Environmental Conditions and the Growth Patterns of *Acacia melanoxylon* in Highland Humid Forests in North Tinderet Forest Block (Kenya)

[1, 2] Kiptoo K. Thomas, [1]Ole Kiyiapi L. James, [1]Sang K. Francis, [1]Odhiambo O. Kenneth and [3]Wanjohi Bernard
[1]Department of Forestry and Wood Science, School of Environmental Science and Natural Resource Management, University of Eldoret, P.O Box 1125-30100, Eldoret–Kenya

[2]Kenya Forest Service, P.O Box 30513-00100, Nairobi Kenya

[3]Department of Wildlife Conservation and Management, School of Environmental Sciences and Natural Resource Management, University of Eldoret, P.O Box 1125-30100, Eldoret–Kenya

Corresponding author's email address: kiprothom@gmail.com

Abstract

Acacia species represent one of the most important alien invasive species in many forest ecosystems. The number of quantitative studies exploring their response to environmental heterogeneity is few, especially in tropical, equatorial forested habitats. Therefore, this study aimed to determine ecological conditions and growth patterns of Acacia melanoxylon in highland humid forests in North Tinderet Forest Block in Kenya. Three (3) transects measuring 500 m long each were established in each of the sampling sites invaded by A. melanoxylon where three plots of 10 m × 10 m sizes were systematically spaced at 235 m intervals. In each of the 10 m × 10 m sized plots, all tree species of diameter at breast height (DBH) $\geq$ 1.3 m and height were measured and recorded. The abundance (ind/m) of plant species was calculated for each site. The study established differences in the DBH, height and abundance of acacia trees relative to environmental variables where the differences occurred mainly due to rainfall, humidity and wind, while altitude, slope, and elevation resulted in negative growth response. These findings suggest that the set of selected environmental variables affected the distribution and growth of A. melanoxylon. It is thus recommended that future studies on ecological conditions for the growth of A. melanoxylon should be conducted in a controlled environment through growth response measurements which were not possible under the current study due to the limitation of time and resources.

Keywords: *Acacia melanoxylon*, Environmental Factors, Invasive Species, Acacia Growth, Tropical Forests

INTRODUCTION

Annually, numerous invasive plant species are transported thousands of kilometers into peculiar landscapes, where they have to survive, propagate and eventually dominate over the native species to become invasive species (Montagnani *et al.*, 2022). Invasive species that exhibit high productivity, a higher tendency to shift their niche more rapidly, rapid establishment, highly adaptable and rapid growth, especially on harsh sites where native tree species do not perform well will ultimately be widely distributed (Redwood *et al.*, 2019; El-Shafie, 2020). Members of the genus *Acacia* (Family Fabaceae) are some of the most transported and introduced species in new environments over the last five decades in virtually every environment except in Arctic and Antarctic regions (Souza-Alonso *et al.*, 2017; Minuto *et al.*, 2020). In their alien environments, acacias establish quickly, grow and dominate the landscape (Gioria *et al.*, 2022; Wells *et al.*, 2023). There are also several documented studies concerning the growth and survival of *A. melanoxylon* in almost all the continents in countries such as Spain (Arán *et al.*, 2013), Australia (Neilsen and Brown, 1996; Medhurst *et al.*, 2003; Arán *et al.*, 2013), South Africa (De Zwaan and Van der Sijde, 1990; Matukana, 2021), New Zealand (Berrill *et al.*, 2007), Argentina (Igartúa *et al.*, 2017), China (Xiaogang *et al.*, 2018). However, knowledge is limited concerning their growth and establishment in tropical, equatorial ecosystems and to the best of our knowledge, no such information is available for *A. melanoxylon* growth in Kenya.

An underlying question of what makes an ecosystem susceptible to invasion by acacias species including *A. melanoxylon* in almost every climatic condition of the world from temperate, to tropical rainforest and savannah, Alpine regions, monsoon, boreal and arid landscapes (Al Dhanhani *et al.*, 2023; Matos *et al.*, 2023) have persuaded intense scientific investigation for several decades. The success of diverse alien acacia species involves a process that is regulated largely by its “match” in its alien environment.

The role of environmental factors in shaping the pattern of establishment, survival, distribution and growth of invasive plant species has attracted much attention from ecologists leading to large research outputs in this realm. Indeed due to the constant variation and unpredictability of the environmental conditions (Salamon-Albert *et al.*, 2022; Zhao *et al.*, 2022), exacerbated by the climate change scenario (Finch *et al.*, 2021) has provided the impetus for determining important stochastic variables affecting the growth of invasive species including members of acacias. As a consequence, plant growth response along environmental gradients has remained a central theme of community ecology from the global, regional to local biotopes (Guilherme *et al.*, 2022; Stefańska-Krzaczek *et al.*, 2022; Ullah *et al.*, 2022). Although the role of environmental factors on plant growth becomes clearer in landscapes with minimal human activities, including in the forest protected areas (Holenstein, 2022; Aththanayaka *et al.*, 2023), there is currently a large data gap on the influence of environmental variables on invasive species growth patterns in many areas in the tropical region, more surprising is the absence of study on *A. melanoxylon* growth in many forests include the protected ones in Kenya.

The environmental characteristics driving the growth of many invasive plants species can be classified as either related to climatic conditions (Tsarev *et al.*, 2021; Vacek *et al.*, 2022) or physiognomic characteristics of the landscapes (Lázaro-Lobo *et al.*, 2020; Berio Fortini *et al.*, 2021). In studies of the growth of invasive acacia species, the climatic factors that have largely limited plant growth are rainfall and humidity, temperature, light and wind characteristics (Zhou *et al.*, 2020). Deficiencies of these factors cause most of the stress in invasive plants and therefore the environmental conditions must be right for optimal growth conditions. Meanwhile, the physiognomic characteristics are related to the physical and spatial structure of the landscape such as altitude, slope, aspects and elevation (Kumar *et al.*, 2022). Among these two broad factors, climatic factor affects plants species directly (direct or distal/proximal gradients) while physiognomic characteristics have no physiological effect on plant growth and are regarded as indirect gradients (Abbas *et al.*, 2021; Presley and Willig, 2023).

There are several studies that have been conducted to determine the influence of single environmental factors on plant species distribution. However, an analysis of the combined influence of these environmental factors is more robust in showing effects as a result of the combined environmental variables. Such studies are still rare in the tropical forested environment. Therefore, this study aimed to determine the environmental conditions and growth patterns of *Acacia melanoxylon* in highland humid forests in North Tinderet Forest Block (Kenya). We hypothesize that the environmental conditions have the effect of reducing growth patterns of *Acacia melanoxylon* in North Tinderet Forest Block in Kenya.

MATERIALS AND METHODS

Study Area

The study was carried out in Timboroa and Nabkoi areas in North Tinderet Forest Block located in Uasin Gishu County, North Rift region, Kenya (Fig. 1). Uasin Gishu County is one of the forty-seven counties of Kenya created under Schedule 5 of Kenya Constitution 2010. Timboroa and Nabkoi area extends between longitudes 34º50' East and 35º37' East and latitudes 0º03' South and 0º 55' North.

The climate of the area is influenced by its high altitude which makes it the wettest zone in Uasin Gishu County. They receive high and reliable annual rainfall ranging between 1,328.9mm to 1,405.4mm which is evenly distributed between March and September with two peaks in May and August. The period from October to February is a dry month. According to the data collected at the area weather station, Temperatures range from an average maximum of 29ºC to an average minimum of 7ºC. Rainfall and temperatures in the county are favourable for tree growth. The study area is the highest point in Uasin Gishu County and is located at an average elevation of 2,730 m asl with gently sloping topography towards the South. In Uasin Gishu County, forests cover an area of about 29,801.92 ha with 56% being indigenous and the rest being exotic plantations. The vegetation cover of the study area is industrial forest plantations, comprising *Cupressus lusitanica* and *Pinus patula*. Indigenous trees are present as thickets and invasions by *Acacia melanoxylon.*

Study Site Selection

Based on topographic aspects, altitude and differences in vegetation formations, the Forest Block were stratified into the upper and lower forests as primary units. This exercise was achieved by conducting a ground pre-survey, guided by existing Maps and literature available.

Forest Sampling and Measurements

Using systematic sampling, line transects running horizontally to the direction of the slope were installed and used to sample the forest compartments. Each compartment was divided into lower and upper sub-compartments with invaded and non-invaded sites. Three transects measuring 500 m long each were established in each of the sampling sub-block where three plots of 10 m × 10 m sizes systematically spaced at 235 m intervals were established along the transect for quantitative sampling of trees (Köhl *et al.*, 2006). In each 10 m × 10 m plot, the *Acacia melanoxylon* data collected was diameter at breast height (DBH) measured at 1.3 m above ground species and height for ≥8 as well as species counts (abundance).

Data Analysis

All data collected were entered, organized and managed using a Microsoft Excel spreadsheet. All statistical analyses were performed using STATISTICA 8.0 (Malfasi *et al.*, 2020) or SPSS 23.0 Statistical Packages (Jarnevich *et al.*, 2022). The mean abundance (ind/m) of plant species was calculated for each site. The spatial differences in species abundance between sites were obtained by One Way ANOVA. Variation in plant abundance was analyzed using a non-parametric Kruskal Wallis ANOVA test. Multiple comparisons of the mean (Post-hoc) were done using Duncan's Multiple Range Test. One-Way ANOVA was used to analyze spatial and temporal variations in plant density and biomass. Relationships between environmental variables with respect to DBH, average height and abundance of *A. melanoxylon* were tested using multiple linear regressions.

Principal Component Analysis (PCA) was used to analyze the spatial relationships between DBH and height of *Acacia melanoxylon*, *Cupressus lustinica* and *Pinus patula* with respect to environmental parameters. This was done through the PCA procedure using multiple regressions to fit attributes to an ordination space as vectors. The significance of Principal Axis Correlation coefficients was tested using a Monte-Carlo procedure.

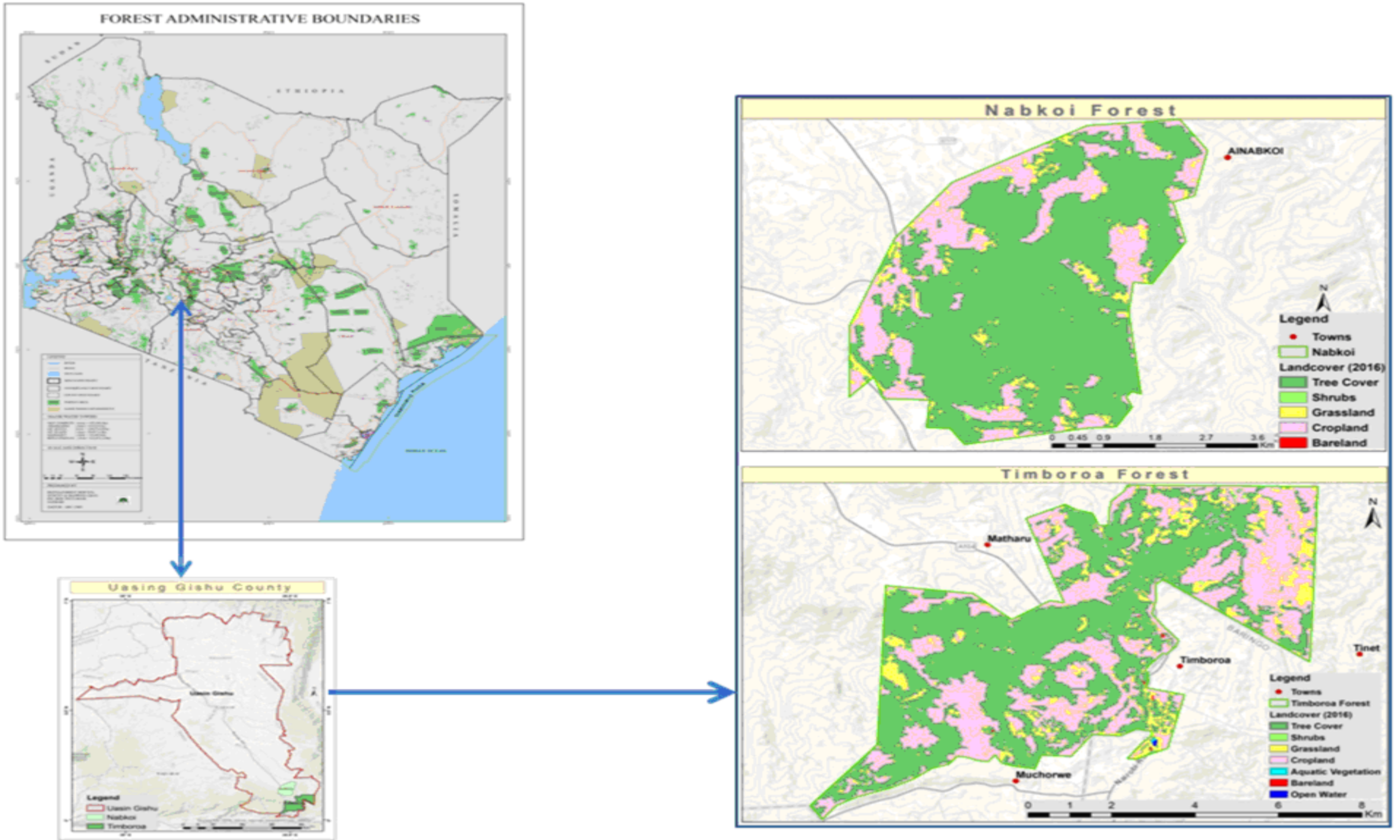

Figure 1: Map of Kenya showing the location of the study area

Results

The mean DBH of *Acacia melanoxylon* at the four forest blocks during the study is provided in Figure 2. The tree DBH growth of *A. melanoxyon* was significantly (One-Way ANOVA: $F_{(3,\ 154)}$ =51.763, P = 0.00000) higher in Timboroa stations block (Timboroa 1A and Timboroa 2) compared to the Nabkoi blocks.

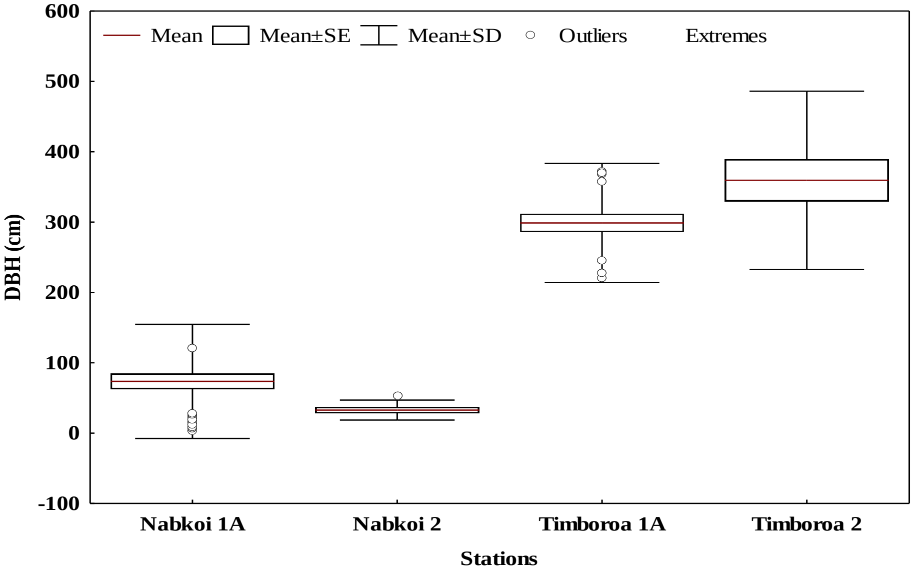

Figure 2: *Acacia melanoxylon* tree diameter at breast height (DBH) at the four sampling locations in Timboroa and Nabkoi Forest blocks

The mean average of *A. melanoxylon* at the four forest blocks during the study is shown in Figure 3. The average height of *A. melanoxyon* was significantly (One-Way ANOVA: $F_{(3,\ 154)}$ = 3.8293, P = 0.01469) higher in Timboroa 2 which was higher than average height at Timboroa 1A and Nabkoi 2, while *A. melanoxylon* at Nabkoi 1 had the least tree average height among the four station blocks.

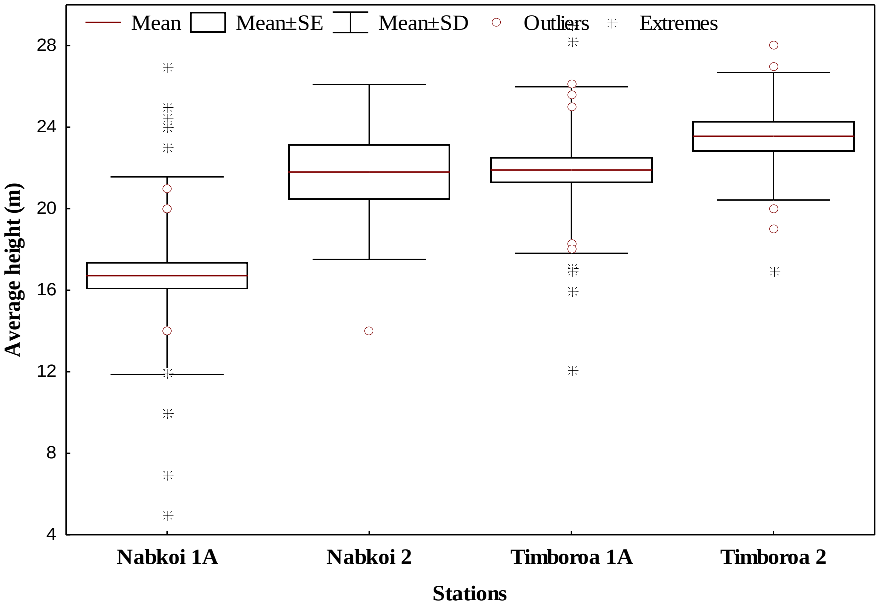

Figure 3: *Acacia melanoxylon* tree average height (cm) at the four sampling locations in Timboroa and Nabkoi Forest blocks

In terms of *A. melanoxylon* abundance at the four forest blocks during the study, the results are as shown in Figure 4. The abundance of *A. melanoxyon* was significantly higher (One-Way ANOVA: $F_{(3,\ 154)} = 29.203$, $P < 0.001$) in Nabkoi 2 compared to Nabkoi 1 and lowest at Timboroa 1A and Timboroa 2 forest station blocks.

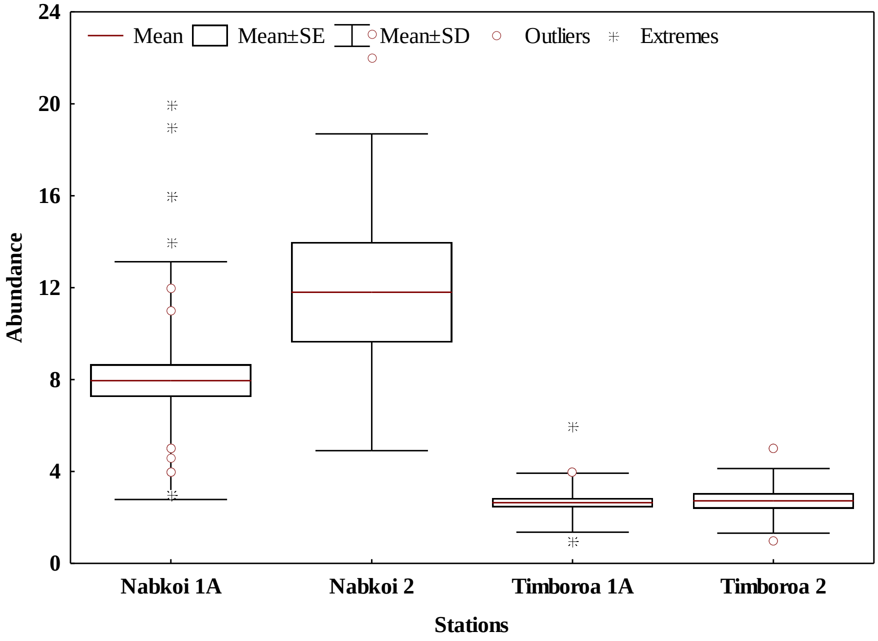

Figure 4: *Acacia melanoxylon* tree abundance at the four sampling locations in Timboroa and Nabkoi Forest blocks

A summary of the environmental parameters for *Acacia melanoxylon* growth at the four sampling stations during the study is shown in Table 1. There were four physiographic characteristics analyzed (Altitude, aspects, slope and elevation). All the analyzed physical aspects of the environmental parameters displayed significant spatial differences ($P < 0.05$). In terms of physical aspects, altitudes in the Nabkoi forest block (Nakoi 1A and Nabkoi 2) were significantly lower than the altitude recorded in the Timboroa forest blocks (Timboroa 1A and Timboroa 2). In terms of slopes, it was generally observed that the slope in the Nabkoi Forest block (Nabkoi 1A > Nabkoi 2) was lower than that of the Timboroa Forest block (Timboroa 1A > Timboroa 2). The aspect was significantly ($P < 0.05$) the lowest at Nabkoi 1A followed by Timboroa 1A, while the highest aspect occurred in Timboroa 2A followed by Nabkoi 2. Elevation followed a similar trend to the altitude where it was recorded to be significantly lower ($P < 0.05$) in Nabkoi Forest Block (Nakoi 1A and Nabkoi 2) compared to Timboroa forest blocks (Timboroa 1A and Timboroa 2).

Table 1: Summary of the environmental parameters for acacia growth at the four sampling stations

Environmental parameters	Sampling stations				ANOVA	
	Nabkoi 1A	Nabkoi 2	Timboroa 1A	Timboroa 2	*F*	*P*
Altitude	2572.8 ± 14.1^{a}	2581.4 ± 7.9^{a}	2784.8 ± 13.6^{b}	2719.6 ± 6.5^{b}	2445.791	<0.0001
Slope	7.8 ± 1.6^{b}	4.5± 1.8^{a}	9.7 ± 1.9^{c}	12.1 ± 2.2^{d}	8.902	0.0002
Aspect	81.8 ± 23.4^{a}	233.8 ± 22.3^{c}	32.9 ± 11.2^{b}	288.9 ± 23.4^{d}	69.937	<0.0001
Elevation	2573.5 ± 29.4^{a}	2586.4 ± 10.6^{b}	2761.3 ± 27.5^{b}	2708.7 ± 39.6^{b}	356.518	<0.0001
Temperature (monthly)	20.4 ± 1.0^{a}	21.1 ± 1.4^{a}	23.2 ± 1.3^{b}	23.7 ± 1.8^{b}	52.294	<0.0001
Rainfall	216.3 ± 3.4^{b}	216.9 ± 2.2^{b}	210.7 ± 2.3^{a}	212.4 ± 3.4^{a}	33.978	<0.0001
Humidity	71.3 ± 4.4b	75.2 ± 3.2^{b}	55.9 ± 6.9^{a}	53.5 ± 5.2^{a}	92.668	<0.0001
Wind speed	18.9 ± 1.5^{b}	21.3 ± 1.1^{c}	15.4 ± 1.9^{a}	15.4 ± 2.9^{a}	41.678	<0.0001

There were four weather-related environmental aspects analyzed (temperature, rainfall, humidity and wind speed). All the analyzed weather-related environmental parameters displayed significant spatial differences ($P < 0.05$). The temperature in the Timboroa forest block (Timboroa 1A and Timboroa 2) was significantly higher ($P < 0.05$) compared to the temperature value recorded in Naboi Forest Blocks (Nabkoi 1A and Nabkoi 2). Meanwhile, rainfall in the Timboroa Forest Blocks (Timboroa 1A and Timboroa 2) was significantly lower ($P < 0.05$) than the rainfall recorded in Nabkoi Forest Blocks (Nabkoi 1A and Nabkoi 2). On a similar note, the humidity values followed those of rainfall where Timboroa Forest Blocks (Timboroa 1A and Timboroa 2) was significantly lower ($P < 0.05$) than the humidity in Nabkoi Forest Blocks (Nabkoi 1A and Nabkoi 2). Finally, wind speed was recorded to be significantly ($P < 0.05$) the highest in Nabkoi 2 followed by Nabkoi 1A and lowest in the twin stations of Timboroa Forest Blocks (Timboroa 1A and Timboroa 2).

The relationships between DBH and single environmental variables are shown in Figure 5 while the combined influence of all the environmental variables on DBH of *A. melanoxylon* is provided in Table 2. Based on the multiple regression statistics, the combined selected environmental attributes were significant in explaining the DBH growth of *A. melanoxylon* ($P < 0.05$). Nevertheless, in terms of individual contribution, altitude, slope, aspects elevation and rainfall were the significant factors affecting the DBH of *A. melanoxylon* while temperature, humidity and wind speeds had no significant effects on the DBH of *A. melanoxylon*. Whereas slope, aspect, and elevation were positively correlated with DBH, the altitude, temperature, rainfall and humidity showed a negative correlation with DBH of *A. melanoxylon*. In terms of contribution to the DBH, elevation and slope followed by slope were the most important factor contributing to the growth of DBH

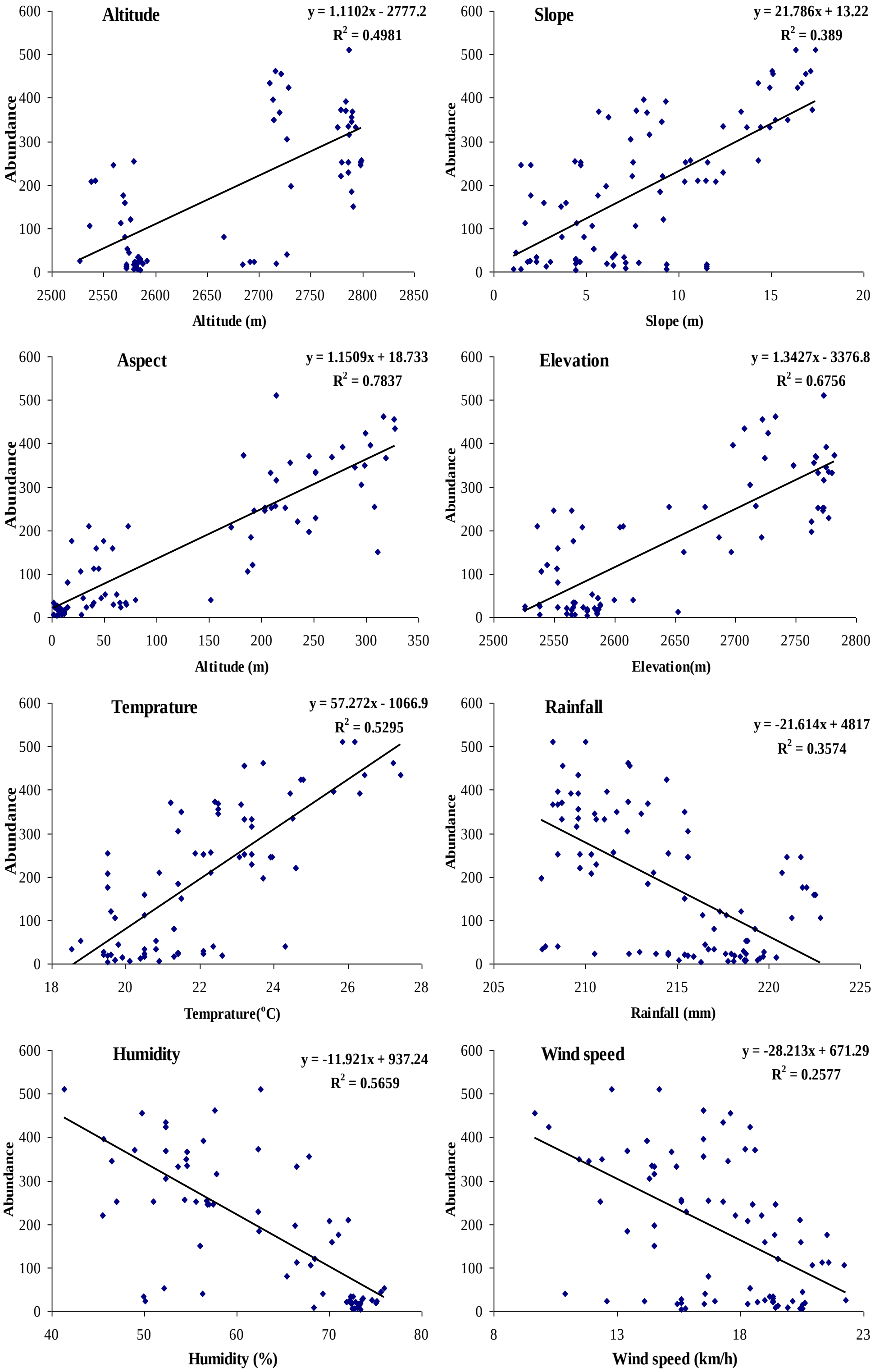

Figure 5: Bivariate regression models showing the relationship between DBH and single environmental parameters

Table 2: Multiple regression analysis showing the relationship between DBH and environmental parameters

Regression Statistics	
Multiple R	0.950
R Square	0.903
Adjusted R Square	0.896
Standard Error of Estimate	49.567
Durbin-Watson	1.983
Change statistics	
R Square Change	0.903
F Change	133.663
Dependent Variable	DBH

Predictors: (Constant), Wind, Slope, Temp, Rainfall, Humidity, Altitude, Aspect, Elevation

ANOVA	*TSS*	*Df*	*MSS*	*F*	*P-value*
Regression	2627260.394	8	328407.549	133.663	<0.0001
Residual	282552.163	115	2456.975		
Total	2909812.556	123			

	Unstandardized Coefficients		Standardized Coefficients		
	B	*Std. Error*	*Beta*	*t Stat*	*P value*
(Constant)	-1183.558	612.683		-1.932	0.056
Altitude	-0.287	0.145	-0.185	-1.978	0.048
Slope	5.554	1.219	0.166	4.555	0.000
Aspect	0.573	0.078	0.430	7.324	0.000
Elevation	0.755	0.180	0.450	4.192	0.000
Temp	-0.638	2.016	-0.016	-0.317	0.752
Rainfall	10.163	3.581	-0.126	-2.838	0.005
Humidity	-1.299	0.964	-0.082	-1.348	0.180
Wind speeds	-0.721	2.472	-0.012	-0.292	0.771
Correlations	Zero-order	Partial	Part	Collinearity Statistics	
(Constant)				Tolerance	VIF
Altitude	0.741	-0.181	-0.057	0.097	10.336
Slope	0.603	0.391	0.132	0.635	1.574
Aspect	0.889	0.564	0.213	0.245	4.074
Elevation	0.843	0.364	0.122	0.073	13.673
Temp	0.720	0.256	0.082	0.428	2.334
Rainfall	-0.778	-0.030	-0.096	0.315	3.175
Humidity	-0.814	-0.125	-0.039	0.230	4.352
Wind	-0.640	-0.027	-0.008	0.465	2.149

The relationships between height and single environmental variables are shown in Figure 6 while the combined influence of all the environmental variables on the average height of *A. melanoxylon* is provided in Table 3. The selected environmental attributes were significant in explaining the average height of *A. melanoxylon* ($P < 0.05$). Nevertheless, in terms of individual contribution, altitude, slope, temperature, rainfall and wind speed were the significant factors affecting the height of *A. melanoxylon* while altitude, aspect, elevation, and humidity had no significant ($P > 0.05$) effects on the height of *A. melanoxylon*. The slope was positively correlated with height, while rainfall, temperature and wind speed showed a negative correlation with the height of *A. melanoxylon*. In terms of contribution to the height, temperature, and rainfall were the most important factor contributing to growth in terms of average height.

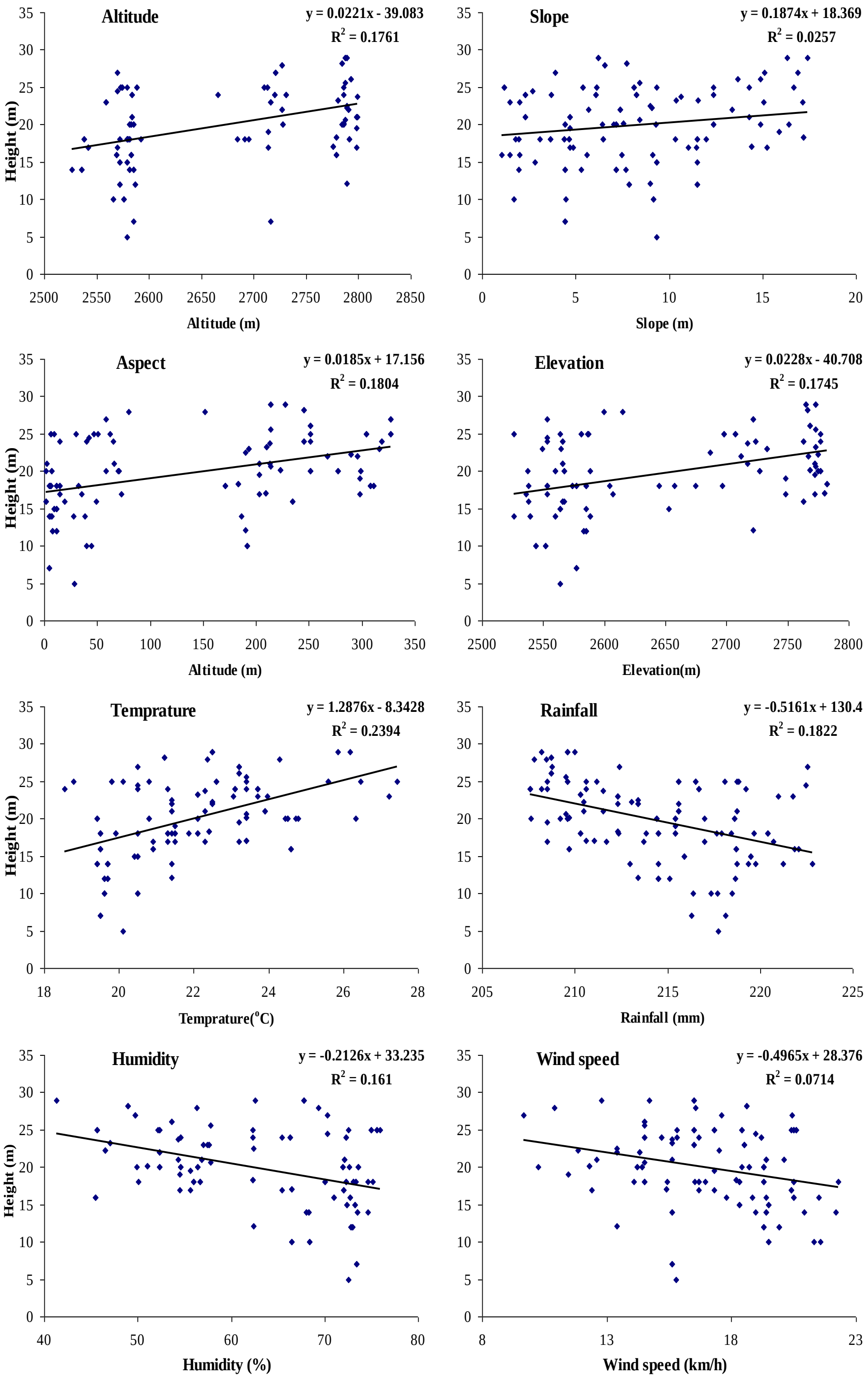

Figure 6: Bivariate regression models showing the relationship between height and single environmental parameters

Table 3: Multiple regression analysis showing the relationship between height and environmental parameters

Regression Statistics	
Multiple R	0.556
R Square	0.309
Adjusted R Square	0.261
Standard Error of Estimate	4.420
Durbin-Watson	1.740
Change statistics	
R Square Change	0.309
F Change	6.442
Dependent Variable	Height (m)

Predictors: (Constant), Wind, Slope, Temp, Rainfall, Humidity, Altitude, Aspect, Elevation

ANOVA	*TSS*	*Df*	*MSS*	*F*	*P-value*
Regression	1006.737	8	125.842	6.442	<0.0001
Residual	2246.550	115	19.535		
Total	3253.287	123			

	Unstandardized Coefficients		Standardized Coefficients		
	B	*Std. Error*	*Beta*	*t Stat*	*P value*
(Constant)	27.686	54.632		0.507	0.613
Altitude	0.013	0.013	0.148	0.994	0.322
Slope	-0.188	0.109	-0.268	-1.731	0.046
Aspect	0.005	0.007	0.119	0.761	0.448
Elevation	-0.004	0.016	-0.070	-0.243	0.808
Temp	0.916	0.319	-0.340	2.869	0.005
Rainfall	-0.272	0.180	-0.309	-1.515	0.047
Humidity	0.007	0.086	0.013	0.081	0.935
Wind	0.392	0.220	-0.202	1.778	0.048

Correlations	Zero-order	Partial	Part	Collinearity Statistics	
(Constant)				Tolerance	VIF
Altitude	0.440	0.092	0.077	0.097	10.336
Slope	0.100	-0.159	-0.134	0.635	1.574
Aspect	0.373	0.071	0.059	0.245	4.074
Elevation	0.440	-0.023	-0.019	0.073	13.673
Temp	0.491	0.258	-0.222	0.428	2.334
Rainfall	-0.398	-0.140	-0.117	0.315	3.175
Humidity	-0.390	0.008	-0.006	0.230	4.352
Wind	-0.204	0.164	0.138	0.465	2.149

The relationships between abundance and single environmental variables are shown in Figure 7 while the combined influence of all the environmental variables on the abundance of *A. melanoxylon* is provided in Table 4. Based on the multiple regression statistics, the combined selected environmental attributes significantly ($P < 0.05$) explained the abundance of *A. melanoxylon*. Nevertheless, in terms of individual contribution, aspect, elevation, rainfall, humidity and wind speed were the significant ($P < 0.05$) factors affecting the abundance of *A. melanoxylon* while altitude, slope and temperature had no significant ($P >$ 0.05) effects on abundance of *A. melanoxylon*. Whereas aspect and humidity were positively correlated with the abundance of *A. melanoxylon*, the elevation, rainfall and wind speed displayed a negative correlation with the abundance of *A. melanoxylon*. In terms of contribution to the abundance of *A. melanoxylon*, elevation and rainfall were the most important factor contributing to the growth of the abundance of *A. melanoxylon* where elevation negatively affected the abundance of *A. melanoxylon*.

Table 4: Multiple regression analysis showing the relationship between abundance and environmental parameters

Regression Statistics	
Multiple R	0.684
R Square	0.468
Adjusted R Square	0.431
Standard Error of Estimate	3.815
Durbin-Watson	1.453
Change statistics	
R Square Change	.468
F Change	12.644
Dependent Variable	Abundance

Predictors: (Constant), Wind, Slope, Temp, Rainfall, Humidity, Altitude, Aspect, Elevation

ANOVA	*TSS*	*Df*	*MSS*	*F*	*P-value*
Regression	1472.359	8	184.045	12.644	<0.0001
Residual	1673.916	115	14.556		
Total	3146.275	123			

	Unstandardized Coefficients		Standardized Coefficients		
	B	*Std. Error*	*Beta*	*t Stat*	*P value*
(Constant)	224.003	47.158		4.750	0.000
Altitude	-0.004	0.011	-0.074	-0.337	0.737
Slope	0.075	0.094	0.069	0.804	0.423
Aspect	0.011	0.006	0.243	2.169	0.040
Elevation	-0.039	0.014	-0.710	-2.821	0.006
Temp	-0.171	0.276	-0.065	-0.622	0.535
Rainfall	-0.535	0.155	-0.418	-3.445	0.001
Humidity	0.081	0.074	0.155	2.095	0.046
Wind	0.362	0.190	0.190	-2.099	0.047
Correlations	Zero-order	Partial	Part	Collinearity Statistics	
(Constant)				Tolerance	VIF
Altitude	-0.585	-0.031	-0.023	0.097	10.336
Slope	-0.033	0.075	0.055	0.635	1.574
Aspect	-0.285	0.163	0.120	0.245	4.074
Elevation	-0.554	-0.254	-0.192	0.073	13.673
Temp	-0.401	-0.058	-0.042	0.428	2.334
Rainfall	0.189	-0.306	0.234	0.315	3.175
Humidity	0.448	0.102	0.074	0.230	4.352
Wind	0.459	0.175	0.129	0.465	2.149

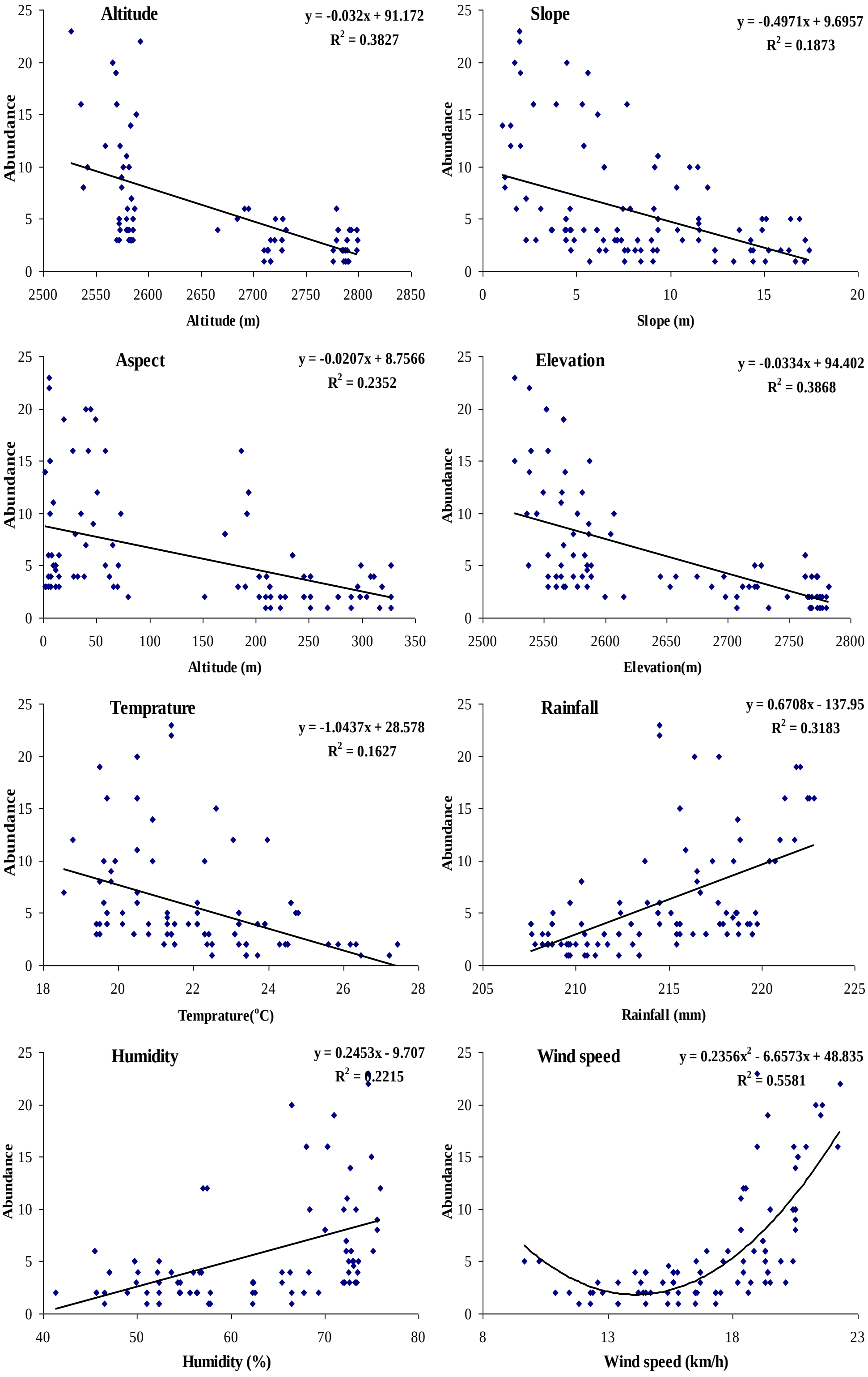

Figure 7: Bivariate regression models showing the relationship between abundance and single environmental parameters

The relationships between DBH and the height of *Acacia melanoxylon*, *Cupressus lustinica* and *Pinus patula* with respect to environmental parameters during the study are shown in Figure 8. There was a clear distinction between DBH and height with environmental parameters in the PCA tri-plot. The DBH and height of *A. melanoxylon* were positively associated with rainfall, humidity and wind speed but negatively correlated with altitude, slope and elevation. Meanwhile, temperature appeared to control the height of *C. lustinica* and *P. patula*. Finally, the aspect appeared to have significant control over the DBH of *C. lustinica* and *P. patula*. It was generally determined that altitude, slope and elevation had negative impacts on all measured parameters.

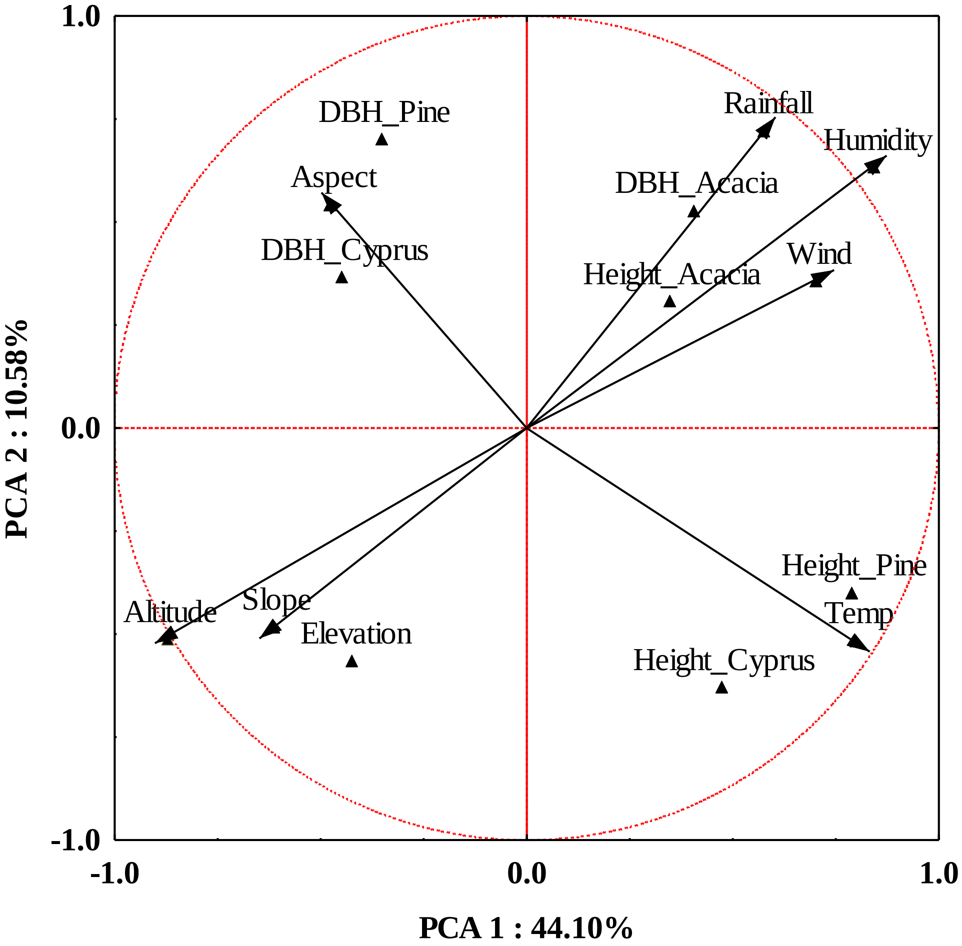

Figure 8: Principal Component Analysis (PCA) triplot for DBH and height of *Acacia melanoxylon, Cupressus lustinica* and *Pinus patula* with respect to environmental parameters in North Tinderet

DISCUSSION

Tropical plantation forests are not resistant to invasion by alien plant species, either through accidental or deliberate introductions. In the North Tinderet Forest Blocks, there is successful colonization and adaptation of the forest by invasive *A. melanoxylon* which has often been reasoned to be due to a suite of environmental conditions due to low amounts of anthropogenic activities within the protected plantation forest biotope. However, there have been few efforts aimed at determining the role of ecological and/or environmental factors in the growth of the invasive species.

During the study, the DBH, height and abundance of *Acacia melanoxylon* at the four forest blocks showed significant variation among the sampling blocks suggesting a response to varying ecological conditions. During the study, rainfall, humidity and wind were found to be the positive growth determinant of the growth of acacia in terms of DBH, average height and abundance. Since the 1800s, when Charles and Francis Darwin discovered that plants responded to the presence of water (Gul *et al.*, 2023), growth limitation of plant physiological processes due to water availability is well grounded (Brendel, 2021), which renders rainfall and humidity significant in controlling plant species distributions, survival and growth (Ouyang *et al.*, 2020; Gong *et al.*, 2021). A wide range of invasive acacias including *A. dealbata*, *A. mangium*, *A. raddiana A. tortilis* and *A. mearnsii*, *A. koa*, and *A. stenophylla* among others are considered water-consuming species (Mendham and White, 2019; Hamad-Sheip *et al.*, 2021), rendering rainfall and humidity instrumental in their growth. The importance of temperature in the regulation of plant physiological growth and development of invasive plant species (Liu *et al.*, 2022), including in invasive species (Kharivha *et al.*, 2022) is well established. The impact of wind, a rather neglected environmental factor on invasive plants largely depends on speed, duration, and the extent to which wind can penetrate canopy layers (Wan *et al.*, 2017; Momberg *et al.*, 2021). Sufficient wind speeds can affect plant development, form and function, shaping plant size and abundance (Nyarobi, 2022). Some studies on *Acacia* spp. showed that in areas where rainfall is high, it does not play a significant influence on the growth of acacia (Floret and Pontanier, 2022). However, a study by Stave *et al.* (2006) assessed the underlying causes of the growth establishment of the tree species *Acacia* in Kenya. They argued that the growth of *Acacia* was induced by prolonged but moderate levels of rainfall. Similarly, Skoglund (1992) stated that the growth of *A. melanoxylon* was discontinuous and confined to years with relatively high precipitation. In addition, Rohner and Ward (1999) reported that several years of high rainfall are necessary for the successful establishment of young *Acacia* trees. Therefore, water and wind were the important single limiting factor in the productivity of many species.

It was also observed that during the study, altitude, slope, and aspects elevation influenced growth parameters negatively meaning that growth increased at low altitude, slope, aspect and elevation. The implication is not negative per se but growth responses are positive at lower values of these physiognomic parameters. The role of the response of vegetation to changes in landscape physiognomy is well established (Froidevaux *et al.*, 2022). Acacia response to a combination of altitude, slope, aspect, and elevation has been shown previously (Zou *et al.*, 2023). Alien invasive species are strongly influenced by altitude where species growth response and diversity generally tend to decrease with increasing altitude. In warm environments, higher elevation and higher altitude often present harsh environments for the growth of plants (Pauchard *et al*. 2022). The combination of these physiognomic characteristics affects temperature, moisture, radiation and atmospheric pressure thereby influencing the growth and development of plants (Gregory *et al*., 2021).

Although the temperature is important in the regulation of plant physiological growth and the development of invasive plant species (Liu *et al.*, 2022), including in invasive species (Kharivha *et al.*, 2022), the current study does not find any significance of temperature in the growth regulation of *A. melanoxylon*. The temperature ranges of the region are probably within the optimal ranges of the physiological function of the invasive *A. melanoxylon*. The lack of response of *A. melanoxylon* to temperature has been observed for several species of invasive plants in several forest environments in the equatorial environment where temperature fluctuations are quite minimal. It appears that the optimal temperature ranges allow for normal physiological functions of plants such as photosynthesis, membrane permeability, respiration etc. In addition, there was no observation of sudden changes in temperature which may cause negatively affect the growth of *A. melanoxylon*.

The current study suggests that environmental characteristics positively drive the growth of *A. melanoxylon* as established elsewhere (Tsarev *et al.*, 2021; Vacek *et al.*, 2022) or negatively respond to physiognomic characteristics of the landscapes (Lázaro-Lobo *et al.*, 2020; Berio Fortini *et al.*, 2021). In the current study, involving the growth of *A. melanoxylon*, the climatic factors that have largely controlled the plant growth, where rainfall humidity, and wind characteristics were more conspicuous. These factors control stress in invasive plants while physiognomic characteristics were optimal for the growth of species at lower levels. Therefore, it was evident that climatic factors affected *A. melanoxylon* directly or distal/proximal gradients, meanwhile physiognomic characteristics also appeared to affect the A. melanoxylon directly but their effects were observed when at lower levels.

In addition, several other abiotic environmental factors such as rainfall deficient conditions, soil properties and topography have been shown to affect the abundance and distribution of the dominant species such as Acacia (Traoré *et al*., 2012). Several authors (Ehrlén and Morris, 2015; Kraft *et al.*, 2015; D'Amen *et al.*, 2018) posit and emphasize, the diverse contexts, in which multiple environmental factors will affect the growth, and establishment of various forms of vegetation including invasive acacia species.

CONCLUSIONS AND RECOMMEDATIONS

There were differences in the DBH, average height and abundance of acacia trees relative to environmental variables. Altitude, slope, aspects elevation and rainfall were the significant factors affecting DBH of *A. melanoxylon* while temperature, humidity and wind speeds had no significant effects. Whereas slope, aspect, and elevation were positively correlated with DBH, the altitude, temperature, rainfall and humidity showed a negative correlation with DBH of *A. melanoxylon*. Altitude, slope, temperature, rainfall and wind speed were the significant factors affecting the height of *A. melanoxylon* while altitude, aspect, elevation, and humidity had no significant ($P > 0.05$) effects on height. Elevation, rainfall, humidity and wind speed were the significant ($P < 0.05$) factors affecting the abundance of *A. melanoxylon* while altitude, slope and temperature had not significant ($P > 0.05$).

Sound comparative studies on the availability of macronutrients between Acacia spp.-invaded sites and mature stands of native Fabaceae species, another research gap is the lack of knowledge about the effects of acacias on net and gross N fluxes, as well as on available micronutrients, in the invaded ecosystems. Moreover, integrated studies on the effects of CO2 increase and changes in temperature, frost risk and water availability could provide a more reliable understanding of the effect of climate change on these invasive species.

In addition to reactive actions, such as eradication, the proactive restoration of areas invaded by these *Acacia* species must be carefully planned to recover the ecosystem composition and function without side effects. However, the complexity of controlling both invasion and restoration side effects highlights the importance of taking a preventive approach. Future studies on ecological conditions for the growth of *A. melanoxylon* should be conducted in a controlled environment through growth response measurements which were not possible under the current study due to the limitation of time and resources

REFERENCES

Abbas, Z., Khan, S.M., Alam, J., Peer, T., Abideen, Z., Bussmann, R.W. and Muhammad, S. (2021). Vegetation dynamics along altitudinal gradients in the Shigar Valley (Central Karakorum) Pakistan: Zonation, physiognomy, ecosystem services and environmental impacts. *Pak. J. Bot*. 53(5): 1865-1874.

Al Dhanhani, A.S.S.J., Mirza, S.B., Alhefeiti, F.R.M.O. and Ridouane, F.L. (2023). Investigating the nutritional potential and vegetation blueprint mapping of Acacia tortilis and Acacia ehrenbergiana from the origin of Fujairah, UAE, for Arabian Tahr as native fodder plants. *Advancements in Life Sciences*. 10(1): 99-103.

Arán, D., García-Duro, J., Reyes, O. and Casal, M. (2013). Fire and invasive species: Modifications in the germination potential of *Acacia melanoxylon*, *Conyza canadensis* and *Eucalyptus globulus*. *Forest Ecology* *and Management*. 302(7-13.

Aththanayaka, C.P., Siyasinghe, D.P., Prakash, S.L., Bloch, C.P. and Surasinghe, T.D. (2023). Native and exotic plant invasions vary across habitat types and anthropogenic disturbances in a tourism-heavy protected area. *Biological Invasions*. 25(2): 411-429.

Berio Fortini, L., Leopold, C.R., Perkins, K.S., Chadwick, O.A., Yelenik, S.G., Jacobi, J.D., Bishaw, K.e. and Gregg, M. (2021). Landscape level effects of invasive plants and animals on water infiltration through Hawaiian tropical forests. *Biological Invasions*. 23(7): 2155-2172.

Berrill, J., Nicholas, I. and Gifford, H. (2007). Preliminary growth and yield models for even-aged Acacia melanoxylon plantations in New Zealand. *New Zealand Journal of Forestry Science*. 37(1): 37-46.

Brendel, O. (2021). The relationship between plant growth and water consumption: a history from the classical four elements to modern stable isotopes. *Annals of Forest Science*. 78(2): 47.

D'Amen, M., Mod, H.K., Gotelli, N.J. and Guisan, A. (2018). Disentangling biotic interactions, environmental filters, and dispersal limitation as drivers of species co-occurrence. *Ecography*. 41(8): 1233-1244.

De Zwaan, J. and Van der Sijde, H. (1990). Early results of three blackwood (Acacia melanoxylon) provenance trials in South Africa. *South African Forestry Journal*. 152(1): 23-25.

Ehrlén, J. and Morris, W.F. (2015). Predicting changes in the distribution and abundance of species under environmental change. *Ecology Letters*. 18(3): 303-314.

El-Shafie, H. (2020). *Invasive Species: Introduction Pathways, Economic Impact, and Possible Management Options*. BoD–Books on Demand.

Finch, D.M., Butler, J.L., Runyon, J.B., Fettig, C.J., Kilkenny, F.F., Jose, S., Frankel, S.J., Cushman, S.A., Cobb, R.C. and Dukes, J.S. (2021). Effects of climate change on invasive species. *Invasive species in forests and rangelands of the United States: a comprehensive science synthesis for the United States forest sector*: 57-83.

Froidevaux, J.S., Duarte, G., Fonseca, A., Zina, V., Conde, S., Ferreira, M.T. and Fernandes, M.R. (2022). The location and vegetation physiognomy of ecological infrastructures determine bat activity in Mediterranean floodplain landscapes. *Agriculture, Ecosystems & Environment*. 332(107929.

Gioria, M., Hulme, P.E., Richardson, D.M. and Pyšek, P. (2022). Why Are Invasive Plants Successful? *Annual Review of Plant Biology*. 74(

Gong, Y., Zhang, X., Li, H., Zhang, X., He, S. and Miao, Y. (2021). A comparison of the growth status, rainfall retention and purification effects of four green roof plant species. *Journal of Environmental Management*. 278(111451.

Guilherme, F.A.G., Júnior, A.F., Pereira, F.C., Silva, G.E. and Maciel, E.A. (2022). Disturbances and environmental gradients influence the dynamics of individuals and basal area in the Cerrado complex. *Trees, Forests and People*. 9(100298.

Gul, M.U., Paul, A. and Chehri, A. (2023). Hydrotropism: Understanding the Impact of Water on Plant Movement and Adaptation. *Water*. 15(3): 567.

Hamad-Sheip, Y., Abdul-Hamid, H., Abiri, R., Saleh, M.-N., Mohamed, J., Jalil, A.-M. and Naji, H.R. (2021). Effect of Acacia mangium canopy on physicochemical characteristics and nutrient concentrations of the soil at Ayer Hitam Forest Reserve, Malaysia. *Forests*. 12(9): 1259.

Holenstein, K. (2022). Permeability of European Protected Areas to Non-Native Species, Université Montpellier.

Igartúa, D.V., Moreno, K. and Monteoliva, S.E. (2017). Acacia melanoxylon in Argentina: heartwood content and its relationship with site, growth and age of the trees. *Forest Systems*. 26(

Jarnevich, C.S., Sofaer, H.R., Belamaric, P. and Engelstad, P. (2022). Regional models do not outperform continental models for invasive species. *NeoBiota*. 77(1-22.

Kharivha, T., Ruwanza, S. and Thondhlana, G. (2022). Effects of elevated temperature and high and low rainfall on the germination and growth of the invasive alien plant Acacia mearnsii. *Plants*. 11(19): 2633.

Köhl, M., Magnussen, S. and Marchetti, M. (2006). *Sampling in Forest surveys*. Springer.

Kraft, N.J., Adler, P.B., Godoy, O., James, E.C., Fuller, S. and Levine, J.M. (2015). Community assembly, coexistence and the environmental filtering metaphor. *Functional ecology*. 29(5): 592-599.

Kumar, A., Adhikari, B.S. and Rawat, G.S. (2022). A hierarchy of landscape-habitat-plant physiognomic classes in the Indian Trans-Himalaya. *Trees, Forests and People*. 7(100172.

Lázaro-Lobo, A., Evans, K.O. and Ervin, G.N. (2020). Evaluating landscape characteristics of predicted hotspots for plant invasions. *Invasive Plant Science and Management*. 13(3): 163-175.

Liu, Z., Yu, H., Sun, X. and Ding, J. (2022). Effects of elevated temperature on chemistry of an invasive plant, its native congener and their herbivores. *Journal of Plant Ecology*. 15(3): 450-460.

Malfasi, F., Convey, P., Zaccara, S. and Cannone, N. (2020). Establishment and eradication of an alien plant species in Antarctica: Poa annua at Signy Island. *Biodiversity and Conservation*. 29(173-186.

Matos, F.A., Edwards, D.P., S. Magnago, L.F., Heringer, G., Viana Neri, A., Buttschardt, T., Dudeque Zenni, R., Tavares de Menezes, L.F., Zamborlini Saiter, F. and Reynaud Schaefer, C.E.G. (2023). Invasive alien acacias rapidly stock carbon, but threaten biodiversity recovery in young second-growth forests. *Philosophical Transactions of the Royal Society B*. 378(1867): 20210072.

Matukana, V. (2021). The Survival of Acacia decurrens, Acacia melanoxylon and Populus alba in Vaalwater, Waterberg Biosphere Reserve, Limpopo Province, South Africa.

Medhurst, J., Pinkard, E., Beadle, C. and Worledge, D. (2003). Growth and stem form responses of plantation-grown Acacia melanoxylon (R. Br.) to form pruning and nurse-crop thinning. *Forest Ecology and Management*. 179(1-3): 183-193.

Mendham, D. and White, D. (2019). A review of nutrient, water and organic matter dynamics of tropical acacias on mineral soils for improved management in Southeast Asia. *Australian Forestry*. 82(sup1): 45-56.

Minuto, L., Casazza, G., Dagnino, D., Guerrina, M., Macri, C., Zappa, E. and Mariotti, M.G. (2020). Reproductive traits of the invasive species Acacia dealbata Link. In the northern Mediterranean basin. *Annali di Botanica*: 13-20.

Momberg, M., Hedding, D.W., Luoto, M. and le Roux, P.C. (2021). Species differ in their responses to wind: the underexplored link between species fine-scale occurrences and variation in wind stress. *Journal of Vegetation Science*. 32(6): e13093.

Montagnani, C., Gentili, R., Brundu, G., Caronni, S. and Citterio, S. (2022). Accidental Introduction and Spread of Top Invasive Alien Plants in the European Union through Human-Mediated Agricultural Pathways: What Should We Expect? *Agronomy*. 12(2): 423.

Neilsen, W. and Brown, D. (1996). *Acacia melanoxylon plantations in Tasmania: research and development*. Forestry Tasmania.

Nyarobi, H. (2022). Morphological and physiological responses of the invasive plant *Gutenbergia cordifolia* to varying biophysical conditions, NM-AIST.

Ouyang, L., Gao, J., Zhao, P. and Rao, X. (2020). Species-specific transpiration and water use patterns of two pioneer dominant tree species under manipulated rainfall in a low-subtropical secondary evergreen forest. *Ecohydrology*. 13(7): e2234.

Presley, S.J. and Willig, M.R. (2023). *Gradients and the Structure of Neotropical Metacommunities: Effects of Disturbance, Elevation, Landscape Structure, and Biogeography, Neotropical Gradients and Their Analysis*. Springer. pp. 419-450.

Redwood, M.E., Matlack, G.R. and Huebner, C.D. (2019). Seed longevity and dormancy state in an invasive tree species: Ailanthus altissima (Simaroubaceae) 1. *The Journal of the Torrey Botanical Society*. 146(2): 79-86.

Salamon-Albert, É., Bartha, D. and Csiszár, Á. (2022). Small-Scale Environmental Heterogeneity Enhances Tree Recruitment through Carbon Recharge and Water Use Diversification. *Forests*. 13(12): 2158.

Souza-Alonso, P., Rodríguez, J., González, L. and Lorenzo, P. (2017). Here to stay. Recent advances and perspectives about Acacia invasion in Mediterranean areas. *Annals of Forest Science*. 74(3): 1-20.

Stefańska-Krzaczek, E., Swacha, G., Żarnowiec, J., Raduła, M.W., Kącki, Z. and Staniaszek-Kik, M. (2022). Central European forest floor bryophytes: Richness, species composition, coexistence and diagnostic significance across environmental gradients of forest habitats. *Ecological Indicators*. 139(108954.

Tsarev, A., Tsareva, R. and Tsarev, V. (2021). Environmental Plasticity and Stability of Introduced Euramerican Poplar Hybrids Depending on Climate Variation: *IOP Conference Series: Earth and Environmental Science*. IOP Publishing, pp. 052062.

Ullah, R., Khan, N. and Ali, K. (2022). Which factor explains the life-history of *Xanthium strumarium* L., an aggressive alien invasive plant species, along its altitudinal gradient? *Plant Direct*. 6(1): e375.

Vacek, Z., Vacek, S., Cukor, J., Bulušek, D., Slávik, M., Lukáčik, I., Štefančík, I., Sitková, Z., Eşen, D. and Ripullone, F. (2022). Dendrochronological data from twelve countries proved definite growth response of black alder ([L.] Gaertn.) to climate courses across its distribution range. *Central European Forestry Journal*. 68(3): 139-153.

Wan, J.-Z., Wang, C.-J. and Yu, F.-H. (2017). Wind effects on habitat distributions of wind-dispersed invasive plants across different biomes on a global scale: Assessment using six species. *Ecological Informatics*. 42(38-45.

Wells, J.J., Stringer, L.C., Woodhead, A.J. and Wandrag, E.M. (2023). Towards a holistic understanding of non-native tree impacts on ecosystem services: A review of Acacia, Eucalyptus and Pinus in Africa. *Ecosystem Services*. 60(101511.

Xiaogang, D., Qian, H., Fangqiu, Z., Jiyue, L., Hongxu, W. and Jing, C. (2018). Optimizing the growth and N status of containerized Australian Blackwood (*Acacia melanoxylon*) seedlings with exponential nitrogen loading. *Forestry and Environmental Science*. 6(127-135.

Zhao, C., Zhao, W., Jin, M., Zhou, J., Ta, F., Wang, L., Mou, W., Lei, L., Liu, J. and Du, J. (2022). Spatial patterns of Picea crassifolia driven by environmental heterogeneity and intraspecific interactions. *Journal of Forestry Research*: 1-14.

Zhou, Q., Wang, L., Jiang, Z., Wu, J., Cui, X., Li, X., Liu, Z., Musa, A., Ma, Q. and Yu, H. (2020). Effects of climatic and social factors on dispersal strategies of alien species across China. *Science of the Total Environment*. 749(141443.

Zou, L., Tian, F., Liang, T., Eklundh, L., Tong, X., Tagesson, T., Dou, Y., He, T., Liang, S. and Fensholt, R. (2023). Assessing the upper elevational limits of vegetation growth in global high-mountains. *Remote Sensing of Environment*. 286(113423.