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Research Article

Landscape Heterogeneity Drives the Growth of Invasive Acacia Melanoxylon in Humid Forests in Kenya (Nabkoi and Timboroa Forests)

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Abstract

Invasion of forest by Acacia species is widespread in many terrestrial environments. However, their response to variation in forest environmental conditions has received less attention. This study determined the influence of landscape heterogeneity on growth of Australian Blackwood (*Acacia melanoxylon*) in tow tropical highland humid forests (Nabkoi Forest and Timboroa Forest) in Kenya. Sampling was done by laying three-500 m long transect, followed by overlaying three plots 0.1 ha. plot (10 m × 10 m) longitudinally at 235 m intervals. Tree density, diameter at breast height (DBH) ≥ 1.3 m, tree height and tree density were measured in each plot. The study established that one of the sites was capable of supporting a larger number of trees (in terms of density) whose growth (in terms of DBH and height) is constrained while the other site supports low density of fast-growing acacia. The tree density, DBH, and height of acacia responded to variation in forest landscape heterogeneity. DBH of the invasive species was significantly ($P < 0.05$) affected by altitude (-ve), slope (+ve), and aspect (+ve). The current study demonstrates that altitude, slope, and aspect significantly influenced the growth of *A. melanoxylon* in the studied forest. To gain insight on how these environmental gradients affect growth of the invasive species without compounding factors, future studies should be conducted under controlled conditions.

Keywords

Acacia melanoxylon, Invasive Species, Landscape Heterogeneity, Nabkoi and Timboroa Forest, Acacia Growth, Tropical Forests

1. Introduction

Acacia (Family Fabaceae) species have wide distribution globally, including in Africa, Europe, Asia, and North and South America [1, 2]. Member of acacia currently rank as one of the most transported and introduced invasive species new environments in the last 50 years [6, 7]. This species has shown remarkable ability to colonize, grow and dominate in

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their new environment [8, 9]. The most problematic and widely discussed acacia species include *Acacia dealbata* Link, *Acacia longifolia* (Andrews) Willd., *Acacia mearnsii* De Wild., *Acacia saligna* (Labill) H. L. Wendl. *Acacia cyclops* few detailed studies touching on *Acacia melanoxylon* R. Br. [3, 4]. *Acacia melanoxylon* is capable of colonizing all environments and has been reported in all the continents in countries such as Spain [14], Australia [14-16], South Africa [17, 18], New Zealand [19], Argentina [20], China [21]. There is limited knowledge on their establishment in tropical, equatorial ecosystem.

A fundamental principle in understanding invasive woody species is the knowledge of their response to environmental heterogeneity. The ability of native species to survive in their environments compared to the native plants have led to their better survival, proliferation and eventual dominance over native species [5]. Landscape factors have remained a major determinant of the colonization, survival, germination, growth and distribution of invasive acacia [10, 11]. There is still large data gap on the how variations in environmental factors drive growth of invasive species. The heterogeneous aspects of landscape that may affect growth of plants include altitude, slope, aspect, and elevation [12, 13]. Nevertheless, very little information is available on the influence of physiognomic factors on the growth response of several acacias.

In Kenya within the Uasin Gishu County, there are seven numerous forest blocks that cover an area of 29,801.92 ha where 56% are indigenous and 44% exotic plantations. The Nabkoi Forest and Timboroa Forest. In these two forests, there are two industrial forest plantations, comprising *Cupressus lusitanica* and *Pinus patula*, which is invaded by *A. melanoxylon*, which appears to be spreading in the area including within cypress and pine plantations.

The area experience a tropical climate based on Köppen-Geiger classification. The forests are located at an altitude 2600-2950 metres Above Sea Level (ASL). Rainfall in the region range from 1,328.9 to 1,405.4 mm, where the long rainy season occur between March and May, short rainy season between August and October the rest being dry months. The temperature in the study area range from an average minimum of 7 ℃ (June –August) to a maximum of 29 ℃. The forests have fertile soils which favour high tree growth. Specifically, the selected study sites, Nabkoi Forest (2634 m asl) and Timboroa Forest (2913 m ASL) are both considered high altitude sites relative to the rest of the County with a difference of close 280 metres - a rather sharp rise considering the distance between them.

This study determined the influence of landscape heterogeneity on growth of Australian Blackwood (*Acacia melanoxylon*) in tow tropical highland humid forests (Nabkoi Forest and Timboroa Forest) in Kenya. It is hypothesized that variation in landscape parameter such as altitude, slope and aspect influence growth patterns of *A. melanoxylon* in named forests in Kenya.

2. Materials and Methods

2.1. Study Area

The study was conducted in Kenya at two forests (Nabkoi and Timboroa Forets) within the larger the North Tinderet forest block in Uasin Gishu County (Figure 1). The Nabkoi forest and Timboroa Forest are located between longitudes 34°50’ E and 35°37’ E and latitudes 0°03’ S and 0°55’ N. The area experience a tropical climate based on Köppen-Geiger classification. The forests are located at an altitude 2600-2950 metres above sea level. Rainfall in the region range from 1,328.9 to 1,405.4 mm, where the long rainy season occur between March and May, short rainy season between August and October the rest being dry months. The temperature in the study area range from an average minimum of 7 ℃ (June – August) to a maximum of 29 ℃. The forests have fertile soils which favour high tree growth. Specifically, the selected study sites, Nabkoi Forest (2634 m asl) and Timboroa Forest (2913 m ASL) are both considered high altitude sites relative to the rest of the County with a difference of close 280 metres - a rather sharp rise considering the distance between them.

The geological formation in the study area is mainly basalt rock boulders dating back to the pre-Cambrian formations. Soils at the plateau are Ferralsols which appear as deep red while at the lower altitude the soils mainly gleysols which is poorly drained. The red loam topsoil is rich in organic matter.

2.2. Selection of Sampling Sites

The field study covered both the dry and rainy season and was conducted from January 2022 to February 2023. A reconnaissance survey in the months of November to December 2021 was done to evaluate the conditions of the study sites before sampling. The sampling sites were selected longitudinally from south to northwards based on invasion status by *A. melanoxylon*. Nabkoi (2634 m asl): and Timboroa (2913 m asl) were chosen to represent the species of interest because of their difference in altitude, slope and aspects. The invaded sites by *A. melanoxylon* within the *Cupressus lusitanica* and *Pinus patula* plantations as well as the uninvaded sites were sampled. For each species a stand not invaded by *A. melanoxylon* was compared with an adjacent stand of the same species invaded by *A. melanoxylon*.

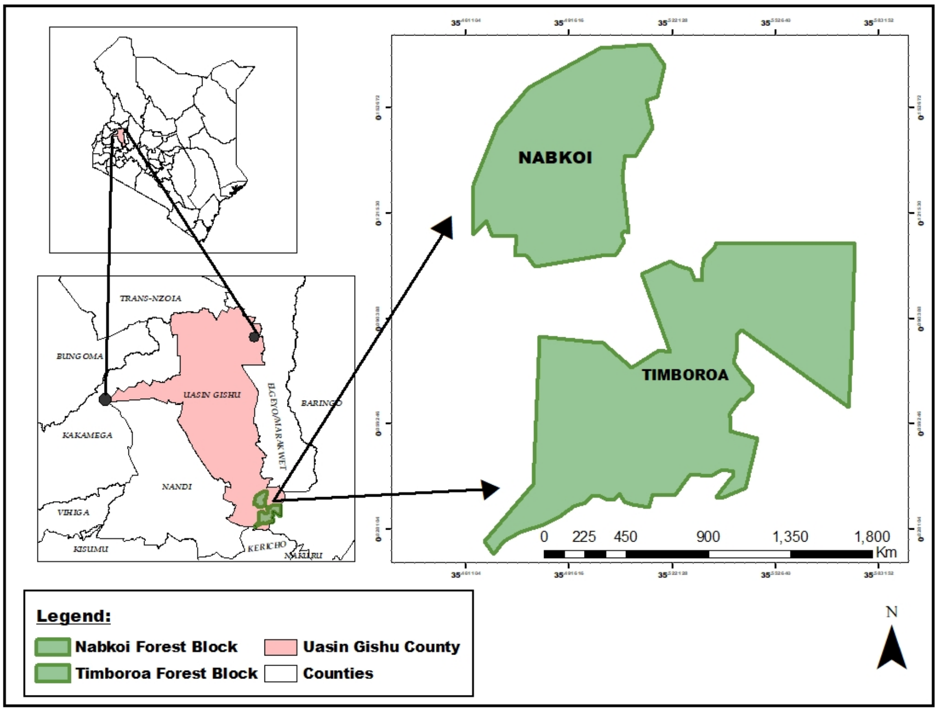

Figure 1. *Uasin Gishu County in Kenya shwing the location of Nabkoi and Timboroa Forests.*

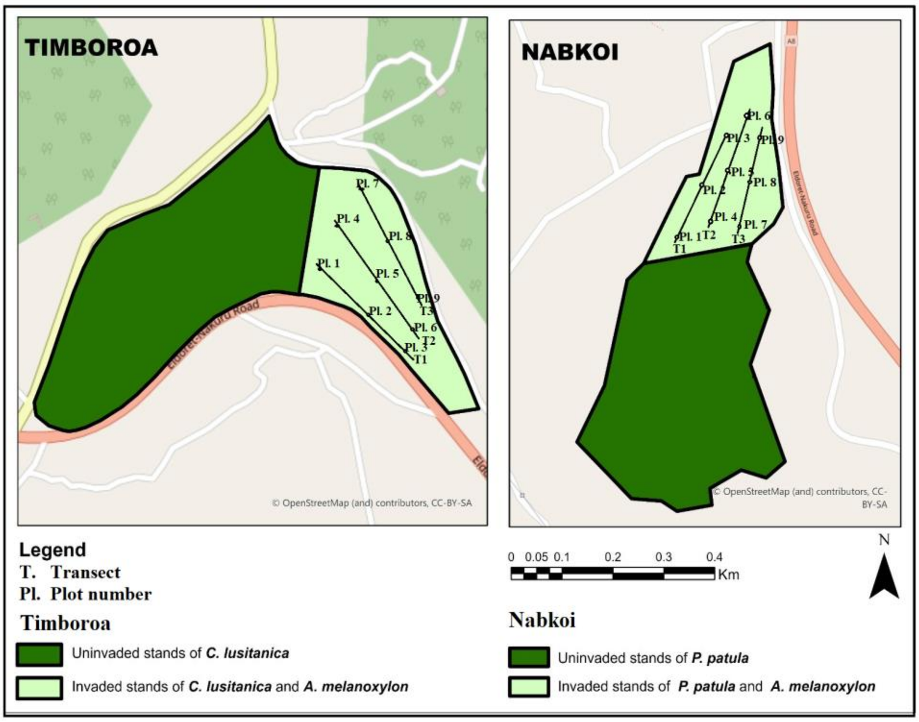

Figure 2. *Typical laying-out of line transects in adjacent stands for Acacia melanoxylon in Nabkoi and Timboroa.*

2.3. Field Measurements

Field measurement were conducted using line transects method where, a 500 m long transect was laid longitudinally, the three 10 by 10 m plots laid at 235 m intervals (Figure 2). From each 9-sample plots were assessed for tree data.

At each site and in each plot, tree density, diameter at breast height (DBH) ≥ 1.3 m, tree height and tree density were measured. The DBH was measured using a diameter tape. Suunto Clinometer was used to measure the height of trees. The scale on the instruments was 1:15 or 1:20.

2.4. Data Analysis

Data collected was organized and managed using a Microsoft Excel spreadsheet which was then converted to STATISTICA 8.0 [22] and SPSS 23.0 Statistical Packages [23] for final analysis. Tree density, dbh and height were presented as means ± Std. Dev. Mean differences in tree dbh and height were analyzed using One Way ANOVA followed by post-hoc's Duncan's Multiple Range Test (DMRT). Differences in tree density was analyzed a non-parametric Kruskal Wallis ANOVA test. Multiple linear regression was used to test the relationships between altitude, slope and aspect with respect to density, DBH and height.

3. Results

3.1. Tree Density, Diameter at Breast Height and Height

The *Acacia melanoxylon* plot density, DBH and height at the two sampling sites are shown in Figure 3. The plot density distribution of *A. melanoxylon* at the Nabkoi sites (700 to 900 trees per ha) was significantly lower ($H_{(3, 154)}$ = 34.3242, P < 0.0001) than in Timboroa forest sites (1600 to 2200 trees per ha). The mean dbh of *A. melanoxylon* in Nabkoi (9.7.5 ± 5.2 cm) was significantly (One-Way ANOVA: $F_{(1, 126)}$ = 35.1247, df = 3, P < 0.0001) lower than in Timboroa site (32.5 ± 7.6 cm). The mean height of the invasive species was higher (One-Way ANOVA: $F_{(1, 126)}$ = 9.1232, df = 3, P = 0.0006) at Timboroa site (46.4 ± 8.7 cm) compared to Nabkoi (25.6.5 ± 4.2 cm).

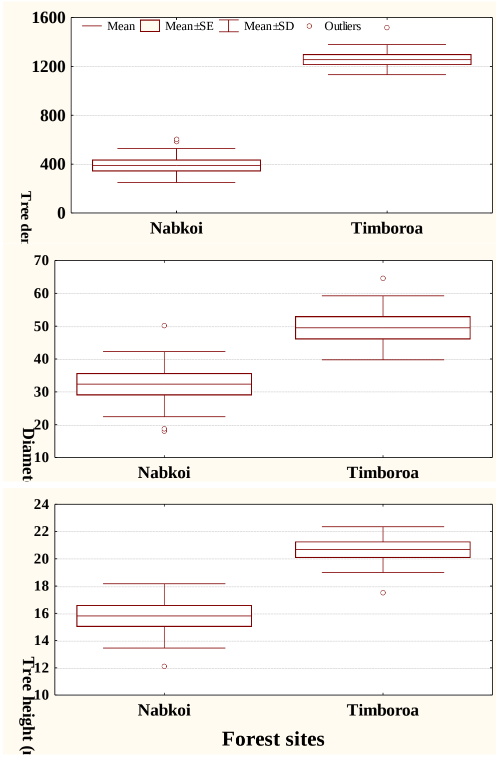

Figure 3. *Acacia melanoxylon density, DBH and height in Nabkoi and Timboroa Forest sites.*

3.2. Landscape Parameters

The landscape parameters for *A. melanoxylon* growth at the two sampling sites are shown in Table 1. Altitudes in Nabkoi forest block was significantly (P < 0.05) lower than that recorded in Timboroa. Slope in Nabkoi Forest stand was lower than that of Timboroa Forest. Meanwhile, lower aspect occurred Nabkoi than Timboroa.

Table 1. *Summarized measures of altitude, slope and aspect for A. melanoxylon at the sampling sites.*

Landscape parameters	Sampling sites		ANOVA	
	Nabkoi	Timboroa	*F*	*P*
Altitude	2572.8 ± 14.1^{a}	2719.6 ± 6.5^{b}	2445.791	<0.0001
Slope	7.8 ± 1.6^{b}	12.1 ± 2.2^{d}	8.902	0.0002
Aspect	81.8 ± 23.4^{a}	288.9 ± 23.4^{d}	69.937	<0.0001

3.3. Relationship Between Density Against Slope and Aspect

The density of A. melanoxylon in relation to slope and aspect is shown in Figure 4, and regression analysis depicting the relationship between variables for the two study sites is provided in Table 2. The A. melanoxylon density in Nabkoi showed positive significant linear relationship with slope. The *A. melanoxylon* density showed negative significant linear relationships with slope in Timboroa. Meanwhile there was a second-order positive quadratic relationship between A.

melanoxylon density and aspect in Nabkoi, showing more trees occurring at moderate slopes. The negative relationship between *A. melanoxylon* density and aspect was not significant ($P < 0.05$) Timboroa.

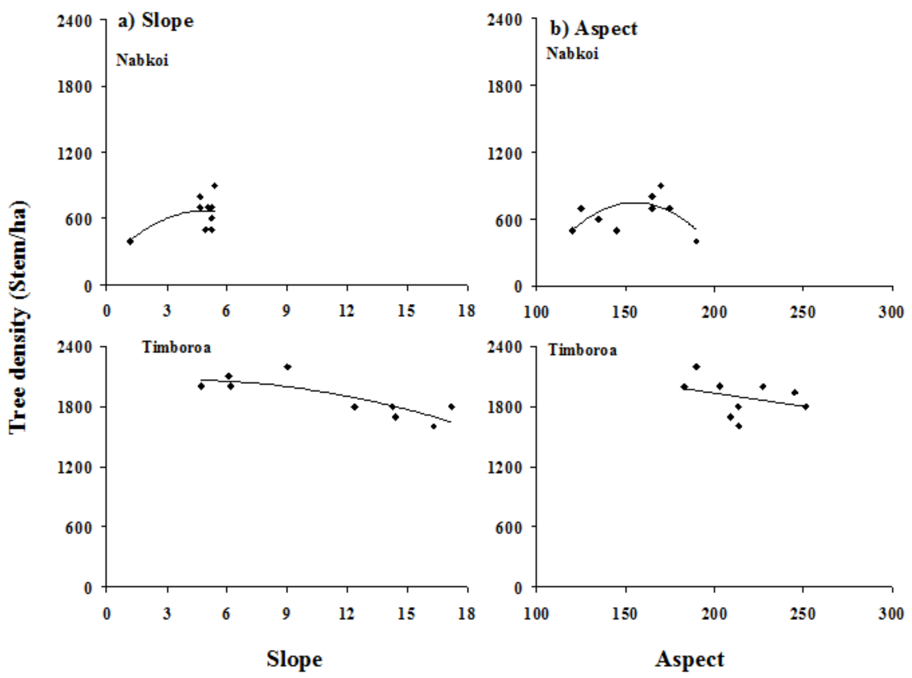

Figure 4. *Tree density of A. melanoxylon at different slopes and aspects at low altitude (Nabkoi site) and high altitude (Timboroa site).*

Table 2. *Regression outputs showing the relationship between tree density/ha with slope and aspect at Nabkoi and Timboroa sites.*

Landscape parameters	Regression Statistics	Nabkoi	Timboroa
Slope	R^2	0.3176	0.6508
	Coefficient	67.442x+332.71	-33.243x+2260.2
	Standard Error	4.2984	9.268
	ANOVA		
	F	46.3453	33.0811
	P-value	<0.0001	<0.0001
Aspect	R^2	0.355	0.1078
	Coefficient	$-0.2001x^2 + 62.074x – 40.653$	-2.609x+2454.23
	Standard Error	0.4086	0.4392
	ANOVA		
	F	1.7527	1.1942
	P-value	<0.0001	0.1234

3.4. Relationship Between Tree Diameter with Slope and Aspect

The *A. melanoxylon* diameter relationships with slope and aspect are shown in Figure 5. The corresponding regression trends on the relationships between tree diameter with slope and aspect are shown in Table 3. Tree diameter of *A. melanoxylon* showed significant binomial relationships with slope in Nabkoi but significant linear relationship with slope in Timboroa. The relationship between DBH and aspect in Timboroa was weak and non significant.

Table 3. Regression outputs showing the relationship between tree diameter at breast height with slope and aspect in Nabkoi and Timboroa sites.

Landscape parameters	Regression Statistics	Sampling sites	
		Nabkoi	Timboroa
Slope	R^2	0.8779	0.6508
	Coefficient	$-0.798x^2 + 3.4559x + 21.729$	$-0.051x^2 + 1.4678x – 80.715$
	Standard Error	1.9557	3.3619
	ANOVA		
	F	18.1613	6.0209
	P-value	0.0037	0.043
Aspect	R^2	0.4624	0.2555
	Coefficient	$-0.1616x + 46.154$	$0.0569x + 50.738$
	Standard Error	3.9349	2.5816
	ANOVA		
	F	2.7238	2.4024
	P-value	0.044	0.1651

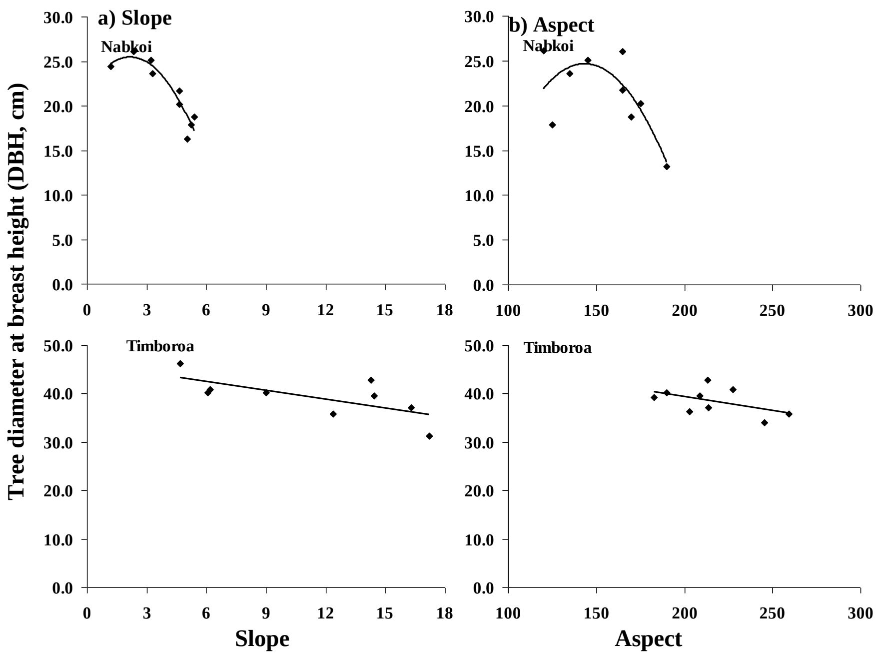

Figure 5. Tree DBH of A. melanoxylon relative to slopes and aspects in low altitude (Nabkoi site) and high altitude (Timboroa site).

3.5. Tree Height-slope and Aspect Relationships

Tree height in relation to slope and aspect in the study sites (Figure 6) and corresponding regression statistics (Table 4) portray weak but positive trends between tree height and slope. The height of *A. melanoxylon* showed positive significant linear relationships relative to the slope for all the sites.

Table 4. *Regression outputs showing the relationship between tree height with slope and aspect in Nabkoi and Timboroa sites.*

Landscape parameters	Regression Statistics	Nabkoi	Timboroa
Slope	R^2	0.4704	0.4142
	Coefficient	$-0.2231x^2 + 64.342x + 17.739$	$-0.4052x + 24.716$
	Standard Error	1.5846	2.454
	ANOVA		
	F	5.3358	4.988
	P-value	0.048	0.0461
Aspect	R^2	0.6177	0.4171
	Coefficient	$-0.0017x^2 + 0.4368x – 11.253$	$0.051x + 9.4035$
	Standard Error	1.7598	1.4894
	ANOVA		
	F	7.3525	5.0085
	P-value	0.0299	0.0452

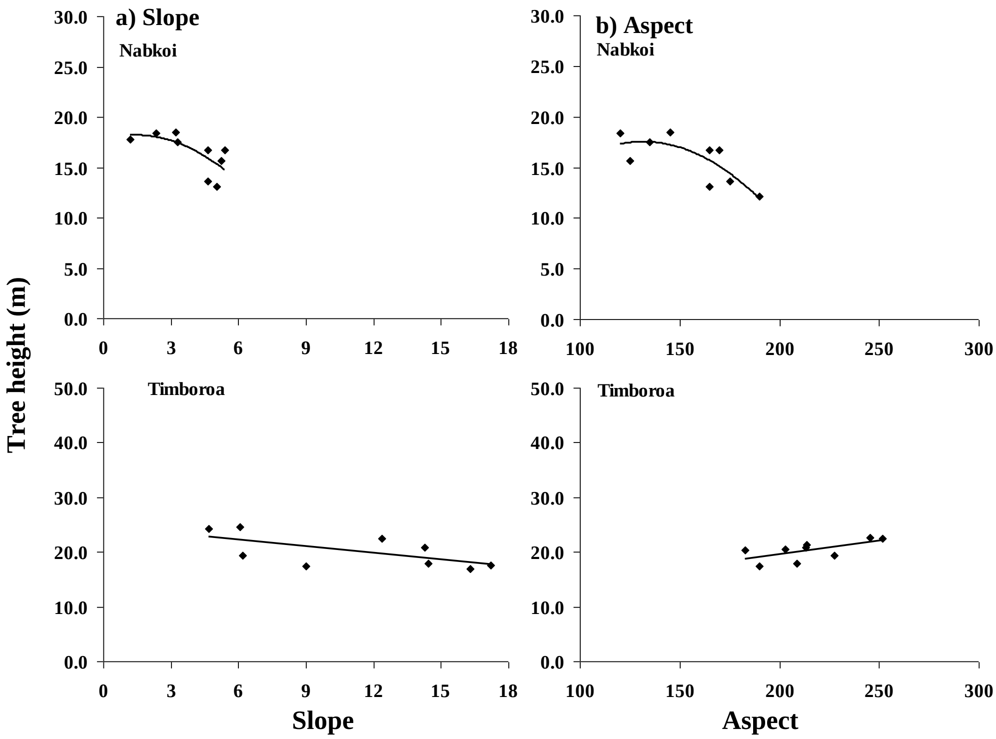

Figure 6. *Tree diameter at breast height of A. melanoxylon relative to slopes and aspects in low altitude (Nabkoi site) and high altitude (Timboroa site).*

4. Discussion

In Nabkoi and Timboroa Forests, there is successful establishment and colonization by invasive *A. melanoxylon*. However, there has been little attempt aimed at determining how landscape heterogeneity affect the growth of the invasive species within the plantation establishment. Therefore, in this study, the growth of invasive *A. melanoxylon* and environmental factors possibly influencing its establishment and growth were investigated.

During the study, the plot density distribution of *A. melanoxylon* at the Nabkoi was lower (approximately 400 to 500 stems per ha) compared to Timboroa forest sites, where the density ranged between 1100 to 1600 trees per/ha. This suggests that there was a higher density of *Acacia melanoxylon* in Timboroa compared to the Nabkoi forest block. The present finding demonstrates that the Timboroa forest site can support a larger density of tree species which may be attributed to the location having better resources [24] that sustain the growth of the tree species, which compares well with several studies [25-27]. It is also possible that *A. melanoxylon* was a better colonizer at the Timboroa forest site.

There was a negative linear relationship between A. melanoxylon densities with slope, suggesting that A. melanoxylon density decreased with increasing slope. However, in the Timboroa forest site, the relationship was not linear but the density of A. melanoxylon was highest at moderate altitudes but low in both low and high altitude areas. The density of *A. melanoxylon* increased with aspect in Timboroa but aspect was not a factor controlling density distribution in Nabkoi site. This may suggest that the angle inclination of the sites was a significant factor controlling the colonization of the area by *A. melanoxylon*.

These results show a positive response to changes in the environmental landscape physiognomy [28, 29]. *Acacia* response to slope and aspect has been shown in several habitats [12, 30, 31]. In the tropics, higher altitudes, steep slopes, elevation, and aspect are harsh environment which may retard the growth of trees [32, 33]. The combinations of aspect and slope may also indirectly affect the growth of invasive plants through their effects on temperature, moisture, and radiation [34].

The distribution of *A. melanoxylon* at the Nabkoi aggregated toward size class 20-29.9cm while in the Timboroa forest site, most of the DBH aggregated towards 40-49.9cm. These findings suggest that tree DBH was higher in Timboroa than in Nabkoi. Higher DBH growth of *A. melanoxylon* at the Timboroa forest site could be due to reduced competition for nutrients and other resource between individual commercial tree and invasive acacia species, as dense understorey vegetation of shrubs, lianas and herbaceous species thus reducing the nutrients required for growth of Acacia. Similar findings have been reported elsewhere [35, 36]. There is also the aspect of better environmental attributes of Timboroa to sustain better growth of tree species. In the absence of previous studies in the region to compare the growth of *A. melanoxylon* in forest locations it would seem that the current explanations remain limited to environmental conditions and nutrients. The DBH of *A. melanoxylon* showed significant positive linear relationships with slope except at Nabkoi, while the aspect significantly influenced the diameter size distribution of *A. melanoxylon*. Indeed, the height of *A. melanoxylon* increased in tandem with the increase in aspect at all sites. In the tropics, moderate to slightly high slopes, and aspect may optimize environmental conditions for tree growth [32, 33].

The height of *A. melanoxylon* showed differences at the forest site where higher heights were recorded in Timboroa compared to Nakoi. Nevertheless, there were intra-site differences in the height of *A. melanoxylon* where the height of *A. melanoxyon* was higher at the Timboroa invaded forest site compared to the Timboroa uninvaded site. The height class distribution of *A. melanoxylon* also showed that the majority of *A. melanoxylon* in Timboroa ranged between 40-49 cm while at Nabkoi the ranges were 20-29 cm. The present results on canopy height are similar to DBH *A. melanoxylon* where Timboroa forest sites have better growth in terms of height. This may be attributed to the area having a higher concentration of nutrients such as nitrogen, phosphorus and organic carbon that drive the growth of plants. The nutrients can improve the growth of the invasive species as found in other habitats [37, 38]. The higher height of *A. melanoxylon* at the Timboroa forest site may also be due to better environmental attributes of Timboroa to sustain better growth of tree species [39, 40] or better physiognomic characteristics of the landscapes [11, 41]. The canopy height of *A. melanoxylon* increased relative to the increasing slope for all the sites. The growth in height of *A. melanoxylon* was positively influenced by increased slope and aspect to some optimal levels beyond which growth inhibition was observed. This suggests positive growth responses at median values of these physiognomic parameters, which clearly shows the effects of this environmental landscape physiognomy on plant growth [42, 43]. In the tropics, moderate altitude, slope, elevation, aspect and h temperature often present optimal environmental conditions for plant growth [32, 33].

5. Conclusions

The study established that one of the sites was capable of supporting a larger number of trees (in terms of density) whose growth (in terms of DBH and height) is constrained while the other site supports low density of fast-growing acacia. Tree density, DBH, and height *A. melanoxylon* displayed differences relative to landscape. Whereas slope and aspect were positively correlated with DBH, the altitude was negatively correlated with DBH of A. melanoxylon. The current study demonstrates that altitude, slope, and aspect positively influence the growth of *A. melanoxylon*.

The current study demonstrates the landscape factors affecting the growth of *A. melanoxylon*. Future control of growth of *A. melanoxylon* may be attempted by manipulating the landscape variables. To gain insight on how these environmental gradients affect growth of the invasive species without compounding factors, future studies should be conducted under controlled conditions.

Abbreviations

ANOVA	Analysis of Variance
ASL	Above Sea Level
DBH	Diameter at Breast Height

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Author Contributions

Thomas Kiprotich Kiptoo: Conceptualization, Methodology, Resources, Writing—original draft preparation, Funding acquisition

James Legilisho Kiyiapi: Conceptualization, Resources, Writing—original draft preparation, Supervision, Funding acquisition

Francis Kiptarus Sang: Writing—review and editing, Supervision

Elijah Oyoo-Okoth: Formal analysis, Data curation

Data Availability Statement

The data is available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

Thomas Kiprotich Kiptoo has PhD in Forestry from the University of Eldoret, He holds a bachelor's degree in Forestry and a Master of Science degree in Tropical Forest Management, from Moi University in Kenya and Technische Universität Dresden in Germany, respectively. He currently, works for the Government of Kenya as a Principal Conservator of Forests at Kenya Forest Service (KFS). He has demonstrated a gesture of hard work and an illustrious career through the accumulation of several awards for exemplary work performance (2014, 2017, and 2023) in his entire life of service delivery to Kenyans in forestry. Additionally, he has also worked for the Food and Agricultural Organization (FAO) as a Field Coordinator for the Sustainable Development Project in the Mau Forest Complex, a project that won an Eduardo Sauma International Award. He has participated in various Scientific Conferences and workshops and has published several articles in refereed journals.

James Legilisho Kiyiapi is a Professor of Forestry and Ecosystem Science at University of Eldoret, Department of Forestry and Wood Science. He hold a PhD in Forestry from the University of Toronto. He obtained his Bachelor of Science Degree in Forestry (First Class Honors) from Moi University. He started career progression as a lecturer at Moi University and was instrumental in curriculum reforms as Head, Department of Forestry and Wood Science, reorienting forestry training and education to be responsive to the market needs. Was among prominent scholars who shaped environmental/conservation agenda post Rio Summit in Kenya. Demonstrated acumen in academic leadership, student supervision, and authored numerous peer review publications and technical reports. Worked with various international and regional organizations on diverse issues of biodiversity conservation and policy aspects. Current research areas include forest ecosystem science, growth and biomass estimation, carbon sequestration and landscape restoration, climate change adaptation and resilience systems.

Francis Kiptarus Sang is a Professor of Forestry at University of Eldoret, Department of Forestry and Wood Science. He obtained his PhD in Forest Pathology at Aberdeen University. Holds a Bachelor of Science Degree in Forestry from Moi University. Started his career ForestDepartment before moving to be a lecturer at Moi University where he moved through ranks to become a professor. He has was among prominent scholars who shaped forestry agenda in Kenya and East Africa spanning a period of over 50 years. He has demonstrated academic leadership, student supervision, and authored numerous peer review publications and technical reports. Worked with various international and regional organizations on diverse issues of forest biodiversity conservation leading to policy development.

Elijah Oyoo-Okoth is has a PhD from the University of Amsterdam (Aquatic Ecology and Ecotoxicology). He obtained his masters of philosophy degree and Bachelor degree in Fisheries and Aquatic Sciences (First Class Honours). He currently work in several project. He has participated and earned several donor funded projects. He currently lecturers at the department of Environmental Biology at the University of Eldoret. He has published 56 papers in refereed journals, attended several conferences and is currently adhoc reviewer in several journals. He is supervised several Mphil and PhD students at the university and currently undertaking research in various projects in Kenya.

Research Field

Thomas Kiprotich Kiptoo: Forest Silviculture, Forest Inventory, Forest Extension, Forest Mensuration, Forest Entomology, Forest Pathology, Climate Change**.** Forest Ecology, Invasive Biology

James Legilisho Kiyiapi: Forest silviculture, Forest inventory, Forest Mensuration, Climate Change**.** Forest Ecosystem management, Forest Policy, Forest Ecology

Francis Kiptarus Sang: Forest Pathology, Forest Entomology, Climate Change**.** Forest Ecosystem management, Forest Biology, Forest Ecology

Elijah Oyoo-Okoth: Forest Hydrology, Forest Genetics, Biostatistics, Biotechnology, Ecology, Invasive Biology, Watershed Management