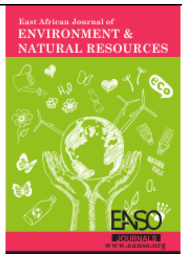

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Original Article

The Status and Extent of Eucalyptus grandis Invasion in Kindoroko Forest Reserve, Mwanga District, Tanzania

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Catchment Forests, Eastern Arc Mountains, Human Disturbances, Invasive Species, Montane Ecosystems.

ABSTRACT

Early detection and the ability to remove new populations of species showing signs of becoming invasive have been acknowledged as the most cost-effective and effective ways of managing invasive alien species globally. This study assessed the status and extent of *Eucalyptus grandis* invasion in the Kindoroko Forest Reserve (KFR), located in Mwanga District, Kilimanjaro Region, Tanzania. Specifically, the study aimed to assess (i) the population status and abundance of *E. grandis* in relation to other woody species in KFR, (ii) the spatial distribution of *E. grandis* in KFR, and (iii) factors influencing the abundance of *E. grandis* in KFR. Vegetation data were collected from 60 concentric sample plots of a 15m radius established along 17 cardinal transect lines across the forest area of 885 ha. The study revealed that *E. grandis* is most abundant near the forest boundary within 50m in comparison with other native species, contributing 44% of the total species counts and accounting for 23% of the overall species counts across the entire forest area. Its abundance and spread are strongly linked to the presence of favourable environmental factors and human disturbances. Canopy cover exhibited a strong negative effect ($p<0.001$), indicating that invasion decreases with high canopy cover, while slope showed a significant positive relationship ($p = 0.044$), suggesting that steeper terrains facilitate *E. grandis* growth. Medium disturbances negatively affected abundance (0.001), meaning decreases in the rate of invasion, whereas high disturbances had a significant positive effect (0.031), meaning invasion increases with increasing disturbances. It is concluded that *E. grandis* is showing all signs of becoming a problematic species in KFR. Thus, forest management efforts should focus on removing the identified population and reducing disturbances currently occurring in the forest reserve to contribute to mitigating the spread of *E. grandis* in the KFR.

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INTRODUCTION

Biological invasion by alien species has been recognized as one of the significant threats to global biodiversity (Brandt *et al*., 2021; Dawson *et al*., 2017; Early *et al*., 2016; Kleunen *et al*., 2019; Wani *et al*., 2022). According to Early *et al*., (2016), about 16% of global biodiversity hotspots are highly vulnerable to invasive alien species (IAS). Trees and shrubs make up almost 0.5 to 0.7% of the world's invasive species outside their natural range (Richardson & Rejmanek, 2011). Already, 622 invasive alien woody species have been identified worldwide, including 357 trees and 265 shrubs (Richardson & Rejmanek, 2011).

Invasion of woody invasive alien species varies greatly worldwide, with some areas being more burdened by these ecological dangers. Australia leads in having 183 invasive woody species, followed by southern Africa with 170, while North America has 163, the Pacific Islands have 147, and New Zealand is up against 107 (Richardson & Rejmanek, 2011). Owing to the scale and extent of invasive alien plants' spread and their impact on biodiversity and ecosystem functioning, new biotic inventories on alien and/or naturalized floras have been conducted in many regions of the world (Wani *et al*., 2022). These include countries and/or regions supporting the global biodiversity hotspots such as Bhutan, China, India, and Nepal (Wani *et al*., 2022) and Africa (Richardson *et al*., 2022). According to Richardson *et al*. (2022), the assessments have indicated that about 10,616 non-native plants have been introduced to Africa, out of which 90% became naturalized and 10% invasive.

In Tanzania, the current data indicate that there are 75 invasive species (26 being trees and shrubs) and 145 potentially invasive species (57 being trees and shrubs), making a total of 220 species in the country (83 being trees and shrubs), which may result to the increased threat on the country's natural ecosystems (URT, 2019). According to URT (2019), the natural vegetation in wildlife-reserved areas such as National Parks and Ngorongoro Conservation Area is being replaced by invasive species, disrupting the resilience of wildlife habitats and affecting animal distribution and abundance, ultimately affecting tourism.

In some reserved forests, such as Kimboza Forest Reserve in the Morogoro region, invasive species are replacing native species, affecting natural biodiversity and flows of ecosystem services (URT, 2019; Kilawe *et al*., 2022). Since at the naturalization phase of the invasion process of exotic invasive plants it is relatively difficult and expensive to devise and implement strategies to manage such a widespread problem species (URT, 2019), early detection, therefore, the ability to remove the new population once detected is of vital importance (Edward, 2007). An important step in prevention is the identification of the species

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capable of becoming invasive, the possible susceptible sites, and, more importantly, the pathways in which they can be introduced (Edward, 2007; URT, 2019).

Kindoroko Forest Reserve (KFR), which was established to preserve water catchment and native biodiversity, is one among the remaining five central government forest reserves found in the North Pare Mountains block, which lie at the northernmost end of the Eastern Arc Mountains in Kilimanjaro region, Tanzania (Doggart *et al*., 2008; Lovett & Pocs, 1993). According to Doggart *et al*. (2008), KFR is ranked second for having a high number of fauna and invertebrate species diversity in the North Pare mountains block. Regardless of this ecological importance, KFR is currently threatened by the spread of *Eucalyptus grandis*, which was initially planted in the late 1960s to delineate the boundaries of the forest reserve (TFS, 2022). This species has multiplied and started to spread inside the forest reserve, posing a serious threat of replacing the native tree species (TFS, 2022). For proper control and management of this species, the determination of the extent to which the species has invaded the natural forest is important. It is hypothezized that human disturbances such as wildfires, illegal logging, and grazing have contributed to the dominance and spread of *E. grandis* in the KFR (TFS, 2022). While several studies have been conducted in KFR, including assessment of vertebrates (Doggart *et al*., 2008), the status and extent of *E. grandis* invasion remain largely undocumented. This study aimed to fill that gap by investigating the distribution of *E. grandis* within KFR and evaluating its potential implications for native forest structure and composition. Understanding the extent of invasion and contributing factors is essential for developing effective control measures and conservation strategies to protect the forest ecosystem. In line with this, the general objective of this study was to assess the status and extent to which *E. grandis* has spread inside the Kindoroko Forest Reserve (KFR) from its original planted location. Specifically, the study aimed to assess: (i) the population status and abundance of *E. grandis* in relation to other native woody species in KFR, (ii) the spatial distribution of *E.grandis* in relation to other native woody species in KFR and (iii) factors influencing the abundance of *E. grandis* in KFR.

MATERIALS AND METHODS

Study Area Description

Kindoroko Forest Reserve (KFR), with a total area of 885 ha, forms part of the Northern Pare Mountains, Mwanga district, Kilimanjaro Region, Tanzania (Figure 1). It lies between latitudes 3°43′S and 3°46′S, and longitudes 37°00′E and 38°00′E at an altitude of 1600 - 2113m.a.s.l (Lovett and Pocs, 1993). KFR was gazetted as a protected area on September 29th, 1961, under variation order GN No. 341 (Lovett and Pocs, 1993). The area receives an estimated annual rainfall of 1400 mm, with a mist effect at higher altitudes (Lovett & Pocs, 1993). The maximum temperature reaches 22°C in March, with a minimum of 17°C in July (Lovett & Pocs, 1993). The main vegetation type is montane forest, dominated by key species such as *Newtonia buchananii* and *Albizia gummifera* (Lovett & Pocs, 1993). The reserve is an important catchment area, supplying water to the dry slopes and basins surrounding it. About 20 villages in the Usangi area receive water from the forest reserve, including Kisangara town on the main road and the neighbouring coffee and sisal plantations. Water is piped straight from the forest to the villages (Lovett & Pocs, 1993). The reserve is managed by the Tanzania Forest Service (TFS) Agency, and eight villages border the reserve (TFS, 2022).

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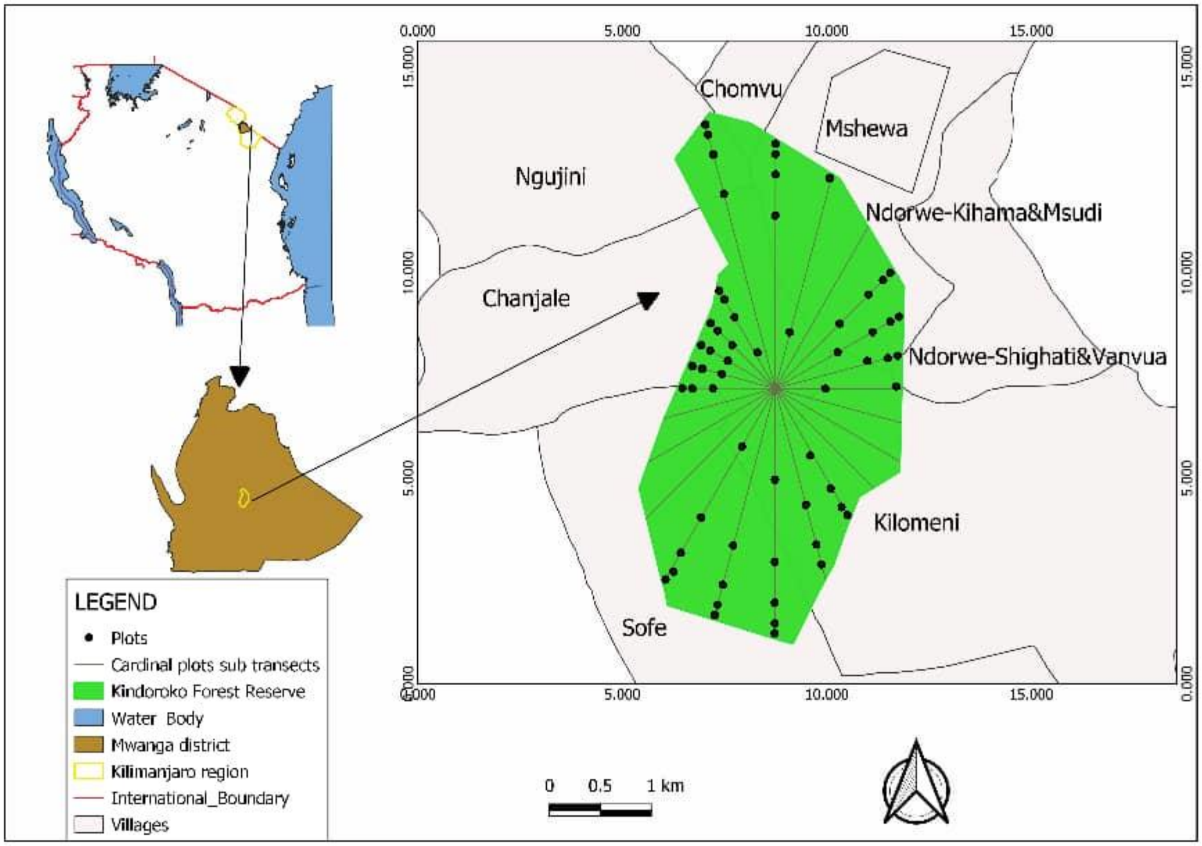
Figure 1: A Map of Tanzania Showing the Location of Kindoroko Forest Reserve in Mwanga District and the Layout of Sample Plots



Data Collection

A field survey was conducted from December 2023 to January 2024. A total of 60 concentric sample plots were systematically established along 17 cardinal transect lines, spaced 15° apart, radiating from the forest boundary to its centre (Popradit *et al*., 2015). The plot interval began at 50m from the forest boundary and doubled progressively towards the forest centre, with 3 to 5 plots per transect depending on transect length and accessibility. Within a 2m radius, all seedlings (DBH<1cm) were counted and recorded; within a 5m radius all saplings (DBH 1-4.9cm) were identified and measured for diameter: within a 10m radius all sub-adults (DBH 5-19.9cm) were identified and measured for diameter and within 15m radius, all adults (DBH ≥ 20) were identified and measured for diameter (Mwaluseke *et al*., 2023). Other variables recorded in the plot were plot coordinates, canopy cover, slope, elevation, and disturbance levels. Plot coordinates and elevation (m) were recorded using a GPS device, tree diameters were measured using a caliper, slope was measured using a clinometer, and the canopy cover was assessed using a densitometer. The average percentage canopy cover for each plot was determined by averaging the number of foliage-filled grid squares recorded from the four cardinal directions and the plot's centre, then multiplying by 100 (Paletto & Tosi, 2009).

Using the entire plot area of 0.071ha, forest disturbances were assessed through direct observation based on their intensity levels: High disturbance, medium disturbance, and no disturbance (Buma & Wessman, 2011). High-intensity disturbances were registered when the assessment of the impact covered >50% of the plot area, typically caused by severe events like large-scale fires or extensive logging and grazing, which led to major vegetation loss and major habitat disruption. Medium-intensity disturbances were

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registered when the assessment of the impact affected >0 but ≤50% of the plot area, involving partial logging and moderate fires, which reduced the canopy but left some vegetation intact. Areas with no disturbances (0%) were those which maintained their original vegetation structure, and there were no signs of disturbances.

Data Analysis

The collected data were analysed for species richness and abundance (total counts) to discern if *E. grandis* is showing signs of dominance both close (≤350m) and away (>350m) from the forest boundary. Species richness was determined as the total number of species found across all 60 sampled plots (including all size categories: seedlings, saplings, sub-adults, and adults). Species abundance was computed as the sum of the counts for a particular species across all 60 sampled plots. Relative abundance (%) was computed as the proportion of counts of species against the total counts of all species multiplied by 100. Data were summarized in tables and figures to illustrate the dominance of *E. grandis* in relation to other native woody species in KFR.

For the spatial distribution analysis, total counts of *E. grandis* and counts of individual life stages (seedlings, saplings, sub-adults, and adults) were plotted against distance from the forest boundary using plot coordinates to discern existing patterns in the KFR. The bubble graph function in the R package and Excel spreadsheet were used to visualize variation in abundance and distribution of *E. grandis* in the study area. The bubble graphs provided insights into how different life stages were positioned across the study area, highlighting clustering patterns and density variations at multiple distances.

For the assessment of factors that influence the abundance and spread of *E. grandis* in the study area, total counts of *E. grandis* and counts of respective life stages (seedlings, saplings, sub-adults, and adults) were modelled against multiple environmental variables (i.e. elevation, slope, canopy cover), the distance of the plot from the forest boundary and disturbance levels categorized as low/no, medium, or high using a Poisson Generalized Linear Model (GLM). However, the residual deviance was significantly higher than the degrees of freedom, indicating over dispersion – a common issue where the variance of the response variable exceeds its mean. A Negative Binomial GLM was employed to address this as it extends the Poisson model by introducing a dispersion parameter, allowing for better handling of over-dispersed count data (Rahman & Govindarajulu, 1997).

The Negative Binomial GLM was fitted using the following predictors:

Distance: The distance of the plot from the forest boundary (m).

Elevation: The altitude of the sampling plot (m).

Slope: The steepness of the terrain (%).

Canopy cover: The percentage of the forest canopy present (%).

Disturbance level: Categorized as low/no, medium, or high (%).

Tree life stage: Adult, sub-adult, sapling, or seedling (total counts).

The model was structured as follows:

$$\text{Log}\ (Counts)=\beta_0+\beta_1(Distance)+\beta_2(Elevation)+\beta_3(Slope)+\beta_4(Canopycover)+\beta_5(Disturbance)+\beta_6\ (life\ stage)$$

Where the response variable Counts follows a Negative Binomial distribution. The significance of the predictors was determined using p-values, providing a robust assessment of their effects (Bolker *et al*., 2008). All analyses were conducted in R package version 4.4.2.

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RESULTS AND DISCUSSION

Population Status and Abundance of *Eucalyptus grandis* in KFR

The results of species abundance with increasing distance from the forest boundary are shown in Figure 2. The abundance of all species tends to decrease as you move away from the forest boundary, with *E. grandis* contributing the most to the total abundance than any other species. At 0-50m distance, *E. grandis* accounted for 44% of the total counts, while other species contributed 56%. At 51-150m, *E. grandis* contributed 10%, and other species 90%, while at 151-350m, *E. grandis* made up 17% and other species 83%. At 351-750m, *E. grandis* contributed 10% and other species 90%, whereas, at 751-1550m, *E. grandis* contributed zero % while other species accounted for 100% of the counts. Overall, *E. grandis* contributed 23% (520 counts) to the total counts of 2,233 for all species (100%) than any other species, while other species accounted for 77% (1,713 counts) (Table 1).

Figure 2: The abundance of Eucalyptus grandis and other native woody species in relation to distance from the forest boundary in Kindoroko Forest Reserve, Tanzania

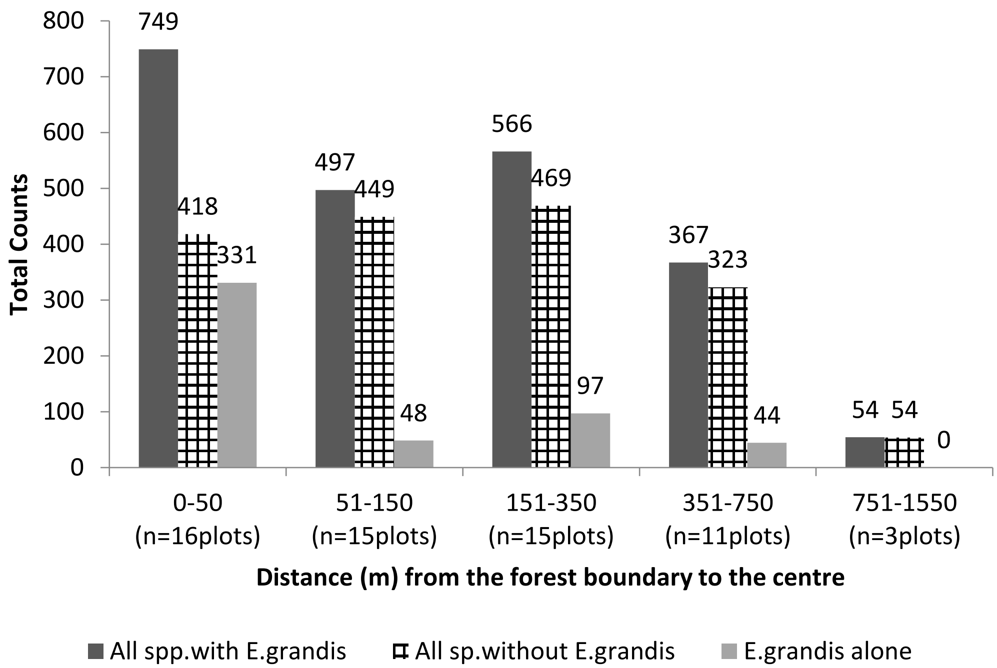

Table 1: The 10 most abundant woody species across all plots (n=60) including all size categories sorted by total counts in Kindoroko Forest Reserve, Mwanga District, Tanzania

S/No.	Name of species	Total counts (Abundance)	Relative abundance (%)
1	*Eucalyptus grandis*	520	23
2	*Newtonia buchananii*	260	12
3	*Xymalos monospora*	245	11
4	*Macaranga kilimandscharica*	204	9
5	*Maesa lanceolata*	118	5
6	*Tabernaemontana ventricosa*	104	5
7	*Piper capense*	91	4
8	*Ficalhoa laurifolia*	90	4
9	*Albizia gummifera*	73	3
10	*Celtis durandii*	52	2

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Similar trends for the *E. grandis* to be more dominant near the forest boundary compared to other woody species were observed when plots close to the forest boundary (≤350 m, 46 plots) were considered (Figure 3, Table 2). Close to the forest boundary (≤350 m), *E. grandis* contributed 26% to the total counts of 1,812 while other species contributed 74%. However, the trends were different when plots away from the forest boundary (>350 m, 14 plots) were considered (Table 3). There was a marked decrease in *E. grandis* abundance away from the forest boundary, although its presence shows the possibility of establishing itself away from the mother trees. Away from the forest boundary (>350 m) *E. grandis* contributed 10% (421 counts) to the total counts, while other species contributed 90% (Figure 3).

Figure 3: The distribution of Eucalyptus *grandis* Abundance and Other Native Woody Species in Relation to Distance from the Forest Boundary in Kindoroko Forest Reserve, Tanzania

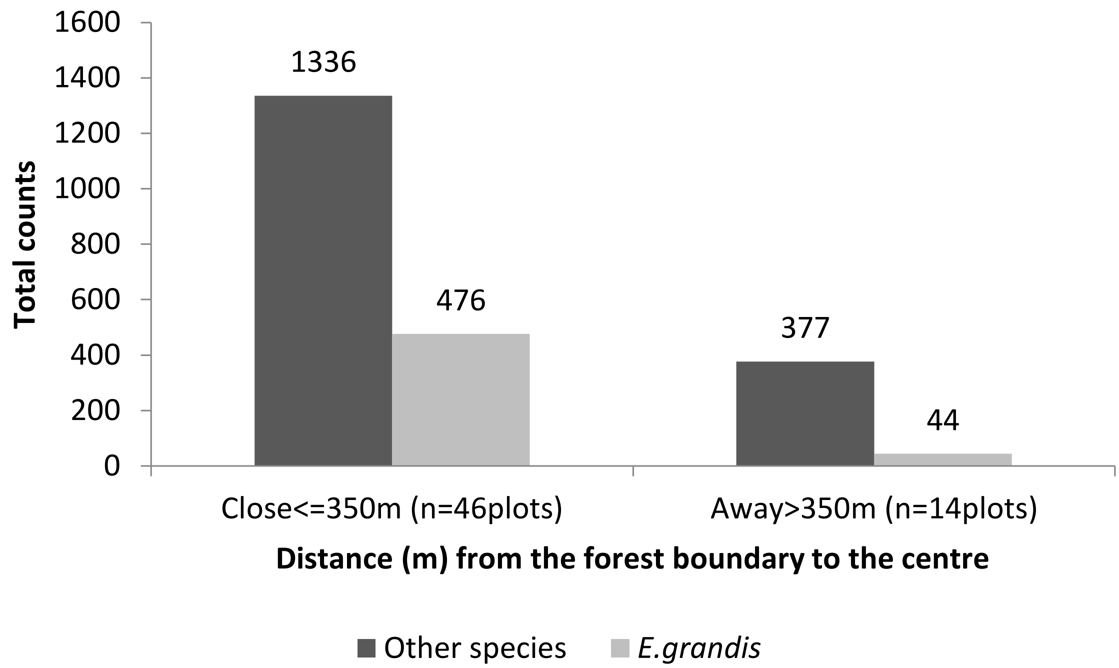

Table 2: The 10 Most Abundant Woody Species Including all Size Categories Close to the Forest Boundary (≤350 m) Sorted by Total Counts in Kindoroko Forest Reserve, Mwanga District, Tanzania

S/ No.	Name of species	Total counts (Abundance)	Relative abundance (%)
1	*Eucalyptus grandis*	476	26
2	*Newtonia buchananii*	195	11
3	*Xymalos monospora*	187	10
4	*Macaranga kilimandscharica*	145	8
5	*Maesa lanceolata*	108	6
6	*Tabernaemontana ventricosa*	82	5
7	*Piper capense*	72	4
8	*Ficalhoa laurifolia*	62	3
9	*Celtis durandii*	52	3
10	*Syzygium owariense*	40	2

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Table 3: The 10 Most Abundant Woody Species, Including all Size Categories Away from the Forest Boundary (>350 m), Sorted by Total Counts in Kindoroko Forest Reserve, Mwanga District, Tanzania

S/No.	Name of species	Total counts (Abundance)	Relative abundance (%)
1	*Newtonia buchananii*	65	15
2	*Macaranga kilimandscharica*	59	14
3	*Xymalos monospora*	58	14
4	*Eucalyptus grandis*	44	10
5	*Albizia gummifera*	36	9
6	*Ficalhoa laurifolia*	28	7
7	*Tabernaemontana ventricosa*	22	5
8	*Rapanea melanophloeos*	20	5
9	*Piper capense*	19	5
10	*Dasylepis integra*	16	4

When comparisons were made between the four life stages, *E. grandis* still emerged as the most dominant species, except at the sapling stage, where it ranked second among the ten most abundant species observed in the study area (Table 4, Figure 4-7).

Table 4: The Summary of the Abundance of Four Life Stages of Eucalyptus grandis and Other Native Woody Species Across All Plots (n=60) in Kindoroko Forest Reserve, Mwanga District, Tanzania

Life stage	Species richness	*E.grandis* (Total counts)	Other species (Total counts)	Overall abundance (Total counts)
Seedlings	28	163	658	821
Saplings	39	44	257	301
Sub-adults	38	125	376	501
Adults	27	188	422	610

Figure 4: The Distribution of Eucalyptus grandis and Other 10 Most Abundant Native Woody Species in Terms of Seedlings Abundance in Kindoroko Forest Reserve, Tanzania

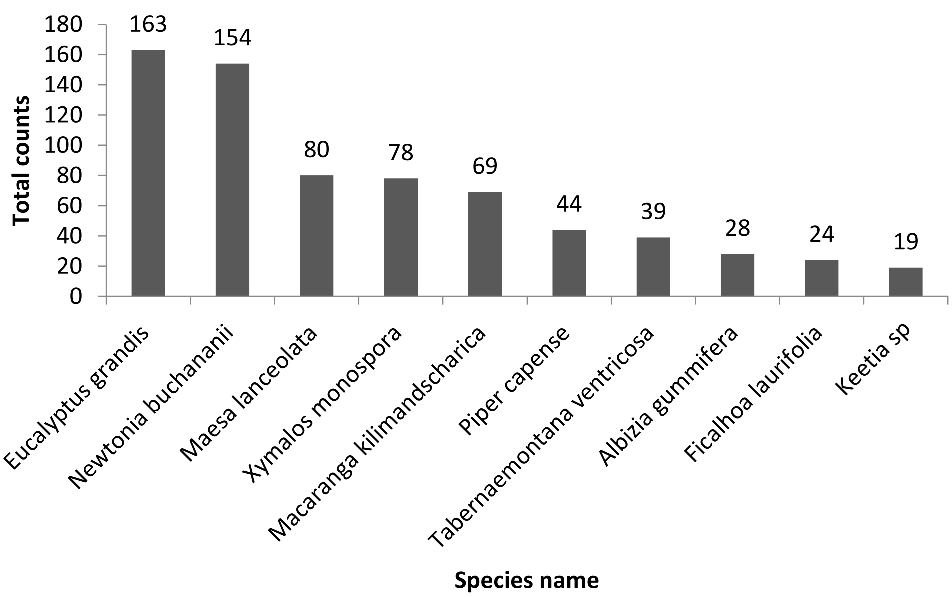

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Figure 5: Tanzania the Distribution of Eucalyptus grandis and Other 10 Native Woody Species in Terms of Saplings Abundance in Kindoroko Forest Reserve, Tanzania

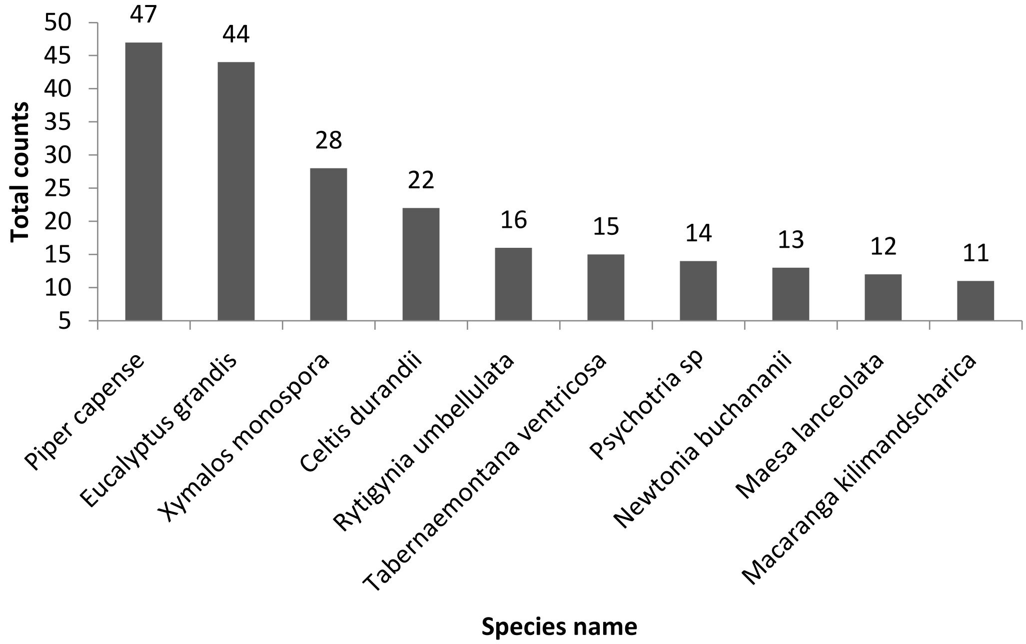

Figure 6: The Distribution of Eucalyptus grandis and Other 10 Native Woody Species in Terms of Sub-adults' Abundance in Kindoroko Forest Reserve, Tanzania

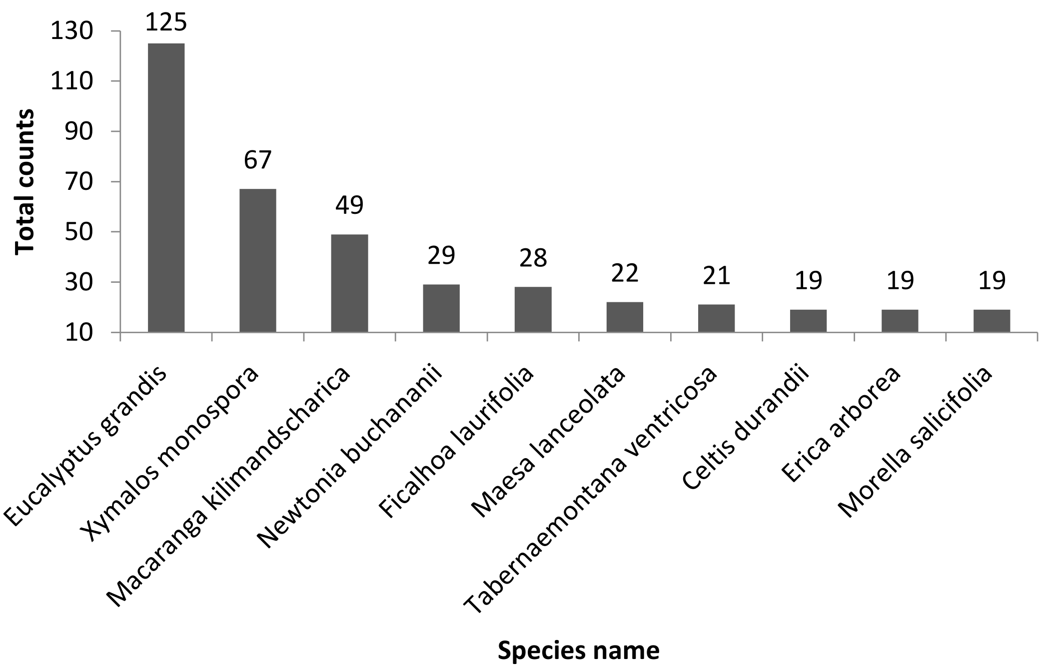

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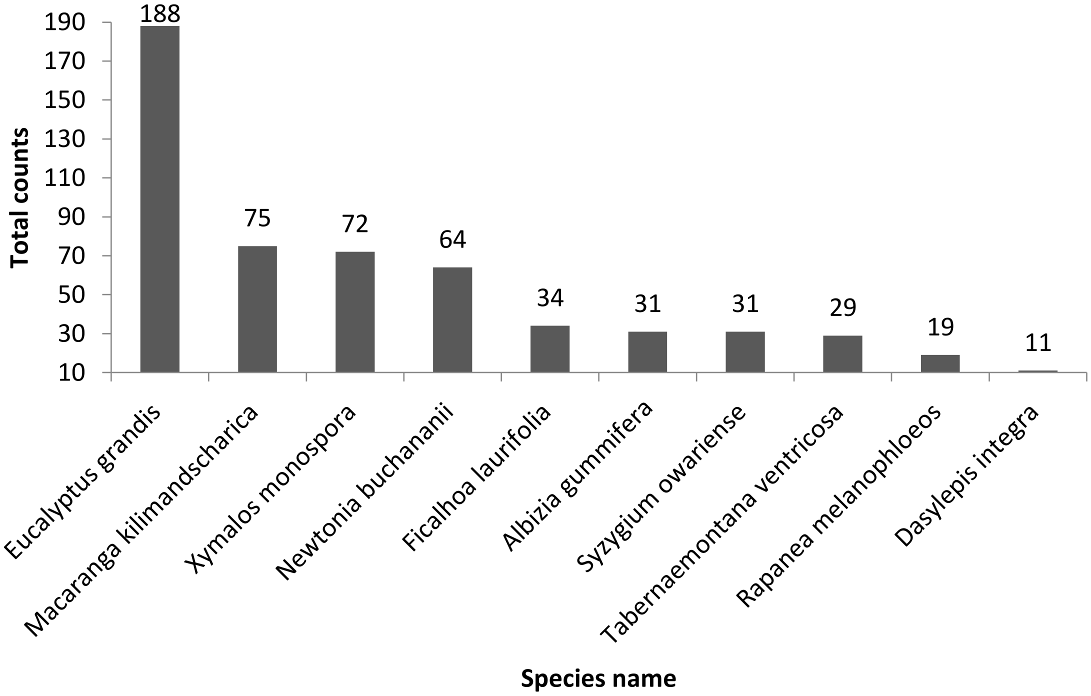
Figure 7: The Distribution of Eucalyptus grandis and the Other 10 Native Woody Species in Terms of Adults' Abundance in Kindoroko Forest Reserve, Tanzania



Population status and abundance of *E. grandis* in Kindoroko Forest Reserve exhibited a clear pattern influenced by proximity to the forest boundary compared to the forest interior. These species tend to thrive in disturbed areas near the edge of the forest, where anthropogenic activities such as logging, grazing, and fire create more open and warmer conditions favourable for their establishment. Forest edges experience greater anthropogenic disturbances (Esseen *et al*., 2016), such as fire setting, grazing, and resource extraction, which create conditions conducive to the proliferation of disturbed-adapted species like *E. grandis* (Harper *et al*., 2015). Similar trends have been observed in other tropical montane forests, where invasive species dominate disturbed zones while native species persist in less disturbed areas (Edward *et al*., 2009; Rosa *et al*., 2025). The species has been found concentrating near the forest edge, with its abundance decreasing toward the interior, where competition from native species increases. This reflects the edge-interior dynamic, where disturbed areas favour pioneer species, while a stable environment of the interior limits their growth (Kupfer & Runkle, 2003). These results were strongly supported by Muñiz *et al*. (2006), who showed that in abandoned pastures, species richness and abundance of primary forest species decreased with increasing distance from the forest border. This trend highlights the critical relationship between forest proximity and biodiversity retention, emphasizing the importance of maintaining forest borders to support species persistence in regenerated landscapes (Santoro *et al*., 2020). The stable microclimatic conditions found in the forest interior, characterized by low light, higher humidity, and cooler temperatures, play a significant role in inhibiting the establishment of *E. grandis*.

The life stage of *E. grandis* provides additional insight into the difficulties it encounters with long-term establishment. While *E. grandis* shows greater abundance in the early stages near the forest edge, its establishment becomes less successful in the later stages of growth, particularly in the sapling stage. This suggests that although *E. grandis* can

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initiate its growth in disturbed environments, its persistence through the later stages of life is compromised by competition with native species (Johnson *et al*., 2011). The sapling stage, in particular, is a critical point where *E. grandis* struggles to maintain its abundance due to the increasing influence of native species and the more shaded conditions deeper within the forest. As the forest recovers and the ecological balance shifts, the ability of *E. grandis* to maintain its presence becomes less certain. Over time, as native species re-establish themselves, the competition for space, nutrients, and light increases, and *E. grandis* faces a greater challenge to maintain its dominance (Kerr & Ruwanza, 2015). This transition underscores the complexities of species invasion dynamics, where early colonizers may fail to establish long-term populations in more stable forest interiors (Wan *et al*., 2019).

The Spatial Distribution of *Eucalyptus grandis* in KFR

The spatial distribution of *E. grandis*, including all life stages together and when the four life stages were considered separately, are shown in Figures 8 and 9, respectively. Similar trends were observed whereby *E. grandis* appeared to be more dominant closer to the forest boundary than away from the forest boundary (Figures 8 and 9). Seedlings exhibited the highest abundance, with large-sized bubbles indicating a high number of counts per plot, and they appeared to be more concentrated within shorter distances (Figure 9). Saplings and sub-adults were less abundant and showed a more restricted distribution. Adults are more widely dispersed across the study area but with varying densities (Figure 9). These patterns highlight differences in recruitment, establishment, and survival across all the life stages of *E. grandis* in the study area.

Figure 8: A Bubble Graph Showing the Spatial Distribution of Abundance (Total Counts) of Eucalyptus grandis in Relation to the Distance from the Forest Boundary in Kindoroko Forest Reserve, Tanzania

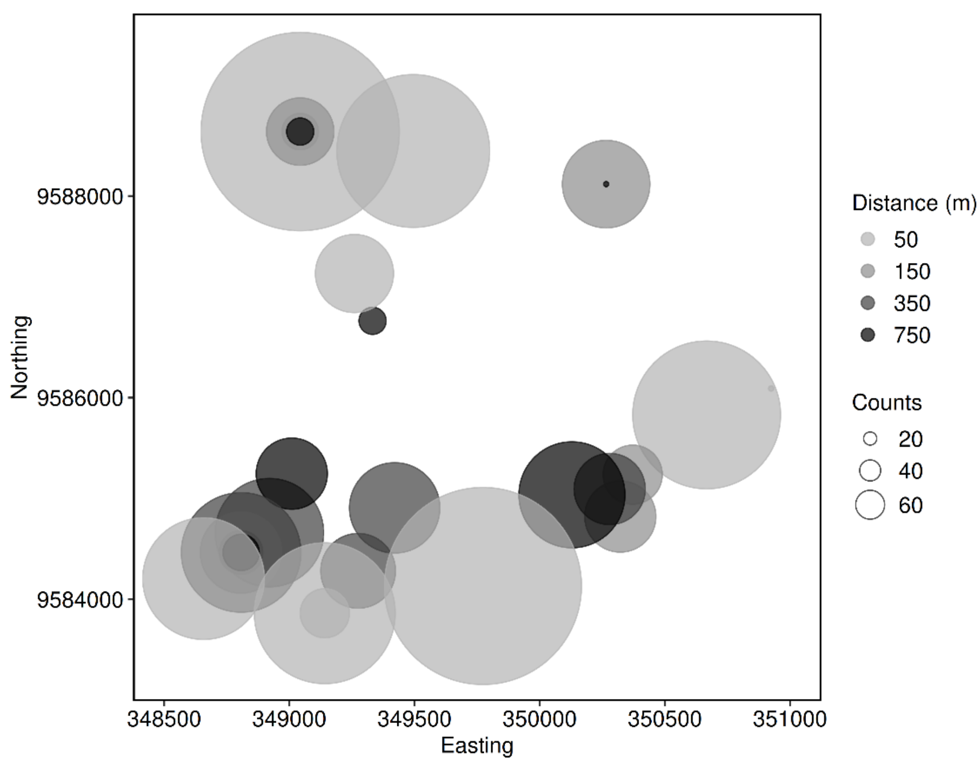

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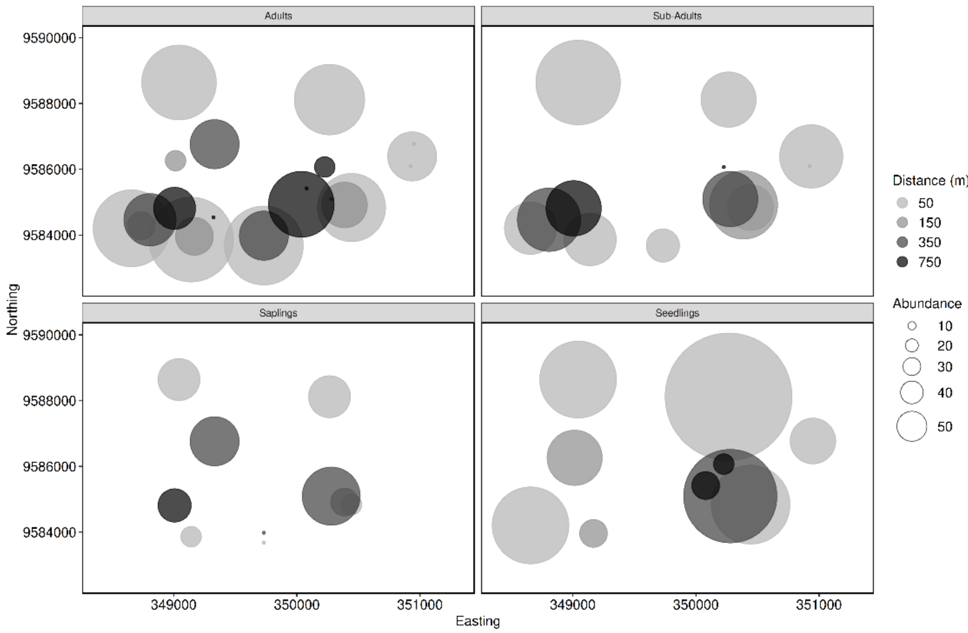
Figure 9: Bubble Graphs Showing the Spatial Distribution of Abundance (Total Counts) of Four Life Stages of Eucalyptus grandis (i.e. Seedlings, Saplings, Sub-adults, and Adults) in Relation to Distance from the Forest Boundary in Kindoroko Forest Reserve, Tanzania



When the influence of disturbances was considered across the abundance of the four life stages, the results showed that highly disturbed areas which in most cases were found close to the forest boundary (short distances) accounted for the highest number of *E. grandis* (total counts) across all four life stages as compared to other native species (Figure 10; Table 5). Surprisingly, a markedly higher number of *E. grandis* were also observed in the undisturbed areas. This could be due to the influence of past disturbances whose signs were unclear during the survey (Table 5). Medium-disturbed areas also showed many *E. grandis* even away from the forest boundary, indicating its ability to establish itself away from the mother trees (Table 6).

Figure 10: Bubble Graphs Showing the Influence of Disturbances on the Abundance of Four Life Stages of Eucalyptus grandis in Relation to the Distance from the Forest Boundary in Kindoroko Forest Reserve, Tanzania

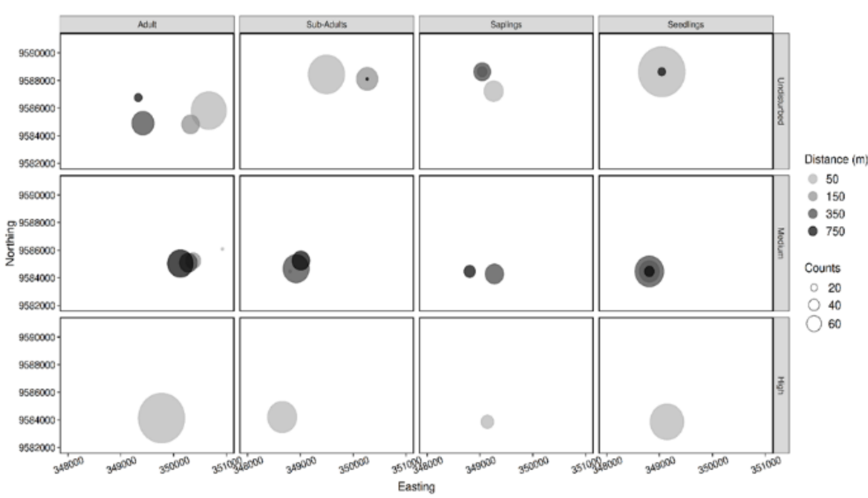


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Table 5: The Influence of Different Levels of Disturbances on the Abundance of Eucalyptus grandis in Kindoroko Forest Reserve, Tanzania

Disturbance levels	No.of plots (n)	Species richness	Total counts of *E. grandis*	Total counts of other sp.
High (>50%)	6	26	150	183
Medium (>0≤50%)	19	31	133	492
No disturbance (0%)	35	43	237	1038
Total	**60**	**54**	**520**	**1713**

Generally, *E. grandis* is more abundant across all disturbance levels, indicating a sign of invasion throughout the forest area (Table 6). Even in undisturbed areas, *E. grandis* was the most abundant species, representing 19% of the total species abundance in relation to other native species in the study area.

Table 6: Influence of Different Levels of Disturbances on the Abundance of Eucalyptus grandis in Relation to the Other 10 Dominant Native Woody Species in Kindoroko Forest Reserve, Tanzania

Disturbance levels	Species name	Abundance (Total counts)	Relative abundance (%)
High (>50%)	*Eucalyptus grandis*	150	45
	Newtonia buchananii	33	10
	Macaranga kilimandscharica	24	7
	Maesa lanceolata	18	5
	Dombeya torrida	17	5
	Celtis durandii	17	5
	Xymalos monospora	16	5
	Cassia sp.	13	4
	Albizia gummifera	9	3
	Ficalhoa laurifolia	8	2
Medium (>0≤50%)	*Eucalyptus grandis*	133	21
	Xymalos monospora	98	16
	Macaranga kilimandscharica	59	9
	Newtonia buchananii	44	7
	Ficalhoa laurifolia	31	5
	Rapanea melanophloeos	31	5
	Albizia gummifera	26	4
	Maesa lanceolata	26	4
	Erica arborea	25	4
	Syzygium owariense	23	4
Undisturbed (0%)	*Eucalyptus grandis*	237	19
	Newtonia buchananii	183	14
	Xymalos monospora	131	10
	Macaranga kilimandscharica	121	9
	Tabernaemontana ventricosa	93	7
	Piper capense	80	6
	Maesa lanceolata	74	6
	Ficalhoa laurifolia	51	4
	Albizia gummifera	38	3
	Celtis durandii	35	3

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The spatial distribution of *E. grandis* demonstrates a discernible trend of increased abundance close to the forest boundary, particularly in disturbed areas where seedlings are most abundant, highlighting the species' resilience and ability to establish in disturbed environments. The species shows natural regeneration even in less disturbed or undisturbed areas, suggesting a potential invasion (Musengi & Archibald, 2017). In regions that have experienced severe disturbances, the conditions become more favourable for other alien species to thrive (Sandoval *et al*., 2022). This severe disturbance can shift the forest's species composition, allowing invasive species like *E. grandis* to spread, ultimately affecting the biodiversity of the Kindoroko Forest Reserve. As observed during the fieldwork, the highest concentrations of *E. grandis* were found closer to the source, particularly in areas where human activities, such as fire, were prevalent. Evidence of fire scars in these areas suggests that the fires have cleared the land, creating favourable conditions for *E. grandis* to thrive and grow in larger numbers. Similar patterns have been noted, where native species are outcompeted by *Eucalyptus* species, which are renowned for their rapid growth (Raveloaritiana *et al*., 2024).

The four life stages of *E. grandis* -seedlings, saplings, sub-adults, and adults differ in their spatial distributions and abundances across the study area. Adult trees show wider distribution patterns over time, suggesting secondary dispersal processes that increase the range of the species. Kowarik and Lippe (2011) observed similar dispersal patterns in their study area, where invasive species dispersed by wind initially accumulated in clusters before gradually spreading outward. This implies that the overall distribution of *E. grandis* over various environments is influenced by both primary and secondary dispersal processes (Musengi & Archibald, 2017). Studies have shown that *Eucalyptus* species exhibited variable growth performance under different moisture conditions, with higher recruitment in moderately wet environments (Steenhuis *et al*., 2023). Similarly, in such environments, *Eucalyptus* species have been documented to thrive in disturbed montane landscapes but struggle to outcompete native species in stable ecosystems (Stanturf *et al*., 2013). The presence of adult *E. grandis* beyond the source (forest boundary) indicates successful establishment, though recruitment and survival vary across life stages. This transition from seedlings to saplings appears to be a bottleneck, likely due to competition and resource limitations, which may restrict further growth. Edward *et al*. (2009) reported that seedlings and sub-adults play a crucial role in population expansion, reinforcing the idea that successful recruitment at these stages is essential for long-term establishment. However, the increase in sub-adults suggests that once saplings overcome these challenges, their chance of reaching maturity improves.

The clustering of seedlings and saplings within shorter distances suggests that *E. grandis* benefits from microsite conditions at the forest edge, including increased light availability and reduced competition from mature forest species. Edge-dwelling species show higher recruitment in disturbed zones but reduced establishment in shaded understories (Benitez, 2003). Exotic species like *Eucalyptus* fail to regenerate under closed-canopy conditions but thrive in light gaps and forest margins (Charbonneau & Fahrig, 2004)

Factors Influencing the Abundance and Spread of *Eucalyptus grandis* in KFR

The results of factors influencing *E. grandis* abundance in the KFR are shown in Table 7. A negative relationship was observed in canopy cover ($p < 0.001$), indicating that higher canopy cover reduces *E. grandis* abundance. This suggests that open forest areas are more prone to invasion. A positive association was found in Slope ($p = 0.044$), implying that *E. grandis* tends to occur more frequently on steeper slopes. Elevation, however, was not a significant factor ($p = 0.656$), implying that altitude does not strongly influence *E. grandis* establishment.

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Distance from the forest boundary (p = 0.119) was also not significantly associated with *E. grandis* abundance, suggesting that proximity to the forest boundary is not the primary driver of invasion. In contrast, disturbance levels significantly influenced the *E. grandis* invasion. Medium disturbance (p = 0.001) showed a negative effect, suggesting that moderate disturbance reduces *E. grandis* abundance, whereas high disturbance (p = 0.031) showed a positive effect, indicating that heavily disturbed areas promote *E. grandis* invasion.

For the four life stages, saplings (p = 0.003) had a significantly lower abundance compared to adults, which may indicate recruitment limitations or high mortality at this stage, whereas seedlings and sub-adults did not show statistically significant differences in abundance compared to adults. These results suggest that canopy openness, slope, and disturbance levels are the key factors influencing *Eucalyptus* invasion, while distance from the forest boundary is not a major determinant. These findings indicate that forest management strategies focusing on maintaining canopy cover and minimizing high levels of disturbance could help control *Eucalyptus* spread in this forest reserve.

Table 7: Results of the Negative Binomial Generalized Linear Model (GLM) Examining Factors Influencing E. grandis Abundance in Kindoroko Forest Reserve, Tanzania

Variable	Estimate	Std.Error	z-value	p-value	
(Intercept)	1.6700	4.4220	00.378	0.706	
Distance	0.0011	0.0007	1.558	0.119	
Elevation	0.0009	0.0021	0.445	0.656	
Slope	0.0270	0.0134	2.012	0.044	*
Canopy cover	-0.0474	0.0107	-4.427	<0.001	***
Distance					
Undisturbed	-	-	-	-	
Medium	-1.1330	0.3543	-3.197	0.001	**
High	1.4580	0.6764	2.155	0.031	*
Life Stage					
Adults	-	-	-	-	
Sub-Adults	-0.3680	0.3323	-1.108	0.268	
Saplings	-1.0616	0.3559	-2.983	0.003	**
Seedlings	0.2839	0.3540	0.802	0.423	

Notes: Statistical significance levels: ***p<0.001, **p<0.01, *p<0.05. Model dispersion parameter: 3.1125. Null deviance: 86.042 (df = 27). Residual deviance: 28.019 (df = 18). AIC: 210.55

The spread of *E. grandis* in KFR is strongly influenced by both environmental variables and anthropogenic disturbances. Key factors include the availability of canopy gaps, the elevation and slope, and human disturbances. One of the primary factors of its spread is the disturbance of the forest canopy. These disturbances, including logging, fire, and grazing, disrupt the natural balance of the forest, creating an environment that favours the establishment of *E. grandis*. Local communities frequently use fires to clear land for farming, but these fires sometimes spread beyond control, reaching forest reserves and exposing them to invasion. The burned logs and fire scars found in the study area suggest that such fires enhanced conditions for *E. grandis* seedlings to establish.

The understory is further disrupted by grazing, which reduces plant density and makes it possible for *E. grandis* to flourish in these disturbed areas. High levels of disturbance create ideal conditions for *E. grandis* to establish (Musengi & Archibald, 2017). This suggests that anthropogenic activities, particularly those causing extensive habitat modification, enhance the likelihood of *E. grandis's* spread and dominance within the invaded ecosystem (Kerr & Ruwanza, 2015). Waddell *et al*.

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(2020) reported that land-use change alters the structure and species composition of native forests, thereby opening the landscape to invasion.

The relationship between canopy cover and *E. grandis* abundance is particularly significant. Dense, closed canopies limit the light available to seedlings and reduce their chance of survival (Kleinschroth *et al*., 2013). A dense canopy creates a shaded understory that is unfavourable for many light-demanding species (Yang *et al*., 2021). On the contrary, an open, disturbed environment, where the canopy has been disrupted, offers ideal conditions for these species to thrive (Gravel *et al*., 2010). The spread of *E. grandis* is heavily reliant on disturbance that creates light gaps and allows the species to outcompete native woody species (Musengi & Archibald, 2017).

The slope of the land has a significant impact on the distribution and abundance of *E. grandis*. The abundance of *E. grandis* is positively correlated with steeper slopes, making these areas more suitable for its establishment (Zerga *et al*., 2021). However, steeper slopes are particularly susceptible to soil erosion and instability, which can significantly affect the competitiveness of native plant species (Gastauer *et al*., 2022). This creates an environment where *E. grandis* may gain an advantage over native plants due to its robust nature and ability to withstand such conditions (Musengi & Archibald, 2017).

While elevation itself does not appear to have a significant impact on the spread of *E. grandis*, other environmental factors such as temperature, moisture availability, and soil composition still influence its dispersal (Wang *et al*., 2019). The plant's capacity to thrive across various elevations demonstrates its remarkable adaptability (Kardol *et al*., 2014). One of the main reasons *E. grandis* has been successful as an invasive plant is its capacity to adapt to a variety of environmental situations (Getachew *et al*., 2024). It may establish itself in a variety of ecosystems due to its adaptability to different elevations and environmental circumstances, which increases its potential for invasion (Pauchard *et al*., 2009).

CONCLUSIONS AND RECOMMENDATIONS

This study found that *E. grandis* is significantly more abundant in disturbed areas, particularly near human settlements, where activities such as logging, grazing, and wildfires are common. These disturbances create open canopy conditions that facilitate the establishment and spread of the species. Environmental factors such as slope were also noted to influence its distribution. This study contributes valuable insights to the theoretical understanding of invasion dynamics, supporting the view that disturbance and ability of early life stages of a plant to establish itself successfully in the dusturbed areas are key factors in the spread of invasive species. The study also highlights the importance of monitoring areas beyond the forest reserve to prevent the species from re-establishing itself within the forest, ensuring that control measures are extended to the surrounding landscapes. Among the notable limitations of the study were due to the fact that other environmental variables such as soil type and microclimatic conditions were not considered, hence they could potentially affect the spread of *E. grandis*. Additionally, this study was confined to the forest reserve, neglecting nearby farms where the species may also be present acting a potential sources of seeds (propogule pressure), which could have also provided a more complete understanding of its spread. To effectively manage the spread of *E. grandis*, forest management efforts should focus on reducing human disturbances, particularly near forest edges, and promoting dense canopy cover to help suppress the species

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