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Population structure and distribution of baobab (*Adansonia digitata*) in Malawi in an era of enhanced forest resource utilization

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Abstract. *Chirwa M, Mazibuko DM, Sagona WCJ. 2024. Population structure and distribution of baobab (*Adansonia digitata*) in Malawi in an era of enhanced forest resource utilization. Asian J For 8: 88-97.* Non-Timber Forest Products (NTFPs) contribute to people's livelihood security, especially those in rural areas. However, there is a growing concern that NTFP-providing trees are declining due to land-use change, use intensification, and over-harvesting, therefore an urgent need for sustainable use. This study was conducted in six districts in Malawi: Mangochi, Salima, Mwanza, Neno, Chikwawa, and Nsanje, to understand the population dynamics of *Adansonia digitata* L., which would inform sustainable management of the species. The study aimed to investigate the ecological conditions supporting *A. digitata* growth and assess human impacts on regeneration and seedling recruitment. The assessments were done on 1,223 trees in baobab clusters overlaid with systematic grids with a 500 m spacing interval between individual plots. The trees' diameter ranged between 230 and 305 cm, translating to yield estimates between 520 and 1,084 fruits per tree for the districts. The species was most prevalent in settlements and farmlands and least likely in grasslands. Population structures showed that the species is unstable in replenishment, with a limited number of saplings and juveniles in the sampled locations. Generally, the baobab population seemed less affected by diseases or pests, as no more than 3 % of the assessed population was infested. Deliberate efforts are required to promote raising baobab trees by nurturing the existing few seedlings and saplings or up-scaled integration of the resource on farmlands.

Keywords: Cluster, human activity, regeneration, stocking density, vegetation

INTRODUCTION

The African baobab (*Adansonia digitata* L.) is an iconic tree belonging to the Malvaceae subfamily Bombacoideae, widespread south of the Sahara, especially in savanna regions (Mpofu et al. 2012). Baobab has multiple uses, both for subsistence and as a source of income (Adesina and Zhu 2022). As an Indigenous Fruit Tree (IFT), it can improve nutrition, enhance food security, promote rural development, and facilitate sustainable landscape management (Pye-Smith 2010). IFTs provide crucial services to rural communities during famine and food scarcity by providing energy and nutrients, including vitamins, minerals, and proteins. Nearly every part of the baobab tree is used by humans (Sidibe and Williams 2002); for example, oil from seed is used in cooking, and leaves are an important vegetable in many parts of Africa, including Malawi (Darr et al. 2022). In West Africa (Buchmann et al. 2010), reports of more than 300 uses of *A. digitata* across ethnicities in 4 agroecological zones have been reported. The baobab fruit pulp is a highly sought-after product (Jäckering et al. 2019). Besides juice making, baobab fruit has huge potential for making jam, oil, and wine (Akinnifesi et al. 2008). Such products are very important for building local economies.

In Malawi, baobab is one of the important trees socially and economically. Traditionally, baobab has a variety of uses. The fruit pulp is widely eaten raw or mixed with porridge to add taste and flavor, fuelwood for smoking fish, baking soda from fruit shells, and the bark is used in making mats and other artworks (Sanchez 2011a). From around the year 2000, efforts to commercialize baobab took hold and changed the dynamics of its utilization (Welford et al. 2015). The fruit pulp is used in jam, juice, and ice-lollies production, and baobab seeds are used to make 'coffee' and cooking oil (Darr et al. 2020). From a socioeconomic perspective, baobab has gained enhanced importance; to some extent, its commercialization has played a role in its socioeconomic status in Malawi. Before the commercialization of baobab fruit, this species was casually used as a local snack by children, and most fruits were eaten by wild animals or left to rot (Welford et al. 2015). Baobab fruit commercialization from around the year 2000 led to high demand for fruits and thus removal of seed from its natural environment thereby affecting natural regeneration. Their study (Chirwa 2006) found low levels of regeneration of the species in the wild, a feature that could partly reflect the effects of commercialization.

In recent years, forests, including baobab populations, have been dwindling rapidly worldwide (Ziangba and Pouakouyou 2007), and in Malawi, forest cover loss has been estimated at 0.6% annually since 2021. This is largely due to biomass energy demand and increased land clearing for farming, a direct consequence of population increase (Oranu et al. 2022). The high demand for baobab products on one side and the undisputed increased negative human impact on the environment, particularly agriculture, which limits seedling recruitment (due to weeding), is noted as a threat to the existence of the *A. digitata* (Chitungo et al. 2022). This scenario has created the need to establish the extent of availability and productivity of baobab in Malawi so that its optimum off-take and silvicultural management options are understood for its improved management and sustainable utilization. Understanding the population structure is one way to inform sustainable management and species conservation options (Mohammed et al. 2021). The structure of the baobab population at a local level has been well documented in Malawi (Chirwa 2006). Models have also been used to simulate the habitat for baobabs in Malawi using secondary data sources (Sanchez 2010). However, its spatial distribution using empirical data at a large scale remained in Malawi.

This work sought to assess the population structure of *A. digitata* in six districts of Malawi. Specifically, we sought to investigate the ecological conditions that support *A. digitata* growth and assess human impacts on regeneration and seedling recruitment to inform baseline silvicultural recommendations for sustainable species management.

MATERIALS AND METHODS

Study sites

The study was conducted in Malawi's southern and central regions in districts with predominant baobab populations: Mangochi, Salima, Mwanza, Neno, Chikwawa, and Nsanje (Figure 1). According to Chirwa (2006), baobab occurs mostly in Malawi's Great Rift Valley area along the lake shore and Shire Valley area, predominantly highly active clay zones with vertisols, luvisols, and cambisols. These areas are generally dominated by undifferentiated woodland species *Vachellia* (previously *Acacia)* and *Combretum* (White et al. 2001). Forest cover loss in the study districts generally increases due to high human population densities (National Statistics Office 2019). The high population has resulted in over-exploiting forest resources to increase crop production through agricultural expansion (Kerr 2005; Malawi Gov 2010).

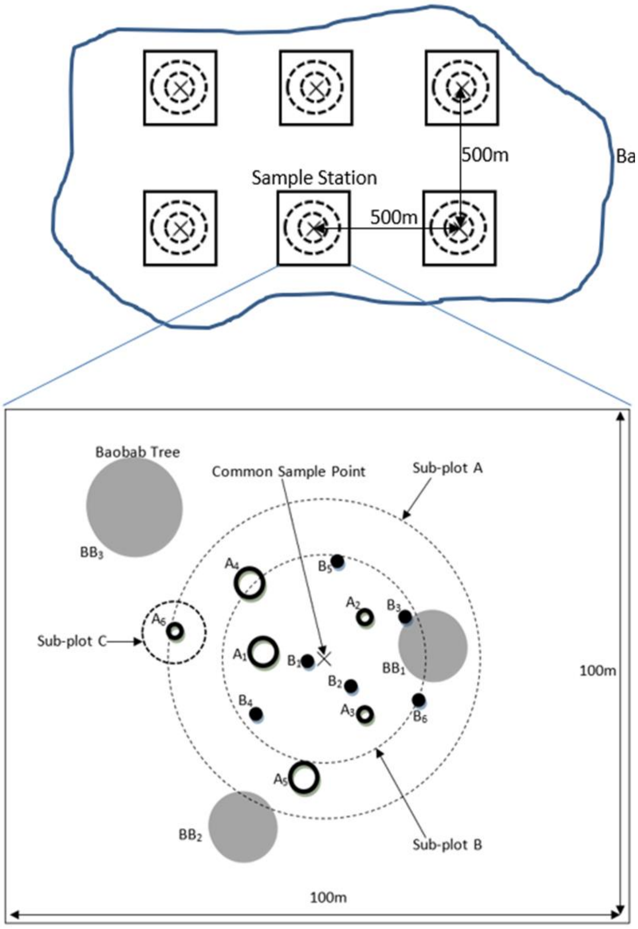

Figure 1. The sampling design used in this study

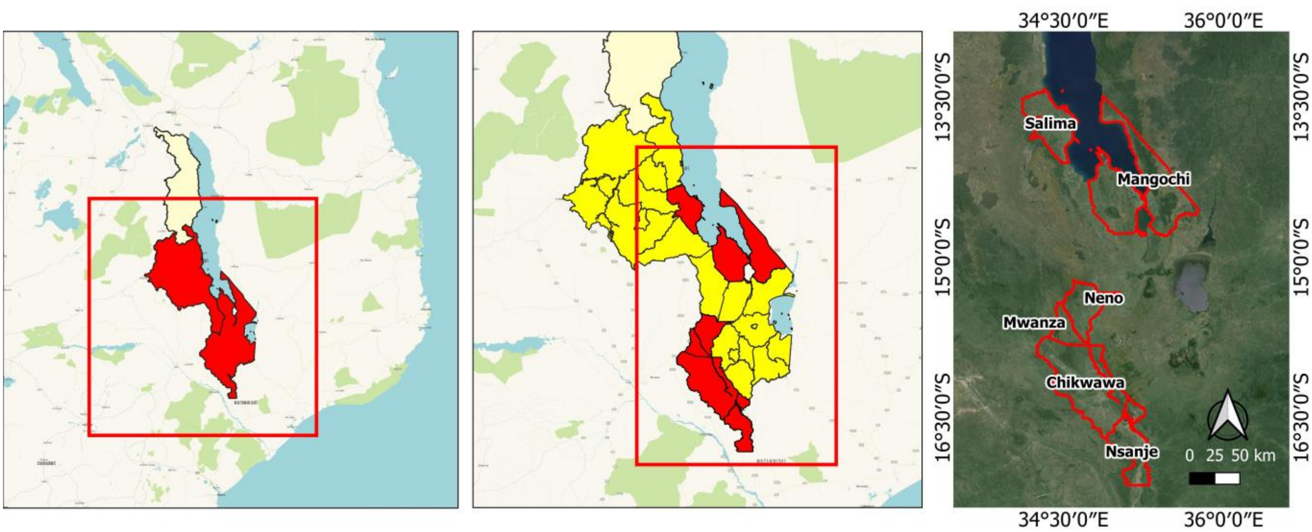

Figure 2. Map of Malawi showing areas where the study was conducted

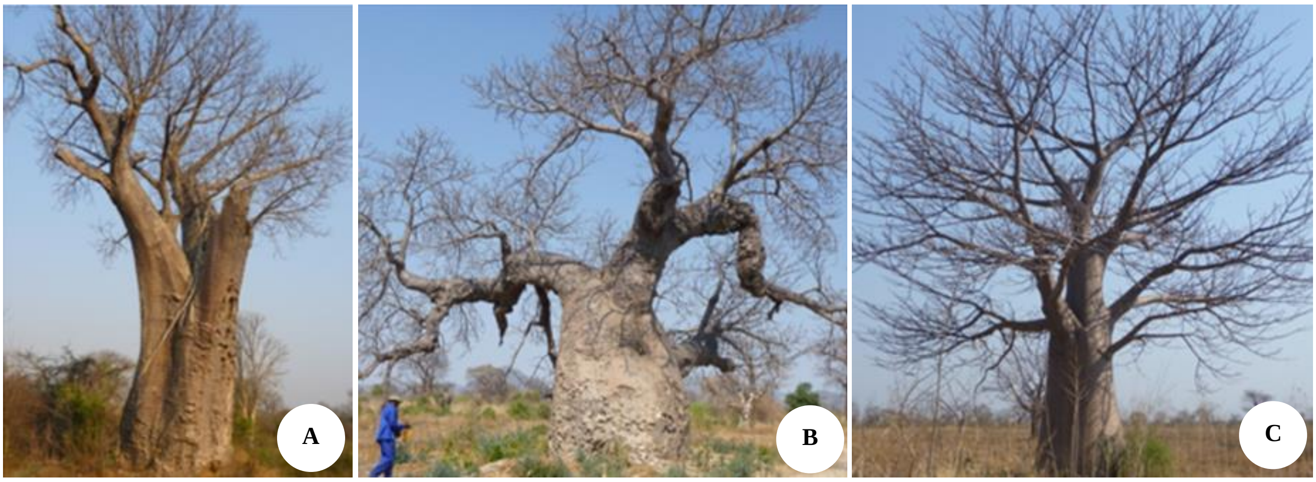

Figure 3. Pictorial view of some growth habits for *Adansonia digitata* from the study sites

Data collection

The survey employed a grid sampling system (Figure 2) within the baobab clusters. The start point was identified using randomly generated distance numbers while the grid was laid systematically over a baobab cluster using a pre-determined interval of 500 m between subsequent plots. GPS receivers were used to locate the subsequent plots with either an east-west or north-south directional orientation from the randomly selected start point. The sample point was also a common center for three k-tree sub-plots, according to Kleinn and Vilčko (2006), for assessing baobab regeneration and associated species.

In each of the three sub-plots, various assessments were made as follows: sub-plot A was for associated tree species >5 cm Diameter at Breast Height (DBH); Sub-plot B was for baobab regeneration and associated tree species <5 cm DBH, while sub-plot C was for associated shrubs and climbers. Sub-plot C was set around the farthest tree either in Sub-plot A or B. All other baobab assessments were assessed in the 1-hectare square plots engulfing the three sub-plots and the associated species.

Therefore, *K*-tree sampling where *k*=6 was employed to assess the associated trees and shrubs, whereby 6 trees or shrubs nearest to the plot center were assessed in each sub-plot. Species were recorded in all the plots while diameters were additionally assessed in sub-plot A (trees >5cm DBH) for determination of relative coverage of the species. Variables assessed for the baobab, irrespective of size, were Diameter at Breast Height (DBH), tree height, bole height, shape of trunk and fruit, and crown width. The choice of the variables was based on their influence on fruit productivity, harvesting techniques, and their relevance to the provision of multiple other products such as biomass, fiber, and fodder. Fruit shape was classified as either round, ovoid, or ovoid pointy. The trunk shapes were classified as pollarded, stunted, and upright (Figure 3.A-C, respectively).

Due to pollarding at some stage of their growth, the stunted trunks comprised trunks whose DBH was hugely disproportionate to growth in height. The crown width was defined as the average measurement of the tree's widest crown diameter and the measurement directly perpendicular to it (Kershaw Jr et al. 2016).

Data processing and analysis

Forest assessment: Statistical Package for Social Sciences (SPSS Version 27, 2019) and Minitab 16.1.1 (Minitab, 2010) were used to analyze the data. The diameter was grouped into the following classes: 1 = (<50 cm), 2 = (51-100 cm), 3 = (101-150 cm), 4 = (151-200cm), 5 = (201-250 cm), 6 = (251-300 cm), 7 = (301-350 cm) and 8 = (>351 cm). These classes were used to calculate stem frequencies in each diameter class per given district. Fruit yield per tree was estimated using a regression function developed by Muchiri and Chikamai (2003):

$$Y = 0.0004X^{2.5897}$$

Where:
Y : Total number of fruits per tree
X : Tree diameter (cm). Fruit yield was estimated to assess baobab productivity.

The data on associated species was analyzed separately to minimize the effect of site and social factors in determining species in a natural community and their abundance. Importance Values (IVs) of the species were determined from the sum of Relative Frequency (RF), Relative Density (RD) and Coverage (RC), which were obtained as follows: RF is frequency of species *i* / sum frequencies of all species multiplied by 100; RD is number of individuals of species *i* / total number of individuals multiplied 100 and RC is total basal area for species *i* / total basal area of all species multiplied 100 (Pereki et al. 2013). Due to time and financial limitations, relative frequency and density were used as an importance value of the shrubs (where shrubs included any trees and saplings less than 5 cm DBH) to a baobab environment, while the sum of relative frequency, density, and coverage was used as an importance value of the associated species greater than 5cm DBH as diameter was also assessed for these trees to represent the coverage. Relative density, frequency, or coverage may be interpreted as an "importance value" depending on which of the values the investigator considers most important for a species, group of species, or community (Brower et al. 1998).

RESULTS AND DISCUSSION

The ecology of *A. digitata* in Malawi

Baobab was found growing in diverse habitats in the study sites. As indicated in the GPS receiver, the altitudinal range of A. digitata in the study area is 73-842 meters above sea level (m asl.). This falls within the range (0-800 m asl.) reported earlier for African baobab (Sanchez 2011b); the Baobab tree is a characteristic species for drier areas. The species generally occurs from sea level to at least 1,500 m asl. and in areas receiving as little as 90 mm of rainfall to as much as 1,400 mm annually (Egbadzor et al. 2023). A common range for baobab sites in Malawi and the greater part of Africa is 0-800 m asl. with a mean maximum temperature from 25°C to 30°C (Sanchez 2011b). This explains the prevalence of baobab in the Great Rift Valley along Lake Malawi, Shire Valley, and Lisungwi Valley. Generally, the study locations were suitable for the African baobab, as documented by (Egbadzor et al. 2023).

An assessment of trees growing in association with *A. digitata* shows slight variation across forest layers. Within the Shrub/Herb layer, the ten most important species had importance values (IV) ranging between 4 and 13% (Table 1). Out of the ten species, *Capparis erythrocarpos* was the most important species recorded in this layer, while *Boscia corymbose* was the least important. The three least important species were *Barleria spinosa*, *Cissus integrifolia,* and *Phyllanthus ovalifolius.* Associated species break the monotony of a species by bringing some ecological balance through species diversity in the event of pests and disease outbreaks and provide shade that may facilitate the germination of *A. digitata* seed (Duvall 2007).

Within the regeneration layer, *Diospyros squarrosa* and *Albizia anthlemintica* were the two most important species in the regeneration layer (Table 1). *Albizia harveyi* (IV = 9%) was also among this layer's five most important species. *Azanza garckeana*, an indigenous fruit tree, was noted as another important species to a baobab habitat, albeit at 14th with an IV of 6 % (data not shown). In that order, this layer's three least important species were *Monodora junodii, Tricalysia micrantha,* and *Combretum paniculatum.*

The tree layer was dominated by *Lannea stuhlmannii* and *Sterculia africana* as two of the most important species (Table 1). *Sclerocarya birrea*, a multipurpose indigenous fruit tree, and *Faidherbia albida*, an agroforestry species, were among this layer's ten most important species in a baobab habitat. Imoro and Barnes (2013) also recorded *F. albida* as a key species that grows associated with baobab. The three least important species recorded in this study for this layer were *Zanha africana, Grewia bicolor,* and *Deinbollia nyikensis*

Species that were present in at least two of the three layers were *Diospyros squarrosa*, *A. anthlemintica*, *L. stuhlmanii*, *A. harveyi*, *Lonchocarpus capassa*, *Combretum mossambicense, Vachellia tortilis,* and *Ehretia amoena*. Most of these species occur in low areas associated with alluvial soils. However, some species' association with baobab was more localized in some areas than others, such as *A. anthlemintica* in Neno. Site conditions could be the major factor attributed to most species' association with baobab. Table 2 shows some most encountered site conditions and the species associated with *A. digitata*.

However, the dominance of *L. capassa* amongst regeneration indicates that some areas are not affected by fire as this species is fire intolerant (Hoffmann et al. 2009). The presence of *Vachellia* species (e.g., *V. tortilis*) may also imply disturbance of some of the sites as *Vachellia* (*Acacia*) species can rapidly colonize disturbed sites, typical of encroaching species (Borah et al. 2021). This may positively and negatively affect baobab regeneration by shading tender baobab seedlings from scorching heat and suffocating regenerating baobab seedlings as they compete for soil nutrients and sunlight during growth. The *F. albida*, an agroforestry species, as noted by (Gning et al. 2023), is found in similar ecosystems to African baobab in Senegal.

Table 1. Top ten species associated with *Adansonia digitata* in different forest layers

Forest layer & top ten important species	IVI
Shrub layer	
Capparis erythrocarpos Isert	0.1265
Diospyros squarrosa Klotzsch	0.0765
Ehretia amoena Klotzsch	0.0668
Combretum mossambicense (Klotzsch) Engl.	0.0657
Boscia salicifolia Oliv.	0.0625
Dregea macrantha Klotzsch	0.0603
Cocculus hirsutus (L.) W.Theob.	0.0597
Dichrostachys cinerea (L.) Wight & Arn.	0.0551
Sesbania tetraptera Hochst. ex Baker	0.0481
Boscia corymbose Gilg	0.0443
Regeneration layer	
Diospyros squarrosa Klotzsch	0.1268
Albizia anthlemintica (A.Rich.) Brongn.	0.1204
Combretum mossambicense (Klotzsch) Engl.	0.0984
Albizia harveyi E.Fourn.	0.0946
Lannea stuhlmannii (Engl.) Engl.	0.0850
Ehretia amoena Klotzsch	0.0829
Lonchocarpus capassa Rolfe	0.0809
Acacia tortilis (Forssk.) Hayne	0.0741
Capparis erythrocarpos Isert	0.0668
Diospyros senensis Klotzsch	0.0655
Tree layer	
Lannea stuhlmannii (Engl.) Engl.	0.5867
Sterculia africana (Lour.) Fiori	0.3428
Lonchocarpus capassa Rolfe	0.2224
Acacia tortilis (Forssk.) Hayne	0.1438
Cordia africana Lam.	0.1417
Albizia anthelmantica (A.Rich.) Brongn.	0.1355
Sclerocarya birrea (A.Rich.) Hochst.	0.1188
Albizia harveyi E.Fourn.	0.0700
Faidherbia albida (Delile) A.Chev.	0.0698
Erythrina livingstoniana Baker	0.0661

Table 2. Species and site conditions associated with *Adansonia digitata* populations from some study areas

Species	Site conditions
L. capassa	Scattered in various woodlands at medium to low altitudes, frequently along rivers.
F. albida	A low veld tree occurs in woodland, wooded grassland, and riverine fringe forest.
V. tortilis	Widespread in low altitude, dry areas, in varied types of woodland.
Diospyros squarrosa	Deciduous woodland and thickets from sea level to around 1,200 m asl.. At higher elevations, the plant is only found on termite mounds
A. anthlemintica	Commonly occurs in deciduous or evergreen bushland and scrubland, especially along seasonal rivers at 80-1,520 m asl.
A. harveyi	*A. harveyi* is found in dry woodland up to 1,450 m asl.
C. mossambicense	This species is found in low-lying, hot, dry areas, on hills, and often near rivers
E. amoena	On sandy and alluvial soils in riverine thickets, open woodland, and along the margins of low-altitude forests, up to 1,150 m asl.
S. birrea	Occurs in medium to low altitudes, open woodland, and bush
A. garckeana	Occurs in almost all types of woodland from sea level to about 1,700 m asl., scattered and never dominant.

Table 3. Area assessed on stems per hectare and population of *Adansonia digitata* across all surveyed districts

District	Stems per hectar (SPH)	Area assessed (Ha)	Total tree count
Chikwawa	6.00	10.00	60.00
Mangochi	6.25	82.00	490.00
Mwanza	3.00	7.00	21.00
Neno	7.50	85.00	608.00
Nsanje	5.00	2.00	10.00
Salima	4.25	8.00	34.00
Total	32.0	194.00	1223.00
Average	5.33	32.33	203.83

The high diversity of associated species may benefit the regeneration of baobab and act as the natural habitat for animals that eat the baobab seed. This may assist in breaking seed dormancy of baobab seed after passing through the animals' digestive system, as observed by (Sidibe and Williams 2002). The shrub, regeneration, and tree layers have different important ecological roles related to baobab population structure. This study has discussed some roles, while others may require further ecological studies to understand their ecological roles and influence on the population structure.

Population structure

Sustainable silvicultural treatments and management require a clear understanding of several aspects of plant species in an ecosystem. These include understanding stand density, a measure that quantitatively expresses the number or count of trees on a unit of land (Sprintsin et al. 2009), used to predict plant growth, tree form, and assessment of forest integrity (Zeide 2005). Size class distributions in trees help in the prediction of future recruitment capacity. Naturally, a tree community comprises many small individuals, with progressively fewer older trees, creating the typical inverted J distribution (Shumi et al. 2019). Therefore, with its close relationship with a plant's photosynthetic capacity, crown diameter is pivotal in assessing stand growth and density (Hemery et al. 2005).

Stand density and stocking

Forty-one sites were assessed for the baobab distribution, representing a total area of 194 ha. A total of 1,223 trees were assessed in all sampled districts, representing an average of 204 baobab trees per district. Sites with high abundances were recorded in Mangochi and Neno (Table 3).

The stocking levels in the sampled districts can be considered scattered, with an overall average of 5.33 stems ha^{-1} and ranging from 3 to 7.5 stems ha^{-1} in different district sites. While Neno district had the highest mean stocking density (7.5 stems ha^{-1}) and Mwanza the least at 3 stems ha^{-1} (Table 3). No significant differences were detected in the stocking among all the six study districts ($F = 0.72$, $p < 0.614$). Elsewhere, (Sanchez 2011a) reported a stocking density of 2 stems ha^{-1} in northern Venda in South Africa, 0 to 2 stems ha^{-1} in agricultural fields in the Kibwesi district in Kenya, and as high and 10-12 stems ha^{-1} in some sites in Malawi; generally, the species stocking could be considered scattered. According to Duvall (2007), baobab habitat preferences correspond to patchiness in its stocking, and land use type impacts the population structure of baobabs.

Additionally, agricultural cropping has been reported to influence the number of surviving seedlings because baobab seedlings are normally removed when weeding crop fields to reduce competition (Lisao et al. 2018). Such observations have been reported in Malawi, Namibia, and South Africa (Chirwa 2006; Venter and Witkowski 2011; Lisao et al. 2018). However, the adult trees are normally retained, resulting in more adult trees in natural populations than those in the seedling stages. Ironically, most large trees, including baobab trees, are protected by cultural norms in African communities (Sidibe and Williams 2002); this may contribute to the high ratio of mature trees to juveniles.

Size Class Distribution (SCD)

Baobab diameter distribution in Malawi depicts a bell-shaped distribution pattern for Neno and Mangochi (Figure 4). There is no pattern for Nsannje and Mwanza distribution right-skewed distribution for Chikwawa and Salima. All studied sites lack smaller diameter classes with populations skewed towards baobab trees over 100 cm in diameter than below this threshold (Figure 5). The lack of seedlings among baobab populations has been noted across most African countries, attributed to herbivory, land clearing by farmers, and fires (Musyoki et al. 2022). The issue of fires can explain the observed low density in the fire-prone grassland of our study.

The negative exponential relationship of tree density to diameter has been observed and considered an indicator of equilibrium forest structure, especially at the stand level (Rubin et al. 2006). Despite Gebauer and Luedeling (2013) observing an inverse J-shaped curve indicating a viable regenerating population in Kordofan, Sudan, they further assert that low recruitment rates and bell-shaped or negatively skewed SCD patterns are typical of baobab populations across Africa. Venter and Witkowski (2011) further posited that such low recruitment patterns are characteristic of long-lived tree species as their recruitment is often episodic.

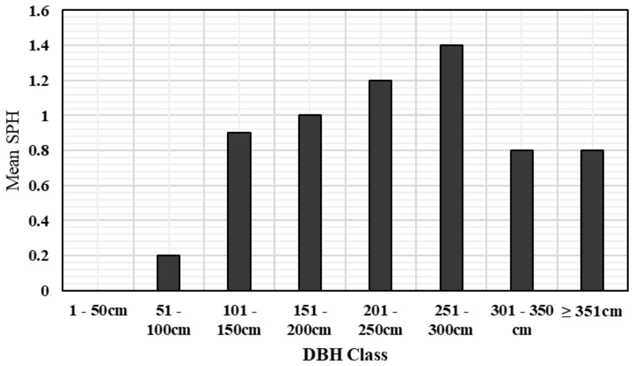

Figure 4. Plant density for diameter class for the whole study data

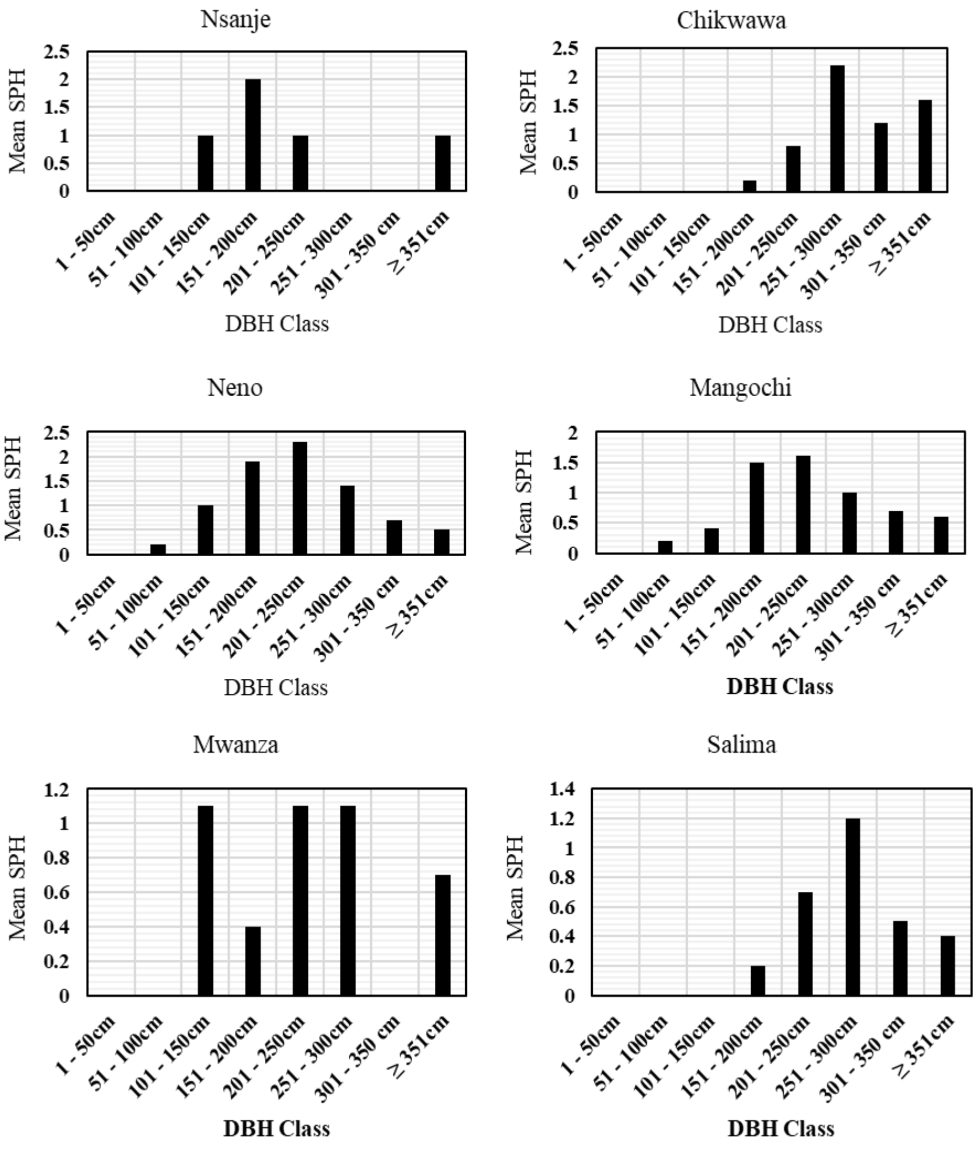

Figure 5. Size class distribution of *Adansonia digitata* from the six surveyed districts

Table 4. The five sampled districts ' total height, bole height, and crown diameter

District	N	Total height (m)	Bole height (m)	Crown diameter (m)
Mangochi	252	16.44	5.98	16.35
Neno	302	18.53	8.95	16.19
Mwanza	12	18.99	7.20	14.59
Nsanje	22	19.28	8.24	17.99
Chikwawa	30	20.02	8.98	17.29

The observed negatively skewed, bell-shaped baobab diameter distribution pattern in this study (Figure 6) could also be attributed to the species seed germination pattern. Studies on seed germination requirements have demonstrated that *A. digitata* seed possesses coat-imposed dormancy inhibiting water and gas uptake (Egbadzor 2020). Salami et al. (2021) observed that baobab seed sown without pre-treatment but only soaked in cold water overnight failed to germinate (0%) after 31 days. However, the seed was still viable (100%) when subjected to cutting tests. Optimum germination was only achieved when the seed was nicked or scarified with a rough surface. They concluded that under natural conditions, *A. digitata* seed takes longer to germinate, suggesting that the species presents a sporadic germination/regeneration pattern. Therefore, the observed diameter distribution pattern in the field confirms the baobab germination study conclusions; the disturbances trigger sporadic regeneration patterns. The lack of smaller diameter classes suggests that *A. digitata* also presents discontinuous recruitment, requiring the occurrence of triggers to seed germination. In this study, most baobab trees were encountered around settlements, followed by farmlands. Some human activities around homesteads and farms could trigger baobab seed germination, hence the high baobab tree densities recorded under these land-use categories. However, Venter and Witkowski (2011) observed that baobab is not seed-limited as it produces abundant viable seeds. Therefore, the microsite conditions such as infrequent rains and livestock browsing likely characterize these sites. Thus, beyond seed pre-sowing to break seed dormancy, there is a need to provide viable microsite management options to improve baobab recruitment. As observed by Venter and Witkowski (2011), these management pathways may include planting saplings as they register higher survival rates than seed and closing baobab regeneration sites to livestock browsing. The study found significant differences in mean diameter growth among study populations ($F = 6.092$, $p < 0.005$). Baobab trees in Chikwawa had the largest mean diameter (305 cm) and were significantly different from those in Mangochi (242 cm) and Neno (230 cm). Gebauer and Luedeling (2013) reported baobab stem diameters ranging between 6 and 477 cm, with most individuals assessed exhibiting diameters greater than 1 m. The authors further indicated that such diameters are in the range observed in Western and Southern Africa (Assogbadjo et al. 2011; Duvall 2007).

Tree heights and crown diameter

Total tree and bole heights can both influence harvesting techniques in baobab (Fischer et al. 2020) which can resultantly impact the health of trees. As such, differences in tree height may be useful in developing future domestication programs. For this study, Table 3 shows total tree height distributions by districts, and the height varied significantly. Mangochi was recorded as the most inferior (16.44 m) ($F = 15.989$, $p < 0.005$), while Mwanza, Nsanje, and Chikwawa as the most superior at 18.99, 19.28, and 20.02 m, respectively. Neno was in between the two subsets at 18.5 m. The morphology of the trunk for the study districts was hugely dominated by the uprights (92 %) followed by the pollarded ones (5%), with the stunted ones (3%) being the least. The pollarded were almost non-existent in Chikwawa, Mwanza, Nsanje, and Salima but were available in Mangochi and Neno at 9 and 3%, signifying the need for management interventions in the latter two. Imoro and Barnes (2013) report that baobabs can attain heights of 18-25 m at maturity. No significant differences were detected between bole heights and crown diameter in the respective study districts (Table 4).

The bole heights ranged between 6 and 9 m. Similarly, no significant differences were detected in crown attainment for the baobabs despite the crowns ranging between 14.6 and 18 m for Mwanza and Nsanje, respectively (Table 4). An increase in the crown diameter of baobab trees represents a potential for the tree to produce more fruits. This equally means all the sites have the same potential to produce fruits, signifying variability in diameter grown as a better predictive variable for fruit production, as reported by Muchiri and Chikamai (2003). Species morphological and phenological characterization of baobab needs to be further studied to understand the influence of variation in tree growth habit and size on fruit production; those studies are important to present empirical evidence of how much of this variation is influenced by the environment.

Productivity and health in Malawi (fruit production)

Baobab is a multipurpose species. However, upon maturity, the most common product from this species is the fruits. In this work, we utilize baobab fruits to assess population productivity. Therefore, using a regression function developed by Muchiri and Chikamai (2003) to estimate fruit production per tree in the study area, it was observed that Chikwawa district had the highest potential of producing more fruits per tree (1,084 fruits per tree) while Neno had the least (520 fruits per tree), Table 5.

Regarding plant health, there was no apparent disease or pest infestation, except for 1% (estimated during survey) of the trees infested by sooty baobab disease. The districts with the high prevalence of baobab, Mangochi, and Neno had their degree of infestation estimated at 3 and 1%, respectively. However, this has been reported as purely a secondary manifestation of a physiological disorder with certain trees afflicted earlier this century having since recovered (Sanchez 2011a). Bark harvesting in baobab enhances vulnerability to bark-targeting fungi, which cause sooty baobab disease (Mugangavari et al. 2021). Tree damage has been reported on baobab trees due to harvesting practices that may not be sustainable in the long term (Rhodes and Setshogo 2012).

Human recruitment impacts on *A. digitata*

The impact of humans on the recruitment of baobab partly emanates from the increasing human population, leading to intensifying land use (Chitungo et al. 2022). An assessment of plant density in different land use types can thus enable one to glean the potential impact of humans on this species. Baobab populations are very variable in different land use types. This could be due to factors like soil requirements, competition for water, disturbances of regeneration by browsing animals, pest attacks, and agriculture (Sanchez 2010). This study revealed more trees per hectare on farmlands and settlement areas in Chikwawa, Mangochi, Nsanje, and Salima (even though not significant, $P \geq 0.05$ Figure 6). This agrees with what (Assogba et al. 2020) found in a study where farmland showed more density than the national park and the buffer zone.

In Neno and Mwanza Districts, more baobab distribution was observed in forest land than in any other land use type, possibly because of immense undergrowth in the forests, making it difficult for animal grazing and browsing. Generally, baobab density may be higher in farmlands as farmers selectively choose to maintain useful trees in their farmlands and clear those that are not very important. Moreover Gebauer and Luedeling (2013) hypothesized that the high baobab abundance in many settlement sites in Africa suggests a strong relationship between trees and people, for example, in Sudan and Kenya, where baobab trees appear to be rarely planted but are commonly protected by households. The relatively low density in forest land could be attributed to competition with other species (Razafimahefa et al. 2022) for growth-supporting nutrients.

The future of baobab in Malawi

The future of baobab population in Malawi is uncertain at best. Challenges to sustainability of baobab populations include climate change effects and land use changes that come with population growth. Climate change, especially increasing temperatures are predicted to lead to contraction of suitable habitats for baobab (Birhane et al. 2020). For southern Malawi, modelling data indicate that suitable habitats for cultivation exist (Sanchez 2011a,b). The current challenge to baobab population in Malawi include reduced recruitment as a byproduct of agriculture, and deforestation. With the predicted population growth for Malawi, pressure for agricultural land is likely to increase, further impacting on baobab recruitment and distribution. Considering these existing challenges, in situ conservation alone is inadequate. Ex situ conservation efforts need to be promoted. Domestication efforts A. digitata led by SADC-ICRAF Agroforestry Regional Programme, date back to the early 2000s (Akinnifesi et al. 2002) but wider adoption has been slow. Currently domestication efforts could benefit from the lucrative participation of baobab products on the Malawian retail market (Meinhold and Darr 2022). Involvement of all players (in conservation efforts) in the baobab value is urgently needed to ensure a sustained future for *A. digitata* in Malawi.

In conclusion, baobab in Malawi is limited to a few areas (Neno and Mangochi Districts) where commercial ventures and improved sustainable management must be focused. The diameter distribution for the resource in Malawi is bell-shaped but more skewed towards adult trees. The lack of saplings and regeneration failure may be attributed to fires, browsing, farming, or the lack of catalytic events that could trigger regeneration. Deliberate efforts should, therefore, be made to promote raising baobab trees either through nurturing existing seedlings and saplings or up-scaled integration of the resource on farmlands. Additionally, factors that can potentially improve the baobab fruit tree should further be explored, including fruit productivity and preferred provenances and/or cultivars, to ensure long-term benefits from the various market opportunities the species offers. Our method can not fully account for existing baobab diversity in the country A nationwise survey of the species in thus recommended.

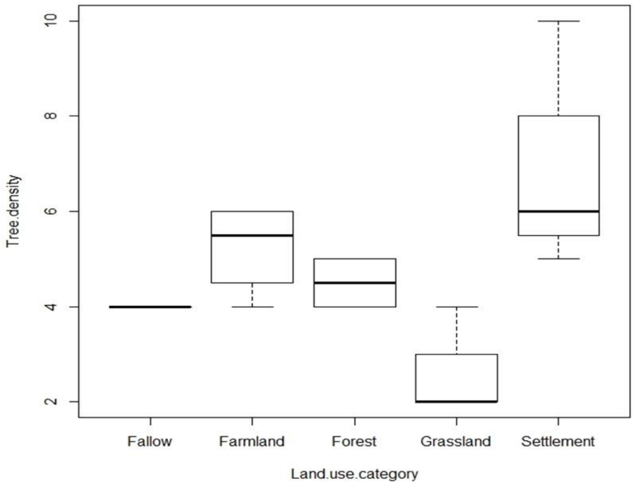

Figure 6. Density of *Adansonia digitata* as observed from different land uses

Table 5. The estimated productivity of *Adansonia digitata* stands from all studied sites

District	Diameter (cm)	Estimated total number of fruits per tree	Tree density (SPH)	Expected number of fruits per hectare
Neno	229.60	520.00	7.50	3902.39
Mangochi	241.53	593.00	6.25	3707.83
Mwanza	253.25	671.00	3.00	2012.12
Nsanje	271.48	803.00	5.00	4014.96
Chikwawa	304.82	1084.00	6.00	6503.37

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