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Environmental and anthropogenic variables influencing the distribution of the non-native tree species in Tropical Montane Forests of West Usambara, Tanzania

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Abstract

A study to determine environmental and anthropogenic factors driving distribution of non-native tree species, *Acacia melanoxylon* and *Eucalyptus grandis* was conducted from January to March 2023 in Magamba Nature Forest Reserve (MNFR), West Usambara, Tanzania. Ninety-six (20 m x 20 m) plots were purposively set in which altitude, slope, soil, human disturbance indices and vegetation data were collected. Redundancy Analysis was employed to identify factors influencing the distribution of the non-native tree species in MNFR. The explanatory variables altitude, slope, human disturbance, soil organic carbon, pH, total nitrogen and bulk density were significant ($p < 0.05$) in influencing the distribution pattern of *A. melanoxylon* and *E. grandis.* Soil sand, silt, clay content, water content, available phosphorus and cation exchange capacity were not important ($p > 0.05$). The association between human disturbance and distribution of *E. grandis* recorded in this study implies that the MNFR faces serious human disturbances that need an urgent management response. We recommend more efforts to be directed towards the control of the human disturbances to circumvent encroachment of the tropical montane forests by non-native tree species. The findings of this study may be valuable for devising forest restoration programmes to sustain the ecosystem functioning in the West Usambara montane forests and similar ecosystems.

Keywords: *A. melanoxylon*, *E. grandis*, ecosystem functioning, forest encroachment, human disturbance

Introduction

The distribution patterns of plant species of any forest ecosystem depend on present environmental settings and level of human influences or disturbances. According to Prada and Stevenson (2016), the environmental variables such as altitude, slope, aspect and soil variables do influence distribution and composition of plant species in tropical forest. However, each variable influences different processes, for instance variation in altitudes lead to differences in environmental condition hence heterogeneity in local species composition (Prada and Stevenson 2016).

Tropical montane forests have customarily been believed as highly resistant to encroachment by non-native tree species due to their high diversity (Denslow and DeWalt 2008) and harsh terrain that limit accessibility. However, several literatures have recently revealed that tropical montane forests are being encroached by non-native plant species (Hulme et al. 2013, Jauni et al. 2015, Piiroinen et al. 2018). Therefore, this growing trend of encroachment of tropical forest ecosystems attests our limited knowledge on how and what factors favour the establishment and growth of the non-native tree species. West Usambara Mountains forests particularly Magamba Nature Forest Reserve (MNFR) harbours non-native trees species, *Acacia melanoxylon* and *Eucalyptus grandis* within its boundary (TFS 2022) both of them being recognized globally as unfriendly species (Forsyth et al. 2004, Kraaij et al. 2023). Similarly, the two non-native tree species have had the negative relationships with the plant community structure of resident woody species in MNFR (Hagwet et al. 2024). Without the knowledge about the factors facilitating the establishment and growth of these non-native tree species, it is difficult to precisely develop specific strategies for their spread and control.

Encroachment success of forest ecosystems is determined by interactions of multiple environmental and human mediated factors. Studies in other areas demonstrated that, the establishment of non-native plant species in natural habitats is mostly influenced by human related disturbances and environmental conditions in that particular area (Andrew 2014, Lázaro-Lobo and Ervin 2021). According to Blair et al. (2010), human disturbances put the tropical forests under the risk of being encroached by non-native plants regardless of the traditional perception that tropical forests are resistant to encroachment by non-native plant species (Denslow and DeWalt 2008). However, in recent decades, human related disturbances have been rapidly increasing in the tropical montane forests (Hitimana et al. 2004) to an extent that the highly disturbed forests become low resistant to encroachment by non-native plants (Fernandes et al. 2016).

It is well known that environmental factors e.g. soil parameters are a good measure of plant species habitat suitability (Zuquim et al. 2020) hence influence species composition and distribution pattern. The main soil parameters that influence plant growth include soil pH, soil organic matter, total nitrogen, available phosphorus, cation exchange capacity, exchangeable potassium and sodium, exchangeable calcium and magnesium (Andersen et al. 2010, Zuquim et al. 2020).

West Usambara Mountains as part of the Eastern Arc Mountains, a global biodiversity hotspot, plays a vital role in provision of ecosystem services in the region. Despite its potential, encroachment by non-native tree species is threatening the sustainability and flow of ecosystem services of the forest (Hagwet et al. 2024). Therefore, an understanding of the distribution pattern of non-native tree species and their driving factors appeared to be crucial to institute better conservation plans of this globally important ecosystem (Burgess et al. 2007, Salinas et al. 2021). This knowledge can objectively guide setting of strategic monitoring and management of the non-native as well as restoration plans in tropical montane forests (Salinas et al. 2021). While several studies have evaluated the influence of environmental variables on species composition and distribution in tropical montane forests (Andersen et al. 2010, Lippok et al. 2014, Prada and Stevenson 2016, Tesha et al. 2023), none of them explored a combined set of environmental and human disturbance factors responsible for distribution pattern of non-native tree species. Therefore, this study investigates the environmental (topographic & edaphic) and anthropogenic factors driving the distribution pattern of non-native tree species in Magamba Nature Forest Reserve, Tanzania.

Materials and Methods

Study area

This study was conducted in Magamba Nature Forest Reserve (MNFR) which is located between latitude 04°40′ and 04°70′S and longitude 38°15′ and 38°29′E in West Usambara Mountains in the north-eastern Tanzania (Figure 1). The topography of the area is undulating with wide altitudinal range from 1650 to 2300 m a.s.l. The area receives bimodal rainfall reaching up to 2000 mm per year, with the long rains from March to May and short rains from October to December (Doggart et al. 2017). The reserve is comprised of montane forests dominated by

Ocotea usambarensis and *Tabernaemontana* species (Doggart et al. 2017). Apart from the native species, the area consists of non-native tree species that were planted in forest plantations including *Pinus patula*, *Cupressus lusitanica*, *Acacia melanoxylon*, *Acacia mearnsii* and *Eucalyptus grandis* as the boundary markings 2022).

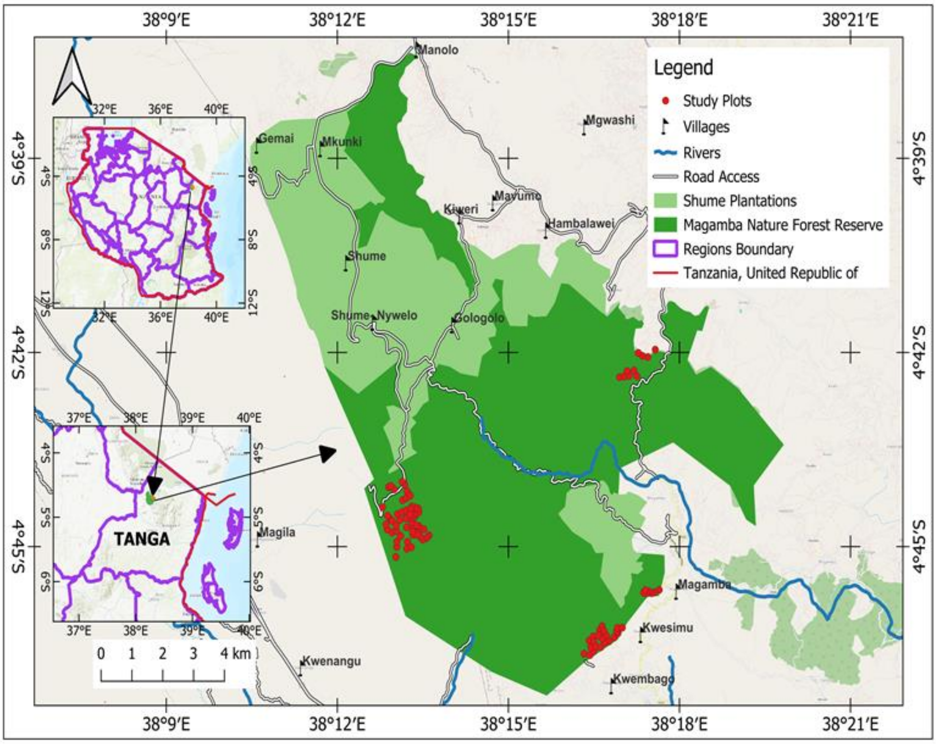

Figure 1: A map to show location of study area and sampling plots in the Magamba Nature Forest Reserve, Tanzania.

Sampling techniques

A total of 96 (20 m x 20 m) plots were established purposively and surveyed to assess the influence of environmental and anthropogenic factors on the distribution of non-native tree species, *Acacia melanoxylon* and *Eucalyptus grandis;* (hereafter referred to: *A. melanoxylon* and *E. grandis* respectively) in Magamba Nature Forest Reserve (MNFR). The distance between plots ranged from 100 to 200 m depending on the presence of the selected non-native tree species.

Vegetation data

The vegetation were sampled following the Modified Whittaker method (Stohlgren et al. 1995). The number of individuals of adult trees of *A. melanoxylon* and *E. grandis* with Diameter at Breast Height (DBH) ≥ 5 cm were counted and recorded within the 20 m x 20 m plots. The tree saplings with DBH ≥ 1 cm but ≤ 4.9 cm were counted and recorded in two nested plots of the size 2 m x 5 m each that were set at diagonal corners but within the bigger plot. Additionally, seedlings (DBH < 1 cm) of the same trees were counted and recorded from two smaller plots of 1 m x 1 m established within the 2 m x 5 m plots.

Environmental and anthropogenic factors

At the centre of each plot of 20 m x 20 m, we recorded altitude using hand held Garmin GPS MAP 64s and slope using SUUNTO PM-5/360.PC. In the same plots, we counted the number of burnt and cut stems and recorded the total value as value for human disturbance. The soil sample for soil bulk density was collected at the centre of each plot using soil core ring with diameter of 5.5

cm and 6 cm height. The same samples were weighted in the field in order to obtain soil fresh weight that was used later to obtain soil water content at Tanzania Forest Research Institute (TAFORI). Three other soil samples were collected randomly within each 20 m by 20 m plot at depth of 0 - 30 cm using soil auger (6 cm diameter) and mixed to make a composite soil sample. The composite samples were split into two portions, one portion was taken to TAFORI centre in Lushoto where the physical parameters including soil porosity, soil silt, sand and clay content were analyzed. The second portion of composite samples were taken to Tanzania Agricultural Research Institute (TARI) at Mlingano for analysis of soil chemical parameters which included soil organic carbon, soil total nitrogen, soil available phosphorus and cation exchange capacity.

Statistical analyses

Prior to statistical analysis the multicollinearity of environmental and anthropogenic variables was checked using Variance Inflation Factor (VIF) in IBM SPSS Statistics (Version 20)(SPSS 2011). When the VIF value was greater than or equal to 5, one of the most correlated variables was dropped from further analysis (Chatterjee and Simonoff 2013) (Table 1). In order to visualize the relationship between plant species and environmental variables recorded, a multivariate analysis technique was used (Kent 2012). Redundancy Analysis (RDA) was used to assess the association of non-native tree species and environmental and human disturbance. The RDA was appropriate due to the shorter gradient length, gradient length of 1.4. However, the conditional effect was used to define the exclusive contribution of each predictor variable while accounting for the effects of other variables and interactions in explaining the variation in distribution pattern of non-native tree species in MNFR. All statistical analyses were done using CANOCO version 5 (Smilauer and Leps 2014) and IBM SPSS version 20 (SPSS 2011). The significant relationships were considered at $p \leq 0.05$.

Table 1: Multicollinearity test for environmental and anthropogenic variables showing the Tolerance index and Variance Inflation Factor (VIF) value.

Variables	**Code**	**Standard unit**	**Collinearity Statistics**	
			Tolerance index	**VIF**
Soil bulk density	BD	(g/cm3)	0.001	*1106.936
Soil water content	WC	(%)	0.821	1.218
Soil porosity	SP	(%)	0.001	*1104.907
Soil silt content	SI	(%)	0.620	1.612
Soil clay content	CL	(%)	0.803	1.245
Soil pH	pH	(No.)	0.813	1.230
Soil total nitrogen	TN	(%)	0.282	3.543
Soil organic carbon	OC	(%)	0.722	1.384
Available phosphorus	P	(mg/kg)	0.691	1.446
Cation Exchange Capacity	CEC	(meq/100g)	0.278	3.596
Altitude	ALT	(m)	0.635	1.574
Slope	SLO	(°)	0.751	1.332
Disturbance	DIST	(No.)	0.655	1.526

* Soil porosity and bulk density have higher Variance Inflation (VIF), meaning that they are highly correlated with each other. The soil bulk density was opted for further analysis as it is the most commonly used variable in explaining plant - soil interactions.

Results

Influence of the environmental and anthropogenic factors on the distribution pattern of non-native tree species

The influence of environmental and anthropogenic factors on the distribution of non-native tree species was best explained by the first two ordination axes. Axis 1 accounted for 73.3 % and axis 2 accounted for 0.47 % of the variance in the total abundance of the non-native tree species, *A. melanoxylon* and *E. grandis*. The permutation test results using 999 permutations revealed that the overall model was significant, F = 19.5, *p* = 0.001. The explanatory variables; altitude, human disturbance, slope, organic carbon, total nitrogen and soil pH explained 73.77 % of the total variation. On the other hand, available phosphorus, cation exchange capacity, soil water content, bulk density, soil silt, sand and clay content were not important ($p > 0.05$) in explaining the distribution pattern of non-native tree species in MNFR (Table 2).

Table 2: Contribution of environmental and anthropogenic variables that explained the distribution pattern of non-native tree species using summarized effects of explanatory variables (conditional effects).

Explanatory variable	Explained %	Variable Scores		F	*p*-value
		Score 1	Score 2		
ALT	50.8	-0.83	0.22	97	0.001**
DIST	7.29	0.54	-0.14	16.2	0.001**
TN	2.84	0.17	0.39	8.3	0.004**
SLO	2.99	0.39	-0.29	7.7	0.01*
BD	3.58	-0.42	-0.38	18.4	0.01*
OC	2.32	-0.48	-0.08	6.3	0.02*
pH	1.39	0.38	0.12	4.3	0.04*
WC	0.72	0.12	0.16	2.2	0.15
CEC	0.79	0.02	0.14	2.5	0.13
SA	0.94	-0.27	0.13	3.0	0.07
SI	0.11	0.37	-0.41	0.4	0.61
P	0.07	-0.3	0.45	0.2	0.68

Full names of explanatory variables and units are shown in Table 1. ** = Highly significant, * = significant.

The first ordination axis correlated strongly with altitude (ALT) and human disturbance (DIST) which is evidenced by the variable scores of 0.81 and 0.54 respectively. Inversely, second ordination axis 2 correlated with available phosphorus (P) and total nitrogen (TN) with variable scores of 0.45 and 0.39 respectively (Table 2). *A. melanoxylon* was strongly associated with altitude and organic carbon while human disturbance, slope and soil pH were correlated with the abundance of *E. grandis* (Figure 2).

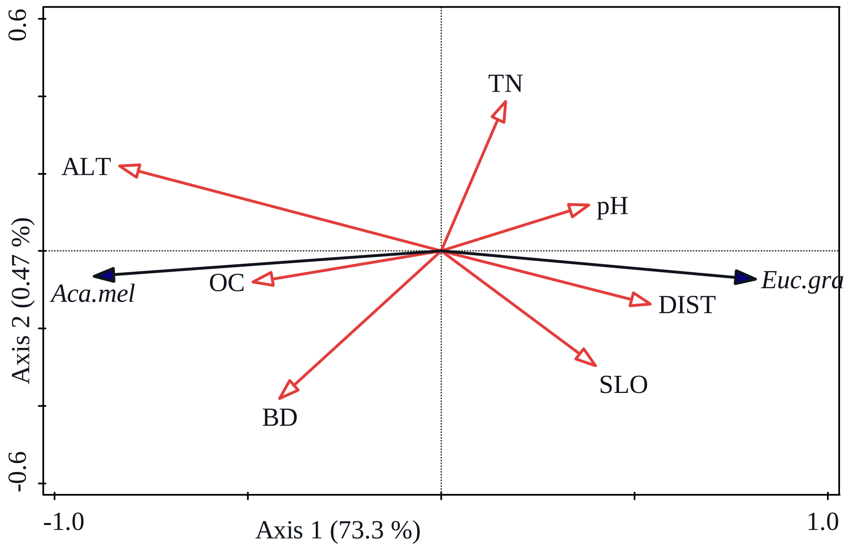

Figure 2: RDA diagram for environmental and anthropogenic variables that explained the distribution of non-native tree species in MNFR, Tanzania. Only significant environmental and anthropogenic variables are displayed in red arrows; while non-native tree species are in black arrows. *Aca.mel* =*Acacia melanoxylon*, *Euc.gra* = *Eucalyptus grandis*. Full names for environmental variables are shown in Table 1.

Effects of environmental and anthropogenic factors on the distribution of *A. melanoxylon*

The association between the environmental and anthropogenic factors and the distribution pattern of *A. melanoxylon* was best explained by the first RDA ordination axis 1 with 45.98% of the variance in total abundance of *A. melanoxylon*. The permutation assessment using 999 permutations revealed that the analysis of the model was significant at: F=3.1, p = 0.003. The explanatory variables; slope, soil silt content, total nitrogen, soil pH and available phosphorus explained about 45.98 % of the total variation. However, soil sand content, cation exchange capacity, human disturbance, altitude, organic carbon and bulk density were not important in influencing the total abundance of *A. melanoxylon* in the area.

However, in considering the dynamic nature of environmental conditions in relation to plant growth stages, we tested the effects of environmental and anthropogenic variables on the abundance of seedlings, saplings and adult trees separately. The effect of environmental and anthropogenic factors was significant only on the abundance of adult trees of *A. melanoxylon*. The overall analysis using 999 permutations showed that the model was significant (F= 4, p = 0.001). The explanatory variables; slope, available phosphorus, soil clay content, human disturbance, total nitrogen, soil silt content and pH were able to explain about 52.43 % of the total variation in abundance of adult trees of *A. melanoxylon*. On the other hand, soil sand content, water content, bulk density, cation exchange capacity and organic carbon were not significant in explaining the variation in the abundance of adult trees of *A. melanoxylon* (Table 3).

Table 3: Effect of environmental and anthropogenic factors on the abundance of adult trees of *A. melanoxylon* in MNFR

Explanatory variable	Explained %	*F*- ratio	*p*- value
SLO	19.97	13.5	0.001**
DIST	8.56	6.4	0.017*
TN	6.12	4.9	0.029*
P	5.32	4.5	0.048*
pH	3.9	3.5	0.054*
SI	4.55	4.3	0.039*
SA	1.08	1	0.328
WC	0.72	0.7	0.43
BD	0.48	0.5	0.495
CEC	0.22	0.2	0.683
OC	0.12	0.1	0.748

Full names of explanatory variables and units are shown in Table 1. ** = Highly significant, * = significant

Influence of environmental and anthropogenic variables on the distribution of *E. grandis*

When the environmental and anthropogenic factors, altitude, slope, soil bulk density, water content, pH, organic carbon, total nitrogen, available phosphorus, soil clay, silt, sand content and human disturbance were subjected to the total abundance of *E. grandis*, there was no significant difference ($p > 0.05$) observed. However, when the same variables were tested against the abundance of seedlings, saplings and adult trees of *E. grandis* separately, the results revealed a significant effect on the abundance of saplings. Altitude, organic carbon, soil bulk density and available phosphorus were significant ($p < 0.05$) explanatory variables; explaining about 49.69 % of the total variation in the abundance of saplings of *E. grandis.* The remaining variables i.e., slope, human disturbance, water content, pH, total nitrogen, soil clay, silt and sand content were not important ($p > 0.05$) in explaining the variation of the abundance of saplings of *E. grandis* in the area (Table 4).

Table 4: Effect of environmental and anthropogenic factors on the abundance of saplings of *E. grandis* in MNFR

Explanatory variable	Explained %	*F*-ratio	*p*- value
ALT	14.9	6.7	0.01*
OC	8.4	4	0.05*
BD	8.2	4.3	0.03*
P	7.9	4.6	0.03*
DIST	4.9	3	0.09
CEC	2	1.2	0.27
pH	1.1	0.7	0.39
TN	0.9	0.5	0.51
CL	1.2	0.7	0.39
WC	0.1	<0.1	0.79
SLO	<0.1	<0.1	0.85
SI	<0.1	<0.1	0.93

Full names of explanatory variables and units are shown in Table 1. * = significant

Discussion

Knowledge on environmental and anthropogenic factors that influence the distribution pattern of non-native tree species normally enhances the sustainable conservation of tropical montane forests. This study found that, the abundance of the non-native tree species, *A. melanoxylon* and *E. grandis* in MNFR was significantly influenced by different factors including altitude, human disturbance, soil bulk density, slope, organic carbon, total nitrogen, soil pH and human disturbance. Altitude was the leading variable with high contribution factors (Table 5) in influencing the abundance of *A. melanoxylon* and *E. grandis* in MNFR. This findings is in agreement with the study in Amazon forest where the topographic factors mainly altitude had higher relative importance compared to other factors such as soil chemistry in explaining the distribution of tree species (Zuleta et al. 2020). Altitude is sometimes considered as the control machine of climatic factors such as temperature and rainfall (Häger 2010) that are used to predict the impact of climate change on vegetation patterns in any forest ecosystem. Therefore, with the increased climate change risks (Bradley et al. 2010), having good knowledge of interaction of non-natives tree species with different factors is crucial in conservation of forest biodiversity.

Human related disturbance was detected to have significant influence on the spatial variation of non-native tree species in MNFR. Specifically, the study showed strong association between disturbance and abundance of *E. grandis* (Figure 2) implying that disturbance was the key factor on explaining the distribution of the species. This finding is congruent with the information on the general management plan of the area that, MNFR experiences human disturbances mainly frequent fire (TFS (Tanzania Forest Services) 2022). It can therefore be assumed that the human disturbances had facilitated the spread and establishment of the selected non-native tree species, *Eucalyptus grandis* and *Acacia melanoxylon* in the area. This finding is consistent with that of Tng et al. (2014) who explained the establishment and survival of *E. grandis* being facilitated by the disturbance particularly caused by intense fires that increase available phosphorus in the soil. Similar to this is the study in Zambia that recognized that fire accelerates the growth of *E. grandis* particularly at younger stage due to the increased phosphorus and nitrogen in the soil (Chungu et al. 2020).

Soil nutrient requirements by plants differ at different stage of plant growth. Despite the fact that, young plants require soil essential nutrients including nitrogen (N), phosphorus (P), and potassium (K), which are critical for early growth and establishment, the demands at seedling stage are commonly low (Wu et al. 2020). This study reported the influence of organic carbon and available phosphorus on the abundance of saplings of *E. grandis* implying that the saplings absorbed less nutrients leaving large amount of nutrients on the soil. Soil organic carbon, total nitrogen and pH were found in this study to have significant contribution in explaining the total abundance of the studied non-native tree species. The mentioned elements are among the most essential soil nutrients for plant growth. These results reflect those obtained by Murphy and Bowman 2012, Zuquim et al. 2020, and Andrew 2024 who demonstrated that soil nutrients in forests are factors controlling the growth and distribution of different plant species. The high soil organic carbon recorded in this study might have been caused by the low microbial activity due to low temperature at high altitude of the study area. This explanation is in agreement with the studies done by Dalling et al. (2016) and De la Cruz-Amo et al. (2020) in tropical montane forests where it was confirmed that high precipitation and low temperature in high elevation lead into low rate of decomposition of leaf litter.

The tropical montane forests are believed to be nitrogen limited compared to lowland forests due to low microbial activities caused by low temperature at higher elevation (Gay et al. 2022). The medium level of total nitrogen with mean of 0.41± 0.18 % recorded in this study is most likely contributed by the high abundance of *A. melanoxylon*, a nitrogen fixing plant. This explanation is supported by different studies showing that Acacia species are potential for increasing soil nitrogen through the process of nitrogen fixation (Power et al. 2003, Belay et al. 2013). Soil pH normally regulate the availability of soil nutrients to plants (Neina 2019). This study observed low soil pH (acidic soils) that was positively associated with the abundance of *E. grandis* (Figure 2). The plausible explanation for this acidic soils in the forests could be the tendency of plants roots releasing organic acids during the nutrients uptake by the plant (Fujii 2014). It is widely known that most of the Eucalyptus species are fast growing plants (Liang et al. 2016), therefore, extract rapidly soil nutrients hence decrease in soil pH. According to Symonds et al. (2001) low soil pH (acidic soils) promotes growth of Eucalyptus species supporting our findings that soil pH had influence on the abundance of *E. grandis*.

Conclusion

Our study shows that among 13 environmental and human disturbance factors tested, seven of them, altitude, slope, soil organic carbon, total nitrogen, soil pH, soil bulk density and human disturbance were the most significant in explaining the distribution pattern of non-native tree species in MNFR. It is well known that human disturbance pave way to encroachment of natural forest by non-native tree species (Jauni et al. 2015) leading to the loss of biodiversity particularly in tropical montane forests (Linders et al. 2019). The strong association observed between disturbance and abundance of *E. grandis* (Figure 2) signify that the establishment and growth of the species was facilitated by the human disturbance. Our study therefore, suggest a consideration of a combined set of the above-mentioned factors when planning for restoration of tropical montane forests. Since, human disturbance was among the leading factors (Table 2) in explaining the distribution pattern of the non-native tree species, efforts need to be directed towards the control of the human disturbances to circumvent encroachment of the tropical montane forests by non-native tree species. The findings of this study may be valuable for devising forest restoration programmes to sustain the ecosystem functioning in the West Usambara montane forests and similar ecosystems.

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Declaration of interest

The authors declare no conflict of interests to reveal.

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