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Ecological impact and spatial distribution of invasive species *Prosopis juliflora* in the lake Natron basin, northern Tanzanian landscapes

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Abstract

Prosopis juliflora, commonly known as Mesquite is an invasive species that poses significant ecological and socio-economic challenges in arid and semi-arid regions worldwide. Its aggressive spread in Tanzania threatens native biodiversity, agricultural productivity, and local livelihoods. This study aimed to assess the population density, distribution, and ecological impact of *Prosopis juliflora* in Monduli, Ngorongoro and Longido districts in the Northern Tanzania. The specific objectives for this study were to i) quantify the density of *Prosopis juliflora* across wards and land use types, ii) analyze its diameter size distribution, iii) comparing forb and grass richness, Shannon diversity index, abundance, and cover in areas uninvaded and invaded with *Prosopis juliflora*, mapping its spatial distribution and iv) evaluating the environmental and anthropogenic factors influencing population density of *Prosopis juliflora*. Data were collected through line transects and quadrants to record the presence and density of *Prosopis juliflora* across wards and land use types. The study revealed significant variability in *Prosopis juliflora* population densities across wards and land use types, with settlement areas and grazinglands showing the highest densities. The presence of *Prosopis juliflora* was associated with a significant reduction in forb and grass richness, Shannon diversity index, grass abundance and cover. Spatial distribution mapping highlighted high-density areas, particularly in Esilalei and Migungani wards, while environmental factors such as temperature, soil properties, and proximity to roads were identified as significant predictors of *Prosopis juliflora* density.

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Introduction

Invasive alien plant species (IAPs) are a significant environmental and socioeconomic challenge globally. These species, which thrive outside their native habitats, often outcompete native flora, leading to biodiversity loss, soil degradation, and changes in ecosystem processes such as hydrology and nutrient cycling (Gentili *et al.*, 2021; Mollot *et al.*, 2017). In Tanzania the spread of IAPs has accelerated, particularly in protected ecosystems like the Ngorongoro National Park and the Serengeti-Mara ecosystem, where species such as *Opuntia stricta*, *Lantana camara*, *Gutenbergia cordifolia* and *Prosopis juliflora* have invaded the area (Bukombe *et al.*, 2021; Ngondya and Munishi, 2021; Witt *et al.*, 2017). Invasive species not only threaten the survival of native plants and animals but also reduce grazing land, disrupt wildlife habitats, and negatively affect human activities such as agriculture and tourism and livelihood (Bekele *et al.*, 2018; Birhane *et al.*, 2017; Senator and Rozenberg, 2017).

Among the most notorious of these invaders is *Prosopis juliflora* hereafter *P. juliflora* which has been introduced in various parts of the world, including Tanzania, due to its ability to thrive in arid, saline, and desert environments (El-Keblawy and Al-Rawai, 2007; Eschen *et al.*, 2024). While *P. juliflora* offers some benefits, such as fuelwood, fodder, ornamental, boundary planting (Ravhuhali *et al.*, 2021; Zeray *et al.*, 2017), it has earned the title of "curse tree" because of its aggressive spread and adverse negative impacts on ecosystems. The species is difficult to eradicate once established and competes with native vegetation, reducing species richness and altering land use patterns (Ravhuhali *et al.*, 2021). This has particularly significant implications for areas like Lake Natron, which is an important Ramsar site and the only regular breeding ground for the Lesser Flamingo in East Africa, which is now under threat from invasive species (Kideghesho *et al.*, 2013b). In Tanzania *P. juliflora* is believed to be unintentionally introduced in 1988 through livestock and donkeys used by traders across the Kenya and Tanzania border. Afterwards peoples due to its diverse environmental adaptability characteristics intentionally grew it in their households (Kilawe *et al.*, 2017). Despite the widespread ecological impacts of *P. juliflora*, there is a critical knowledge gap in understanding its current status and the full extent of its effects on native ecosystems in Tanzania. Specifically, little is known about the population density, spatial distribution, and ecological consequences of *P. juliflora* in regions such as Lake Natron, where its spread could have far-reaching implications for biodiversity and local livelihoods. This gap is particularly concerning given the Ramsar status of Lake Natron and its global importance as a biodiversity hotspot.

Our study aimed to address this knowledge gap by determining the *P. juliflora* distribution and structure and quantify the impacts of invasive plant, *P juliflora* on grass and forbs diversity and cover in grazing land community around Lake Natron Ramsar site Tanzania. Specifically, we aimed to (1) quantify the density of *P. juliflora* across different land use types, (2) analyze its size structure this is usefully to later understand which management intervention can be applied and uses of the trees (3) assess the impact of *P. juliflora* on native grass and forb richness, Shannon diversity index, abundance, and cover, (4) map its spatial distribution for species management purposes, and (5) evaluate the environmental and human factors influencing its spread. By filling this knowledge gap, the study will provide critical insights for managing invasive species in Tanzania's vulnerable ecosystems and help inform future conservation strategies.

Materials and methods

The study area is located between 35.70°E and 36.30°E and between 2.10°S and 3.60°S, encompassing eight wards: Mto wa Mbu, Esilalei, Selela, Majengo, Migungani, and Engaruka in the Monduli district, and Pinyinyi and Gelai Lumbwa in the Ngorongoro and Longido districts, respectively (Fig. 1).

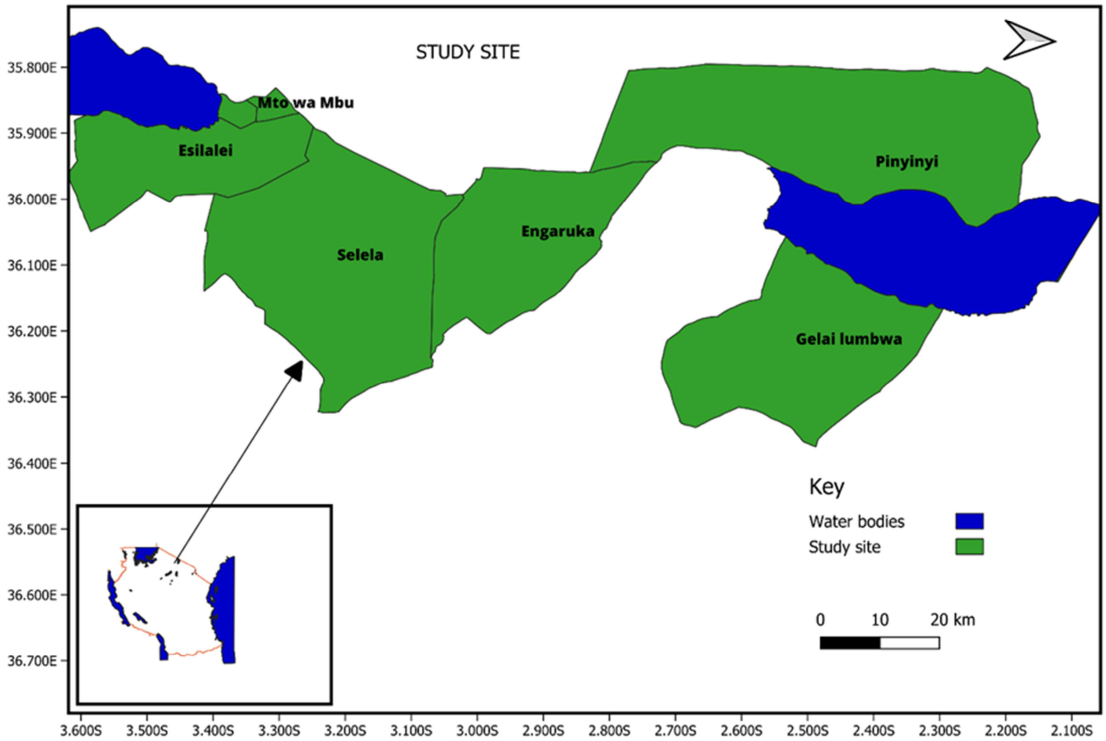

Fig. 1a. Map showing the spatial location of the surveyed wards

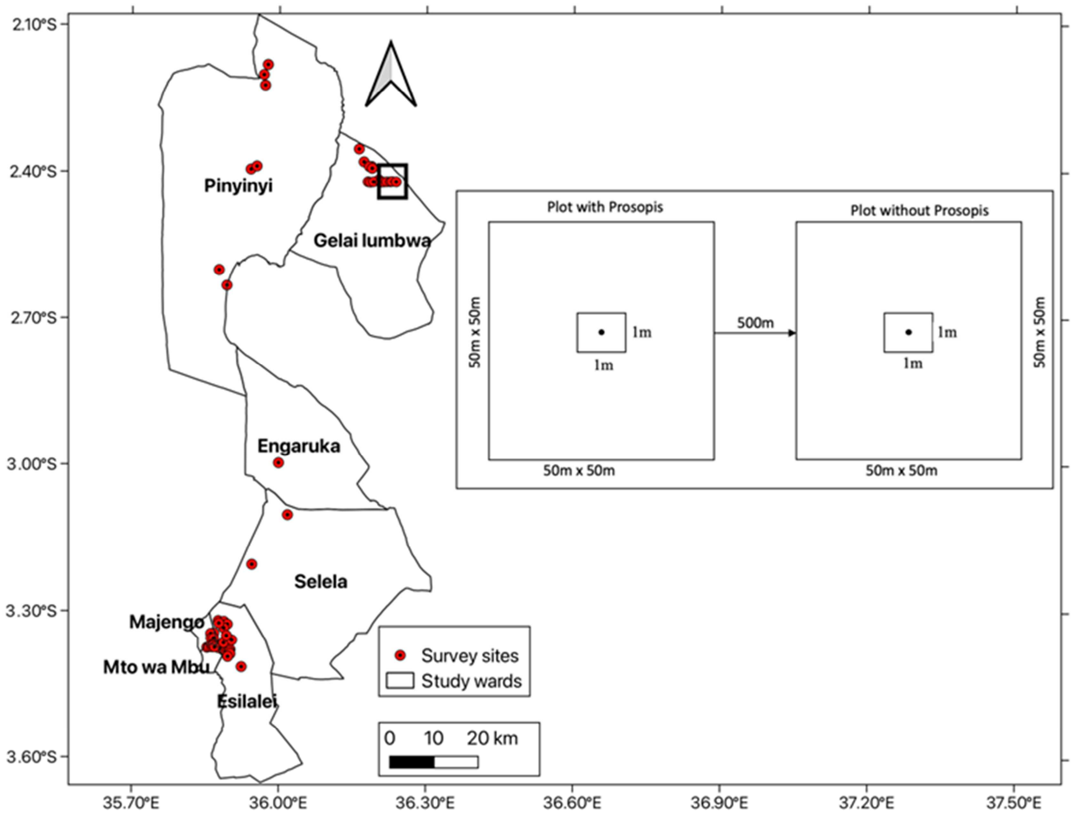

Fig. 1b. The map illustrates the locations of survey sites (marked with red dots) of *P. juliflora* within the study wards

Migungani ward this is a new administrative area cut from the Selela ward. While the Majengo ward is found in the Southern part near the lake Manyara and is bordered with Mto wa Mbu and Esilalei wards. According to (Kalacska *et al.*, 2017) the climate of the study area can be divided into four distinct periods: the short rains from November to January, a short dry period until March, the long rains from late March to May, and a long dry period from June to October. The Monduli area receive an average annual rainfall of 650 mm, while Ngorongoro and Longido districts parts receive about 1,100 mm (Verhoeve *et al.*, 2021). The mean monthly temperature is highest in October and November, averaging 33°C, while the coolest months are June and July, with average temperatures of 23°C. Relative humidity in the region is generally low, ranging from 30% to 50%.

The vegetation in the study area is classified into four main types: grassland, woodland, bushland, and wetland. Grasslands, found in open flat areas, are dominated by short grasses such as *Cynodon dactylon*, *Eleusine jaegeri*, and *Sporobolus ioclados*. Woodland vegetation features scattered trees and shrubs, including *Acacia tortilis*, *Acacia brevispica*, and *Commiphora africana*. Bushland vegetation comprises dense thickets of shrubs like *Dodonaea viscosa* and *Maerua crassifolia*. The soils around Lake Natron are predominantly volcanic, resulting from eruptions of the Oldoinyo Lengai mountain (Milyaso *et al.*, 2015).

These soils include basalts, trachytes, phonolites, and tuffs, and are typically shallow, less than one meter deep, often covered by a thin layer of vegetation. High temperatures lead to high rates of evapotranspiration, resulting in soils with low water holding capacity and high levels of aluminum exchange, which can limit plant growth.

Pastoralism is the dominant land use type in the area, with Maasai pastoralists practicing grazing. Livestock rearing is vital for local communities, and the Maasai have a deep cultural attachment to their cattle. Agriculture is also practiced in the Lake Natron Basin, with crops such as maize, beans, and vegetables grown in areas with access to water sources like rivers or springs. The transect lines were established towards north directions where *P. juliflora* is presents while uninvaded quadrants were established towards east direction.

Study design

In November 2023, we conducted a Participatory Rural Appraisal (PRA) across the study area wards to gather preliminary information on the presence of the invasive plant *P. juliflora* in the study area. The PRA engaged 96 key informants, including members of environmental committees and ward/village executive officers from each ward, the team was responsible to give prior information on areas in which *P. juliflora* is found in their areas. Moreover, the PRA team enables to identify demarcation of the settlements, farmlands and grazingland, land use types. Through this process, we obtained preliminary insights on the specific wards and villages (Table 1) where community representatives reported the presence of *P. juliflora*. This information served as a foundation for our main field data collection on understanding areas to establish a line transects. The minimum number of trees set in order to establish a quadrant within a line transect were 5 and a distance between one quadrant and the other was 500m.

Table 1. Preliminary information on the presence of *P. juliflora* in various wards and villages within the study area as reported by community representatives during the PRA workshop conducted in November, 2023.

District	Ward	Village
Monduli	Esilalei	Mongere
		Baraka
		Losilwa
		Esilalei
	Mto wa Mbu	Magadini
	Selela	Mbaashi
	Engaruka	Engaruka
	Majengo	Majengo A
	Migungani	Kigongoni
Longido	Gelai Lumbwa	Wosiwosi
Ngorongoro	Pinyinyi	Pinyinyi

Population density and structure of P. juliflora across the wards and land use types

We purposively selected villages with *P. juliflora* and conducted surveys across various land use types, including grazingland, farmland, and settled areas. We established line transects with a width of 1 km on each side. When encountering a *P. juliflora* patch containing more than five trees, we set up a 50m × 50m square quadrant in the line transect with a distance of 500m from one quadrant to another the line transects were established from the first point where *P. juliflora* found towards north direction till the boundary of that village which was used as demarcation. Motor bicycles was used to facilitate movement in the line transect.

Parameters recorded include tree diameter, height, seedling counts, quadrant center coordinates, land use type, altitude, and any additional invasive species found. Tools used were Calliper for measure tree diameter, Sunto for measure height and Global Position System (GPS) to record altitude and coordinates.

For data analysis, we calculated descriptive statistics, including totals, means, standard errors, minimum, and maximum values for mature trees and seedlings across different wards and land use types. We used measures of central tendency (mean) and dispersion (standard error) to summarize density data. To assess differences in mature tree and seedling densities across wards, we applied the Kruskal-Wallis test to identify statistically significant variations. Additionally, we used the Kruskal-Wallis test to compare densities across different land use types (farmland, grazing land, and settlements).

Population structure of P. juliflora by diameter sizes across the wards

Understanding the *P. juliflora* population in each of the invaded villages in the surveyed wards was very important as this information can later breakdown for management practices; determine tools to be used for the removal of the trees, and final uses like fuelwood, charcoal and timber. In this section, we categorized *P. juliflora* trees into four diameter size classes (1-10 cm, 11-20 cm, 21-30 cm, and >30 cm) and calculated the total number of trees in each diameter class for each ward and land use. We then used the Chi-Square test to assess whether the distribution of trees across these diameter classes differed significantly between wards. The Chi-Square statistic and the associated p-value helped determine the significance of observed differences in diameter class distribution. To visually represent these distributions, we created bar plots with color coding to differentiate between the diameter classes, illustrating the variation in tree diameters across different land uses.

Ecological impact of P. juliflora on native grasses and forbs

To assess the ecological impact of *P. juliflora* on native grasses and forbs in grazinglands. A 50m × 50m quadrant established in a line transect that containing *P. juliflora* in grazing areas. 1m × 1m quadrant established at the center of the quadrant and other four replicate quadrant at the corner points of the quadrant. The control quadrant of 50m × 50m was placed towards the East direction in uninvaded area just after the invaded quadrant. The control quadrants were limited within 500m East direction from the center of *P. juliflora* invaded quadrant.

In case the distance from the center of the invaded quadrant to the uninvaded quadrant is more than 500m in East direction the $50m^2$control quadrant was established in either direction adjacent to the invaded quadrant in order to maintain habitat homogeneity. The 1m × 1m quadrant was established at the center of the uninvaded quadrant and the other at the corner points. The line transects were established from the first point where *P. juliflora* patch of at least 5 trees was found towards the end of the village. The villages were used as boundary between one transect and the other. The $50m^2$ quadrants were repeatedly established within the transects and adjacent to the transect as control quadrants throughout until the end of the transect and the distance between the $50m^2$ quadrants within the line transect was 500m. In both quadrants, we identified and recorded the number of grass and forb species present. Additionally, we estimated the percentage of ground cover by native grasses and forbs using the Likert scale: 0-25% (low coverage), 25-50% (moderate coverage), and above 50% (high coverage).

For data analysis, we calculated descriptive statistics, including the mean, standard error, and total values for grass diversity and cover in areas with and without *P. juliflora*. To compare median grass richness and cover between these areas, we used the Wilcoxon Rank-Sum test, a non-parametric method. We calculated the test statistic and p-value to determine the significance of differences. Bar plots with error bars illustrated mean grass diversity and cover, with significant differences between groups marked by letters (e.g., "a" and "b"). By comparing species diversity in both the *P. juliflora*-infested and control quadrants, we aimed to evaluate the ecological impact of *P. juliflora* on native vegetation.

Spatial distribution of P. juliflora across the wards and land use types

We used a similar sampling approach. We recorded GPS coordinates for each *P. juliflora* quadrant. These GPS coordinates enabled us to extract additional anthropogenic and environmental factors from the WorldClim and International Soil Reference and Information Centre (ISRIC) databases. We performed a spatial distribution analysis using kernel density estimation to calculate and visualize *P. juliflora* stem density per square kilometer in ArcMap. This analysis resulted in a color gradient map, where darker colors indicated lower densities and lighter colors represented higher densities of *P. juliflora*.

Environmental and anthropogenic factors influencing the population density of P. juliflora

We used a Generalized Linear Model (GLM) with a Negative Binomial distribution to assess the effects of environmental and anthropogenic factors on *P. juliflora* population density. This model was chosen to address the over dispersion in our data, where the variance exceeded the mean. Prior to modeling, we conducted a multicollinearity test on our variables, including anthropogenic factors (land use types, distance to roads), climate variables (elevation, mean annual temperature, annual precipitation), and soil factors (sand, clay, and silt content). Only variables with correlation coefficients below 0.7 were selected, ensuring acceptable multicollinearity levels. All statistical analyses were performed using R software version 4.3.2.

Results and discussion

Population density of P. juliflora trees and seedling across the wards and land use types

The population density analysis of *P. juliflora* trees across different wards and land use types reveals significant variability in tree density and seedling establishment. While Esilalei ward exhibited higher values with 292 trees (mean = 18.25, SE = 5.21) and a total density of 1620 trees and 1944 seedlings per hectare. This variability caused by several factors including time of introductions and adoption rates of the community members in other areas (Table 2).

Across different land use types, the population density of trees and seedling of *P. juliflora* also varied significantly Table 3. The results showed that settlements had high density of *P. juliflora* trees 2832 per hectare and 4220 number of seedlings compared to the grazingland that has an average of 800 and 3056 density of trees and seedlings respectively. This is because at first this species were planted along the households and later pods moved to the grazinglands by livestocks.

The farmlands results underscore the influence of land use types, and possibly management practices on the growth and spread of this invasive species. For instance, wards like Esilalei and Gelailumbwa exhibit high densities and active regeneration of *P. juliflora* because of the presence of several *P. juliflora* nursery owners who are selling the seedlings to the community. In Gelailumbwa the high density is influenced by the cattles and water which is the main drivers for the spread of the *P. juliflora* seedlings in the area. Also Gelailumbwa grazing area is found is the lower elevation this makes the seedling brought by the water from upper area to accumulate in the grazing land. This is also supported by (Kamiri *et al.*, 2024) that *P. juliflora* seedlings are brought by the drivers in the lower lands. This findings are consistent with studies that have identified *P. juliflora* as a highly adaptable species capable of thriving in a variety of environmental conditions, particularly in arid and semi-arid regions (Pasiecznik *et al.*, 2001) . The high density of seedlings in these wards indicates a strong potential for further spread if left unmanaged, which aligns with findings by (Mwangi and Swallow, 2005) that highlight the aggressive nature of *P. juliflora* in favorable conditions. In contrast, the limited or absent regeneration in wards like Engaruka, Majengo, and Selela suggests the influence of land use types on the distribution and density of *P. juliflora* as the species is found in the settlement areas where frequently removal of the seedlings are conducted also the *P. juliflora* pods are collected for feeding livestocks during the dry season.

Table 2. Population density of mature and seedlings of *P. juliflora* across the surveyed wards

Ward	Metric Density per ha	Total	Mean	Std Error	Min	Max	No. of quadrants
Engaruka	Count of mature trees	8.00	8.00	NA	8	8	1
	Density of mature trees	32.00	32.00	NA	32	32	1
	Count of seedlings	0.00	0.00	NA	0	0	1
	Density of seedlings	0.00	0.00	NA	0	0	1
Esilalei	Count of mature trees	292.00	18.25	5.21	6	79	16
	Density of mature trees	1620.00	101.25	24.84	24	316	16
	Count of seedlings	486.00	30.38	8.60	0	123	16
	Density of seedlings	1944.00	121.50	36.31	0	492	16
Gelailumbwa	Count of mature trees	224.00	14.00	2.16	1	21	16
	Density of mature trees	1000.00	62.50	8.94	4	84	16
	Count of seedlings	1253.00	78.31	11.38	8	160	16
	Density of seedlings	2606.00	162.88	30.30	8	604	16
Majengo	Count of mature trees	56.00	11.20	0.86	9	14	5
	Density of mature trees	224.00	44.80	4.80	36	56	5
	Count of seedlings	42.00	8.40	2.58	2	16	5
	Density of seedlings	128.00	25.60	9.22	8	64	5
Migungani	Count of mature trees	241.00	24.10	9.97	10	107	10
	Density of mature trees	920.00	92.00	72.77	40	428	10
	Count of seedlings	66.00	6.60	3.54	3	17	10
	Density of seedlings	256.00	25.60	11.97	12	68	10
Mto wa mbu	Count of mature trees	48.00	9.60	1.33	8	14	5
	Density of mature trees	220.00	44.00	4.58	32	56	5
	Count of seedlings	0.00	0.00	NA	0	0	5
	Density of seedlings	0.00	0.00	NA	0	0	5
Pinyinyi	Count of mature trees	80.00	8.00	1.74	1	14	10
	Density of mature trees	392.00	39.20	7.01	4	56	10
	Count of seedlings	52.00	5.20	1.80	4	23	10
	Density of seedlings	144.00	14.40	5.20	4	36	10
Selela	Count of mature trees	17.00	8.50	1.50	6	11	2
	Density of mature trees	68.00	34.00	10.00	24	44	2
	Count of seedlings	4.00	2.00	2.00	0	4	2
	Density of seedlings	0.00	0.00	NA	0	0	2

This is supported by research indicating that *P. juliflora* can be successfully managed through a combination of physical removal, grazing management and utilization (Kamiri *et al.*, 2024; H. Shiferaw *et al.*, 2004). On the other hand the lower level it indicates that the species is at establishment stage. Effective control of *P. juliflora* requires ongoing monitoring and intervention, particularly in areas that has not yet invaded and those with low trees and seedling densities. The high variability in seedling density between land use types highlights the potential for future spread within and out of the current invaded areas. The intervention efforts is very important to mitigate the environmental and socio-economic impacts of *P. juliflora* (Choge *et al.*, 2007).

The variation in *P. juliflora* densities across land use types highlights the adaptability of this invasive species to different environments and the significant influence of land management practices on its spread.

In farmland, where regular cultivation likely disrupts seedling establishment and *P. juliflora* densities are relatively low. This is consistent with research indicating that active land management, such as plowing and crop cultivation, can effectively limit the spread of *P. juliflora* by disturbing the soil and preventing seedlings from establishing (Pasiecznik *et al*., 2001). In contrast, grazing lands and settlement areas, which may experience less intensive land management, provide conditions conducive to the species' proliferation. Grazinglands, in particular, have been identified as environments where soil disturbance from livestock can facilitate the germination and spread of *P. juliflora* (Mwangi and Swallow, 2005). The particularly high density of seedlings in settlement areas is concerning, as it indicates a strong potential for future spread. This finding aligns with previous studies that have shown how human activities in settlements, such as the movement of people, vehicles, and livestock, can inadvertently contribute to the dispersal of *P. juliflora* seeds (Shiferaw *et al*., 2022; Shiferaw and Demissew, 2023). The high seedling density suggests that *P. juliflora* is not only well-established in these areas but also poses a growing threat to local ecosystems and livelihoods, as the species is likely to expand further if left unmanaged. These results underscore the necessity for targeted management strategies to control the spread of *P. juliflora*, particularly in areas where it is most abundant, such as grazing lands and settlements. Effective management could include measures to reduce soil disturbance, prevent seed dispersal, and enhance the competitive ability of native vegetation (Choge *et al*., 2007). Without intervention, the high seedling densities observed in these areas may lead to increased mature tree densities in the future, further entrenching *P. juliflora* in these landscapes and exacerbating its ecological and socio-economic impacts.

Table 3. Population density of mature and seedlings of *P. juliflora* across land use types

Land use	Metric (ha)	Sum	Mean	SE	Min	Max	No of quadrants
Farm land	Count of mature trees	37.00	9.25	1.65	6	11	4
	Density of mature trees	148.00	37.00	6.69	24	44	4
	Count of seedlings	19.00	4.75	2.39	0	9	4
	Density of seedlings	76.00	19.00	9.57	0	36	4
Grazingland	Count of mature trees	200.00	11.11	1.86	1	21	20
	Density of mature trees	800.00	44.44	7.40	4	84	20
	Count of seedlings	764.00	42.44	9.79	0	151	20
	Density of seedlings	3056.00	169.78	39.15	0	604	20
Settlement	Count of mature trees	708.00	12.55	2.11	4	107	36
	Density of mature trees	2832.00	50.57	8.47	16	428	36
	Count of seedlings	1055.00	18.84	5.03	0	123	36
	Density of seedlings	4220.00	75.36	20.12	0	492	36

Table 4. Population density of *P. juliflora* by diameter sizes across all the surveyed wards

Ward	1-10 cm	11-20 cm	21-30 cm	>30 cm	Total
Engaruka	6	2	0	0	8
Esilalei	260	184	26	2	472
Gelailumbwa	154	50	0	0	204
Majengo	34	21	0	0	55
Migungani	131	65	9	0	205
Mto wa Mbu	38	19	0	0	57
Pinyinyi	64	20	0	0	84
Selela	11	6	0	0	17
Total	698	367	35	2	1102

Population structure of P. juliflora by diameter sizes across all the surveyed wards

The population structure *P. juliflora* varies significantly (X-squared = 49.852, df = 21, p-value = 0.000383) across the study wards Table 4.

The majority of *P. juliflora* trees across all wards are in the smaller diameter classes (1-20 cm), indicating that the populations are relatively young. Very few trees fall into the larger diameter classes (21-30 cm, >30 cm). The data shows a notable difference in the distribution of tree sizes between land use types. Despite the high abundance of *P. juliflora* in the settlement area and grazingland trees with big diameters and heights are found on the farmland. This disparity is attributed by the silvicultural practices performed by farmers, such as thinning and pruning. These practices create space for crops, which in turn favour the growth of the remaining trees. On the other hand in the settlements and grazingland the trees with big diameters are likely to be felling down for fuelwood, and other uses. Additionally, farmers often leave some trees in boundary areas for demarcation purposes this isolation reduces competition between trees, allowing these trees to grow larger. This finding aligned with (Balcha, 2022) reported that farmers may experience little negative impacts of the *P. juliflora* and are likely to become reluctant on adopting integrated management approach. The dominance of smaller diameter classes suggests a high rate of seedling establishment and rapid growth under unmanaged conditions. In the case of *P. juliflora* the invasion level plays an important role (Bekele *et al.*, 2018) found in Ethiopia and Kenya that impacts on agro-pastoralists varies with the invasion level of *P. juliflora*. While lower invasion levels have an overall positive impact on farmers or are perceived as positive, higher invasion levels have a negative overall impact or are perceived as negative. Also (Shiferaw *et al.*, 2022) found this for livestock-keeping agro-pastoralists. In a much earlier study, also (Mwangi and Swallow, 2008) found that farmers are facing increasing clearing costs once the invasion level is advanced and the farm increasingly surrounded by *P. juliflora*. This pattern is typical of invasive species like *P. juliflora*, which can quickly colonize new areas, especially in disturbed habitats (Ravhuhali *et al.*, 2021). The ability of *P. juliflora* to establish dense populations in a short timeframe poses significant challenges for managing its spread and mitigating its impacts on local ecosystems. On the other hand despite the low abundancy of *P. juliflora* seedlings in the farmland if the area is left uncropped for some reason such as drought it is easier for the invasion to increase the expansion and increase the farm cultivation costs (Al-Assaf *et al.*, 2020; Pandey *et al.*, 2019).

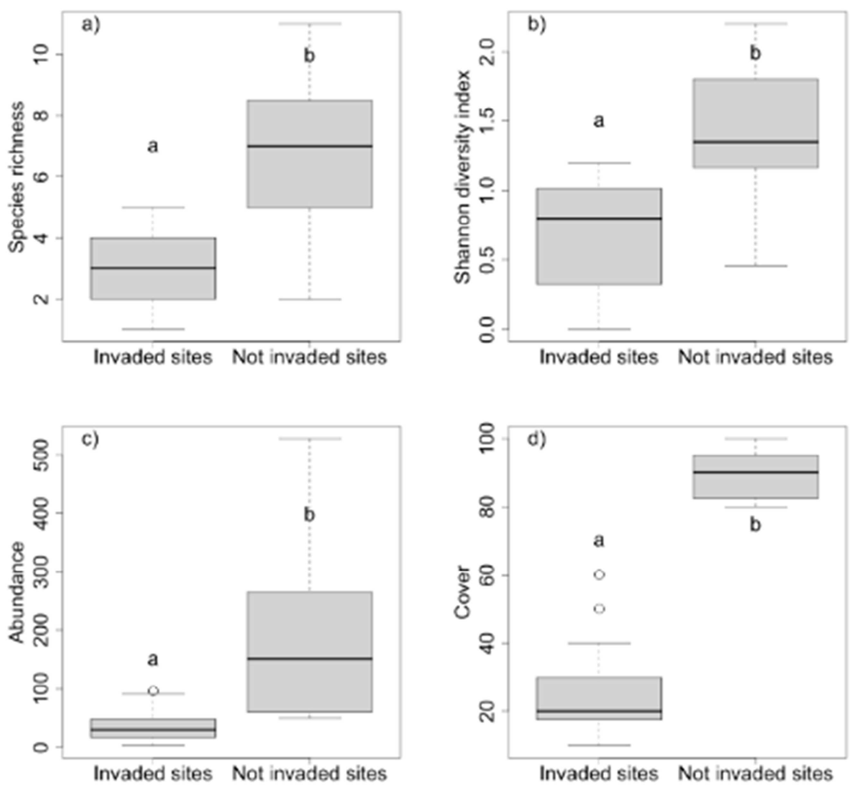

Fig. 2. Boxplots comparing Invaded sites and Not invaded sites for four response variables

Ecological impacts of P. juliflora on native grasses and forbs

In the uninvaded sites, a total of 3022 forb and grass individuals were recorded, distributed among 68 different species. In contrast, in the invaded sites, a total of 559 forb and grass individuals were observed across 45 different species. Based on Wilcoxon test in all four response variables (species richness [(p= 0.001), Shannon diversity index (p =0.001), abundance (p <0.001), and cover (p <0.001)], uninvaded sites show significantly higher values compared to invaded sites. The significant letters (a and b) across all plots indicate that the differences between the invaded sites and uninvaded sites are statistically significant for all variables (Fig. 2). This suggests that uninvaded sites are generally more species-rich, more diverse, have higher species abundance, and greater cover compared to invaded sites.

The results presented in the boxplots align with findings from many studies in invasion ecology that investigate the impact of invasive species on biodiversity and ecosystem structure (Ricciardi *et al.*, 2017; Simberloff and Rejmanek, 2019; Vilà *et al.*, 2011). The significant differences between invaded and uninvaded sites in species richness, Shannon diversity, abundance, and cover suggest that *P. juliflora* have detrimental effects on native biodiversity and ecosystem functioning.

Invasion ecology literature consistently reports reductions in species richness and species diversity in ecosystems that have been invaded by non-native species (Gentili *et al.*, 2021; Mollot *et al.*, 2017). This often attributed to competitive exclusion, where invasive species outcompete native species for resources such as light, nutrients, and space, leading to a decline in native species populations. Moreover a comprehensive review by (Shiferaw *et al.*, 2019; Vilà *et al.*, 2011) found that invasive species significantly reduce species richness and diversity across various ecosystems. The reduction in richness and diversity observed in the Lake Natron basin in the Northern Tanzania supports these findings.

Invasive plants often form dense monocultures that dominate the landscape, limiting the available space and resources for native species. Similar findings were noted by (Simberloff and Rejmanek, 2019) observed that invasive plants such as *P. juliflora* reduced native plant abundance in arid and semi-arid ecosystems. The differences in cover between invaded and uninvaded sites also reflect the typical outcome of biological invasions. Furthermore (Novoa *et al.*, 2018) found that invasive species in South African fynbos ecosystems significantly reduced native plant cover and altered ecosystem functions. In the current analysis, the higher cover in uninvaded sites suggests that native species are better able to establish and maintain populations when invasive species are absent, which is consistent with the findings of (Brooks *et al.*, 2004) in their study of invasive species effects on desert ecosystems.

Spatial distribution map of P. juliflora across the wards

P.juliflora is distributed in all wards with the worst invasion in Esilalei (Fig. 3). This ward has the most significant infestation, particularly in the 97-141 and 141-162 individual count categories in Fig. 3, indicating severe spread of the species. Mto Wa Mbu follows closely, with similarly high concertation, especially near its intersection with Majengo and Esilalei, where counts reach up to 141-162 individuals. Gelai Lubwa is heavily infested, with many occurrences in the 141-162 range, showing a significant presence of *P. juliflora*.

Engaruka comes next, with a notable but slightly lower concentration, generally within the 23-46 individual count range. Esilalei shows a more scattered distribution, with counts mostly in the lower ranges, indicating a moderate level of infestation. Selela exhibits fewer and more dispersed occurrences, mostly in the 23-46 range, suggesting a relatively lower level of infestation compared to the other wards. Finally, Pinyinyi has the least concentration of *P. juliflora*, with only a few smaller clusters, indicating minimal presence of the species in this ward.

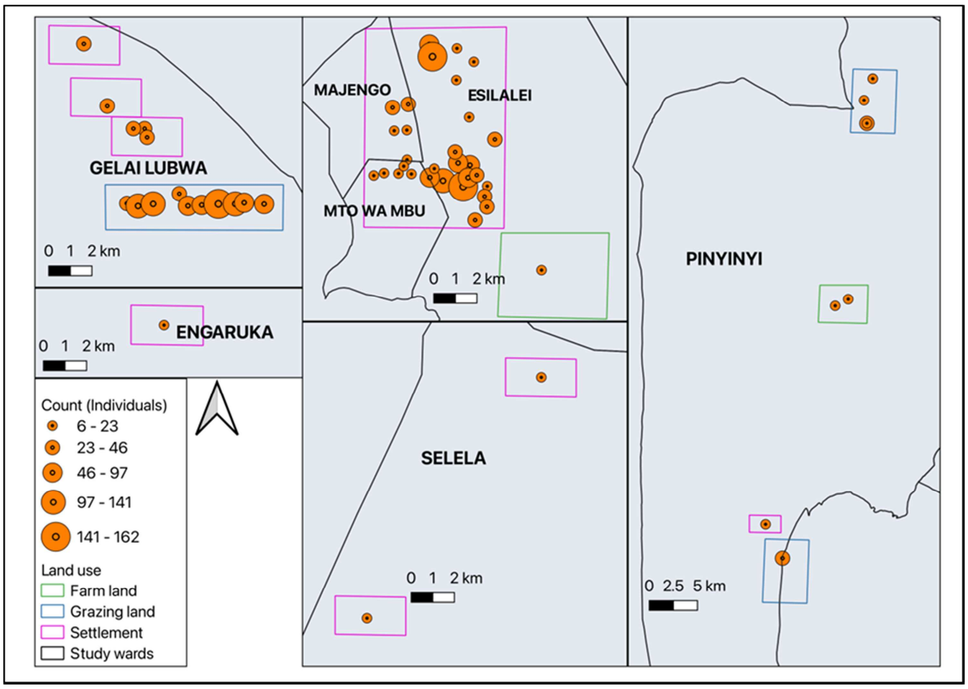

Fig. 3. The spatial distribution of P. juliflora (indicated by orange dots) across study wards and land use types, with the count of individuals represented by the size of the dots

Environmental and anthropogenic factors influencing the population density of P. juliflora

The negative binomial regression analysis results (Table 5) indicate that the density of *P. juliflora* is influenced by several environmental and geographical factors. The model shows that land use plays a significant role, particularly in settlement areas, where the density of *P. juliflora* is significantly higher compared to grazingland and farmland. This suggests that settlement areas is the place where this tree species introduced first and their pods eaten by livestocks and spread to other land use types with the help of other drivers such as wind and water that moves the seeds to the lower lands. A study conducted in Baringo in Kenya showed the land use change influence the spread of *P. juliflora* (Mbaabu *et al.*, 2019). Temperature is another important factor, with higher temperatures being associated with increased *P. juliflora* density, indicating that the species thrives in warmer climates. The findings align with (Sintayehu *et al.*, 2020) who found the increase of the spread of the *P. juliflora* to the areas that initial were unsuitable due to the global increase of climate change effects.

Table 5. Summarizes predictor variables that contribute to the variation in *P. juliflora* density in the study areas

Parameters	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	-44.5000	17.3200	-2.5690	0.0102*
Land use Farm land	Reference category			
Land use Grazing land	0.5182	0.3847	1.3470	0.1780
Land use Settlement	1.2000	0.3924	3.0580	0.0022**
Annual mean temperature	0.2589	0.0984	2.6310	0.0085**
Annual precipitation	-0.0010	0.0017	-0.5700	0.5685
Elevation	0.0001	0.0009	0.1440	0.8853
Distance to roads	0.0000	0.0000	-2.1280	0.0334*
Distance to rivers	0.0001	0.0001	1.0190	0.3081
Clay content	0.4670	0.1735	2.6920	0.0071**
Silt content	0.2799	0.1707	1.6400	0.1010
Sand content	0.4350	0.1752	2.4830	0.0130*

Soil properties particularly clay and sand content are also significant predictors of *P. juliflora* density. Higher clay and sand content in the soil are associated with increased density, suggesting that these soil types offer favorable conditions for the species' proliferation. Proximity to roads is another significant factor; the analysis reveals that *P. juliflora* tends to be more densely populated closer to roads, possibly due to disturbances or human activities that facilitate its spread.

In contrast, other factors such as precipitation, elevation, and distance to rivers do not show statistically significant effects on *P. juliflora* density in this model however this was due to the facts that *P. juliflora* in the Lake Natron basin are at establishment stage and this study did not take into account on the number of *P. juliflora* seeds that are found in the soil and along the water sources. The relationship between, elevation, and distance to rivers and *P. juliflora* density is negative, although not significant, suggesting that increased of these factors might not favor the species density. This differs from other studies (Kamiri *et al.*, 2024; Mbaabu *et al.*, 2019) that found distance from the river and elevation influence *P. juliflora* distribution.

The study findings underscore the complex interplay of environmental and anthropogenic factors that influence the density of *P. juliflora*. The significant role of land use, temperature, soil properties, and proximity to roads highlights the need for targeted management strategies that consider these variables. For instance, controlling the spread of *P. juliflora* in settlement areas and along roadways may require specific interventions, such as improved land management practices, active restoration of native vegetation, and monitoring of disturbed areas. The non-significant effects of precipitation, elevation, and distance to rivers suggest that *P. juliflora* is a highly adaptable species capable of thriving in a variety of environments.

This adaptability poses a challenge for management efforts, as the species can potentially invade and establish in diverse habitats. By considering multiple environmental and anthropogenic factors in managing the spread of *P. juliflora* it helps in addressing the key drivers of its proliferation, particularly in areas where it is most likely to spread. Hence management efforts can be more effectively targeted, reducing the impact of this invasive species on native ecosystems and local livelihoods (Mwangi and Swallow, 2005; Pasiecznik *et al.*, 2001; Shiferaw *et al.*, 2004).

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Conclusion

This study provides a comprehensive analysis of the factors influencing the population density and distribution of *P. juliflora* across different land use types, as well as its impact on native grass species diversity and cover. The population structure of the *P. juliflora* in the lake Natron basin-Northern Tanzania is now at the establishment stage where by 63% of all trees fall into diameter class of 1-10cm, 33.3% above 10-20cm while only 4% are above 20cm.

The study further reveals that land use, temperature, soil properties, and proximity to roads are critical factors in determining the density of *P. juliflora*. While the impact of *P. juliflora* on grass cover appears to be minimal at this stage, its significant reduction of grass species richness poses a long-term threat to biodiversity and ecosystem stability. Lastly, these study findings emphasize the need for localized, multifaceted management approaches that consider the specific environmental and anthropogenic factors driving the spread of *P. juliflora*.

Recommendations

1. Establish designated cattle pathways that minimize contact with dense *P. juliflora* areas to reduce seed dispersal. Implementing rotational grazing practices can help control cattle movement and mitigate the spread of the species.
2. Foster collaboration with local communities to promote awareness about the ecological impacts of *P. juliflora*. Educational programs can empower residents to adopt sustainable land use practices and engage in monitoring efforts.
3. Promote the cultivation of native fodder species that can serve as alternatives to *P. juliflora* for livestock. This can include replanting native grasses and other species to support ecosystem stability that can help reduce grazing pressure on areas where the species proliferates.
4. Advocate for the development of policies that regulate the planting and management of invasive species like *P. juliflora*. Tree growers should be banned from planting and selling *P. juliflora* seedlings. Support from local and regional authorities can enhance management efforts.
5. Frequent surveillance particularly along the Lake Natron shore and other water sources should be conducted in order to collect the seeds and uproot the seedlings. During the ecological survey data collection, we found some *P. juliflora* seedlings along the lake shore which seem to be brought by water runoff during the rainy seasons also seedlings are likely to be found there due to cattle pathways.
6. While the GLM provides valuable insights, further research is needed to fully understand the complex interactions between environmental variables and *P. juliflora* invasion dynamics in the Lake Natron basin. Long term monitoring studies, experimental manipulations, and spatial modelling approaches could help elucidate the underlying mechanisms driving the species' distribution and spread.

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