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Original Research Article

Demography of baobab (*Adansonia digitata L.*) population in different land uses in the semi-arid areas of Tanzania

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A B S T R A C T

Baobab is a deciduous non-timber tree species that are facing severe threats from both anthropogenic and climatic pressures across its range states. This study assessed natural rates of recruitment and associated threats of baobabs within and across different land-use types in semi-arid areas of Tanzania. The study was based on a stratified random sampling design composed of the following land-use types: strictly protected areas, non-strictly protected areas, and unprotected areas. Rates of recruitment were measured from a total of 337 grids (representing 40% of semi-arid land) in three different land-use types in a plot measuring 1 km long and 50 m wide. Results show that juvenile, sub-adult and adult baobab populations varied significantly ($p < 0.001$) within and across land-use types with only 4.7% of surveyed plots having a few juveniles (about four stems per plot) across the study area. The density of adult, sub-adult and juvenile populations were 1.53 ± 0.105, 0.82 ± 0.149 and 0.33 ± 0.253 plants/ha respectively with strictly protected areas (national parks) supporting the most abundant (53%) of the adult trees. Furthermore, the results show inverse *J*-shaped and bell-shaped distribution in the strictly protected areas and unprotected areas, respectively. The densities of mature baobabs were found to be higher than juvenile baobabs in all three land-use types. The number of baobabs damaged was higher than undamaged in all land-use types. Our results suggest that anthropogenic threats are higher than biophysical factors in driving the species to mortality and population extirpation. Likely, baobab size and distribution across land-use types are mostly influenced by herbivory and fire that likely limit the establishment in most of these areas. Strategies promoting the recruitment and sustainable harvesting practices of baobab would perhaps be the best options to support the population persistence in different land uses in semi-arid areas. The study recommends more studies to understand the factors affecting germination and recruitment rates in order to predict future distributions in semi-arid environments. Also in defining and planning for different land-use system, baobab species should be taken into consideration and in particular in agroforestry farms can easily qualify as a tree crop. Promotion of active recruitment through planting especially in communal lands and protection from herbivory is required if we are to overcome the recruitment bottlenecks as influenced by increasing impacts of land use and climate

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change and overexploitation. The intentional growing of trees and shrubs in combination with crops cultivation and forage production is also recommended to smallholder farmers.

1. Introduction

Understanding how different land uses and their practices as well as climatic conditions influence distribution and structure of tree species such as African baobab (*Adansonia digitata L.*) is of paramount importance for enhancing sustainable management of trees and during the restoration of natural woodlands in Africa. The baobab tree has multi-purpose uses as it produces significant non-timber forest products (NTFPs) and every part of the plant is reported to be useful (Sidibe and Williams, 2002; De Caluwé et al., 2009; Nguta et al., 2010). The baobab is very important to humans and animals in the dry areas of Africa. It offers shelter, a source of nutrition, clothing as well as raw material for many useful items. For example, baobab oil extracted from the seed is used in the cosmetics industry and is also sold internationally (Gruenwald and Galiza, 2005). Furthermore, baobab fruit pulp has been approved for sale in the European Union countries and the United States of America (De Smedt et al., 2010). Lisao et al. (2018) reported that the bark is an essential part of the baobab and humans have harvested it for fodder and medicinal purposes. Also, elephants (*Loxodonta africana*) have been observed to utilise baobabs, especially in times of resource inadequacy (O'Connor et al., 2007; Biru and Bekele, 2012; Msalilwa et al., 2019a).

Land-use intensification has been predicted to increase pressure on baobab populations in the future (Wilson, 1998; Schumann et al., 2010; Schumann et al., 2012; Van den Bilcke et al., 2013). There is a need to conduct studies on baobab population structure in different land uses. Furthermore, human activities affect land and natural resources due to population growth and food requirement. The rise in human population growth has further increased pressure on exploited plant resources for subsistence use and may result in a reduction of baobabs in Tanzania. Many studies have shown that land-use and human activities influence the population structure of the baobab due to economic and socio-cultural uses of the tree (Wilson, 1988; Schumann et al., 2012). The baobab appears to thrive well in human settlements and crop fields while in other areas it is only in well-protected areas, supposedly with little human disturbance (Assogbadjo et al., 2005; Duvall, 2007; Venter and Witkowski 2013). A study by Schumann et al. (2010) found that land-use type had a significant impact on the populations of the baobabs between the protected area and unprotected communal area. In West Africa, there is a high population of baobabs in human-dominated landscapes, especially near homesteads (Duvall, 2007; Schumann et al., 2012). In Schumann et al. (2010) study, they observed an inverse '*J*-shape' for the park stands while the curve of the unprotected area stands was bell-shaped. The observed bell-shaped curve indicates large baobabs are prominent in many land uses in African savannas, with apparent lack of young trees suggesting limited and possibly episodic recruitment and this can happen over large areas related to good rainfall periods corresponding with periods of good fruit/seed production (Venter and Witkowski, 2010). A study by Venter and Witkowski (2013) reported a microsite establishment with poor recruitment in natural areas and good recruitment in communal areas near homesteads and cultivated areas. The main reasons for this recruitment pattern were due to herbivory and infrequent rainfall that affects the survival and establishment of seedlings (Venter and Witkowski 2013; Lisao et al., 2018). Baobabs need to be protected against animals, especially during the juvenile stage (ICUC, 2002). Thus, there is an urgent need to conduct studies across different land-uses to determine the current status of *A. digitata* in protected areas and the surrounding communal areas in the semi-arid areas. Therefore, studying the population structure of the baobab across different land-use types is key to understanding factors that shape the population structure. Those factors will assist on which the tree domestication, conservation, management and improvement strategies can be modelled.

Population structure determines population stability (Shen et al., 2013). A population with an inverse *J*-shaped size class distribution curve, with large numbers of juveniles relative to adults (higher recruitment), shows a healthy and potentially growing, stable population. Lack of juveniles indicates a declining population (Condit et al., 1998; Miller, 2008). However, this may not hold for larger and longer-lived species such as the baobab where trees can withstand population levels with low or episodic recruitment. Baobab population structure has been observed to display a bell-shaped distribution suggesting a higher proportion of trees in the middle size classes (Venter and Witkowski, 2010). The bell-shaped distribution could be due to episodic recruitment and considered normal for baobab (Venter and Witkowski, 2010).

Despite the importance of the baobab products to local communities in the semi-arid areas of Tanzania, information on the population structure of the species is limited. It is crucial to conduct baobab population structure assessments to determine changes in population size and age distribution for sustainable utilization and conservation of baobab species. This study assessed demographic structure of baobabs within and across land-use types, assessed rates of threats facing populations in different land-use types, proposed possible future ways of sustaining populations in these land-use types in the semi-arid areas of Tanzania.

2. Methods

2.1. Study area description

Baobab population structure was assessed in the semi-arid areas in Tanzania (Latitude: 2°39′ 5.225″S, Longitude: 34° 8′ 29.364″ E) and (Latitude: 8° 2′53.048′ S, Longitude: 35° 3′ 18.731″E). The area included strictly protected areas (National Parks and Forest Reserves), non-strictly protected areas (Game Controlled Areas, Game Reserves, Open Areas and Wildlife Management Areas) and unprotected areas (croplands, pastures and settlements) (Fig. 1). The altitude of the area ranges from 490 m to 1400 m above mean sea level. The annual rain of the study area is less than 800 mm. The mean monthly minimum and maximum temperatures are 26 °C and 30 °C respectively. Semi-arid areas are characterized by low amount of rainfall, high evapotranspiration rates and erratic temporal and spatial distribution of rainfall (Nieuwolt, 1973). As a consequence, the semi-arid areas have an inherently low and unreliable crop and livestock production (Hatibu et al., 1999). Human population density of the semi-arid areas is approximately 62 persons per square kilometer (World Bank, 1994). The main human activities practiced in the farmlands in semi-arid areas are mainly livestock keeping and smallholder, rainfed farming practices

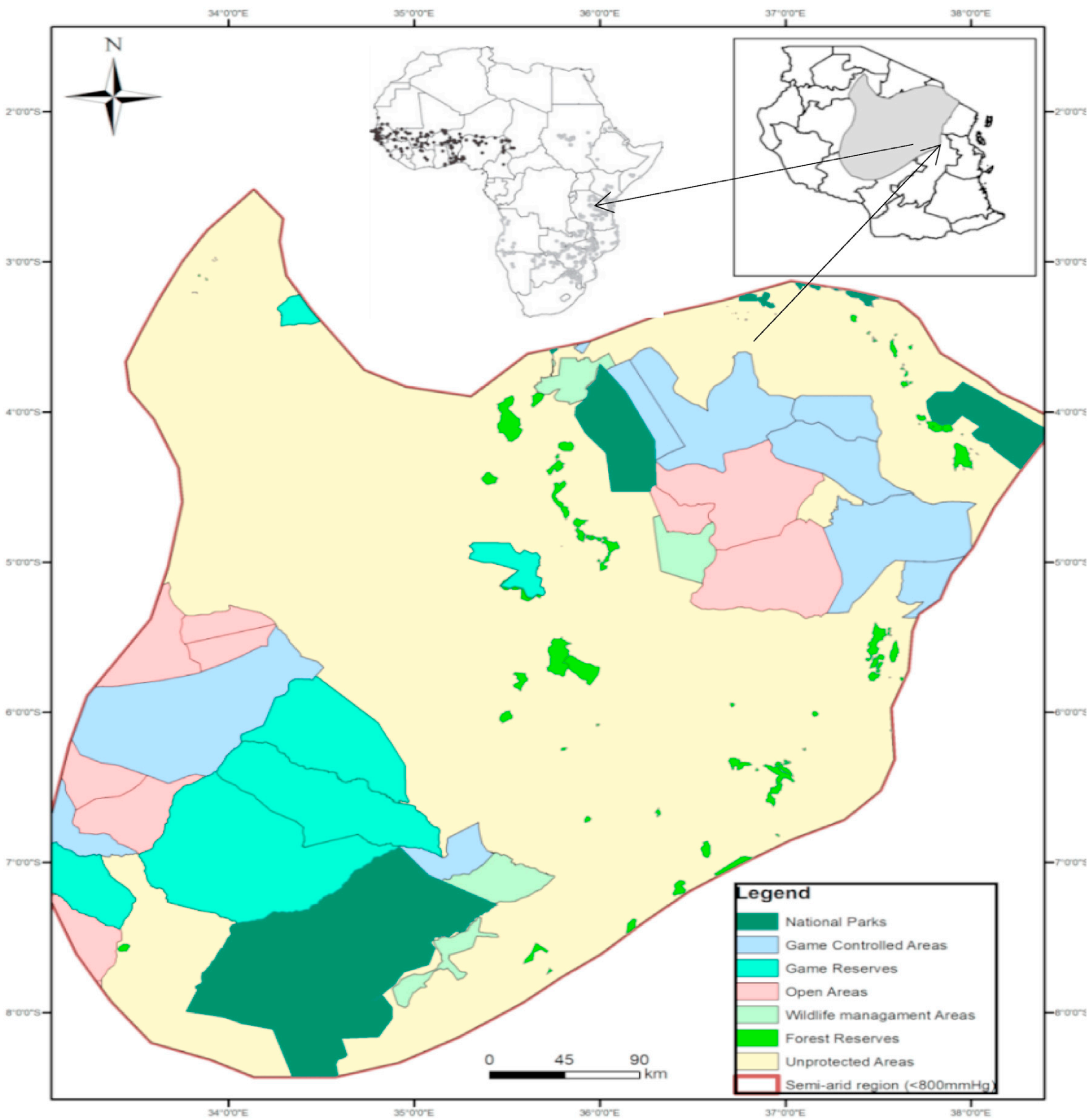

Fig. 1. Map showing the location of the study area in Tanzania.

cultivating seasonal crops that include maize, millet, ground nuts and sorghum which are sometimes grown together with baobab trees.

2.2. Research design and sampling strategy

A stratified systematic random sampling design was conducted using a topographic map of the study area. This topographic map was marked with equal grid squares of 20 km × 20 km size (from here onwards defined as grid squares; Fig. 2) on a geographic information system (GIS) platform. Initially a reconnaissance survey was done to determine the location and the size of each grid and ensure proportionate distribution of the sample points in different land-use types. Stratification was done using the existing land-use systems and baobab distribution and this reconciled the reality with information obtained from a topographic map. Ground-truthing was done during data collection to verify the exact land use. The land-uses in this study were: (1) strictly protected areas (National Parks, Nature Reserves and Forest Reserves); (2) non-strictly protected areas (Game Controlled Areas, Game Reserves, Open Areas and Wildlife Management Areas) and (3) unprotected areas (croplands,

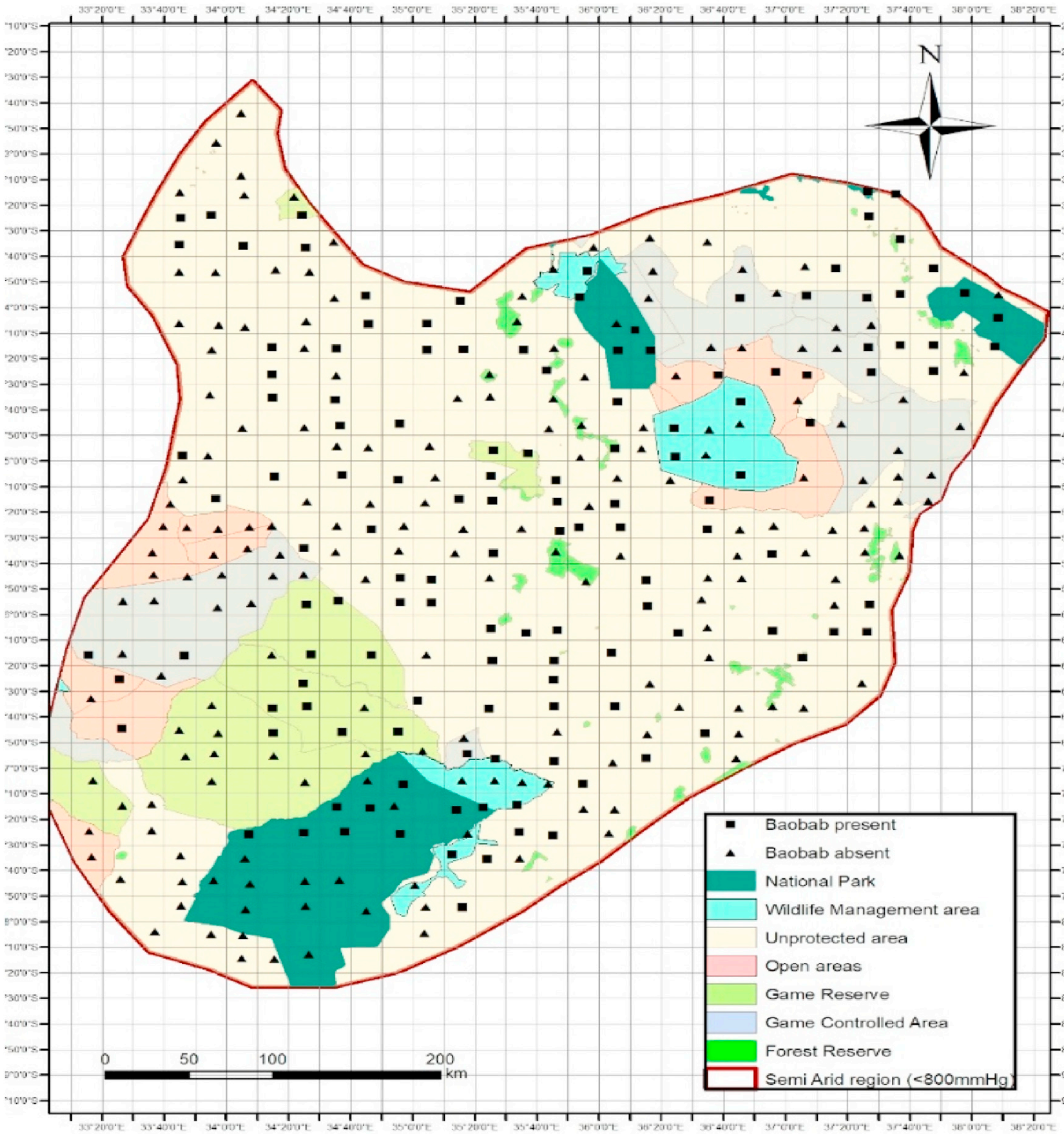

Fig. 2. Map showing a presence and absence of the baobab stands in the surveyed grids in the semi-arid areas of Tanzania.

pastures and settlements). The protected area categories here followed the standard designated categories of protected areas as classified by International Union for Conservation of Nature and Natural Resources [IUCN] (Dudley and Stolon, 2008).

The research design was cross-sectional, where data collection was done once. A total of 337 (40%) from a total of 842 grid squares were randomly selected, using the topographic semi-arid map of our study area. The number of the selected grid squares in each land-use depended on the relative size of each land use. In each selected grid square, a belt transect of 1 km length and 50 m wide (5 ha, from here onwards defined as selected grid square) was established in the North- West corner of the grid square. At each land-use type, the selected grid square was navigated, following the GPS reading until the GPS direction became perpendicular to the direction that could be used to reach the desired grid square. Coordinates of all selected grid squares were loaded into a GPS and generated and plotted on the map of the study area. A total of 115 (34.12%) of the 337 selected grid squares were found to have baobabs (Fig. 2).

2.3. Data collection

In each selected grid square, all baobab trees found were marked, enumerated, identified and recorded by trees height, basal circumference (= girth), level of damage and status (dead or alive), presence of fruits/flowers/leaves, and land-use type. Tree height was measured with a clinometer. Basal girth of each stem was measured at breast height (1.3 m) to the nearest centimeter, using a flexible 50 m tape measure, expressed as stem girth at breast height (D/GBH). Where plant height was less than 1.3 m, basal stem girth was measured just above the buttress swelling (after Mpofu et al. (2012). For multi-stemmed plants, if the division was above the GBH, it was considered as one tree and if it was below, they were considered as two or more trees. Evidence of plant disturbances such as debarking, uprooting, leaf harvesting, tree stump and fire damages was also recorded. The level of damages (by animals or humans), were assessed to scale from 0 to 4, as follows: (0)-no damage, (1)-slight elephant damage-few scars, (2)-moderate damage-scars more numerous, (3)-severe damage-scarred deeply, and (4)-tree completely damaged-dead (Swanepoel and Swanepoel, 1986; Edkins et al., 2008; Gandiwa et al., 2011). The proportion of baobab stem damaged by fire was assessed to three levels: (0)-no damage, (1) - intermediate damage, and (2)-severe damage-scars more numerous.

2.4. Data analysis

Data were summarized by descriptive statistics (means and standard errors) per each belt transect before further analyses. A test for normality of the data was carried out on DBH classes between land-use types using the Kolmogorov-Smirnov test, before ANOVA procedures. Population structure of baobab in different land-use types in the semi-arid areas of Tanzania was based on baobab stem density in different age categories (juvenile, sub-adult and adult) and size classes, reproductive status (juvenile/mature ratio) and health status.

2.4.1. Population density per land-use types

Baobab density was calculated from the following formula: density = numbers of baobab in a belt transect and then converted to ha^{-1}. Tree numbers were converted into densities (plants/ha), and girth to diameter at breast height (DBH) in centimeters (cm). SPSS 17.0 (IBM Corp. Chicago IL) was used for analyses. Analysis of Variance (ANOVA) followed by Fisher's Least Significant Difference (LSD, $p < 0.05$) test was used to compare different baobab age category densities within and between land-use types.

2.4.2. Size-class distributions

The basal stem girth was converted to stem diameter (DBH) before the analysis. Baobab size class distribution, adopted from Swanepoel and Swanepoel (1986), was based on 50 cm (D)GBH intervals, i.e. 0-50 cm; 51–100 cm; 101–150 cm; 151–200 cm; 201–250 cm; 251–300 cm; 301–350 cm, 351–400 cm, 401–450 cm, 451–500 cm, 501–550 cm, 551–600 cm, 601–650 cm and 651–700 cm. Population structure was described as stem diameter distributions, based on the stem density in the different size-classes as per above increment intervals listed earlier in DBH. Demographics of sampled baobabs were presented as a number of individuals per size-class. In this study, the Juvenile baobabs considered to have stems <5 m height, the sub-adult baobabs were stems ≥5 m height and ≤1 m DBH, while adult baobabs were trees with DBH >1 m (after Venter and Witkowski 2013). Trees were also categorized in terms of fruit production. Seedlings were <1 cm DBH, juvenile (not yet producing fruit) were <1 m DBH and mature (producing fruit) were trees ≥1 m DBH class (after Venter and Witkowski, 2010).

To obtain the status of baobab over four time periods, baobab population size-class distribution of similar even-aged cohorts was generated following Swanepoel and Swanepoel (1986) and Geldenhuys (2010) with minor modifications, whereby we compared baobab stems in four size categories across the three land-use types: classes 1 to 3 up to 150 cm (time period I); classes 4 to 6 up to 300 cm (time period III); classes 7 to 9 up to 450 cm (time period III); and all classes above 450 cm (time period IV). To allow for visual comparisons, size-class distributions (SCDs) were constructed and displayed graphically. Kolmogorov-Smirnov tests were used to compare size-class distributions and to test the prediction that all size-classes occurred in similar proportions among land-use types. Chi-square was done, using an equal number of baobabs sampled on each land-use type. ANOVA was used to compare DBH between land-use types following Edkins et al. (2007).

2.4.3. Population occurrence and distribution

Trees were divided into juveniles (generally not yet producing fruit), sub-adults and adults (producing fruit), based on fruit production per tree size class (U.L. Msalilwa, unpublished data). Kernel density in ArcGIS was used to generate baobab age-class distribution maps for different land-use types. Densities of juvenile, sub-adult and adult plants were reported for each land-use type. ANOVA followed by Fisher's least significant difference (LSD) was used to compare the density of juvenile, sub-adult and adult populations within and across land-use types. A general linear model (GLM) ANCOVA in SPSS17.0 (IBM Corp. Chicago IL) using land-use type and age category as fixed factors was run. ANOVA test was used to find if the means of baobab age categories were different within and between land-use types. Where a significant difference was observed, a *post hoc* test by Fisher's Protected Least Significant Difference (LSD) at the $p < 0.05$ level of probability was used to determine significant differences among age category and land-use types.

3. Results

3.1. Size class distribution of baobab in different land uses

In this study, the class distribution showed inverse *J*-shaped distributions in strictly protected areas versus bell-shaped distributions in non-strictly protected and unprotected areas, respectively (Fig. 6). The more or less similar pattern was observed when the size classes of baobab stems were grouped into four even cohort categories and compared by different land uses (Fig. 6). Strictly protected areas had the lowest diameter size-classes and fewest trees in the large size-classes. The highest numbers of trees were found in the 1–50 cm and 50–100 cm size classes in strictly protected areas. In non-strictly protected areas, the trees showed bell-shaped diameter distributions with the highest number of trees in the middle size classes i.e., 151–200 cm, 201–250 cm and 251–300 cm and the lowest in small diameter classes and large in higher diameter classes. The bell pattern of size-class distribution was observed with the majority of baobabs in diameter class ranges from 50 to 400 cm in unprotected areas. Chi-square independence test for comparing baobab DBH size class distribution showed no significant difference ($\chi^2 = 168.0$, df = 156, $p = 0.242$) in strictly protected areas. Furthermore, there was no significant difference ($\chi^2 = 140.0$, df = 130, $p = 0.259$) in DBH size-class distribution in non-strictly protected areas. Also, there was no significant difference ($\chi^2 = 154.0$, df = 143, $p = 0.25$) in DBH size class distribution of baobabs in unprotected areas.

Baobab stems in time period I suggest that the highest number of stems for the strictly protected areas compared to the other land-use types (Fig. 6). For time period II, the highest number of baobab stems was recorded in the non-strictly protected areas, while for time period III, the number of stems was more or less the same across the three land-use types. Within time period IV, the number of stems was slightly higher for the strictly protected areas compared to the other land-use types.

There was a significant difference ($F_{2,\,1027} = 24.776$, $p < 0.001$) in baobab stem height between land-use types. The average baobab tree heights were 15.26 ± 6.03 m, 14.32 ± 4.6 m and 12.46 ± 5.38 m for strictly protected areas, non-protected areas and unprotected areas respectively (Fig. 7). The average height for baobab trees across the semi-arid areas of Tanzania was 13.45 ± 5.46 m.

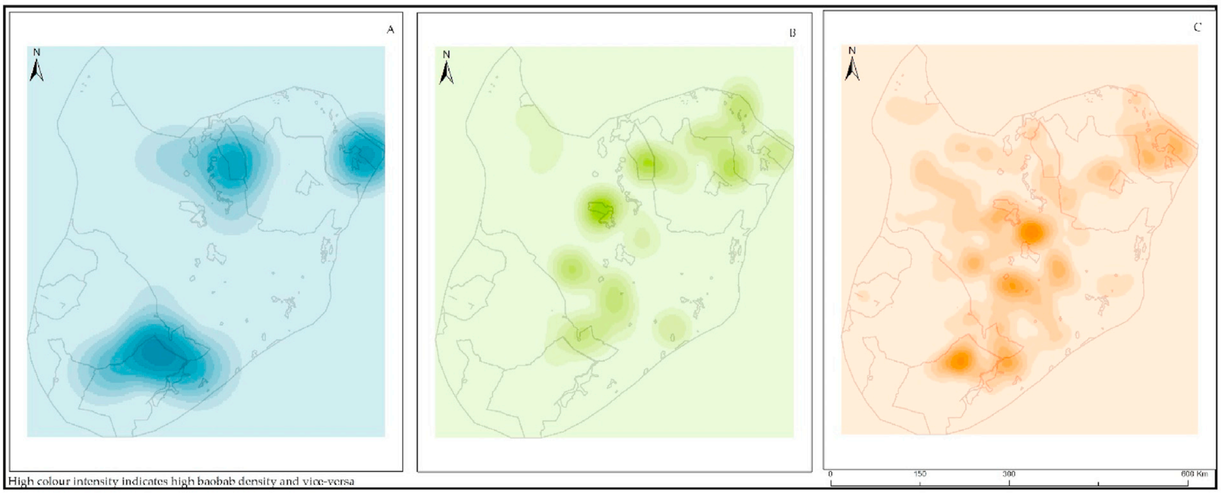

Fig. 3. Baobab age-class: juvenile (A), sub-adults (B) and adults (C) distribution in the semi-arid areas in Tanzania.

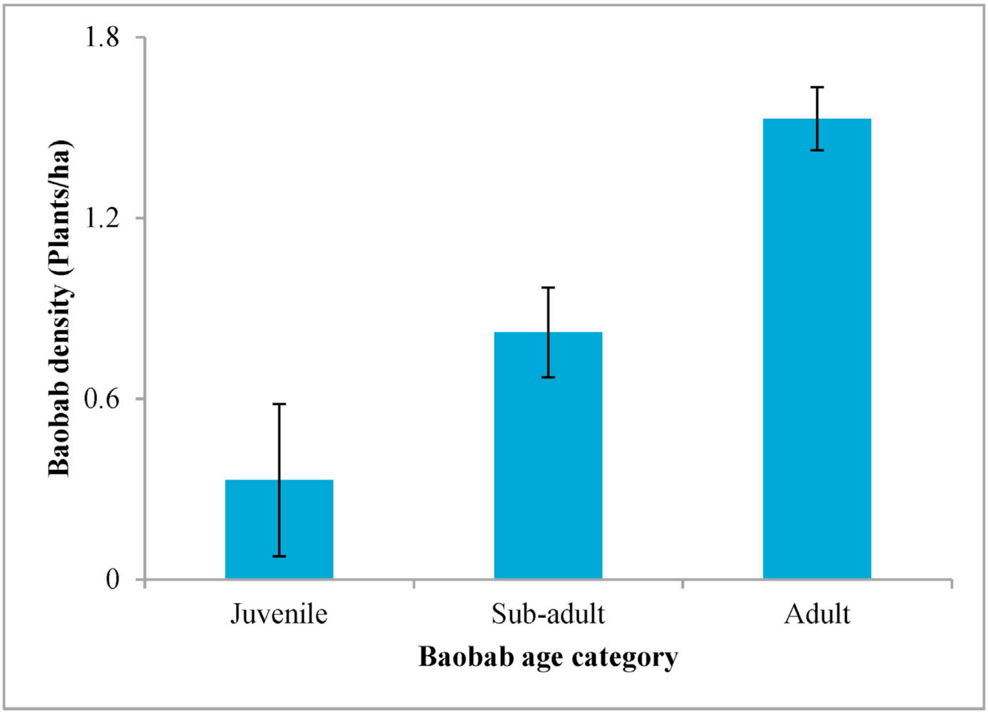

Fig. 4. Density (mean ± SE) of juvenile, sub-adult and adult baobab populations across semi-arid areas of Tanzania. Bars marked with different letters (*a* and *b*) are significantly different (Fisher's LSD, $p < 0.05$).

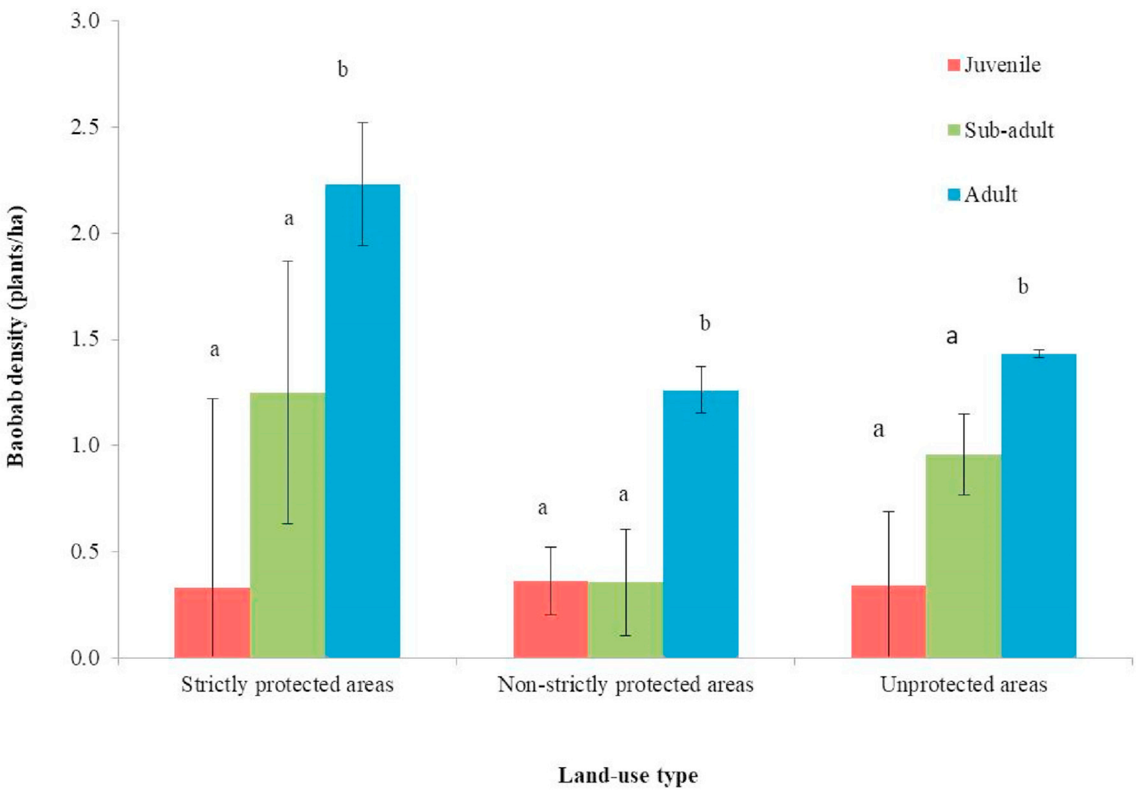

Fig. 5. Density (mean ± SE) of juvenile, sub-adult and adult baobab populations in different land-use types. Bars marked with different letters (*a* and *b*) are significantly different (Fisher's LSD, $p < 0.05$).

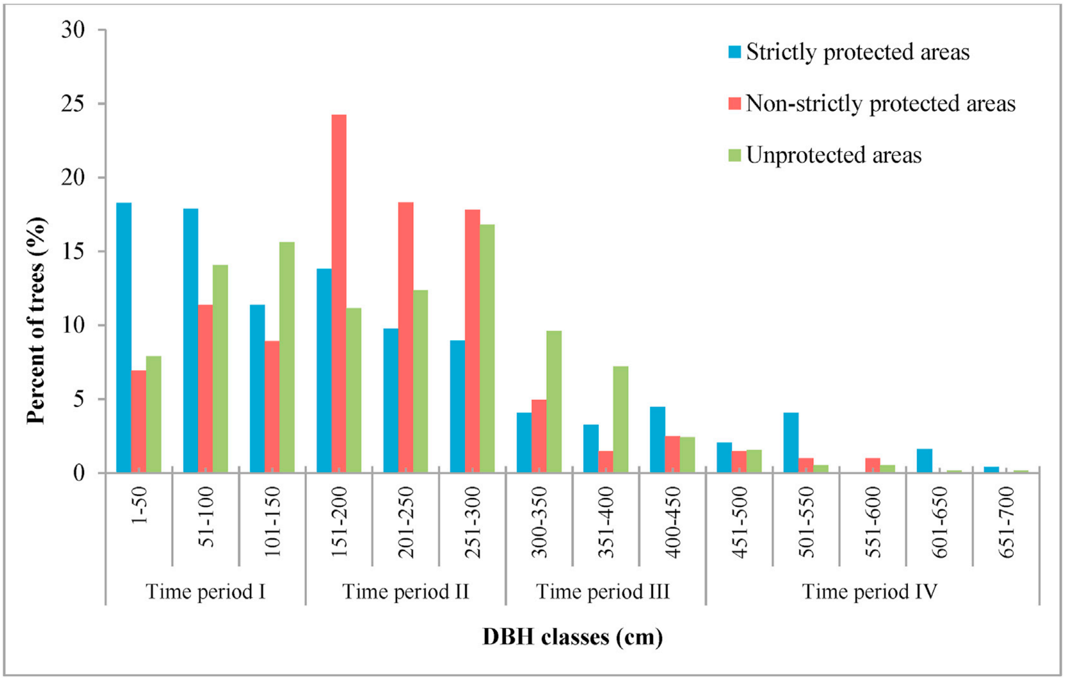

Fig. 6. Comparison of the status of baobab over four time periods in different land-use types in the semi-arid areas.

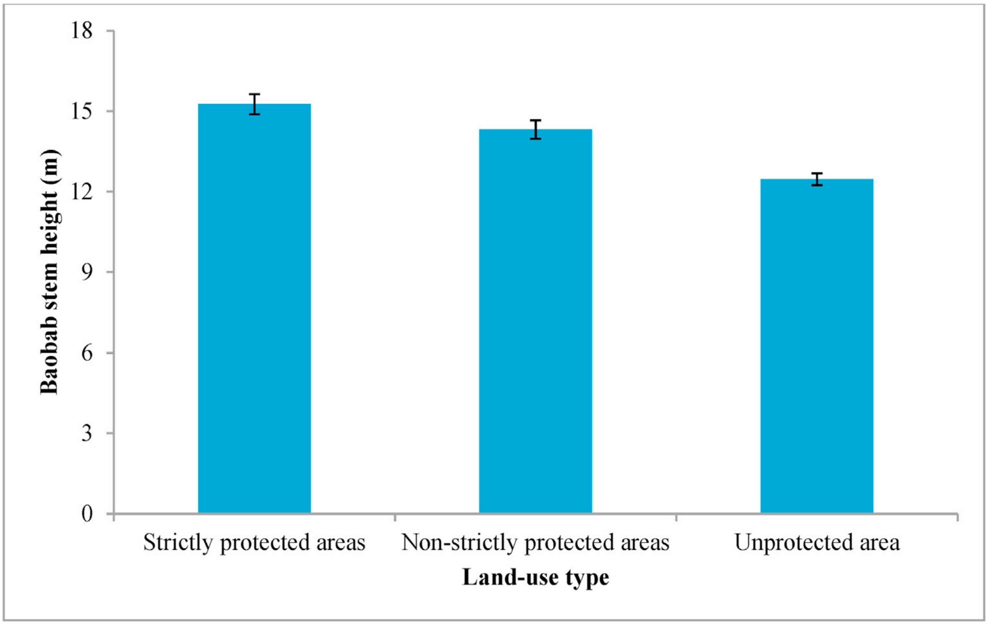

Fig. 7. Baobab stems height (mean ± SE) in different land-use types in the semi-arid areas.

3.2. Baobab spatial distribution and population density by age categories in different land uses

Approximately, 34% of the selected grid squares were found to have baobabs, with the grid squares distributed as follows across the land use types: 21 in strictly protected areas; 26 in non-strictly protected areas and 68 in unprotected areas, covering approximately 40% of the entire semi-arid areas (Fig. 2). A total of 1033 baobab stems were recorded (246 stems in strictly protected areas, 201 stems in non-strictly protected areas and 586 stems in unprotected areas). Baobab population density across different land-use types ranged from 0.3 to 2.23 plants/ha.

Land-use type ($F_{2, 165} = 8.201$, $p = 0.001$) and age category ($F_{2, 153} = 5.194$, $p = 0.018$) and the land-use type x age category interaction ($F_{5, 153} = 2.288$, $p = 0.049$) significantly affected baobab density across the semi-arid areas. The distribution of the recorded stems over age class categories was 73% adults, 24% sub-adults and 3% juveniles. Very few juvenile baobabs were recorded across all land-uses in the semi-arid areas, with less than four (4) stems per selected grid square and only 16 (4.7%) of the 337 grid squares surveyed contained juveniles. Based on *post hoc* LSD multiple comparisons, the density of the baobab population varied substantially and significantly ($F_{2, 165} = 15.472$, $p < 0.001$) as follows: 1.53 ± 0.105 adults/ha, 0.82 ± 0.149 sub-adults/ha and 0.33 ± 0.253 juveniles/ha. The difference between juvenile and adult population densities was significant ($p < 0.001$), but the difference between juvenile and sub-adult population densities was not significant ($p = 0.096$) (Fig. 4).

Most juveniles were recorded in the strictly protected areas, especially towards the boundary of the national parks where most of the sub-adult baobabs were found, in the mainly unprotected central part of the semi-arid region. Adult baobabs were uniformly distributed across all land uses, with higher than average numbers in some of the National Parks (Ruaha and Mkomazi) (Fig. 3). Sub-adults age group was in second position in semi-arid region.

In strictly protected areas, baobab population density did not vary significantly across age categories ($F_{2, 24} = 4.404$, $p = 0.085$), but the difference between adult and juvenile populations was marginally significant ($p = 0.057$). Population density was 2.23 ± 0.29 plant/ha for adults, 1.25 ± 0.62 plants/ha for sub-adults and 0.3 ± 0.89 plants/ha for juveniles (Fig. 3). The higher percentage (53%) of adult baobabs was found in National Parks.

In non-strictly protected areas, baobab population density varied significantly across age categories ($F_{2, 44} = 4.365$, $p = 0.001$; Fig. 3). Population density was 1.26 ± 0.11 plant/ha for adults, 0.36 ± 0.25 plants/ha for sub-adults and 0.35 ± 0.16 plants/ha for juveniles. Based on *post hoc* LSD multiple comparisons, adult and juvenile population densities differed significantly ($p = 0.003$), as did the adult and sub-adult populations ($p = 0.001$), but sub-adult and juvenile populations did not differ significantly ($p = 0.98$).

In unprotected areas, baobab population density varied significantly across age categories ($F_{2, 44} = 5.022$, $p = 0.008$). Population density was 1.43 ± 0.14 plant/ha for adults, 0.96 ± 0.19 plants/ha for sub-adults, and 0.34 ± 0.35 plants/ha for juveniles (Fig. 5). Based on *post hoc* LSD multiple comparisons, adult and juvenile population densities differed significantly ($p = 0.05$), adult and sub-adult population densities differed marginally significantly ($p = 0.45$), but sub-adult and juvenile populations did not differ significantly ($p = 0.125$).

3.3. Mature and juvenile baobab densities

The densities of mature baobabs were found to be higher than juvenile baobabs in all three land-use types, representing 70% of all recorded trees, with 72% in strictly protected areas, 70% in was no significant difference ($p > 0.05$) baobabs was significantly ($F_{3, 20} = 3.177$, $p = 0.046$) higher in strictly protected areas than in other land-use types, and lowest in unprotected areas, especially in cultivated lands. Paired t-tests showed significant differences between mature and juvenile baobab densities within strictly protected and non-strictly protect areas ($p < 0.05$) but was not significantly different in unprotected areas. The differences between juvenile and mature baobab population density between all land-use types were not significant ($p > 0.05$). In all land uses, there was lack of regeneration because no seedlings were recorded in all land-use categories (baobab stem >1 cm DBH). The immature and mature stems ratios were 0.567 in strictly protected areas, 0.224 in non-strictly protected areas and 0.281 in unprotected areas (Fig. 8).

3.4. Health status of baobab stems in different land uses

The health status of baobab populations in the three land-use types was assessed in terms of presence of fruits and number of dead trees and stem damage by elephants and people. The difference between baobab trees with and without fruits was significant ($F_{2, 1026} = 5.332$, $p = 0.005$). Baobab trees with fruit represented 84.4% of all trees, with 76.4% (188 trees) in strictly protected areas, 72.6% (146 trees) in non-strictly protected areas and 59.9% (348 trees) in unprotected areas. The difference between baobab trees with and without leaves was not significant ($F_{2, 1026} = 2.806$, $p = 0.061$). Baobab trees with leaves represented 84.2% of all trees, with 99.6% (245 trees) in strictly protected areas, 96.0% (193 trees) in non-strictly protected areas, and 97.1% (561 trees) in unprotected.

The difference between alive and dead baobab trees was strongly significant ($F_{1, 1029} = 68.332$, $p < 0.001$), with an estimated 96.13% (993 trees) alive and only 3.87% (40 trees) dead (Plate 1B). About 57% of the dead trees were recorded in unprotected areas (death caused by human damages), with 83% of the dead trees in farmland, 35% in non-strict protected areas caused by both human and elephant damages, and only 7.5% in strictly protected areas, mainly caused by elephant damage in the parks.

The number of damaged baobab tree stems was higher than undamaged stems in all land uses. The main causes of baobab damage in the semi-arid area were fire, humans and elephants (Fig. 9). Human damages through debarking by machetes (Plate 1A) and use of fire were significantly different between the four levels of damage ($F_{2, 1029} = 18.951$, $p < 0.001$). Severe stem damages (harvesting of bark) by humans were higher in non-strictly protected and unprotected areas, with more baobab stems harvested for bark in unprotected areas than other land-use types. The number of stems between the four levels of damage by elephants was significantly different ($F_{2, 1029} = 385.375$, $p < 0.001$). Most baobab stems damaged by elephants and termites were observed in strictly protected areas, with severe elephant damages mostly observed in the Parks (Plate 1C). Fire affected baobab populations in all land uses, with fire damage to the stem significantly different ($F_{2, 1032} = 30.784$,

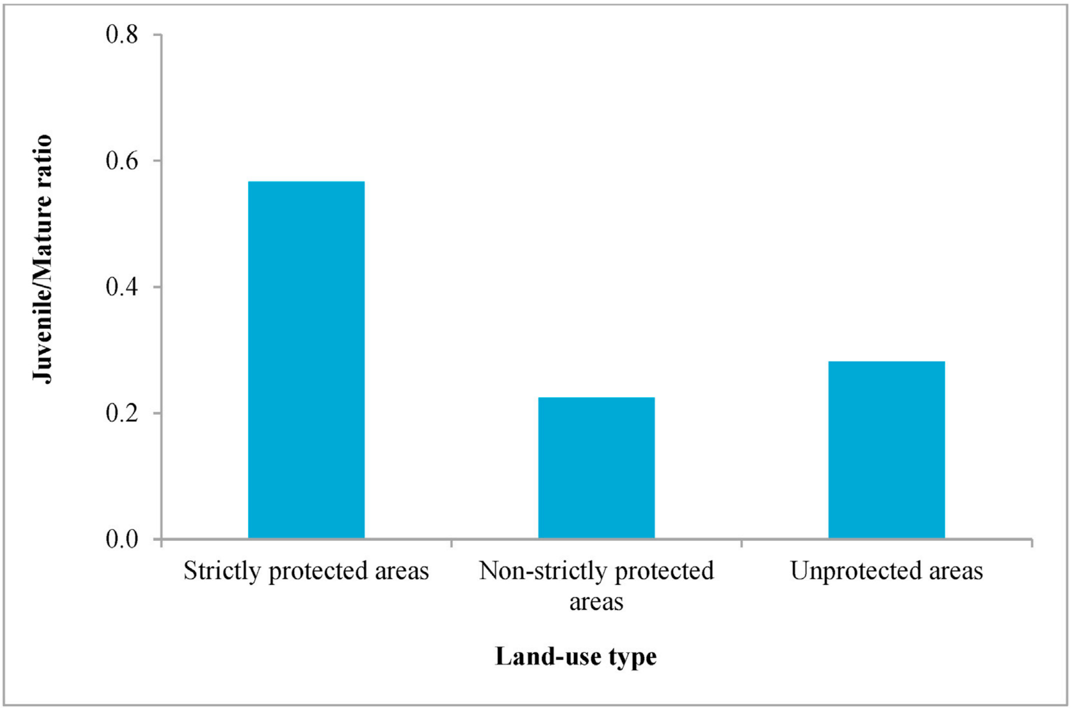

Fig. 8. Baobab juvenile/mature ratio in different land-use types in the semi-arid areas.

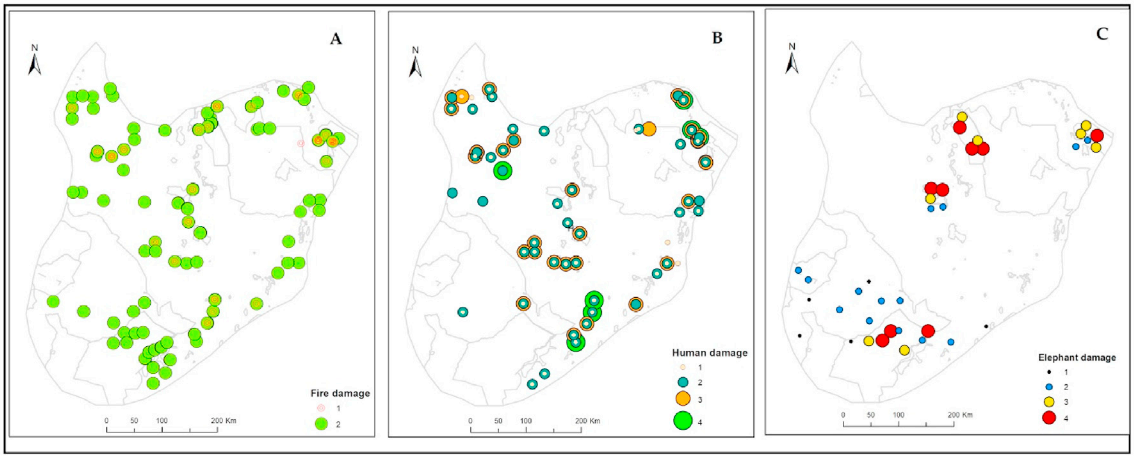

Fig. 9. Maps showing baobab stems damage levels (A-Fire, B-Humans and C-Elephants) in the semi-arid areas in Tanzania.

$p < 0.001$), with about 68% of fire damaged stems at level 2 (severe damage-scars more numerous). The proportion of fire damaged stems was 80.5% in strictly protected areas, 57.7% in non-strictly protected areas and 74.6%% in unprotected areas. The health status of baobab trees varied between land-use types, with 80.5% of baobab trees in strictly protected areas, 47% in non-strictly protected areas and 66.5% in unprotected areas in an intermediate health status. In this study, human damages in unprotected areas and elephant damages protected areas were the major threats to baobab populations.

4. Discussion

4.1. The size class distribution across different land uses

Baobab trees with smaller diameters were observed in all land-use types. The size class distribution curve of strictly protected areas stands was an inverse '*J*-shape' which indicates good rejuvenation, while the curve of non-strictly protected

Plate 1. Baobab debarked by humans in Dodoma (A), killed baobab by elephant in Ruaha National Park (B) and severely damage by elephant in Tarangire National Park (C).

areas and unprotected areas stands was bell-shaped, indicating a lack of recruitment. Schumann et al. (2010) revealed that the recruitment of baobab was higher inside the protected area than it was outside, despite human utilization and elephant presence in the park. This study found that land-use type has an impact on the population structure of the baobab. A *J*-shape describes a curve of a number of trees over DBH that is steeply and steadily declining (Rubin et al., 2006). It was observed that the diameter distribution follows a reversed *J*-shape meaning the number of lower diameter class (young) trees is higher, an indication of adequate recruitment. In such cases, the frequency of small trees is higher compared to the old ones. That pattern indicates a balance between recruitment and mortality of baobabs (Wilson and Witkowski, 2003). This suggested that baobab recruitment in strictly protected areas was relatively high and represents a steady-state and transitional increasingly viable baobab population (Lykke, 1998), despite high elephant damage and high fire frequency within this particular land-use type. The classic inverse-shaped size class distribution is generally used by biologists as an indication of a healthy, recruiting population, and deviation from this would normally be a cause for concern (Wilson &Witkowski, 2003). The argument is that a healthy viable and potentially growing population has a reverse size-class distribution, with a mono-modal distribution in numbers from a maximum in the juvenile size class (Condit et al., 1998; Edkins et al., 2007). Baobab size class distribution in unprotected areas had a positively skewed-sized class distribution which indicated the existence of irregular growth patterns (Wickens and Lowe, 2008). Therefore, the present study highlighted and indicated a concern over the unbalanced size class structure distribution of baobabs in unprotected areas, which suggested a baobab recruitment bottleneck. This study displays the concept of regeneration niche (Grubb, 1977) that species-environment interaction may vary with plant life stage (size class); thus, juvenile baobabs could have different requirements from adults and may, therefore, have different distribution patterns from adults. However, a large number of seedlings were recorded in unprotected areas. Selective protection of bigger baobabs by communities may contribute to the high densities and occurrence of trees in bigger size classes in comparison to juveniles.

Bell-shaped size class distributions (Fig. 6) for non-strictly protected areas and unprotected areas may not necessarily be an indicator of an unstable population. Baobab can sustain population levels with low or sporadic recruitment (Venter and Witkowski, 2013). The lack of baobab plants of <2 m DBH in the semi-arid areas indicates high rates of seedling mortality that may be due to elephant damage and human use of baobab seeds. The lack of plants in some size classes may be a result of a natural disaster such as drought, flood, fire or diseases as this may result in death of cohorts. Long-term monitoring of these populations may yield results that will assist in understanding baobab population dynamics in the semi-arid areas of Tanzania.

The population status of baobab over four-time period across the three land-use types (Fig. 6) suggest that some trees in the 'even'-aged cohort grow faster and some grow slower, and the height of the curve lowers because of differential growth and mortality, and different factors in each land use type caused mortality in the different land uses (Geldenhuys, 2010). It is speculated that this may relate to factors other than the specific land use such as different growth in rocky areas, and differential intensities and frequency in rainfall at local level across the different parts of the landscape. In their study in Namibia, Lisao et al. (2018) found that the proportions of baobab damage by humans and wildlife (e.g. elephants) (herbivory) varied spatially and was as well influenced by resources (e.g. rainfall) distribution and amount. Overall, there seem to be enough younger trees in each land use, and this might be due to combination of biotic and abiotic factors occurring at local level which may then have feedback into the local baobab population. These historical and emerging factors might act in time and space driving dynamics of baobab population in different land-use types differently, thus, contributing to better or poorer survival, such as people uprooting younger trees when cultivating fields, or higher mortality caused by larger numbers of elephant, or more fire damage.

4.2. Baobab spatial distribution and population density by age categories

Juveniles showed the lowest presence and density of the age categories, and most juveniles were observed at the edge of the protected areas. This is probably because juvenile baobabs are facing grazing pressure from both livestock and elephants during dry seasons. For example, in protected areas, juveniles are destroyed by elephants, and in unprotected areas, juveniles are destroyed by humans and browsed by livestock. Harvesting juveniles for food and medicine might be among the reasons for few juveniles in unprotected areas. Most of mature fruits are harvested and taken away with the seeds resulting in few seedlings in the unprotected areas. Sub-adult baobabs were mostly observed in unprotected areas. This might be due to land transformation resulting from agricultural activities and grazing. These activities are detrimental to baobab trees with large diameters.

It was observed that strictly protected areas supported few large parent baobab trees and reasonable seedlings of DBH less than 50 cm. Grazing and herbivory by both elephants and livestock, fire and debarking by humans were the main factors driving those DBH distribution categories in each of the land uses. It is possible that outside these well protected areas, cutting has removed most large trees and remaining adults are small producing relatively few seeds. Furthermore, some general factors affecting recruitment include location and elevation perhaps indicative of higher precipitation might have influenced baobab age categories and population densities across the semi-arid areas.

Baobab size (i.e., stem diameter and plant height), a good indicator of photosynthetic growth, significantly differed across land-use types; baobabs in strictly protected areas were relatively larger and taller than in unprotected areas. This study observed the mean baobab density in the semi-arid areas ranged between 0.3 and 2.23 plants/ha. This is within the range of other recorded baobab densities in other African countries (Venter and Witkowski, 2010; Ndoro et al., 2014; Msalilwa et al., 2019a). The density of the baobab juvenile, sub-adult and adult populations varied across all land-use types in the semi-arid areas. The observed significant differences in stand density between different land uses were related to causal factors for the differences. These were assumed to be caused by differences in the land-use types as well as biological factors such as herbivory and fruit predation. Furthermore, the observed density differences in baobab population probably resulted from edaphic factors such as differences in soil nutrients, soil depth, soil drainage, soil moisture, and climatic induced aridity droughts.

4.3. Mature and juvenile densities

Land-use type is a significant factor that impacts on the population structure of baobabs (Schumann et al., 2010; Venter and Witkowski, 2010). Agricultural cropping may result in fewer seedlings because baobab seedlings are usually removed when clearing new sites for growing crops, to reduce competition with their crops (Lisao et al., 2018), with similar observations in other countries (Dhillion and Gustad, 2004; Venter and Witkowski, 2013). However, the adult trees are normally retained, resulting in more adult trees than those in the juvenile stages. Traditionally, important large trees, such as baobab, are protected by cultural norms in African communities (Sidibe and Williams, 2002; Lisao et al., 2018). This may contribute to the high ratio of mature trees to juveniles. The same trend has been reported in other parts of Africa (Dhillion and Gustad, 2004; Edkins et al., 2007; Cuni Sanchez et al., 2010; Schumann et al., 2010; Munyebvu, 2015). Cattle and goats are common domestic animals that occur in the semi-arid areas. While these are dispersers, they may also destroy seeds when feeding and therefore negatively impact on recruitment. Seeds may also be dispersed to areas where suitable germination conditions are not met and therefore fail to establish. Venter and Witkowski (2013) indicated that baobab seedlings might be destroyed by repeated browsing by livestock, contributing to lack of juveniles. The lack of juveniles may indicate a high rate of destruction of seeds before the establishment or destruction of fruits before maturing, resulting in a reduction of viable seeds. Geminated baobab seedlings may likely be browsed by cattle, goats and donkeys which are found in high densities in those areas. Local communities in the semi-arid areas use oil extracted from baobab seeds and therefore reduce the number of viable seeds that may potentially establish. Additionally, fire scars observed on stems may potentially destroy juveniles before recruiting into larger trees, which are more resilient to fire.

4.4. Health condition of baobab stems

The high rate of damage of stems in the semi-arid areas is a combination of stripping by elephants and harvesting of bark by humans. Most baobab stems were pruned and debarked in villages, croplands and settlements. Nearly all baobabs had fire scars and elephant damages in the strictly protected areas. Debarking and pruning by a human were somehow size specific. Pruning of the baobab tree of tree-size had a significant impact on fruit production. The bark is harvested by humans, mainly for use in administering various ailments (Munyebvu, 2015; Lisao et al., 2018). Baobab bark is the most important part of the baobab tree (Lisao et al., 2018), but the use of baobab bark needs to be regulated. Sustainable harvesting is recommended with recovery periods of 8 years for bark thickness and 12 years for fibre quality (Romero et al., 2001). The study identified that baobab populations in the non-strictly protected areas and unprotected areas might be exposed to local extinction. Investigation of seedling regeneration in unprotected areas is critical for conservation of baobab. Regardless of the resilient nature of the baobab stems, excessive bark harvesting increases the vulnerability of the trees to diseases (Kassa et al., 2014). The observed rates of damage to the baobab trees may not be sustainable. Recovery periods are recommended to allow the bark to recover before harvesting fully. Studies to investigate population genetics is critical to ensure genetic diversity is maintained and for better conservation strategies. Additionally, baobab trees play essential ecological roles as a keystone species. It has been shown by the presence of beehives and bird nests observed on the trees. Conservation of this species is therefore important in maintaining stability in the ecosystem.

Elephants are a significant contributor to baobab bark damage, especially in the dry seasons (Weyerhauser, 1985; Romero et al., 2001; Msalilwa et al., 2019b). As a succulent, it can serve as a source of water. Mudavanhu (1998) found a relationship between bark harvesting and sooty disease. Ndoro et al. (2014) observed that elephants damaged 98% of baobab trees in a National Park in Zimbabwe. Elephants strip damage the bark of older baobab trees, weakening the tree and making them more prone to disease infections and fire. A study in Zimbabwe has indicated that some trees may not produce fruits for up to four years due to depleted resources as a result of elephant damage to the bark (Swanepoel, 1993). Fire and elephant damage play a vital role in the dynamics of many similar woodlands in East Africa (Mwalyosi, 1990); both are common in the semi-arid areas. Furthermore, termite activity, which is a feature of many woodlands and dry forests (Menaut et al., 1995), affecting soil characteristics such as structure, texture, moisture status and organic matter and hence vegetation productivity, structure, and dynamics, is quite frequent in the semi-arid areas. A study by Menaut et al. (1995) reported that the role of fire, regeneration capacity, and the role of termites played a key role in the woodland dynamics. In general, animals are important for seed dispersal and for shaping the woody vegetation through browsing. Heavy browsing and grazing of baobab trees by goats and cattle were observed in the semi-arid areas. It has been established that cattle browsing and trampling play a significant role in the early growth and subsequent development of the baobab population (Menaut et al., 1995; Eshete, 2000).

5. Conclusions and recommendations

5.1. Conclusions

The study assessed the baobab population structure in the semi-arid areas of Tanzania and found significant differences in DBH and height between different land-use types. The results revealed that there is a lack of baobab trees in the juvenile life stage in the semi-arid areas. Stem diameter class distributions revealed fewer young trees than adults in non-strictly protected areas and unprotected areas, whereas a higher number of young than adult trees were observed in strictly protected areas, indicating a young and stable population. However, if factors that affect regeneration are not monitored, the population of baobab may become threatened. Nevertheless, protection is accorded to adult trees by locals. Therefore, this contributes positively to the population structure of baobab. The study indicated that a significant number of trees had damaged stems, making them vulnerable to infections of the damaged stems. Though baobab recruitment is sporadic, factors that disturb and reduce numbers of baobab seedlings need to be monitored to ensure higher proportions of young trees in order to conserve baobab in the semi-arid areas of Tanzania.

This study further concludes that despite the land-use impact and the intense harvesting, baobabs are still well preserved in the semi-arid areas due to their longevity, extremely low adult mortality rates and traditional management practices. However, land-use intensification may lead to increasing pressure on baobab populations in the future. Therefore, improved management strategies are needed to guarantee the persistence of this vital species and to avoid a shortage of baobab products. Overall, the baobab population is currently considered stable in the semi-arid areas of Tanzania. However, factors that negatively impact the recruitment and establishment of baobab required to be controlled to ensure a higher proportion of young trees survive. Sustainable harvesting practices of baobab bark are recommended in unprotected areas. Active protection of established baobab seedlings and transplanting seedlings to desirable areas by local communities is recommended in order to ensure successful recruitment and maintain stable populations. This may also contribute to the conservation of the local genetic pool in future populations.

5.2. Recommendations

The present study recommended that protected area management in the semi-arid areas of Tanzania should consider establishing long-term baobab monitoring programmes, i.e. monitoring plots in strategic baobab stands for conservation. Long-term continuous monitoring of baobab populations is necessary in order to identify the dynamics and the trend in the population structure.

Training programmes are needed on how to propagate the baobabs and practice traditional agro-forestry systems to minimize destruction of baobab juveniles during land tilling. In addition, farmers may need training on identifying germinating baobab seedlings and on enhancing baobab recruitment. Protection of young seedlings is crucial in areas where the seedlings are easily monitored and better protected such as within fenced fields and villages. Where farmers have enough land size, they should be encouraged to grow trees in combination with crops. Baobab conservation should be considered when revising agricultural and forest policies because of the national importance of the species for both food and conservation value. Areas not gazetted as strictly protected areas are under pressure from incremental and intensified agricultural land use systems. This should be controlled and regulated to avoid further transformation of most land cover types leading to loss and extinction of baobab.

Author contributions

In this paper, the authors' contribution was as follows: Upendo Msalilwa - conceived of the research idea, data collection, wrote the manuscript; Linus K. Munishi - conceived of the research idea, data collection and analysis, wrote and edited the manuscript; Edna Makule and Patrick Ndakidemi - data collection and analysis. All authors discussed the results and commented on the manuscript.

Data availability

The data that support this research article is available from the corresponding author upon reasonable request.

Declaration of competing interest

None.

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Appendix A. Supplementary data

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References

Assogbadjo, A.E., Sinsin, B., Codjia, J.T.C., Van Damme, P., 2005. Ecological diversity and pulp, seed and kernel production of baobab (Adasonia digitata) in Benin. Belg. J. Bot. 138, 47–56.
Biru, Y., Bekele, A., 2012. Food habits of african elephant (*Loxodonta africana*) in babile elephant sanctuary, Ethiopia. Trop. Ecol. 53 (1), 43–52.
Condit, R., Sukumar, R., Hubbell, S.P., Foster, R.B., 1998. Predicting population trends from size distributions: a direct test in a tropical tree community. Am. Nat. 152 (4), 495–509.
Cuni Sanchez, A.C., Osborne, P.E., Haq, N., 2010. Identifying the global potential for baobab tree cultivation using ecological niche modeling. Agric. Syst. 80, 191–201.
De Caluwé, E., Halamová, K., Van Damme, P., 2009. Baobab (*Adansonia digitata* L.): a review of traditional uses, phytochemistry and pharmacology. In: Rodolfo, H., Simon, J.E., Ho, C.T. (Eds.), African Natural Plant Products: New Discoveries and Challenges in Chemistry and Quality. Oxford University Press, USA, pp. 51–84.
De Smedt, S., Alaerts, K., Kouyaté, A.M., Van Damme, P., Potters, G., Samson, R., 2010. Phenotypic variation of baobab (*Adansonia digitata* L.) fruit traits in Mali. Agrofor. Syst. 82, 87–97.
Dhillion, S.S., Gustad, G., 2004. Local management practices influence the viability of the baobab (Adansonia digitata Linn.) in different land-use types, Cinzana, Mali. Agric. Ecosyst. Environ. 101 (1), 85–103.
Duvall, C.S., 2007. Human settlement and baobab distribution in southwestern Mali. J. Biogeogr. 34 (11), 1947–1961.
Dudley, N., Stolton, S. (Eds.), 2008. Defining Protected Areas: an International Conference in Almeria, Spain. IUCN, Gland, Switzerland, p. 220.
Edkins, M.T., Kruger, L.M., Harris, K., Midgley, J.J., 2007. Baobabs and elephants in kruger national park: nowhere to hide. Afr. J. Ecol. 46 (2), 119–125.
Eshete, G., 2000. Population structure and regeneration of the main tree species in the acacia woodlands of the rift valley of Ethiopia. J. Trop. For. Sci. 12 (4), 747–760.
Gandiwa, E., Magwati, T., Zisadza, P., Chinuwo, T., Tafangenyasha, C., 2011. The impact of African elephants on Acacia tortilis woodland in northern Gonarezhou National Park, Zimbabwe. J. Arid Environ. 75, 809–814.
Geldenhuys, C.J., 2010. Managing forest complexity through application of disturbance-recovery knowledge in development of silvicultural systems and ecological rehabilitation in natural forest systems in Africa. J. Res. 15, 3–13.
Grubb, P.J., 1977. The maintenance of species-richness in plant communities: the importance of the regeneration niche. Biol. Rev. 52, 107–145.
Gruenwald, J., Galizia, M., 2005. Market Brief in the European Union for Selected Natural Ingredients Derived from Native Species. *Adansonia Digitata* L, Baobab. United Nations Conference on Trade and Development, UN.
Hatibu, N., Lazaro, E.A., Mahool, H.F., Rwehumbiza, F.B., Bakari, A.M., 1990. Soil and water conservation in semi-arid areas of Tanzania: national policies and local practices. Tanzania J. Agric. Sc. 2 (2), 151–170.
International Centre for Underutilized Crops Icuc, 2002. Fruits for the Future Baobab (Fact Sheet No. 4). Retrieved 12 September 2017 fromhttp://www/icuc-iwmi.org/Publications/Factsheets/index.html. International Centre for Underutilized Crops.
Kassa, B.D., Fandohan, B., Azihou, A.F., Assogbadjo, A.E., Oduor, A.M.O., Kidjo, F.C., Babatound, S., Liu, J., Kakai, R., 2014. Survey of *Loxodonta Africana* (elephantidae) - caused bark injury on Adansonia digitata (malavaceae) within pendjari biosphere reserve. Benin. Afr. J. Ecol. 52, 385e394.
Lisao, K., Geldenhuys, C.J., Chirwa, P.W., 2018. Assessment of the African baobab (*Adansonia digitata* L.) populations in Namibia: implications for conservation. Glob. Ecol. Conserv. 14, e00386.
Lykke, A.M., 1998. Assessment of species composition change in savanna vegetation by means of woody plants' size class distributions and local information. Biodivers. Conserv. 7 (10), 1261–1275.
Menaut, J.C., Lepage, M., Abbadie, L., 1995. Savannas, woodlands and dry forests in Africa. In: Bullock, S.H., Mooney, H.A., Medina, E. (Eds.), Seasonally Dry Tropical Forests. Cambridge University Press, New York, pp. 64–92.

Miller, R.C.G., 2008. The Geology of Namibia, Volume 1. Archean to Mesoproterozoic. Geological Survey of Namibia, Ministry of Mines and Energy, Windhoek.

Mpofu, E., Gandiwa, E., Zisadza-Gandiwa, P., Zinhiva, H., 2012. Abundance, distribution and status of African baobab (*Adansonia digitata* L.) in dry savanna woodlands in southern Gonarezhou National Park, southeast Zimbabwe. Trop. Ecol. 53, 119–124.

Msalilwa, U.L., Munishi, L.K., Makule, E.E., Ndakidemi, P.A., 2019a. Pinpointing baobab (*Adansonia digitata* [Linn. 1759]) population hotspots in the semi-arid areas of Tanzania. Afr. J. Ecol. 1–13, 00.

Msalilwa, U.L., Munishi, L.K., Makule, E.E., Ndakidemi, P.A., 2019b. Emerging issues and challenges associated with conservation of the African baobab (*Adansonia digitata* L.) in the semi-arid areas of Tanzania. J. Biodivers. Environ. Sci. (JBES) 15 (5), 76–91.

Mudavanhu, H.T., 1998. Demography and Population Dynamics of Baobabs (*Adansonia Digitata*) Harvested for Bark in South-Eastern Zimbabwe. MSc Dissertation. University of Zimbabwe, Harare.

Munyebvu, F., 2015. Abundance, Structure and Uses of Baobab (*Adansonia Digitata* l.) Populations in Omusati Region, Namibia. PhD thesis. Faculty of biodiversity management and research, University of Namibia, p. 152Pp.

Mwalyosi, R.B.B., 1990. The dynamic ecology of Acacia tortilis woodland in Lake Manayara National Park, Tanzania. Afr. J. Ecol. 28, 189–199.

Ndoro, O., Mashapa, C., Kativu, S., Gandiwa, E., 2014. A comparative assessment of baobab density in northern Mana Pools National Park, Zimbabwe. Afr. J. Ecol. 53, 109–111.

Nguta, J.M., Mbaria, J.M., Gakuya, D.W., Gathumbi, P.K., Kiama, S.G., 2010. Antimalarial herbal remedies of Msambweni, Kenya. J. Ethnopharmacol. 128, 424–432.

Nieuwolt, S., 1973. Rainfall and Evaporation in Tanzania. BRALUP Research Paper No. 24. University of Dar es Salaam, p. 47pp.

O'Connor, T.G., Goodman, P.S., Clegg, B., 2007. A functional hypothesis of the threat of local extirpation of woody plant species by elephant in Africa. Biol. Conserv. 136 (3), 329–345.

Romero, C., Dovie, D., Gambiza, J., Luoga, E., Schmitt, S., Grundy, I., 2001. Effects of Commercial Bark Harvesting on Adansonia Digitata (Baobab) in 131 Save-Odzi Valley, Zimbabwe, with Considerations for its Management (IES Working Paper No. 18). Hotspring Working Group, Harare, Zimbabwe.

Rubin, B.D., Manion, P.D., Faber-Langendoen, D., 2006. Diameter distributions and structural sustainability in forests. For. Ecol. Manag. 222, 427–438.

Schumann, K.W., Wittig, R., Thiombiano, A., Becker, U., Hahn, K., 2010. Impact of land-use type and bark- and leaf-harvesting on population structure and fruit production of the baobab tree (*Adansonia digitata* L.) in a semi-arid savanna, West Africa. For. Ecol. Manag. 260, 2035–2044.

Schumann, K.W., Wittig, R., Thiombiano, A., Becker, U., Hahn, K., 2012. Uses, management and population status of the baobab in eastern Burkina Faso. Agrofor. Syst. 85, 263–278.

Shen, Y., Santiago, L.S., Ma, L., Lin, G., Lian, J., Cao, H., Ye, W., 2013. Forest dynamics of a subtropical monsoon forest in Dinghushan, China, recruitment, mortality and the pace of community change. J. Trop. Ecol. 29, 131e145.

Sidibe, M., Williams, J.T., 2002. Baobab. *Adansonia Digitata*. Fruits for the Future, vol. 4. International Centre for Underutilized Crops, Southampton, UK, p. 100pp.

Swanepoel, C., 1993. Baobab damage in mana pools national park, Zimbabwe. Afr. J. Ecol. 31, 220–225.

Swanepoel, C.M., Swanepoel, S.M., 1986. Baobab damage by elephant in the middle Zambezi, Valley, Zimbabwe. Afr. J. Ecol. 24, 129–132.

Van den Bilcke, N., De Smedt, S., Simbo, D.J., Samson, R., 2013. Sap flow and water use in African baobab (*Adansonia digitata* L.) seedlings in response to drought stress. South Afr. J. Bot. 88, 438–446.

Venter, S.M., Witkowski, E.T.F., 2013. Where are the young baobabs? Factors affecting regeneration of Adansonia digitata L. in a communally managed region of southern Africa. J. Arid Environ. 92, 1–13.

Venter, S., Witkowski, E., 2010. Baobab (*Adansonia digitata* L.) fruit production in communal and conservation land-use types in Southern Africa. For. Ecol. Manag. 261, 630–639.

Weyerhaeuser, F.J., 1985. Survey of elephant damage to baobabs in Tanzania's lake manyara national park. Afr. J. Ecol. 23 (4), 235–243.

Wickens, G.E., Lowe, P., 2008. The Baobabs: Pachycauls of Africa, Madagascar and Australia, p. 498pp.

Wilson, B.G., Witkowski, E.T.F., 2003. Seed banks, bark thickness and change in age and size structure (1978–1999) of the African savanna tree, *Burkea Africana*. Plant Ecol. 167 (1), 151–162.

Wilson, R.T., 1998. Vital statistics of the baobab (*Adansonia digitata*). Afr. J. Ecol. 26, 197–206.

World Bank, 1994. Tanzania Agricultural Sector Memorandum Volume II: Main Report. July 29 1994.