainforest, Dry Rainforest, Dry Sclerophyll Rainforest, Grassy Bald, and Notophyll Forest.

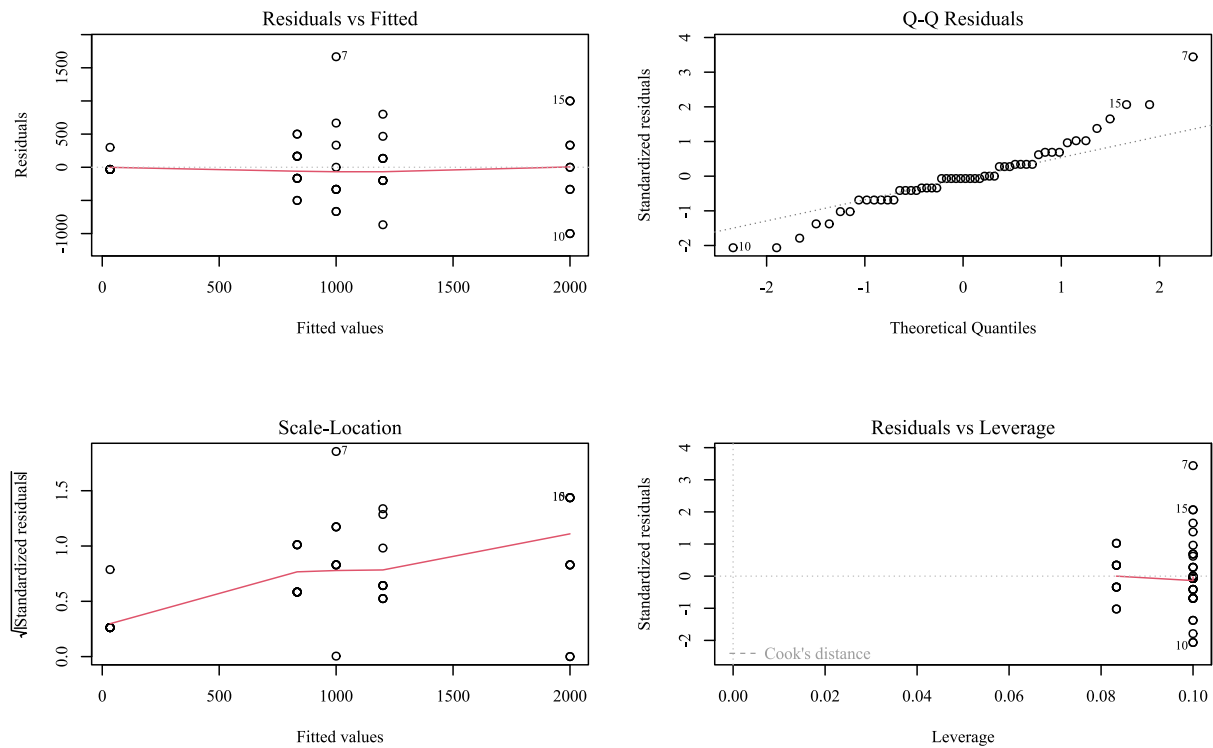
**Table 1**

Tukey HSD Test for Multiple Comparisons of Tree Density Between Ecosystems.

Comparison		Mean Difference (I – J)	95% Confidence Intervals		Adjusted p-value
(I) Ecosystem	(J) Ecosystem		Lower Bound	Upper Bound	
NF	AMRF	366.7	-253.5	986.8	0.457
	<b>DRF</b>	<b>-800</b>	<b>-1447.8</b>	<b>-152.2</b>	<b>0.009</b>
	DSF	200	-447.8	847.7	0.904
	<b>GB</b>	<b>1166.7</b>	<b>518.9</b>	<b>1814.4</b>	<b>0.000</b>
GB	<b>AMRF</b>	<b>-800</b>	<b>-1420.2</b>	<b>-179.8</b>	<b>0.006</b>
	<b>DRF</b>	<b>-1966.7</b>	<b>-2614.4</b>	<b>-1318.9</b>	<b>0.000</b>
	<b>DSF</b>	<b>-966.7</b>	<b>-1614.4</b>	<b>-318.9</b>	<b>0.001</b>
DSF	AMRF	166.7	-453.5	786.9	0.940
	<b>DRF</b>	<b>-1000</b>	<b>-1647.8</b>	<b>-352.2</b>	<b>0.001</b>
DRF	<b>AMRF</b>	<b>1166.7</b>	<b>546.5</b>	<b>1786.8</b>	<b>0.000</b>

Note. Abbreviations: AMRF = *Araucarian Microphyll Rainforest*, DRF = *Dry Rainforest*, DSF = *Dry Sclerophyll Forest*, GB = *Grassy Bald*, NF = *Notophyll Forest*.

According to the residual diagnostic plots in Figure 3, the Q-Q plot showed greater extremities than expected for a normal distribution. Subsequently, the non-parametric Kruskal-Wallis test determined significant differences in tree density distributions from at least one ecosystem ( $DF = 4$ ,  $X^2 = 34.1$ ,  $p < 0.05$ ). From this, a post-hoc Wilcoxon Rank-sum test also identified significant pairwise comparisons ( $p < 0.05$ ) in tree density distributions between the grassy bald and all other ecosystems (Table 2). The test also revealed significant relationships between the dry rainforest and auracarian microphyll rainforest and the dry rainforest and dry sclerophyll forest. This opposed the previous parametric result which stated that the notophyll forest was also significantly different from the dry rainforest. It is important to note, however, that the notophyll forest and dry rainforest relationship neared a significant result ( $p = 0.061$ ).



**Figure 2.** Diagnostic plots for the residuals of the average tree density across ecosystems ANOVA model. The Residuals vs Fitted plot shows homoscedasticity, the Q-Q plot assesses normality of residuals, the Scale-Location plot checks for constant variance, and the Residuals vs Leverage plot highlights potential influential data points.

**Table 2**

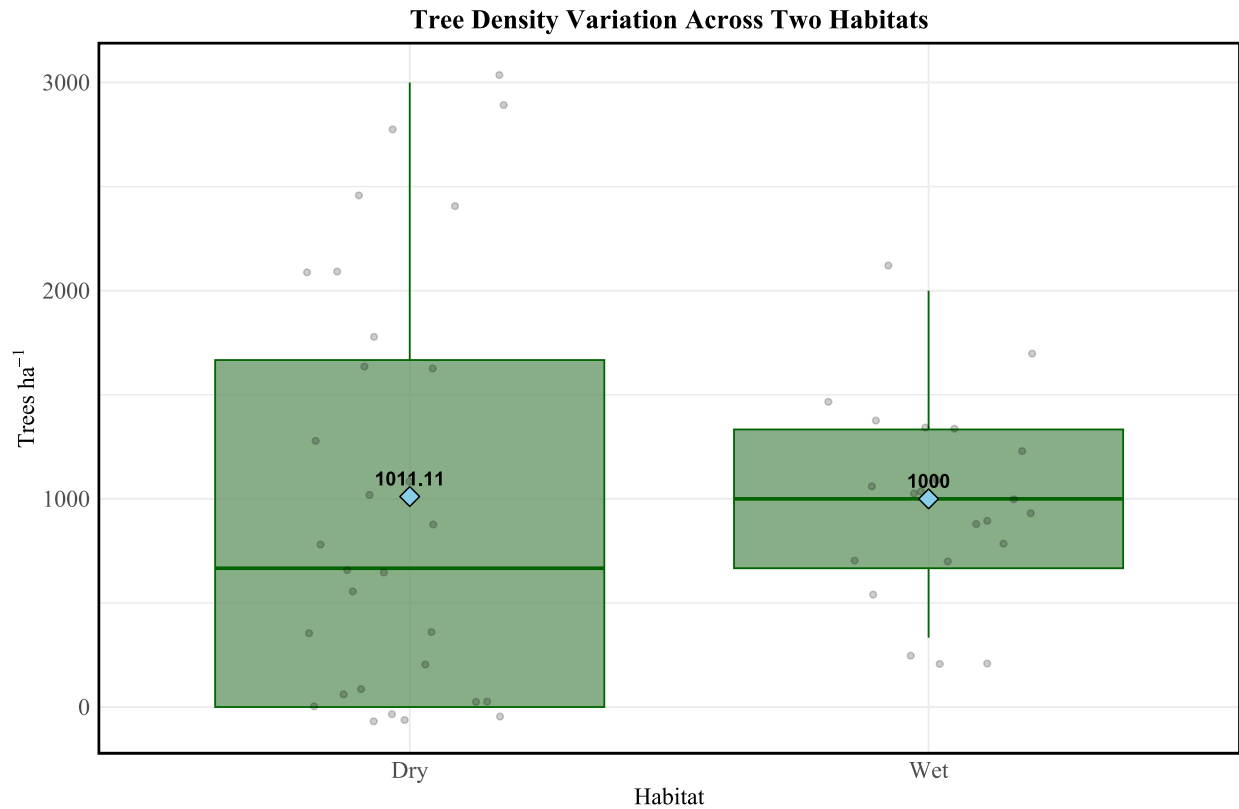
Wilcoxon Rank-sum Pairwise Comparisons of Tree Density Between Ecosystems

Comparison		Adjusted p-value (I vs J)
(I) Ecosystem	(J) Ecosystem	
NF	AMRF	0.132
	DRF	0.061
	DSF	0.409
	<b>GB</b>	<b>0.001</b>
GB	<b>AMRF</b>	<b>0.001</b>
	<b>DRF</b>	<b>0.001</b>
	<b>DSF</b>	<b>0.001</b>
DSF	AMRF	0.973
	<b>DRF</b>	<b>0.034</b>
DRF	<b>AMRF</b>	<b>0.003</b>

Note. Abbreviations: AMRF = *Araucarian Microphyll Rainforest*, DRF = *Dry Rainforest*, DSF = *Dry Sclerophyll Forest*, GB = *Grassy Bald*, NF = *Notophyll Forest*.

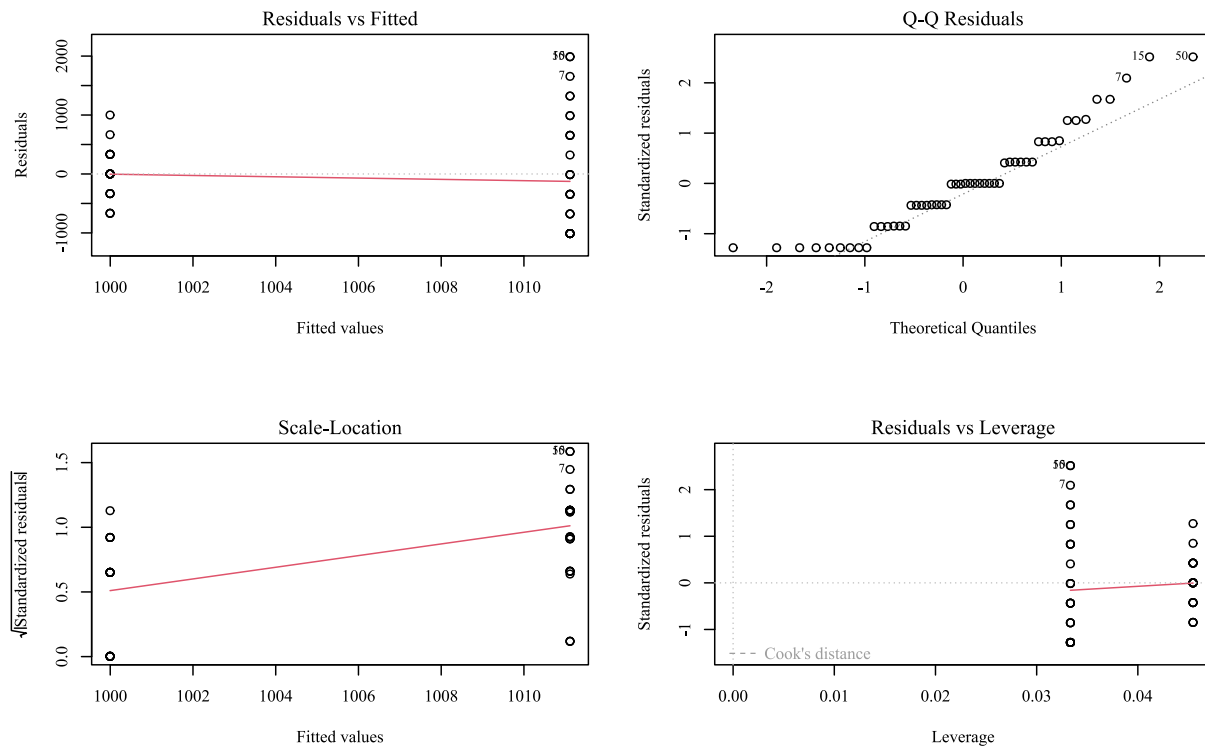
### 3.1.2 Habitats

The variance in average tree density between dry and wet habitats was not significant ( $DF = 1$ ,  $F = 0.002$ ,  $p > 0.05$ ), with mean densities of 1011 and 1000 trees  $ha^{-1}$ , respectively (Figure 4). This suggests that differences in tree density may be driven by more specific factors rather than broad habitat classification.



**Figure 3.** Boxplot showing the distribution of tree density (Trees ha<sup>-1</sup>) across two different habitats with the habitats categorised as dry and wet. Means are indicated by the blue diamond.

The diagnostic plots for tree density and habitats in Figure 4 all indicate ideal conditions for the assumptions of normality, homoscedasticity and linearity, and no influential points severely affected the model.



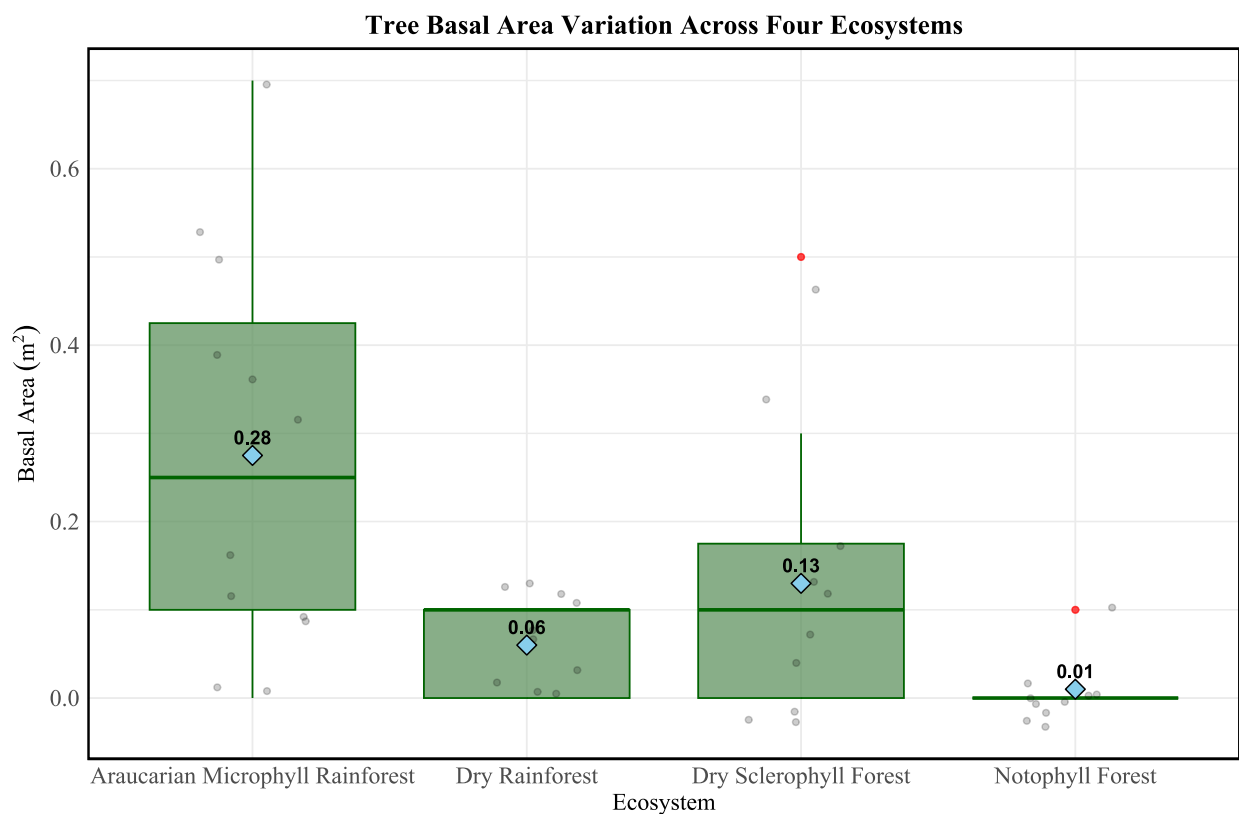
**Figure 4.** Diagnostic plots for the residuals of the average tree density across habitats ANOVA model. The Residuals vs Fitted plot shows homoscedasticity, the Q-Q plot assesses normality of residuals, the Scale-Location plot checks for constant variance, and the Residuals vs Leverage plot highlights potential influential data points.

## 3.2 Basal Area

### 3.2.1 Ecosystems

The araucarian microphyll rainforest exhibited the greatest effect on average tree basal area ( $0.275 \text{ m}^2$ ), while dry sclerophyll forest and dry rainforest were observed to be lower, with averages of  $0.13$  and  $0.06 \text{ m}^2$ , respectively. Surprisingly, the notophyll forest displayed the lowest average of  $0.01 \text{ m}^2$ . These differences were statistically significant between ecosystems ( $DF = 3$ ,  $F = 6.734$ ,  $p < 0.05$ ). Following the significant ANOVA test, the Tukey HSD test produced significant differences between the following ecosystems as shown in Table 3:

- The average basal area of trees in the notophyll forest was significantly lower than the araucarian microphyll rainforest (mean difference = -0.27, CI 95% [-0.44, -0.09],  $p < 0.05$ ).
- The average basal area of trees in the dry rainforest was significantly lower than the araucarian microphyll rainforest (mean difference = -0.22, 95% CI [-0.39, -0.04],  $p < 0.05$ ).



**Figure 5.** Boxplot showing the distribution of tree basal area ( $\text{m}^2$ ) across four different ecosystems. Outliers are indicated by red points outside the whiskers and means are indicated by blue diamonds. Ecosystem categories include Araucarian Microphyll Rainforest, Dry Rainforest, Dry Sclerophyll Rainforest, and Notophyll Forest.

**Table 3**

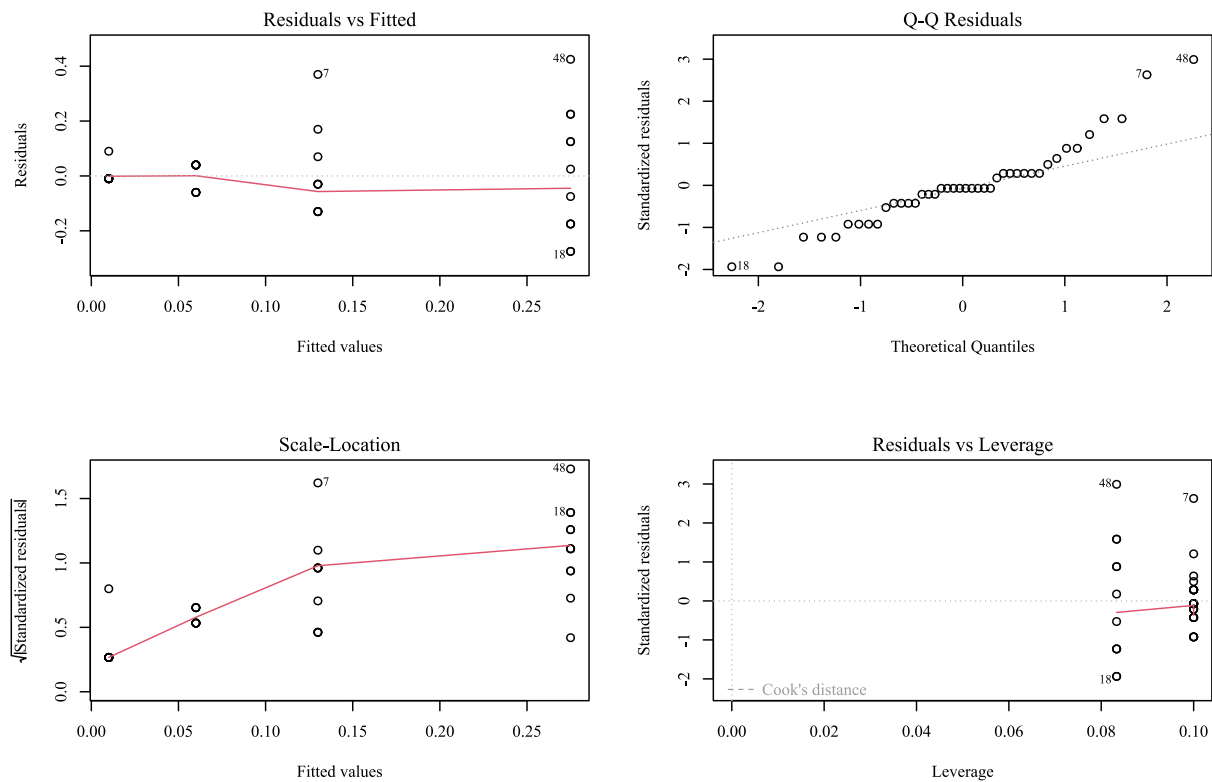
Tukey HSD Test for Multiple Comparisons of Tree Basal Area Between Ecosystems.

Comparison		Mean Difference (I – J)	95% Confidence Intervals		Adjusted p-value
(I) Ecosystem	(J) Ecosystem		Lower Bound	Upper Bound	
NF	<b>AMRF</b>	<b>-0.27</b>	<b>-0.44</b>	<b>-0.09</b>	<b>0.001</b>
	DRF	-0.05	-0.23	0.13	0.875
	DSF	-0.12	-0.30	0.06	0.285
DSF	AMRF	-0.15	-0.32	0.03	0.120
	DRF	0.07	-0.11	0.25	0.718
DRF	<b>AMRF</b>	<b>-0.22</b>	<b>-0.39</b>	<b>-0.04</b>	<b>0.009</b>

Note. Abbreviations: AMRF = *Araucarian Microphyll Rainforest*, DRF = *Dry Rainforest*, DSF = *Dry Sclerophyll Forest*, GB = *Grassy Bald*, NF = *Notophyll Forest*.

The diagnostic plots in Figure 6 demonstrated inconsistencies with the assumptions of homoscedasticity and normality due to deviations for both extremes within the Q-Q plot and an increasing spread in the Scale-Location plot. Following the concern of a heteroscedastic and non-normal dataset, the Kruskal Wallis test produced a significant result for the differences in basal area distributions across ecosystems ( $DF = 3$ ,  $X^2 = 14.893$ ,  $p < 0.05$ ). A Wilcoxon Rank-sum test then confirmed significant differences in basal area for only one pairwise comparison (Table 4), the notophyll forest and araucarian microphyll rainforest. This disputed the parametric test which stated that the dry rainforest was also significantly different from the araucarian microphyll rainforest.





**Figure 6.** Diagnostic plots for the residuals of the average basal area across ecosystems ANOVA model. The Residuals vs Fitted plot shows homoscedasticity, the Q-Q plot assesses normality of residuals, the Scale-Location plot checks for constant variance, and the Residuals vs Leverage plot highlights potential influential data points.

**Table 4**

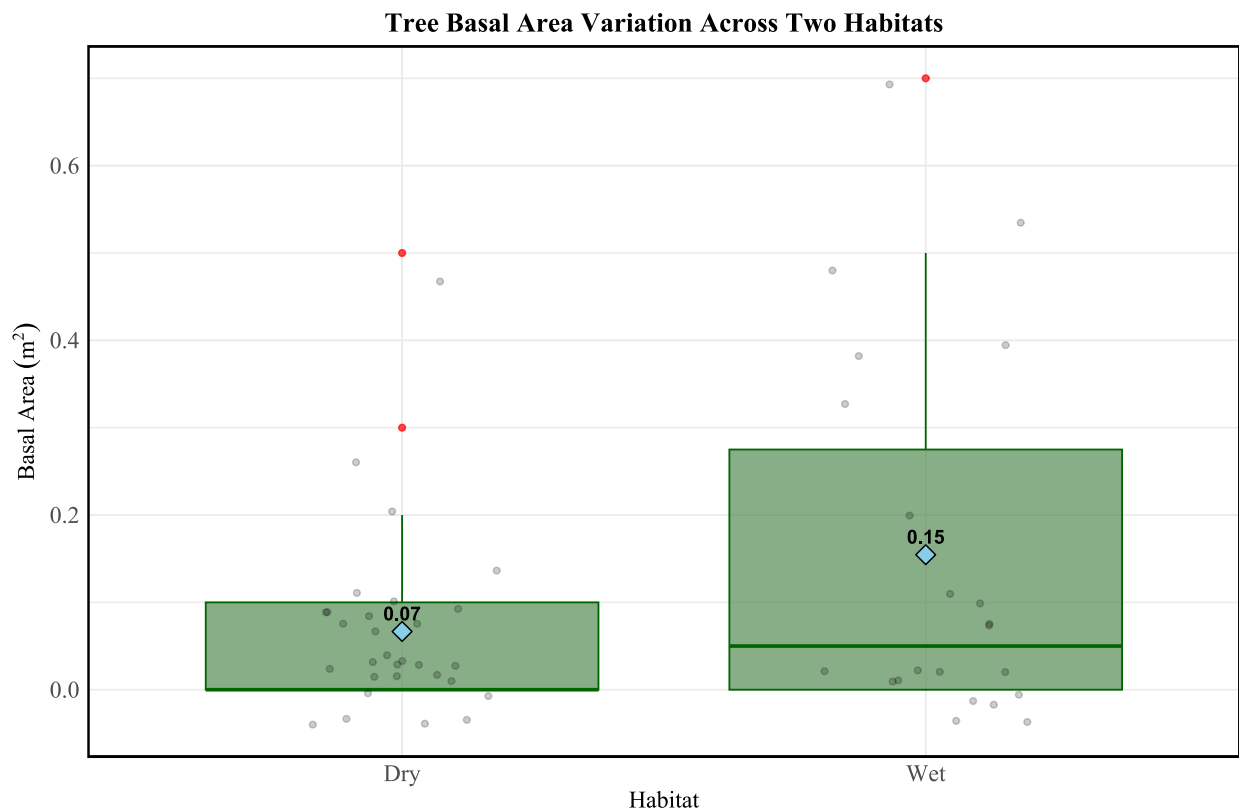
Wilcoxon Rank-sum Pairwise Comparisons of Basal Area Between Ecosystems

Comparison		Adjusted p-value (I vs J)
(I) Ecosystem	(J) Ecosystem	
NF	<b>AMRF</b>	<b>0.005</b>
	DRF	0.09
	DSF	0.09
DSF	AMRF	0.242
	DRF	0.485
DRF	AMRF	0.086

Note. Abbreviations: AMRF = *Araucarian Microphyll Rainforest*, DRF = *Dry Rainforest*, DSF = *Dry Sclerophyll Forest*, GB = *Grassy Bald*, NF = *Notophyll Forest*.

### 3.2.2 Habitats

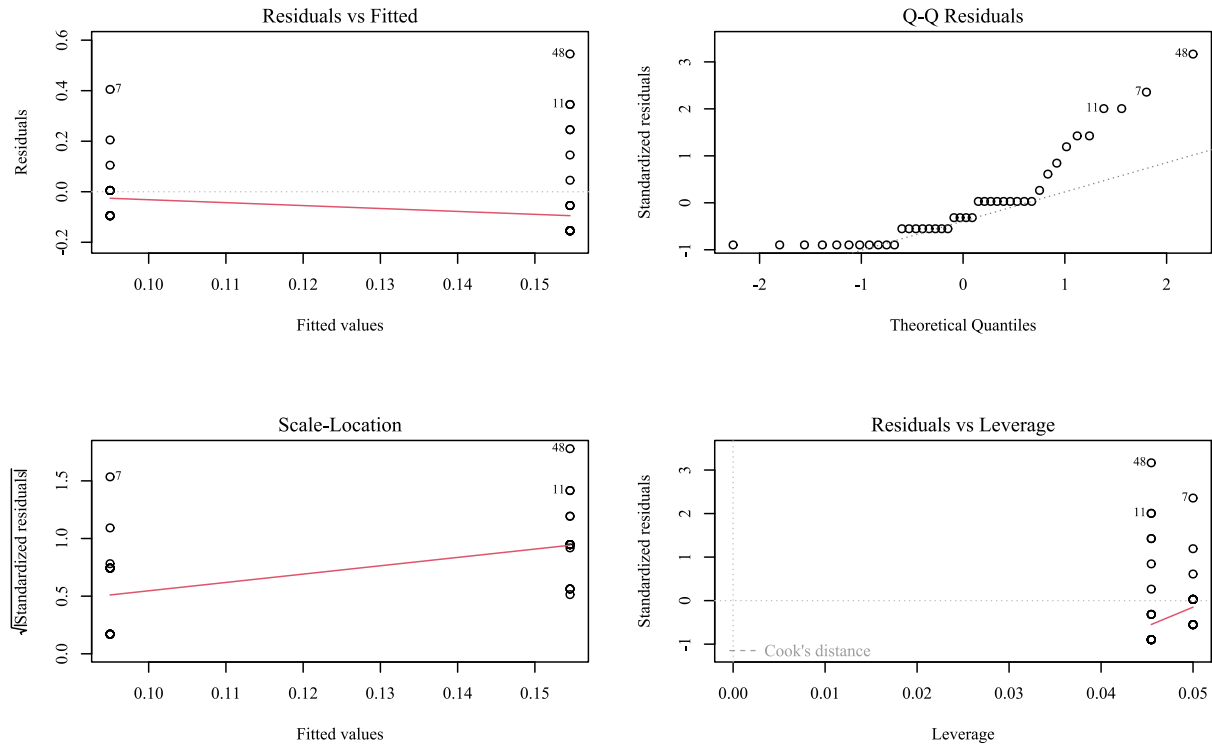
The effect of dry and wet habitats on average tree basal area was insignificant ( $DF = 1$ ,  $F = 1.194$ ,  $p > 0.05$ ), with mean basal areas of  $0.095$  and  $0.155 \text{ m}^2$  for dry and wet habitats, respectively. This indicated that basal areas may not be defined by generalised habitat characteristics such as dry and wet.



**Figure 7.** Boxplot showing the distribution of basal area ( $\text{m}^2$ ) across two different habitat categorisations, dry and wet.

The Q-Q plot in Figure 8 highlighted a distinct violation of a normal distribution, shown by deviations in the upper tail. From determining a non-normal distribution, the Kruskal Wallis test indicated an insignificant relationship between the habitats and basal area distributions ( $DF =$

1,  $X^2 = 0.035$ ,  $p > 0.05$ ), strengthening the claim that basal area may be affected by more complex systems.

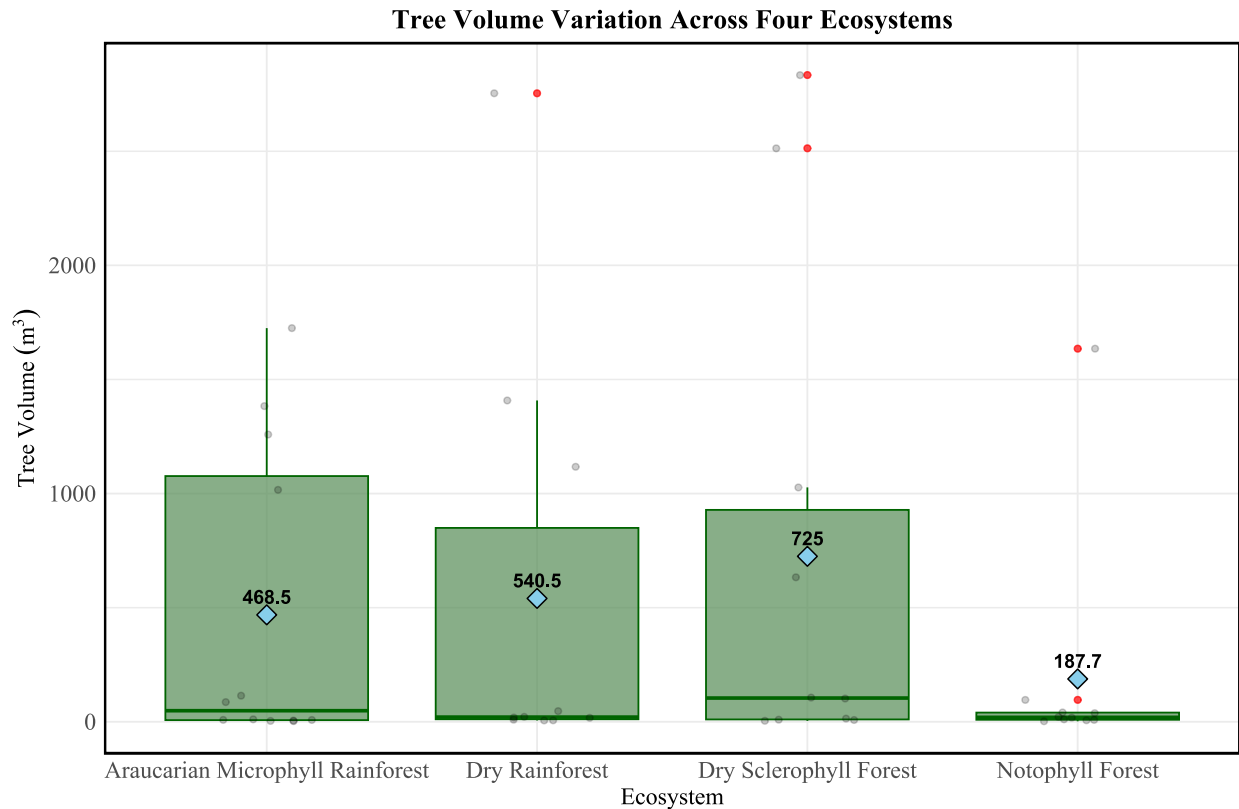


**Figure 8.** Diagnostic plots for the residuals of the average basal area across habitats ANOVA model. The Residuals vs Fitted plot shows homoscedasticity, the Q-Q plot assesses normality of residuals, the Scale-Location plot checks for constant variance, and the Residuals vs Leverage plot highlights potential influential data points.

### 3.3 Tree Volume

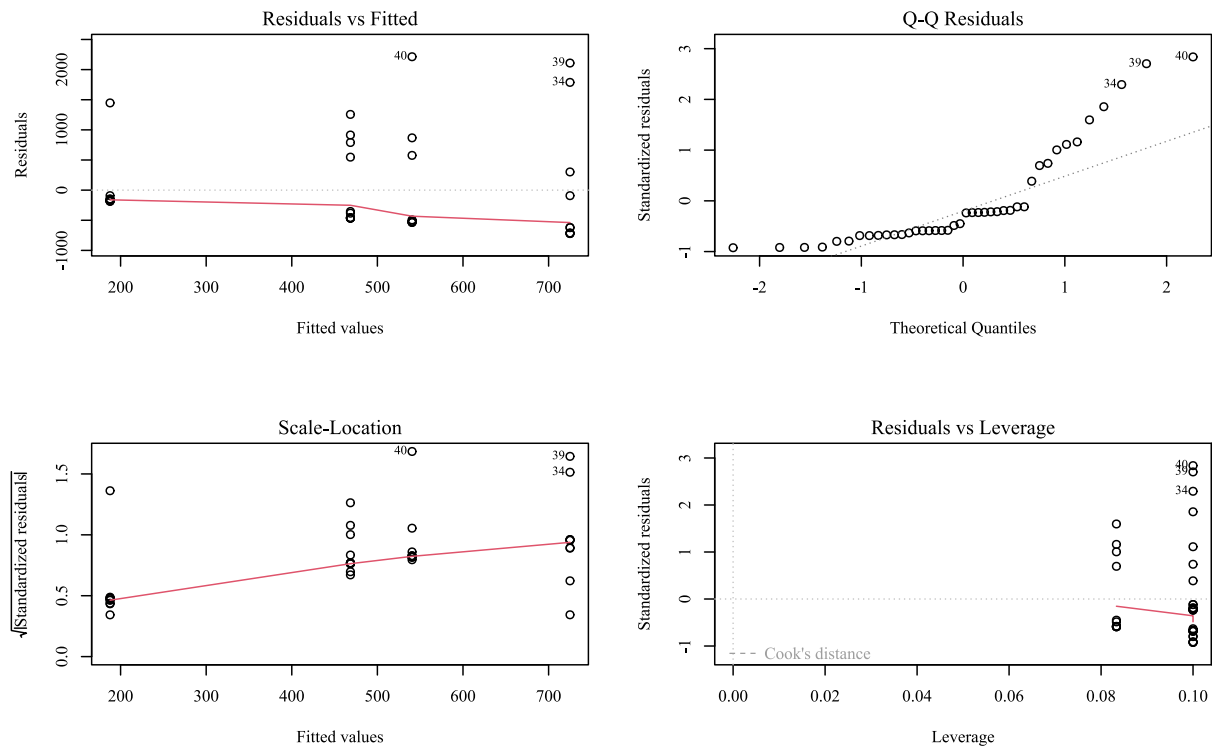
#### 3.3.1 Ecosystems

Figure 9 depicted the highest tree volume averages in the dry sclerophyll forest and dry rainforest (725 and 540.5 m<sup>3</sup>, respectively), followed by the araucarian microphyll rainforest and notophyll forest (468.5 and 187.7 m<sup>3</sup>, respectively). These differences in average tree volumes were found to be statistically insignificant (DF = 3,  $F = 0.736$ ,  $p > 0.05$ ).



**Figure 9.** Boxplot showing the distribution of tree volume (m<sup>3</sup>) across four different ecosystems. Outliers are indicated by red points outside the whiskers. Ecosystem categories include Araucarian Microphyll Rainforest, Dry Rainforest, Dry Sclerophyll Rainforest, and Notophyll Forest.

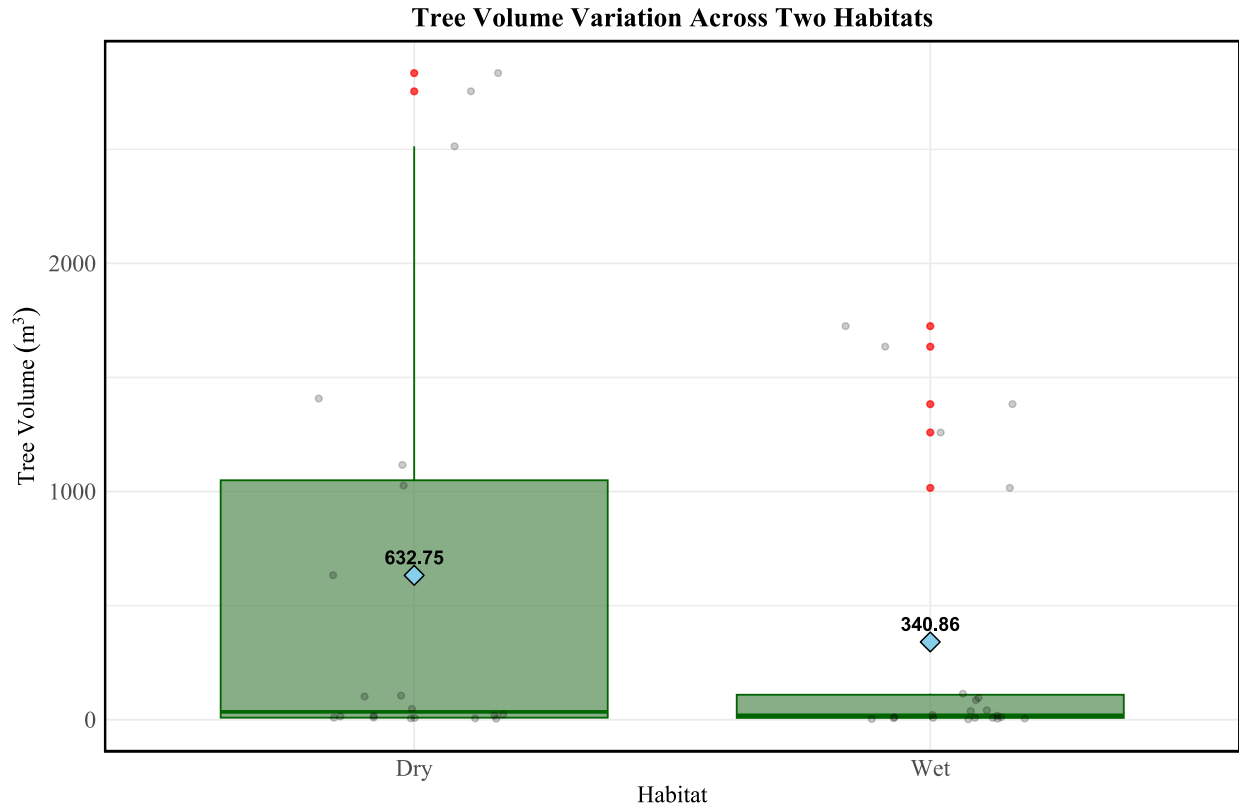
The assumption of normality for average tree volume distributions was violated, explained by the strong deviation in the upper tail of the Q-Q plot in Figure 10. Subsequently, the non-parametric Kruskal Wallis Rank-sum test produced an insignificant result (DF = 3,  $X^2 = 1.366$ ,  $p > 0.05$ ).



**Figure 10.** Diagnostic plots for the residuals of the average tree volume across ecosystems ANOVA model. The Residuals vs Fitted plot shows homoscedasticity, the Q-Q plot assesses normality of residuals, the Scale-Location plot checks for constant variance, and the Residuals vs Leverage plot highlights potential influential data points.

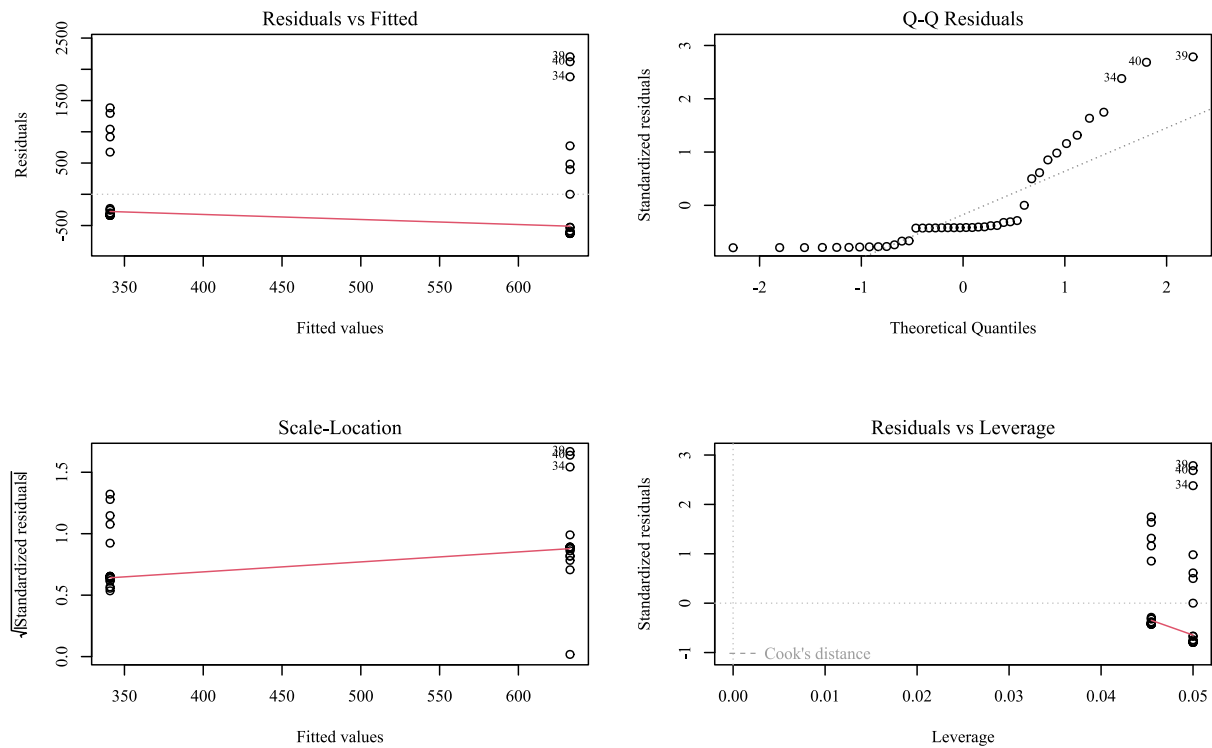
### 3.3.2 Habitats

The mean tree volume for the dry habitat, shown in Figure 11 ( $632.8 \text{ m}^3$ ), was greater than the wet habitat ( $340.9 \text{ m}^3$ ). Despite this, these habitats did not significantly explain the variation in average tree volumes ( $DF = 1$ ,  $F = 1.358$ ,  $p > 0.05$ ).



**Figure 11.** Boxplot showing the distribution of tree volume (m<sup>3</sup>) across two different habitat categorisations, dry and wet.

According to the Q-Q plot in Figure 12, the assumption of normality was violated. This was highlighted by the deviated extremities in the upper tail of the plot. A Kruskal-Wallis test then confirmed from a non-parametric perspective, that the effect of habitats on tree volumes remained insignificant ( $DF = 1$ ,  $X^2 = 1.067$ ,  $p > 0.05$ ).

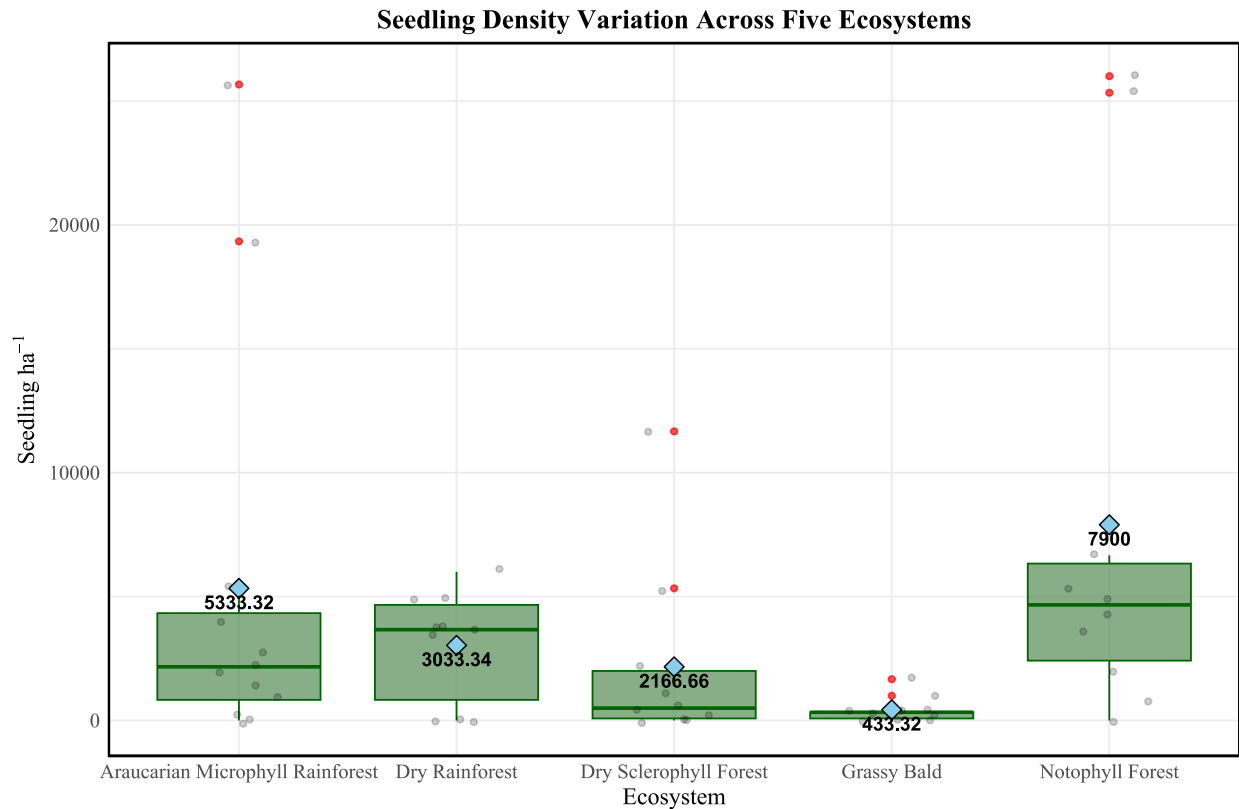


**Figure 12.** Diagnostic plots for the residuals of the average tree volume across habitats ANOVA model. The Residuals vs Fitted plot shows homoscedasticity, the Q-Q plot assesses normality of residuals, the Scale-Location plot checks for constant variance, and the Residuals vs Leverage plot highlights potential influential data points.

### 3.4 Seedling Density

#### 3.4.1 Ecosystems

Average seedling populations ranged from 7900 seedlings  $\text{ha}^{-1}$  in the notophyll forest to 433.3 seedlings  $\text{ha}^{-1}$  in the grassy bald (Figure 13). Despite this, differences in ecosystem did not sufficiently explain the variation in seedling densities ( $DF = 4$ ,  $F = 2.29$ ,  $p > 0.05$ ).

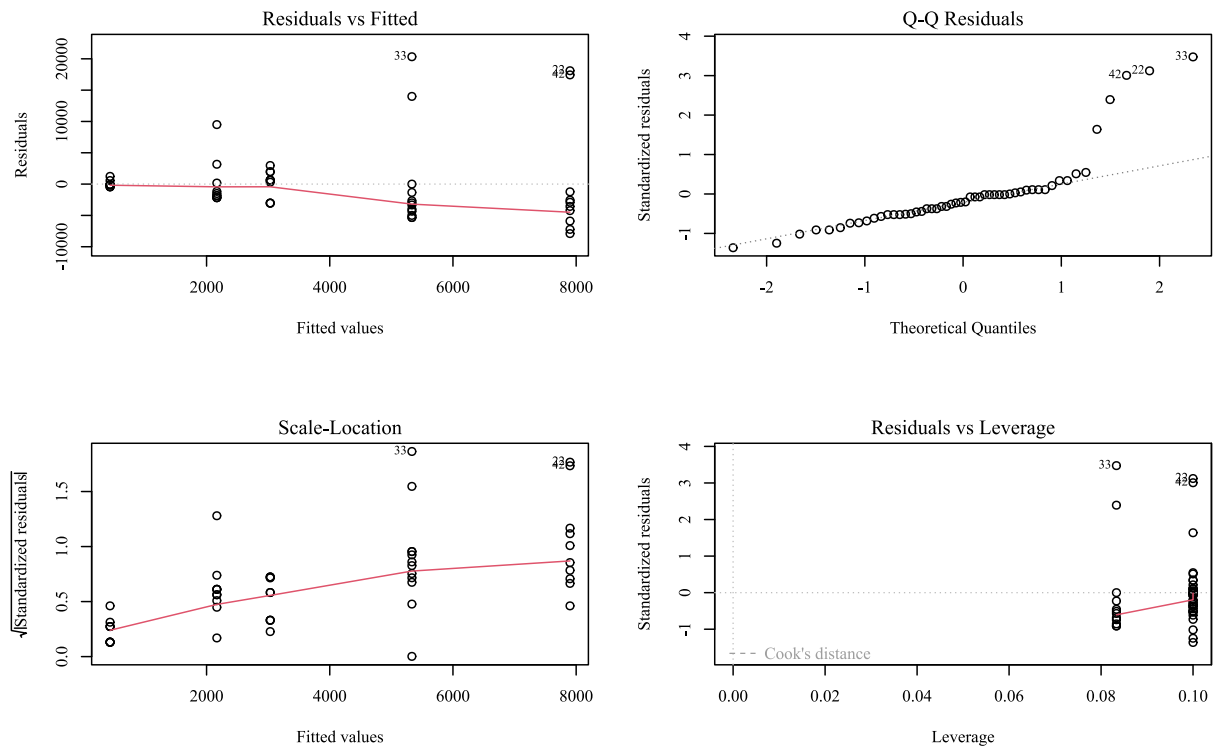


**Figure 13.** Boxplot showing the distribution of seedling density (Seedlings ha<sup>-1</sup>) across five different ecosystems.

Outliers are indicated by red points outside the whiskers. Ecosystem categories include Araucarian Microphyll Rainforest, Dry Rainforest, Dry Sclerophyll Rainforest, Grassy Bald, and Notophyll Forest.

The assumption for normality was violated, shown by the deviations in the upper tail of the Q-Q plot in Figure 14. A Kruskal-Wallis test then determined the relationship between ecosystems and seedling population density distributions as significant ( $DF = 4$ ,  $X^2 = 11.515$ ,  $p < 0.05$ ). Following this, a post-hoc Wilcoxon Rank-sum test produced a significant pairwise comparison between the notophyll forest and the grassy bald (Table 5).





**Figure 14.** Diagnostic plots for the residuals of the average seedling density across ecosystems ANOVA model. The Residuals vs Fitted plot shows homoscedasticity, the Q-Q plot assesses normality of residuals, the Scale-Location plot checks for constant variance, and the Residuals vs Leverage plot highlights potential influential data points.

**Table 5**

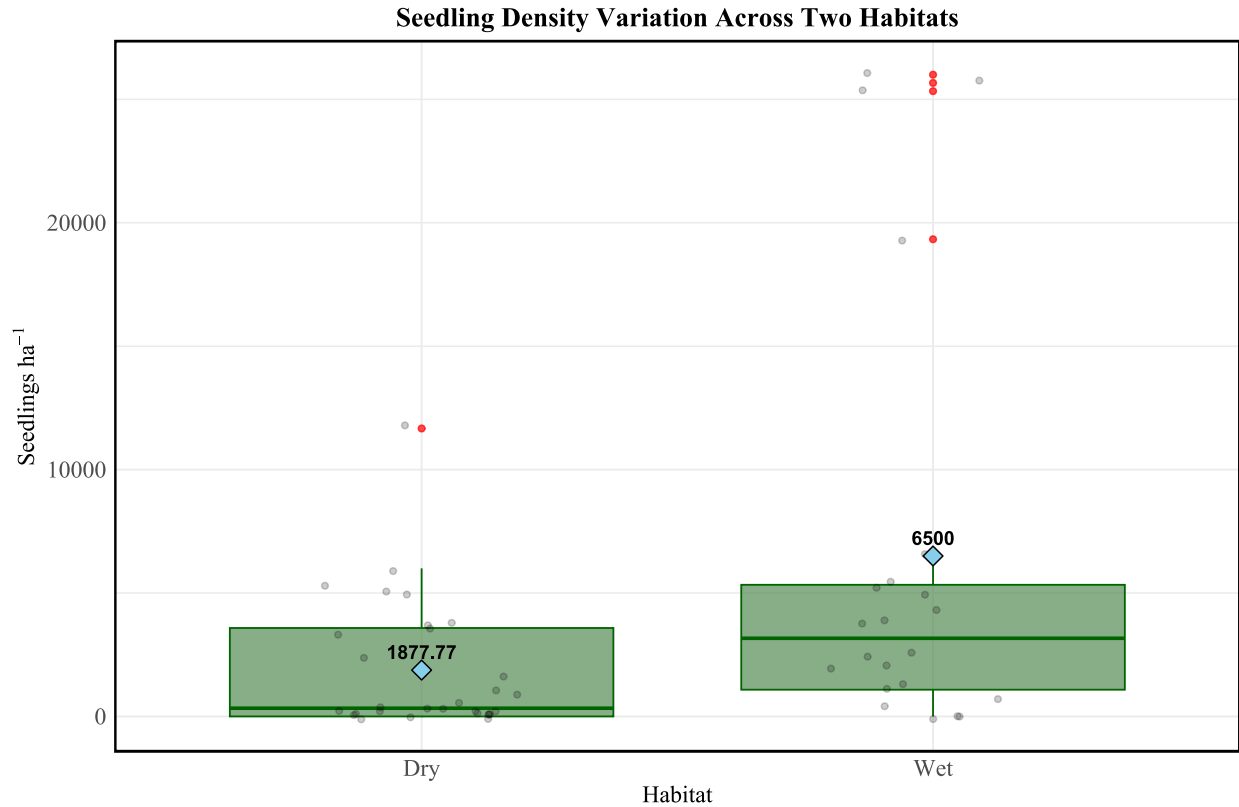
Wilcoxon Rank-sum Pairwise Comparisons of Seedling Density Between Ecosystems

Comparison		Adjusted p-value (I vs J)
(I) Ecosystem	(J) Ecosystem	
NF	AMRF	1.000
	DRF	1.000
	DSF	0.460
	<b>GB</b>	<b>0.029</b>
GB	AMRF	0.156
	DRF	0.460
	DSF	1.000
DSF	AMRF	1.000
	DRF	1.000
DRF	AMRF	1.000

Note. Abbreviations: AMRF = *Araucarian Microphyll Rainforest*, DRF = *Dry Rainforest*, DSF = *Dry Sclerophyll Forest*, GB = *Grassy Bald*, NF = *Notophyll Forest*.

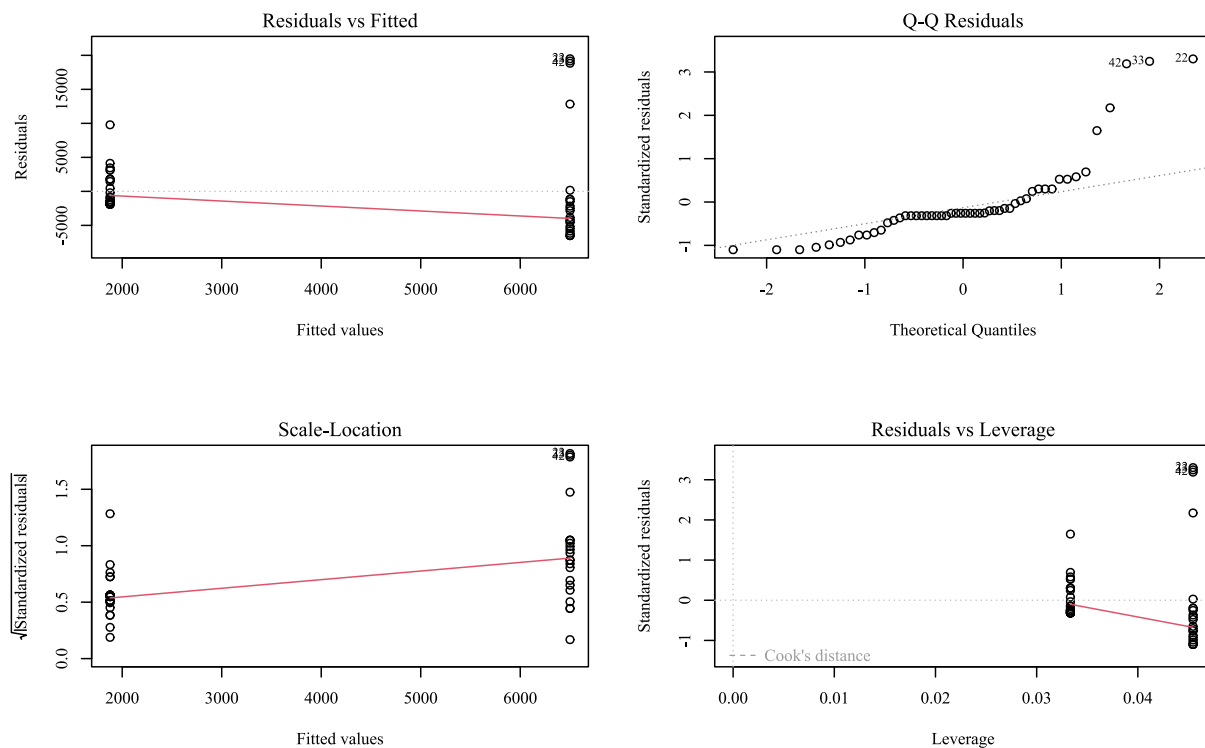
### 3.4.2 Habitats

On average, seedling population density differed significantly between habitats ( $DF = 1$ ,  $F = 7.421$ ,  $p < 0.05$ ). The densities in the dry habitat (1877 seedlings  $ha^{-1}$ ) were presented as far lower than the wet habitat (6500 seedlings  $ha^{-1}$ ).



**Figure 15.** Boxplot showing the distribution of seedling population density (seedlings ha<sup>-1</sup>) across two different habitat categorisations, dry and wet.

The residuals presented in Figure 16 indicate a violation of the expected normal distribution for an ANOVA model, illustrated by the deviated upper extremities in the Q-Q plot. Despite the violation, the difference in seedling densities between habitats remained significant ( $DF = 1$ ,  $X^2 = 6.312$ ,  $p < 0.05$ ).

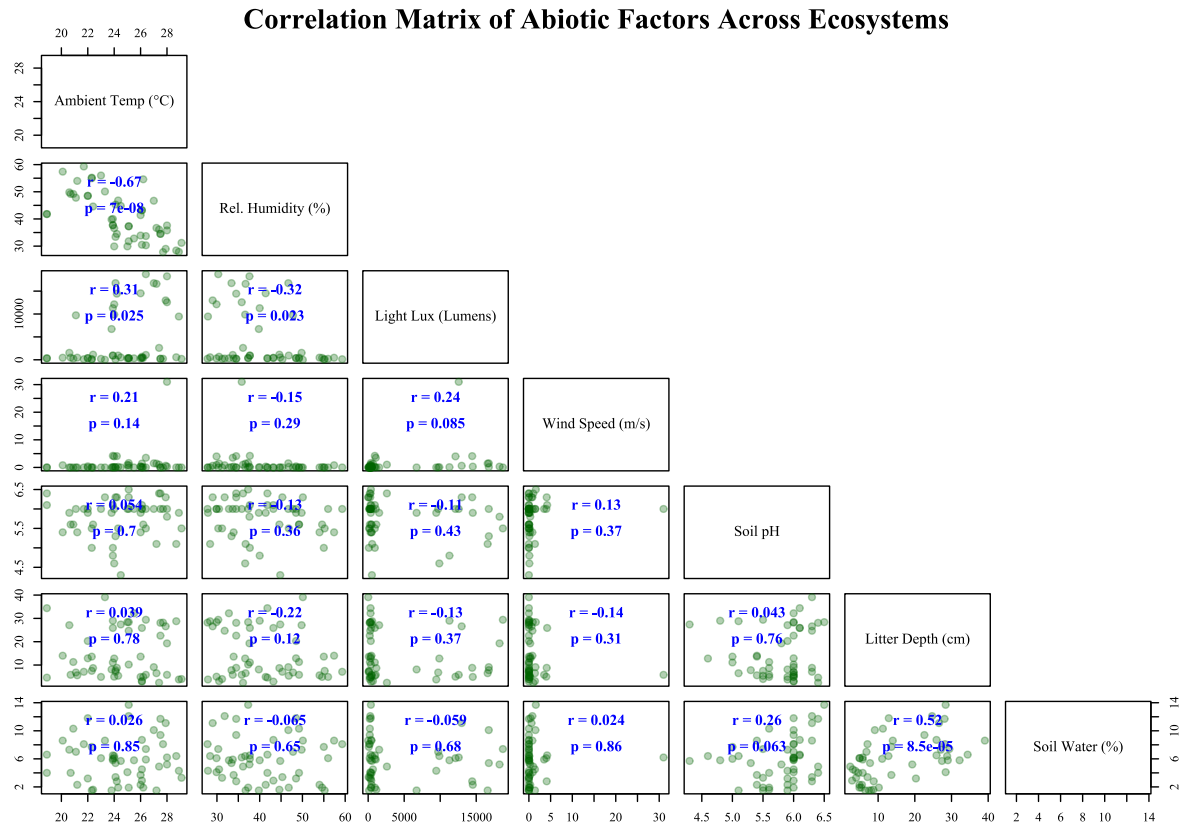


**Figure 16.** Diagnostic plots for the residuals of the average seedling density across habitats ANOVA model. The Residuals vs Fitted plot shows homoscedasticity, the Q-Q plot assesses normality of residuals, the Scale-Location plot checks for constant variance, and the Residuals vs Leverage plot highlights potential influential data points.

### 3.5 Abiotic Factors

#### 3.5.1 Correlations

Significant correlations were revealed between ambient temperature and relative humidity ( $r = -0.67$ ,  $p < 0.001$ ), as well as between ambient temperature and light lux ( $r = 0.31$ ,  $p = 0.025$ ). In contrast, wind speed and soil pH presented no significant relationships with other factors ( $p > 0.05$ ); however, soil water content was strongly positively correlated with litter depth ( $r = 0.52$ ,  $p < 0.001$ ).



**Figure 17.** Correlation matrix of abiotic factors across ecosystems in the Bunya Mountains. Pearson correlation coefficients ( $r$ ) and  $p$ -values are displayed for each pair of variables. The matrix shows positive and negative relationships between ambient temperature, relative humidity, light lux, wind speed, soil pH, litter depth, and soil water content. Note. Abbreviations: Ambient Temp = *Ambient Temperature*, Rel. Humidity = *Relative Humidity*.

### 3.5.2 Principal Component Analysis

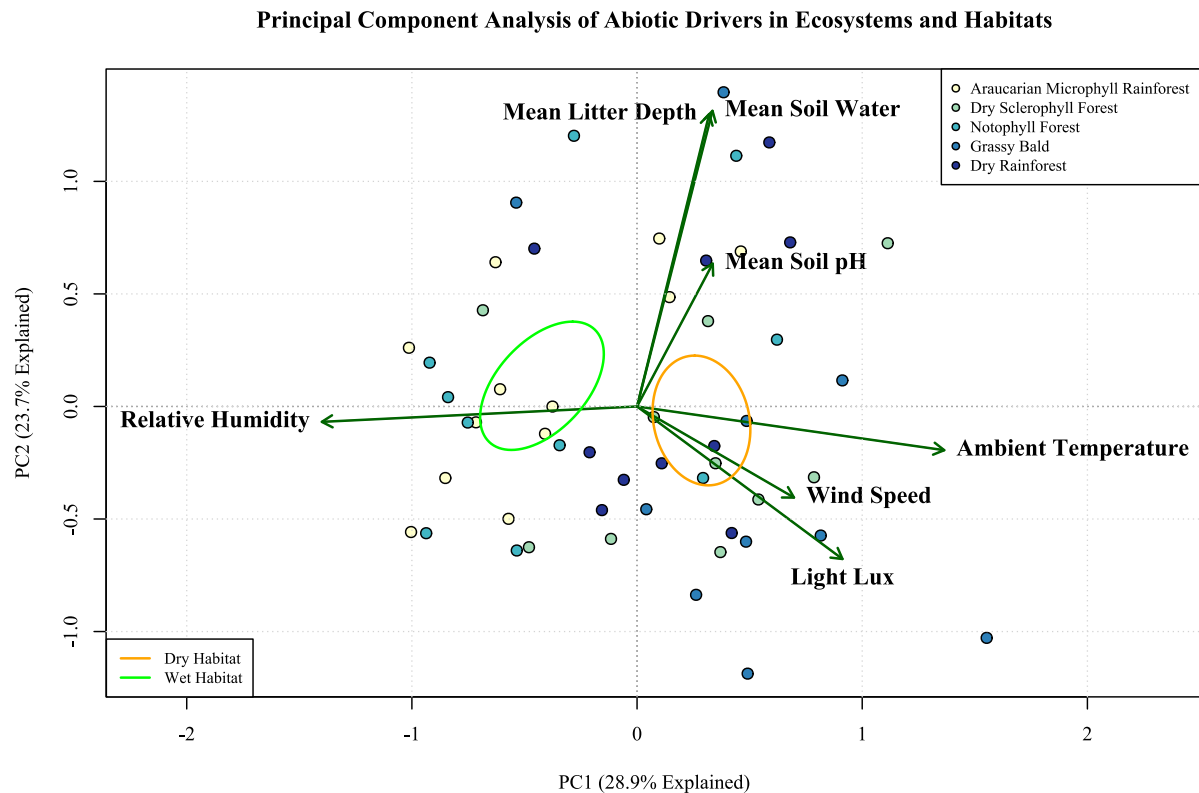
According to the PCA in Figure 18, relative humidity and ambient temperature were key drivers in environmental variability, with PC1 scores of -1.399 and 1.364 respectively (Table 6), and were inversely proportional to one another. Wind speed and light lux were positively associated with ambient temperature, with less impactful PC1 scores (0.697 and 0.912, respectively). Notably, soil water, litter depth, and soil pH PC2 scores were all positively related

to each other, and mostly unrelated to all other abiotic factors (1.313, 1.299, and 0.634, respectively).

**Table 6**

Principal component analysis of abiotic factors measured across all ecosystems

Abiotic Factor	PC1	PC2	PC3	PC4	PC5	PC6
Ambient Temperature	<b>1.364</b>	<b>-0.194</b>	0.255	-0.433	0.263	-0.522
Relative Humidity	<b>-1.399</b>	<b>-0.068</b>	0.334	0.455	-0.101	-0.285
Light Lux	<b>0.912</b>	<b>-0.678</b>	0.169	0.714	-0.910	0.164
Wind Speed	<b>0.697</b>	<b>-0.405</b>	-0.991	0.735	0.706	0.167
Mean Soil pH	<b>0.336</b>	<b>0.634</b>	-0.185	-0.676	-0.496	0.228
Mean Litter Depth	<b>0.321</b>	<b>1.299</b>	0.571	0.313	0.223	0.571
Mean Soil Water	<b>0.335</b>	<b>1.313</b>	-0.190	0.571	-0.199	-0.631



**Figure 18.** Principal component analysis plot of abiotic drivers across all ecosystems within the Bunya Mountains. These factors included ambient temperature, relative humidity, light lux, wind speed, soil pH, litter depth, and soil water content.

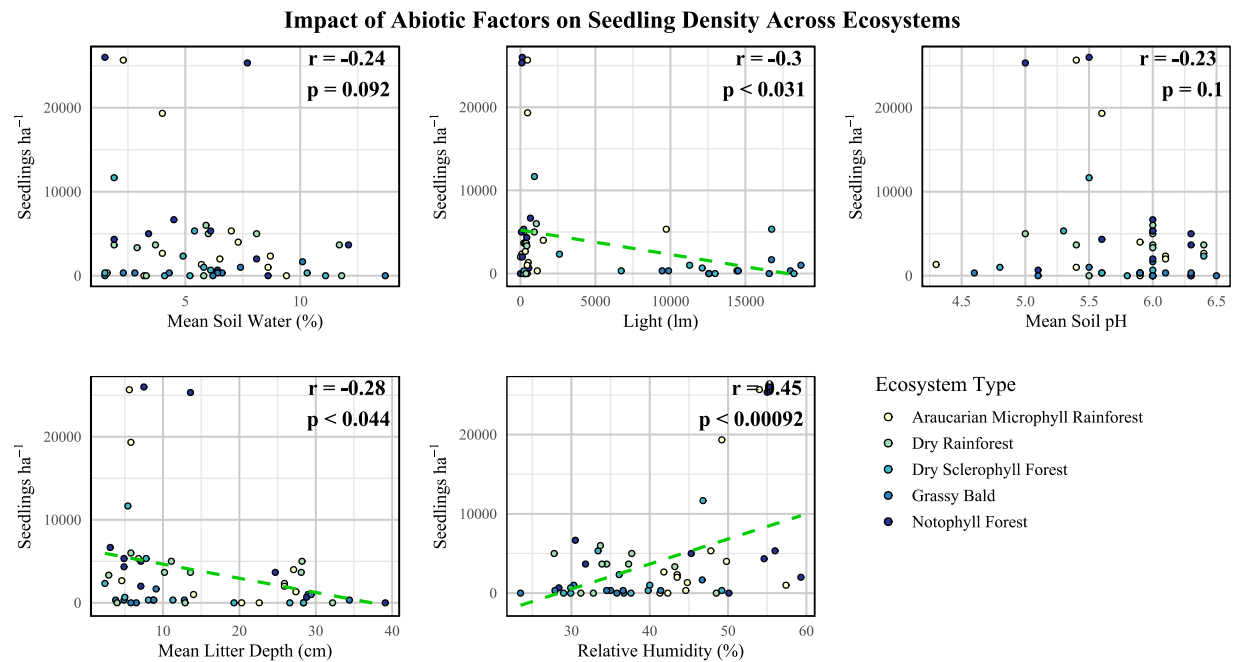
### **3.5.3 Ecosystems**

A PERMANOVA was conducted to test for differences in abiotic factors between ecosystems, producing a significant result ( $DF = 1$ , pseudo- $F = 10.54$ ,  $p = 0.001$ ). From this, the following significant pairwise comparisons of abiotic factors between ecosystems were identified:

- Araucarian microphyll rainforest vs dry sclerophyll forest ( $p < 0.005$ )
- Araucarian microphyll rainforest vs grassy bald ( $p < 0.005$ )
- Araucarian microphyll rainforest vs dry rainforest ( $p < 0.05$ )
- Notophyll forest vs grassy bald ( $p < 0.05$ )

### **3.6 Seedlings and Abiotic Factors**

Litter depth, light conditions, and relative humidity were all significantly related to seedling densities across the five ecosystems, while soil water and soil pH had no apparent effect (Figure. Both litter depth and light conditions showed moderately negative linear correlations with seedling density ( $r = -0.28$ ,  $p < 0.05$  and  $r = -0.3$ ,  $p < 0.05$ , respectively), whereas relative humidity appeared to be a stronger positive factor in explaining seedling density ( $r = 0.45$ ,  $p < 0.001$ ).



**Figure 19.** Pearson's correlation plots demonstrating the relationships between seedling density and abiotic factors across five ecosystems. The associated  $r$  correlation coefficients and  $p$  values for each relationship are given on each plot and the dashed green lines represent the line of best fit for significant relationships ( $p < 0.05$ ).

## 4.0 Discussion

Tree and seedling population dynamics are reliant on a sleuth of variables. Despite this, the markedly different ecosystems in the Bunya Mountains provided valuable insights into how range-wide abiotic and local biotic factors contribute to plant community structures at varying scales.

### 4.1 Tree Density, Basal Area, and Volume

Tree population density and basal area demonstrated significant differences between ecosystems, while their generalised habitats showed no apparent effect. Notably, the dry rainforest ecosystems displayed lower average basal areas and higher average densities (0.06 m<sup>2</sup> and 2000 trees ha<sup>-1</sup>, respectively), whereas the araucarian rainforest presented higher average



basal areas and lower average densities ( $0.28 \text{ m}^2$  and  $833 \text{ trees ha}^{-1}$ , respectively). An inversely proportional relationship such as this suggests that a favourable trade-off exists within the local environment.

In comparable studies, Sussman & Rakotozafy (1994) noticed a clear difference between tree species depending on their proximity to a water source. Furthermore, Segura et al. (2003) identified lower stand densities and higher tree basal areas in regions that contained both high nutrient and water availability. Considering that the araucarian rainforest experiences higher rainfall frequencies due to its higher altitude than that of the dry rainforest, the subsequently higher basal areas are consistent with the observations made by Segura et al. and Sussman & Rakotozafy. Additionally, lower rainfall frequencies restricts the growth of larger hoop pines and thus allows for more light to penetrate the canopy, explaining the dense multi-layered understory of smaller trees.

In addition to favourable environmental drivers, the recorded tree densities and basal areas may be partly or entirely driven by species competition. The bunya pines found in the araucarian rainforest can prevent nearby establishments through branch-shedding and the production of exceptionally large cones (Department of Environment, Science and Innovation, 2023). Similar to the araucarian rainforest, the complex notophyll vine forest is also classed as a wet habitat, but it is not dominated by larger trees that can prevent establishments. The ecosystem instead contains fast-growing trees with smaller basal areas and larger leaves such as the Giant Stinging Tree (*Dendrocnide excelsa*). This is because they are largely in competition with vines and lianas for light access (Campbell & Newbery, 1993; Putz, 1984; van der Heijden et al., 2008).

#### ***4.1.1 Implications and Recommendations***

From the evidence gathered, it is apparent that the overarching topography and species competition both play significant roles in defining tree densities and basal areas. The differences between the araucarian rainforest and the notophyll vine forest have especially highlighted that trait-based differentiation may be a more prominent factor in plant community structures. Additionally, tree volume was insignificant within the bounds of the study. This may imply that tree volume is driven by more neutral circumstances, following a random distribution across all study sites. It is recommended that tree volume be measured under this assumption.

#### **4.2 Seedling Density and Abiotic Factors**

Seedling densities were more adequately explained by the broader characterisation of habitat types as opposed to individual ecosystems. The wet habitat produced an average seedling density of 6500 seedlings ha<sup>-1</sup>, while the dry habitat produced only 1878 seedlings ha<sup>-1</sup>. A difference in habitat types implies that overriding abiotic factors that typically indicate dry or wet conditions are more suitable for determining seedling densities. Surprisingly, however, the PERMANOVA revealed that the notophyll forest was statistically similar to the ecosystems characterised by the dry habitat.

An important feature of both the dry rainforest and the notophyll vine forest is their placement along the slopes of the mountains (Department of Environment, Science and Innovation, 2023) . The steeper relief of the underlying landform would allow for the efficient drainage of the substrate, avoiding soil waterlogging and maintaining an optimal field capacity to support seedling establishments. Although both ecosystems share this in common, there is a vast difference in seedling density. Several studies that have explored abiotic factors affecting seedling establishments have found that excessive light availability negatively affects seedling

survival rates. Additionally, moisture had a strong positive effect on prolonging their survival (McLaren & McDonald, 2003; Mensah et al., 2020). In conjunction with this, the wet habitats displayed higher relative humidity and lower light availability. It is then reasonable to conclude that, although the seedlings in the dry rainforest benefit from a higher soil water content (Figure 19), a more open canopy severely inhibits seedling survival rates by increasing light stress and evaporation rates. This highlights the importance of considering both facilitation through nursing species that provide shade and shelter for seedlings, and the underlying soil properties of the ecosystem.

The difference in seedling density between habitats may also be attributed to trait-based differentiation. Drier ecosystems are known to increase greatly in light availability, which is known to inhibit seedling survivorship. Although this is true, Wood et al. (2017) discovered additional controls for seedling establishments. When investigating encroachments of woody pioneer species in montane grasslands in Tasmania, they noticed that the thick tussocks of the poa grass prevented seedling establishments. A similar interspecific competition was also found by Fensham & Fairfax (2006) in the Bunya Mountains. In conducting burning trials in the grassy balds, Fensham & Fairfax found that fire disturbances tend to facilitate the encroachment of eucalypts into the grasslands as they are obligatory species to fire disturbances. Additionally, after a burning trial occurred, the grasses were no longer able prevent seedlings from reaching maturity. By adapting to the destructive effects of fire disturbances, this species reproduces in longer intervals, thus resulting in lower seedling densities. It is important to note, however, that this is one example of differentiation and further research should be applied to the propagation of species in dry habitats.

#### ***4.2.1 Implications and Recommendations***

The similarities found between the notophyll forest and the dry ecosystems uncovered an important consideration. The characterisation of wet and dry habitats may distort observations regarding abiotic factors. It was noticed that the notophyll forest was conducive to an exceptionally high seedling density, while exhibiting properties of both the wet and dry habitats. This suggests that seedling densities should be measured on both a meso- and microscale, as abiotic factors due to topographic causes seem to greatly influence seedling survivorship and species are known to be highly variable in reproductive rates. Additionally, the species of each study site should be recorded.

### **5.0 Conclusion**

This study has highlighted the influence of both biotic and abiotic factors on tree and seedling dynamics across the diverse ecosystems of the Bunya Mountains. Tree and seedling population dynamics were found to be significantly influenced by environmental drivers and species interactions, with tree density and basal area showing clear variation between ecosystems. Species interactions may play a more prominent role in determining community structures than environmental drivers. Meanwhile, seedling densities were more closely aligned with broader habitat classifications, with wet habitats supporting far greater densities than dry habitats. An important consideration to make, however, is the scale at which the abiotic and biotic factors are measured. Ultimately, this report has provided valuable knowledge to inform and improve methods of conservation in response to a changing climate.

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