

Is there a regeneration crisis? SEEA Species Accounts for the Baobab (*Adansonia digitata*) in Benin: Implications for Africa

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Abstract:

A pilot study evaluated whether natural regeneration can sustain the existing *Adansonia digitata* population through the end of this century. The study examined the species' spatial distribution, population structure, and regeneration status across Benin, West Africa, covering all major climatic, ecological, and land-use zones. This national-scale approach enabled a comprehensive assessment of how rainfall variability, agricultural expansion, deforestation, and protected-area coverage influence the species' current and future viability.

Using 300 georeferenced citizen-science photographs representing individual trees, the study applied the System of Environmental-Economic Accounting (SEEA) Species Accounts framework—specifically stock, condition, reproduction, pressure, and ecosystem accounts—to produce the first experimental SEEA species account for *A. digitata*. Spatial data processing and species distribution mapping were conducted in QGIS 3.44.11, while Python 3.14, implemented through Visual Studio Code, supported data organisation, analysis, and visualisation. The pilot study demonstrates that SEEA Species Accounts, combined with citizen-science observations, offer a standardised, cost-effective, and spatially explicit method for monitoring population status, regeneration dynamics, and long-term conservation prospects of culturally and ecologically important tree species. These results provide a strong foundation for a full-scale investigation into the regeneration capacity and future persistence of *Adansonia digitata*.

Key words: *Adansonia digitata*, Africa, species, rainfall, and regeneration

Introduction

This pilot study is the first experimental, documented global attempt to construct a SEEA-aligned species account for the African baobab, *Adansonia digitata*. Existing SEEA pilots focus almost exclusively on birds, mammals, and selected threatened species. No national statistical office or research institution has produced a spatially explicit, condition-integrated species account for *Adansonia digitata* or any African tree species. *Adansonia digitata* qualifies as a Class A biological asset because its products are commercially recoverable, rural communities actively use its populations, and its harvest contributes directly to household income, women's cooperative development, and local poverty alleviation. By demonstrating how a culturally

significant, climate-resilient keystone species can be incorporated into the SEEA framework, this work addresses a critical scale and monitoring gap in species accounting. It provides a replicable template for African governments seeking to integrate iconic species into natural capital accounting. It also addresses a critical decision-support gap, as SEEA species accounts provide condition-based information on species responses that can inform biodiversity management and climate-change scenario planning.

Background

The Evolutionary legacy of *Adansonia digitata* has contributed to its longevity, drought tolerance, and ability to persist in nutrient-poor soils, reflecting evolutionary strategies suited to highly variable climatic conditions (Mayne et al., 2022). However, contemporary genetic research confirms that land-use fragmentation and the isolation of remnant adult trees increasingly compromise this genetic resilience (Omonhinmin et al., 2023; Cheptou et al., 2017; Nazrin et al., 2025; and Hendre, 2025). Increasing regeneration failure and the collapse of African straw-coloured fruit bat pollination networks have also heightened the urgent need for conservation due to hunting pressure, roost disturbance, and habitat loss (Peel et al., 2017; Monadjem et al., 2016; Rainho, 2020). *Eidolon helvum*, the African straw-coloured fruit bat, is listed as “Near Threatened” on the IUCN Red List, indicating that the species is close to qualifying for a threatened category such as “Vulnerable”. Research estimates a 25–30% population loss over the past 15 years. This is the case in West, Central, and East Africa, and in areas migrating into Southern Africa (Cancino, 2024; Cooper-Bohannon et al., 2020; Webala, 2012; Mickleburgh et al., 2008; IUCN, 2011; Magloire et al., 2018; Singh, 2023). The IPBES global pollinator assessment, together with subsequent syntheses (Potts et al., 2016; Dicks et al., 2021; Stout and Dicks, 2022; Sadafale et al., 2025; Siviter et al., 2023; Kluser and Peduzzi, 2007; Thomann et al., 2013; Brunet and Fragoso et al., 2024; Feuerbacher, 2025; Kremen and Ricketts, 2000), documents widespread declines in pollinator abundance, diversity, and distribution across continents. These declines are primarily driven by habitat loss, pesticide exposure, climate change, and agricultural intensification, all of which may further exacerbate genetic isolation and reduce reproductive success in long-lived, pollinator-dependent species such as baobab.

Context

Adansonia digitata is an ecologically, culturally, and economically important species whose condition is influenced by environmental conditions and anthropogenic pressures (Adesina & Zhu, 2022). Its phenological cycles—including leaf emergence, flowering, and fruiting—are closely linked to rainfall and temperature regimes, making phenology a potentially valuable indicator of environmental variability and species condition (Venter & Witkowski, 2019). Changes in population structure, regeneration, and phenological patterns can provide insights into broader changes in ecosystem health, resource availability, and community resilience.

The species faces multiple pressures, including land-use change, habitat degradation, harvesting, fire, grazing, and increasing climatic variability. Emerging evidence of regeneration constraints in parts of West Africa highlights the need for systematic monitoring of population distribution, condition, and the pressures affecting the species. However, assessing these dimensions consistently across large areas remains challenging because species observations are spatially uneven, condition indicators are not routinely integrated with distribution data, and information on pressures is often fragmented.

Advances in citizen-science platforms, remote sensing, and geospatial technologies offer new opportunities to address these monitoring challenges by generating spatially extensive data on species occurrence, condition, phenology, and environmental pressures (Barnard et al., 2017; Gallagher et al., 2025; Conrad & Hilchey, 2011; Maxwell et al., 2020). Integrating these data

into the SEEA framework can transform disparate observations into a structured species account that supports assessment of environmental change, identification of key threats, and evidence-based conservation and climate-change planning.

Trends

Ecological trends reveal a population structure dominated by mature individuals (Fischer et al., 2020; Venter & Witkowski, 2013), a pattern that is particularly concerning given the escalating threats faced by *Eidolon helvum*, one of the tree's main pollinators. Over the past decade, systematic persecution of the African straw-coloured fruit bat has intensified, driven by entrenched cultural superstitions that portray these animals as harbingers of calamity and compounded by widespread concerns about their perceived role as viral reservoirs (Cancino, 2024). As *E. helvum* encounters these threats across multiple countries, the cumulative pressures place the species at increasing risk. Environmental trends point to intensifying climatic and anthropogenic pressures on dryland ecosystems, with *Adansonia Digitata* responses increasingly functioning as early-warning signals of broader biodiversity stress. Data trends reflect the rapid expansion of georeferenced citizen-science observations and high-resolution remote imagery, enabling more spatially explicit and temporally resolved assessments of species condition and distribution. Monitoring trends indicate an emerging need to integrate species-level information into natural capital accounting frameworks, such as the SEEA, to support more systematic, repeatable, and policy-relevant biodiversity monitoring.

Objectives

The overall aim of this study is to assess whether natural regeneration is sufficient to replace the existing and future *Adansonia digitata* population. The study is guided by three core research questions: (i) How can climate-scenario models for *Adansonia digitata* be strengthened to represent its most likely ecological responses under future climate conditions? (ii) What are the major environmental and anthropogenic threats affecting *Adansonia digitata* in Benin, and how do these pressures influence its population condition, regeneration, and long-term persistence? (iii) What cost-effective conservation and management strategies can address these threats while maintaining viable populations and conserving the genetic diversity of *Adansonia digitata*?

Contribution to the Field

This study provides the first structured SEEA Species Accounts of *Adansonia Digitata* populations in Benin and the first global example of a SEEA-aligned species accounting for an African tree. It demonstrates how culturally significant, climate-resilient species can be integrated into natural capital accounting and offers a replicable methodology for other African countries. By combining social, spatial, and ecological evidence, the study delivers new insights into regeneration dynamics, pollination dependencies, and ecological vulnerability. It establishes an empirical foundation for linking *Adansonia Digitata* condition to ecosystem resilience and provides practical guidance for biodiversity management, policy development, and long-term monitoring.

Key Threats and Solutions

In this section, the future viability of *Adansonia digitata* is assessed through climate-scenario modelling to provide insight into the species' potential for long-term replacement. The review examines the suitability of projected environmental conditions—including rainfall patterns, drought frequency, and temperature extremes—and evaluates how these factors may influence baobab populations' capacity to regenerate and persist under future climate change. It then analyses present-day environmental conditions and anthropogenic pressures, highlighting their

consequences for current regeneration dynamics and implications for the likelihood of future climate-driven outcomes. The section concludes with cost-effective strategies aimed at addressing these challenges and supporting the continued persistence of *A. digitata*.

This section begins with a brief introduction to the species' history. *Adansonia digitata* has historically exhibited substantial genetic diversity, enabling it to withstand environmental challenges such as drought, heat and disease, and to persist over many centuries (Stange et al., 2021; Des Roches et al., 2021; Mable, 2019). This genetic variation reduces extinction risk because populations are not uniformly vulnerable to the same threats (Stange et al., 2021). Moreover, *A. digitata* shows strong local adaptation across its range, evolving traits suited to specific environmental conditions (Ellegren & Galtier, 2016; Scotti et al., 2016).

However, genetic resilience alone does not guarantee long-term persistence if the environmental conditions that support the species begin to shift. Across Sub-Saharan Africa, future climate-driven species distribution models increasingly project contraction of *A. Digitata* habitat, particularly in regions experiencing intensifying aridity and altered rainfall seasonality (Assogba et al., 2022; Chitungo et al., 2022; Atakpama et al., 2023; Gadallah et al., 2025; Amevivi et al., 2025; Tagliari et al., 2021). These continental-scale trends highlight growing uncertainty about where suitable conditions will remain stable. Within this broader pattern, Benin occupies a critical transition zone between humid southern ecosystems and the drier northern savannas, where climatic suitability may be maintained, reduced, or fragmented depending on future scenarios. This raises a key question: to what extent will environmentally suitable conditions for *Adansonia digitata* in Benin persist under future climate change, and how can observed changes in the species' distribution be used to evaluate and refine these projections? Recent research indicates that the Benin landscape currently provides highly suitable environmental conditions for *Adansonia digitata*. Moreover, projections from Assogba et al. (2022) suggest that these areas of environmental suitability are likely to remain largely stable under future climate scenarios. However, other studies using similar climate scenarios point to a gradual contraction in the species' suitable climatic range. Chitungo et al. (2022) projected that, under future climate change scenarios, only a small proportion of the species' current distribution across Africa will retain suitable environmental conditions. The remaining suitable habitats are expected to be concentrated primarily in Malawi and Mozambique, with smaller refugial areas occurring in Benin, Senegal, Burkina Faso, Zimbabwe, Botswana, Tanzania, and Madagascar. Similarly, Atakpama et al. (2023), using future climate projections, identified Burkina Faso, Benin, Senegal, and Togo as among the most suitable countries in West Africa for cultivating and conserving *A. digitata*, with 85% of West African countries considered not to have highly suitable environmental conditions. More recently, Dogbo et al. (2025) modelled future environmental suitability for twelve key multipurpose tree species, including *A. digitata*, under two Shared Socioeconomic Pathways (SSPs). Their findings revealed a concerning trend: 67% of the assessed species were projected to experience substantial losses of suitable habitat. Although protected areas provided some degree of buffering against these projected changes, their effectiveness varied considerably among species, highlighting the differential vulnerability of multipurpose tree species to future climatic shifts (Dogbo et al., 2025). Overall, these findings suggest that while parts of West Africa—particularly Benin, Burkina Faso, Senegal, and Togo—may continue to provide important refugia for *A. digitata*, climate change is likely to progressively reshape the species' distribution and increase the importance of targeted conservation and adaptive management strategies. These findings suggest climate scenarios provide an important framework for assessing potential future changes in species distributions.

However, as Pielke and Richie et al. (2020) note, climate scenarios were originally developed as plausible alternative futures without associated likelihoods, but have increasingly been used as baseline expectations for projecting future climate impacts. This distinction matters when

interpreting projections for *Adansonia digitata*, as scenario-based assessments describe potential future conditions rather than necessarily representing the most likely ecological outcome. The resulting projections are also dependent on the assumptions, models, spatial scales and species-occurrence data used in the assessment.

How can climate scenario models for A. digitata be strengthened to represent the most likely ecological outcome? Understanding this will enable the evaluation of whether natural regeneration can sustain the existing *Adansonia digitata* population through the end of this century. In this context, species accounts developed within the System of Environmental-Economic Accounting (SEEA) could provide an important empirical complement to long-term climate scenarios. SEEA Species Accounts are structured, spatially based statistical records that track the stock, condition, pressures, and reproduction status of individual species to support biodiversity monitoring and decision-making (UNEP-WCMC, 2016). The SEEA Species Account for *A. digitata* is proposed as an annual feedback mechanism to systematically assess observed changes in species stock and condition against projected future climate scenarios. Where observed trajectories diverge materially from projected outcomes, the evidence generated through the species account can trigger a review and, where justified, amendment of the assumptions, parameters or projections underlying the relevant climate-impact scenarios. Collecting and validating citizen-science observations into annual SEEA species accounts could generate a continuously updated evidence base for documenting changes in the distribution, abundance and condition of *A. digitata*. While climate scenarios provide a long-term representation of potential future environmental conditions, annual species accounts could provide empirical evidence of the species' realised response to environmental change. The observations could also provide a mechanism to evaluate and progressively update long-term projections. Observed changes in *A. digitata* could be compared with modelled changes in habitat suitability to identify where projected and realised distributions converge or diverge. Persistent discrepancies could then be used to validate and recalibrate species-distribution models, improve their ecological assumptions and update projections. Where probabilistic approaches are applied, accumulating empirical observations could further be used to update the likelihood assigned to alternative ecological outcomes under different climate scenarios. In this sense, SEEA species accounts would not directly "correct" the climate scenarios themselves; rather, they could provide an empirical basis for progressively updating the likelihood and uncertainty associated with the ecological responses projected under those future climate scenarios.

What other major threats does the species face?

Many threats affect the survival of *Adansonia digitata*, including land-use change, environmental degradation, habitat loss, deforestation, habitat fragmentation, bark harvesting, and livestock browsing (Kamins et al., 2011). However, across many African countries, there is a consensus that the populations of *A. digitata* are described as ageing; this is a major threat, with limited natural regeneration and recruitment, raising concerns about the long-term persistence of the species (Fischer et al., 2020; Venter & Witkowski, 2013; Dhillon & Gustad, 2004; Sanchez, 2011). Poor seedling establishment and low recruitment appear to be particularly important bottlenecks.

In southern Africa, studies have reported low rates of *A. digitata* seedling establishment. Early sapling growth and survival are often constrained by moisture stress and grazing pressure, making this developmental stage critical for successful regeneration and restoration (Venter & Witkowski, 2013). In southern Malawi, some areas have low densities of *A. digitata* trees because of limited natural regeneration (Sanchez, 2011). Similarly, in Zimbabwe, germination and seedling growth are largely restricted to the short rainy season.

Because rainfall is often insufficient to support successful seedling establishment, young *A. digitata* seedlings are rarely observed, resulting in generally low regeneration rates and raising concerns about the continued survival of the species in affected areas (Nzengya & Mutasa, 2007). More recent evidence from southern Africa further indicates that poor natural recruitment is associated with browsing and increasingly erratic rainfall patterns (Khwilimba et al., 2026). Populations in southern Malawi have also been characterised as ageing, with low recruitment and a substantial proportion of diseased mature trees (Sanchez, 2011; Venter & Witkowski, 2013). Regeneration challenges have also been documented in eastern Africa. In Ethiopia, evidence of natural seedling production suggests that *A. digitata* can regenerate; however, many seedlings fail to survive and reach maturity. Land clearing and anthropogenic fires associated with agricultural practices, together with browsing and trampling in forest environments, can severely affect seedlings and saplings (Abere et al., 2023). In Tanzania, age-structure data indicate a decline in recruitment over the past 25 years, potentially associated with increasing elephant densities (Barnes, 1980). In Kenya, a high proportion of small *A. digitata* individuals have been reported to be stunted, although the causes of this stunting remain unclear (Fischer et al., 2020). Another study sheds light on stunted growth. Baobab seedlings become stunted during long droughts because they shut down growth to survive. They protect the taproot and enter dormancy. This keeps them alive, but it prevents height growth. If drought is extremely long or repeated, the seedling may die before it ever becomes a tree (Bilcke et al., 2013). Similar constraints have been reported in West Africa, where seedling survival is often poor because of the combined effects of drought and browsing. These studies have highlighted the importance of protecting young plants from livestock and disturbance during field clearing and weeding, as well as providing supplementary watering during dry periods (Gijsbers et al., 1994). Bushfires, overexploitation, agricultural expansion, agroforestry practices, and grazing have likewise been identified as important threats to *A. digitata* regeneration in West Africa (Sidibé & Williams, 2002; Assogbadjo et al., 2005). In North Africa, regeneration of *A. digitata* in West Kordofan State, Sudan, has also been reported to be poor, highlighting the urgency of conservation interventions (Eltahir et al., 2015).

The studies above provide evidence of the extent of regeneration issues; however, for the current pressures and environmental conditions to inform any future environmental conditions and climate scenario outcomes, there is a need for regeneration thresholds to provide adequate understanding of how declines in younger tree cohorts may compromise the long-term persistence of adult populations. Table 1 synthesises evidence from several studies to explore the potential for benchmarking the relationship between seedling- and sapling-to-adult trees as indicators of regeneration condition, and to assess the extent of regeneration from good and adequate to severe failure.

Table 1: Ratio for sapling/seedling to adult trees benchmark

Regeneration: adult ratio	Proposed condition class	Interpretation	Supporting evidence
$\geq 1.00:1$	Good/adequate regeneration	At least one seedling, sapling or juvenile is present for every adult tree.	Tsegay (2026) uses 1:1 as a benchmark for a self-sustaining population. Grandjean et al. (2026) recorded juvenile and infant ratios of approximately 1.58:1 and 2.05:1, respectively, demonstrating that regenerating populations can have younger cohorts exceeding adults.
0.50-0.99:1	Moderate regeneration constraint	Younger individuals are present but occur at fewer than one individual per adult, suggesting reduced recruitment relative to the adult population.	Tsegay (2026) found a sapling ratio of 0.68:1 and a seedling ratio of 0.42:1, both interpreted as constrained recruitment. Lokonon et al. (2022) similarly found ratios <1 to be associated with discontinuous regeneration and low recruitment.

0.10–0.49: 1	Strong regeneration stress	The younger cohort is substantially smaller than the adult cohort, indicating a pronounced recruitment deficit and potential difficulty replacing mature trees.	Tsegay (2026) provides an empirical example of 0.42:1 for seedlings, which the authors classified as constrained recruitment. The lower end of this range also aligns with the severe age-structure imbalance observed in baobab populations.
< 0.10: 1	Severe regeneration failure /	Fewer than one younger tree for every ten adults, indicating an extreme demographic imbalance and a potentially severe failure of population replacement.	Msalilwa et al. (2020) found only 3% juveniles compared with 73% adults in Tanzanian baobab populations. This corresponds to approximately 0.04 juveniles per adult, while juvenile density was only 0.33 ha ⁻¹ compared with 1.53 adult trees ha ⁻¹ (≈0.22:1). Juveniles occurred in only 16 of 337 surveyed grid squares.

The evidence in Table 1 provides an adequate benchmark for assessing the relationship between adult and young trees to determine the extent of recruitment success or failure.

Another important issue is how to address these threats to *A. digitata*. Which combinations of low-cost regeneration interventions can most effectively improve recruitment while conserving the genetic diversity and adaptive potential of the species populations across different African environments?

Vickers et al. (2019) established the underlying management challenge: successful regeneration is fundamental to species such as *A. Digitata*, but the regeneration outcomes are difficult to predict, and failures can be costly and time-consuming to rectify. Their work demonstrates that managers need indicators that can show not only whether trees are present, but whether regeneration is progressing successfully across landscapes. Löf et al. (2019) place this challenge within the much larger context of global forest restoration. Large areas of degraded land are being considered for restoration, but implementation is constrained by restoration costs, shortages of regeneration material, and the need for restored forests to benefit local communities. Brancalion et al. (2019) reinforce this scale challenge. Their analysis highlights the enormous extent of global restoration commitments and the need to direct limited investment towards areas where restoration is both feasible and likely to generate substantial benefits. In this context, monitoring becomes part of the resource-allocation problem. It is not enough to commit resources to restoration; decision-makers need evidence to evaluate where regeneration is occurring, where it is failing, and how conditions are changing. A monitoring system that depends entirely on intensive professional field surveys may itself be too costly to operate at the scale required by ambitious restoration programmes.

Beckage et al. (2005) note that conventional estimates of seedling survival generally require marking individual seedlings and relocating them across successive surveys. This approach provides detailed information, but it is labour-intensive and time-consuming and therefore tends to restrict the spatial and temporal extent of monitoring. They explicitly note that large samples are needed to capture the substantial variability in regeneration across both space and time. Importantly, Beckage et al. demonstrate an alternative approach based on repeated counts rather than tracking individual seedlings, showing that survival can be estimated with reduced field effort. Their results also illustrate why broad temporal coverage matters: annual variation in seedling survival was substantially greater than spatial variation in their study.

This points directly towards the potential value of citizen science. The gap is therefore a scale and monitoring gap: existing methods can provide detailed estimates of regeneration and survival, but they are difficult to apply consistently over the large spatial areas and long periods required for restoration policy and environmental accounting. Citizen science offers the possibility of increasing the volume and geographical coverage of observations while reducing reliance on specialist field teams. Rather than replacing rigorous ecological monitoring, citizen science could complement it by providing repeated observations of species

presence, recruitment and regeneration across a much broader area. The SEEA Species accounts provide the framework for measuring these observations.

Research method and design

Data

For the maps, the study used 4,500 GBIF- and iNaturalist/GBIF-geo-referenced (citizen science) individual African Baobab trees (*Adansonia digitata*) and 1,578 African straw-coloured fruit bats (*Eidolon helvum*). Additional data included rainfall datasets from the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS v3), providing rainfall estimates from rain gauge and satellite observations, an agricultural-deforestation dataset from the World Resource Institute, and data from the World Database on Protected Areas. QGIS 3.44.11 was used for spatial data processing, mapping and construction of the spatial distribution maps. Python 3.14, implemented through Visual Studio Code, was used for data processing, organisation, analysis and visualisation. For the SEEA Species Accounts, the study used 300 geo-referenced citizen science photographs to evaluate the stock (age structure, phenology). Condition (health condition, leaf cover, dieback severity and physical damage). Reproduction (pollination pressure and state of flowering). Pressure (human use and leaf condition). Ecosystem services account (potential benefits to local community).

Study Site

The study was conducted across Benin, West Africa, covering the country's major climatic, ecological and land-use zones. The national-scale study area enabled assessment of *A. digitata* distribution in relation to rainfall, agricultural expansion, deforestation and protected areas. *Eidolon Helvum* was also mapped to assess pollination.

Design

The study employed a mixed-methods, spatially explicit research design structured into three integrated stages, each contributing a distinct analytical layer to understanding the distribution, condition and regeneration dynamics of *Adansonia digitata*.

Stage 1 developed three spatial maps that together provided a landscape-scale assessment of ecological pressures. Map 1 examined the geographic distribution of *A. digitata* and its key pollinator, *Eidolon helvum*, and highlighted areas of spatial overlap and potential pollination support. Map 2 illustrated land-use pressures associated with agricultural expansion and deforestation, identifying zones where habitat loss may constrain baobab regeneration. Map 3 mapped protected areas to assess the extent of formal conservation coverage for baobab populations. These three maps formed the core spatial evidence base for interpreting distribution patterns and environmental pressures.

Stage 2 analysed climatic context through five rainfall graphs spanning three decades (1991–2025). This long-term dataset provided insight into how spatial patterns of rainfall correspond with baobab occurrence, offering additional background on climatic suitability, moisture constraints and potential environmental drivers of regeneration dynamics.

Stage 3 integrated the spatial, climatic and ecological information into a SEEA-aligned Species Account for *A. digitata*. This final stage assessed the species' distribution, condition, pressures and regeneration dynamics within a structured accounting framework, enabling a comprehensive interpretation of ecological status and supporting the development of a repeatable monitoring approach.

Procedure / Methods

A total of 300 geo-referenced photographs of individual baobab trees were analysed to develop the SEEA species account for *A. digitata*. The sample size was informed by previous studies

of *A. digitata* that assessed between 117 and 240 trees, including Mpofu et al. (2012), Assogbadjo et al. (2005), Munyebvu et al. (2018), Lisao et al. (2018), and Gebauer and Luedeling (2013). The 300-tree sample therefore provided a comparatively larger observational basis for assessing baobab population characteristics and ecological condition. The geo-referenced observations were imported into QGIS 3.44.11, where spatial layers were processed, overlaid and used to construct the three distribution maps. Rainfall, agricultural/deforestation and protected-area datasets were subsequently integrated with the baobab observations. Python 3.14 and Visual Studio Code were used for data cleaning, organisation, processing and analysis.

Limitations of Study

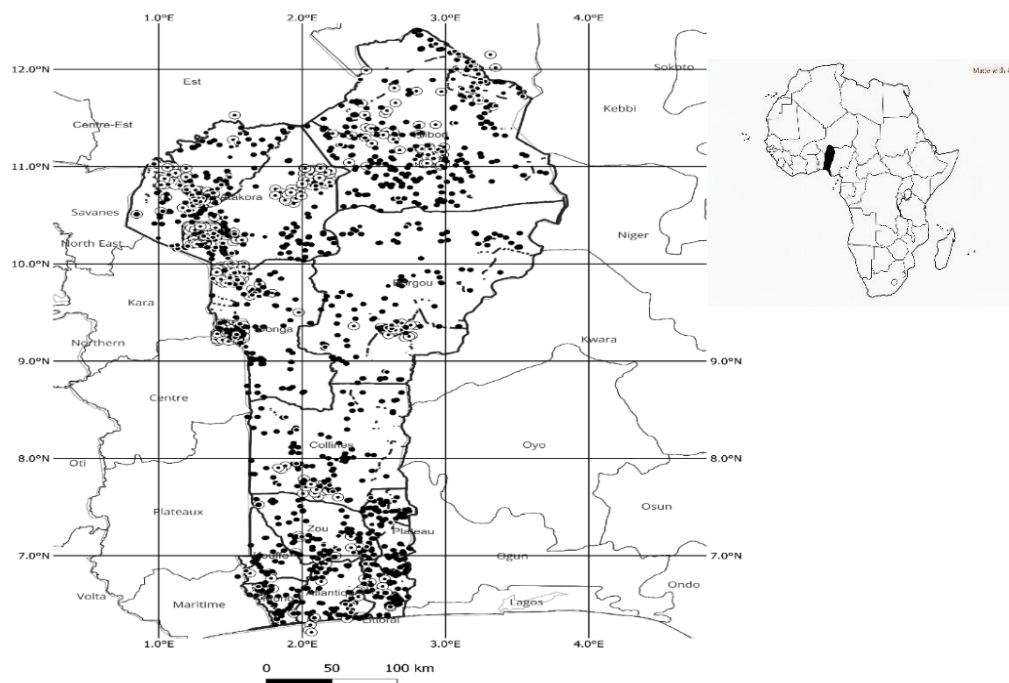
This study relies exclusively on secondary data sources, and no field surveys or direct engagement with local communities were undertaken at this stage. As a result, the analysis is constrained by the quality, completeness, and spatial distribution of available datasets, particularly for assessing regeneration dynamics and age-class structure. These limitations are recognised, and they reflect the exploratory nature of this pilot study, which was designed primarily to determine whether observable signals of regeneration imbalance exist within the baobab population structure in Benin.

A full-scale investigation is planned as the next phase of research. This will involve comprehensive field assessments, demographic surveys, and community-based inquiries to evaluate regeneration capacity, ecological condition, and long-term persistence of *Adansonia digitata* in Benin and across Africa. The present study therefore serves as an initial diagnostic step, identifying whether regeneration concerns are evident and warrant deeper, on-the-ground ecological and socio-environmental investigation.

Results

Stage 1: National Spatial and Distribution Findings

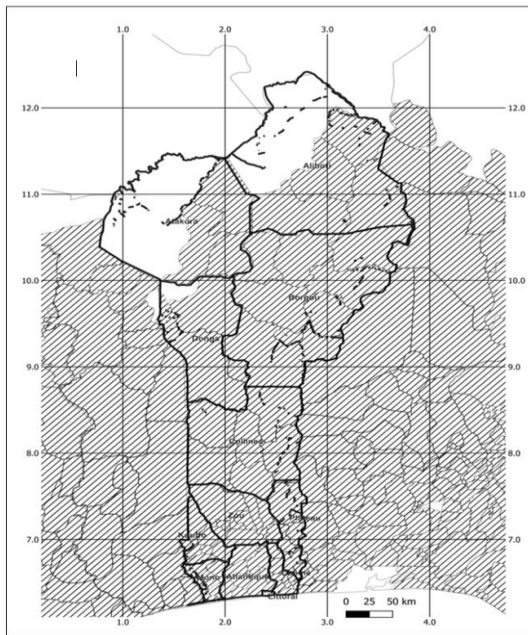
Map 1: *Adansonia Digitata* and African *Eidolon helvum*



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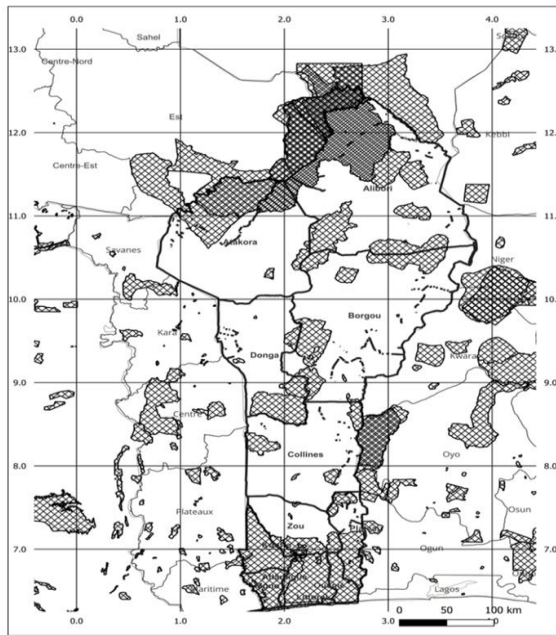
Data Source: GBIF.org (2026). Occurrence data for *Adansonia digitata* and *Eidolon helvum*

Map 2: Agri-Deforestation



Data Source: WRI (2023), Agriculture-Linked Deforestation.

Map 3: Protected Areas



Data Source: UNEP-WCMC & IUCN (2026). WDPA June 2026.

Map 1 shows the occurrence data for *Adansonia digitata* (black dots) and *Eidolon helvum* (black dots enclosed within a circle). The distribution of *A. digitata* is particularly dense in the northern departments of Alibori (11.0°–12.5° N, 2.0°–3.5° E) and Atakora (10.5°–11.5° N, 1.0°–1.8° E). Alibori is characterised largely by a dry savanna climate, while Atakora includes mountainous terrain and the Pendjari National Park, an area of high biodiversity. The northern region therefore shows relatively high concentrations of *A. digitata*, with a more continuous and uniform distribution across the landscape. *E. helvum* is also present at notable densities in these areas.

The relatively high occurrence of both species in Alibori and Atakora may be associated with protected areas, shown as grey shaded crosses in Map 3. These protected areas limit agricultural expansion and, consequently, reduce deforestation in some parts of the two departments (shown as grey areas in Map 2). The persistence of natural vegetation may therefore provide more suitable habitat for *A. digitata* and roosting or movement sites for *E. helvum*.

The southern departments of Benin also show relatively high densities of *A. digitata*. These include Zou, Plateau, Kouffo, Mono, and Atlantique, where *E. helvum* is also recorded. However, unlike the more continuous distribution observed in parts of the north, the central region shows a more fragmented and sparser pattern of occurrence.

This fragmentation corresponds to specific latitudinal and longitudinal zones across the central and northern corridor of Benin, including Collines (7.5°–8.5° N, 1.5°–2.7° E), Borgou (8.8°–10.5° N, 2.0°–3.7° E), and Donga (approximately 8.5°–10.0° N, 1.4°–2.4° E). Within this central corridor, the map shows a distinct reduction in continuous *A. digitata* clusters, with populations occurring instead in isolated pockets.

This pattern may be linked to agricultural intensification and land-use change.

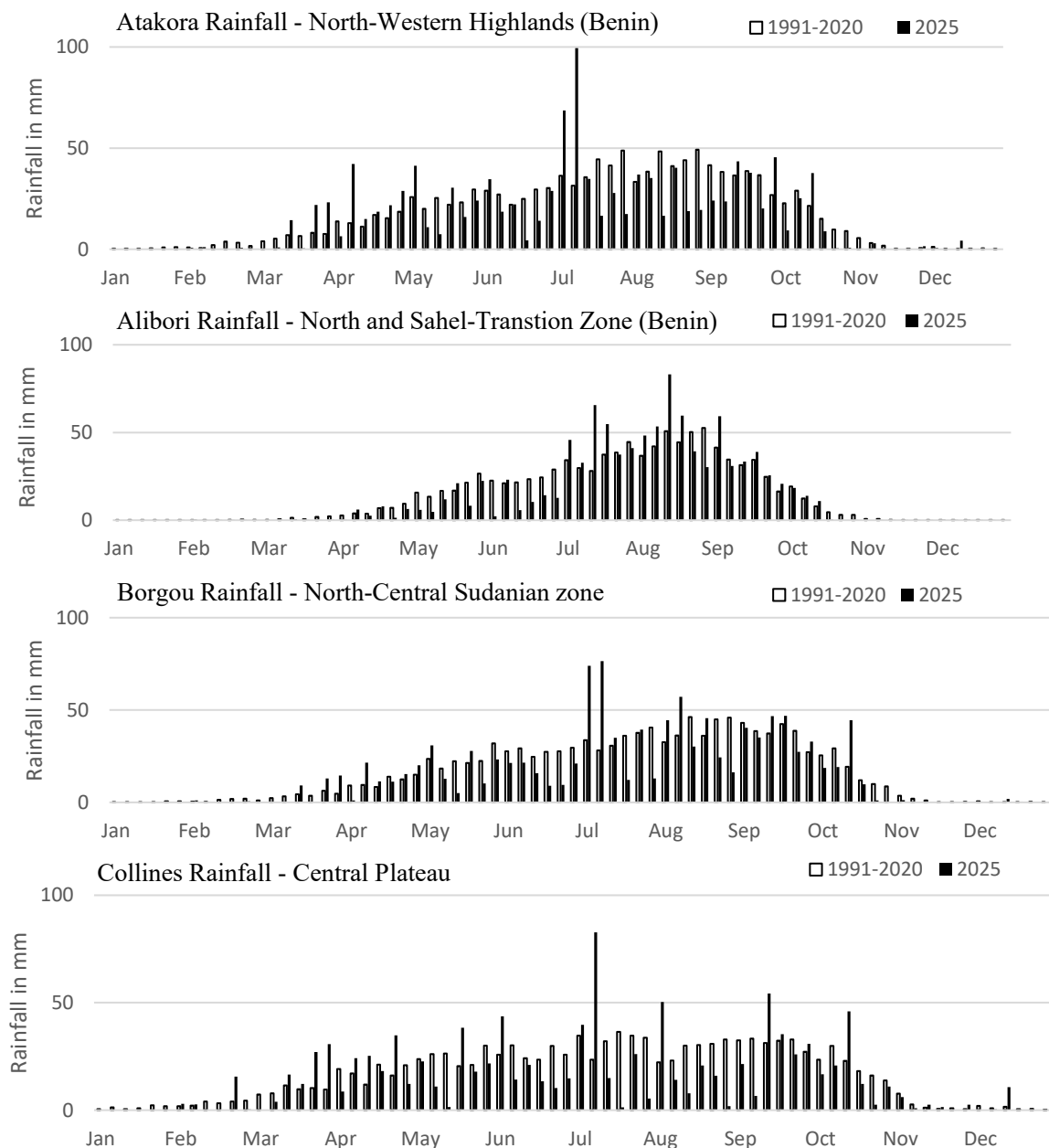
Converting natural woodland to agricultural land can fragment suitable habitat, leaving *A. digitata* as isolated trees within cultivated landscapes rather than as components of connected woodland systems.

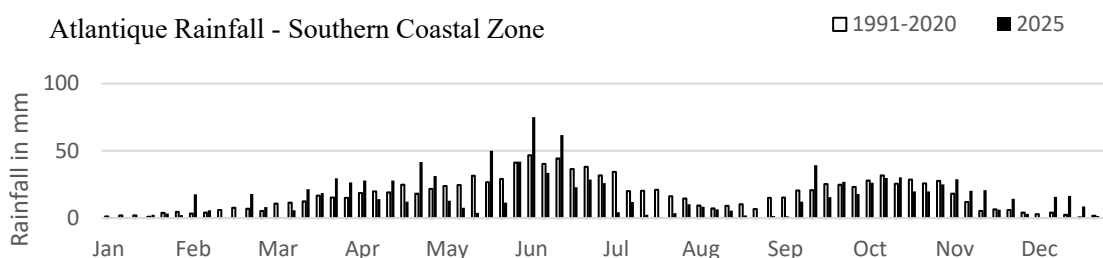
The fragmented distribution may also affect *E. helvum*, which depends on suitable tree cover and roosting sites for movement across the landscape. The loss and fragmentation of tree cover in the central region may reduce the availability of continuous or strategically located roosting sites between northern feeding areas and southern forested regions. Consequently, bats may

need to travel farther across agricultural and deforested areas. This increased spatial separation could reduce how often *E. helvum* interacts with isolated *A. digitata* trees and may limit opportunities for pollination and seed dispersal.

Overall, the spatial pattern shown in Map 1 suggests a relationship between the distribution of *A. digitata* and *E. helvum* and the degree of habitat protection, vegetation continuity, and agricultural disturbance across Benin. Higher concentrations in northern protected landscapes and parts of the south contrast with the fragmented distribution in the central corridor, where agricultural intensification and habitat loss appear to have produced more isolated populations.

Stage 2: Rainfall Data
Figure 1: Five Rainfall Graphs





Data: CHIRPS: Rainfall Estimates from Rain Gauge and Satellite Observations

Figure 1 shows five graphs illustrating rainfall patterns across northern, central, and southern Benin, including the main zonal regions. The northern regions—particularly Atakora, Alibori, and Borgou—generally receive less rainfall and have shorter wet seasons. In 2025, rainfall appears to be becoming more intense rather than more prolonged, with heavier rainfall concentrated over shorter periods and longer dry intervals between rainfall events. Such variability may create challenging conditions for young baobab seedlings, as intense rainfall can be followed by extended periods of moisture stress.

In the central region, particularly Collines, rainfall conditions are relatively more favourable for seedling establishment. However, pronounced mid-season rainfall peaks are evident. While these rainfall events may support germination and early growth, subsequent rapid declines in rainfall could expose seedlings to moisture stress, potentially reducing their establishment and survival.

In the southern region, particularly Atlantique, rainfall is generally higher and more evenly distributed. These conditions may provide a more favourable moisture regime for baobab seedlings, supporting germination and early development and potentially improving their chances of survival during the critical establishment phase.

Overall, the 2025 rainfall pattern across Benin suggests that adult baobab trees are likely to remain relatively resilient because of their established root systems and greater access to deeper soil moisture. In contrast, seedlings and young saplings are likely to be more vulnerable, particularly in the northern and central regions, where intense rainfall is followed by prolonged dry periods. These rapid fluctuations can support initial germination but may subsequently cause moisture stress during early establishment. Although conditions in southern Benin, particularly Atlantique, are generally more favourable, irregular rainfall may still affect young plants. Thus, while established adult trees are expected to survive these rainfall conditions, seedling and sapling recruitment and survival may become a major constraint for baobab regeneration across Benin.

Stage 3: Species Accounts SESA

1. Stock Account

Indicator	Value	Percentage
Age Structure		
*Total individuals	300	N/A
Mature	283	94.333%
Saplings	13	4.333%
Seedlings	3	1
Dead	1	0.333%
Land Ownership & Control of Land		
**% Indigenous Peoples and Local Communities	8,964,531 ha	77.9%
% acknowledged by government	1,920,000 ha	16.7%
% not acknowledged by government	7,044,531 ha	61.2%

Phenology		
Fruit Maturation	77	26%
Flowering Peak	90	30%
Leafless, Dormancy	51	17%
Fruit Development	39	13%
Leaf Flush	25	8%
Leaf Buds	18	6%

Data Source: *GBIF (2026), **Landmark (2025)

The stock account establishes the observed state of the *A. digitata* population and records changes in the stock from one accounting period to the next. The government and communities should know how many trees exist, where they occur, and who owns and controls the land, which is directly linked to customary laws governing trees, age structure, mortality, and stock changes.

The above stock account shows a population structure strongly dominated by mature trees, with very limited representation of younger individuals. The high proportion of mature trees suggests that the existing baobab population is relatively well established and that adult trees are likely to be resilient to current environmental conditions. However, the very low proportion of seedlings and saplings raises concerns about natural regeneration and long-term population replacement. Only 16 individuals (approximately 5%) were recorded in the sapling and seedling stages combined, indicating limited recruitment into younger size classes.

The phenology account demonstrates that the adult baobab population was predominantly in active reproductive stages, particularly flowering and fruit maturation, while a smaller proportion was undergoing vegetative regeneration or dormancy. The presence of trees at different phenological stages indicates some degree of variation in the timing of reproductive and vegetative processes. Rainfall patterns, soil moisture availability, temperature, and individual tree characteristics may influence this variation. Given the increasingly irregular rainfall pattern observed across Benin, such climatic variability could affect the timing and success of flowering, fruit development, and leaf production, with potentially greater consequences for seedlings and saplings than for established adult trees

2. Condition Account

Group	Indicator	Value	Percentage
Overall, Health Condition			
Good condition	High + Medium-High	219	73%
Moderate condition	Medium	55	18%
Poor condition	Low-Medium + Low	22	7%
Non-visible	Non-visible	3	1%
Dead	Dead	1	<1%
Leaf Cover			
High leaf cover	Full + Moderate	109	36%
Low leaf cover	Sparse	126	42%
Very low leaf cover	Defoliated	60	20%
Non-visible	Non-visible	5	2%
Canopy density			
Dense canopy	Dense	43	14%
Moderate canopy	Moderate	73	24%
Sparse canopy	Sparse	67	22%
Leafless canopy	Leafless	112	37%
Non-visible	Non-visible	5	2%
Dieback severity			
Dieback present	Severe + Moderate + Mild	39	135%
No dieback	None	256	85%

Non-visible	Non-visible	5	2%
Physical Damage			
Bark damage present	Yes	50	17%
No bark damage	No	246	82%
Non-visible	Non-visible	4	1%
Fire damage	Fire damage	0	0%

In total, the condition account suggests that established adult baobab trees remain relatively resilient, with 91% classified as medium to high condition and 85% showing no dieback. However, the high prevalence of sparse foliage, defoliation, and leafless canopies indicates that many trees are experiencing seasonal or environmental stress. When considered alongside the earlier stock account—where 94% of individuals were mature trees but only 5% were seedlings and saplings—the findings suggest that adult trees are surviving relatively well, while regeneration and the establishment of younger individuals remain more vulnerable.

This distinction is important under the observed rainfall conditions across Benin. Mature baobabs, with their established root systems and substantial water-storage capacity, are better equipped to withstand periods of moisture stress. Seedlings and saplings, however, have less-developed root systems and are likely to struggle when intense rainfall is followed by prolonged dry periods. Consequently, the main conservation concern may not be immediate mortality of adult trees, but rather poor recruitment and survival of younger trees, which could affect the long-term sustainability of baobab populations.

3. Reproduction Account

Indicator	Value	Percentage
Flowering	26	9
Non-Flowering	274	91
Immature Pods	109	36
Mature Pods	3	1
Non-Fruiting Pods	188	63
Pollination pressure (High)	36	12
Pollination pressure (Medium)	38	13
Pollination pressure (Low)	217	72
Pollination pressure (None)	2	1
Pollination pressure (non-visible)	7	2

Overall, the data suggest that the baobab population was actively reproducing, with flowering and fruit development occurring at substantial levels, but most individuals had not yet progressed to fully mature fruit. The phenology account, particularly the 30% peak flowering, 26% fruit maturation, and 13% fruit development, indicates a population undergoing active reproductive cycling. The reproduction account reinforces this pattern through the relatively high proportion of trees with immature pods (36%), although the low proportion of mature pods (1%) indicates that fruit maturation was still incomplete at the time of assessment.

Importantly, these findings should be interpreted alongside the very low proportion of seedlings and saplings in the stock account. The presence of flowering trees and developing fruits demonstrates that the adult population has reproductive capacity, but reproductive activity does not automatically translate into successful regeneration. Low pollination pressure, incomplete fruit maturation, seed germination conditions, and especially the irregular rainfall pattern may all influence the transition from mature fruit to viable seedlings.

Thus, adult baobab trees appear capable of reproducing under prevailing conditions, but successful recruitment of seedlings and saplings may remain a bottleneck. The rainfall pattern—characterised by intense rainfall events followed by prolonged dry intervals—may be

particularly important at the establishment stage, where young seedlings have limited root systems and are more vulnerable to moisture stress.

4. Pressure Account

Indicator	Value	Percentage
Fire damage	N/A	N/A
Bark harvesting (human use)	56	19
Bark damage	50	17
Sparse leaf	126	42
Defoliated	60	20
Full Leaf	54	18

The pressure account indicates that human use and leaf-condition stress are the main pressures affecting the surveyed baobab population, while fire damage was not assessed. Bark harvesting for human use was recorded for 56 individuals (19%), and visible bark damage occurred on 50 individuals (17%). The close relationship between these two figures suggests that bark harvesting may be an important contributor to physical damage in the population. Although most trees did not show bark damage, the proportion affected is high enough to warrant attention, particularly because repeated or excessive bark removal can compromise tree health and reduce resilience.

The most prominent pressure-related indicators were associated with leaf condition. 126 individuals (42%) had sparse leaves, while 60 (20%) were defoliated. In contrast, only 54 individuals (18%) had full leaves. Therefore, a substantial proportion of the population showed reduced foliage at the time of assessment. This finding is consistent with earlier condition and phenology accounts, which showed considerable leaflessness and dormancy. The reduced foliage may partly represent the natural seasonal cycle of baobab, but it may also reflect water stress associated with irregular rainfall and prolonged dry periods. This distinction matters because mature trees may tolerate these conditions, while younger individuals are more vulnerable. No numerical information was available for fire damage (N/A), so it should not be interpreted as evidence that fire was absent. Rather, fire damage was either not recorded or not applicable in the assessment.

5. Ecosystem Services Account

Indicator	Value	Percentage
Fodder availability high	53	18
Fodder availability medium	45	15
Fodder low	55	18
Fodder none	140	47
Fodder non-visible	7	2
Potential Human Usage (Multiple)	54	18
Potential Human Usage (Fruit)	63	21
Potential Human Usage (Fodder)	60	20
Potential Human Usage (None)	116	39
Potential Human Usage (Non-visible)	6	2
Potential Human Usage (Bark)	1	0

The ecosystem services results demonstrate that the surveyed baobab population provides several potential benefits to local communities, particularly through fodder and fruit resources. Fodder availability was classified as high for 53 individuals (18%), medium for 45 (15%), and low for 55 (18%). However, 140 individuals (47%) had no available fodder, while 7 (2%) were non-visible. This indicates that although a considerable proportion of trees can contribute fodder, nearly half of the population did not provide fodder at the time of assessment. This may

be influenced by seasonal leaf shedding and the high proportion of trees with sparse or absent foliage.

Potential human use was particularly associated with fruit and fodder. Fruit use was identified for 63 individuals (21%), while fodder use was recorded for 60 (20%). A further 54 individuals (18%) had multiple potential uses, demonstrating that baobabs can provide several ecosystem services simultaneously. In contrast, 116 individuals (39%) had no identified potential human use, while 6 (2%) were non-visible.

Taken together, the results indicate that the baobab population has considerable ecological and livelihood value but faces multiple pressures. Fruit and fodder are important potential resources, while bark harvesting represents a notable form of human pressure. At the same time, the high proportion of trees with sparse foliage or defoliation suggests that environmental stress may be affecting the availability of these services.

The findings are particularly important when considered alongside the previous stock, condition, and reproduction accounts. Adult trees remain relatively resilient and constitute the majority of the population, but there are very few seedlings and saplings. Continued bark harvesting, combined with rainfall variability and moisture stress, could further pressure the population and potentially affect long-term regeneration.

Conclusion

This pilot study shows that *Adansonia digitata* faces multiple environmental and anthropogenic pressures, with emerging evidence of regeneration constraints not only in West Africa but increasingly across the African continent. The SEEA-aligned species account proved essential in clarifying the ecological condition of the species, its climate vulnerability, and the demographic pressures shaping long-term viability. By providing a structured, repeatable framework, the SEEA approach strengthens both present-day assessments and future climate-scenario modelling for understanding how *A. digitata* is likely to respond under changing environmental conditions.

A central finding of this pilot study is the severe imbalance in population structure. Benchmark guidance indicates that healthy regeneration requires at least one seedling, sapling, or juvenile per adult tree ($\geq 1.00:1$), while moderate constraints occur when fewer than one juvenile is present per adult ($0.50\text{--}0.99:1$). In contrast, the SEEA Species Stock Account for Benin records 283 adult baobabs and only 16 juveniles, producing a ratio of $1:0.0565$. This falls far below the $<0.10:1$ threshold defining severe regeneration failure, meaning that fewer than six juveniles exist for every hundred adults. The demographic structure is critically imbalanced, and the current population is not producing enough younger individuals to replace mature trees. Without intervention, long-term population decline is inevitable.

These findings underscore the need for coordinated, continent-wide action. Benin—and other African countries within the baobab's range—should undertake comprehensive surveys to establish current regeneration ratios and identify the drivers of recruitment failure. The priority is to rebalance the ratio toward moderate regeneration levels, with a long-term aim of achieving good to adequate regeneration. Bi-annual SEEA Species Accounts should be adopted to monitor demographic trends, track improvements, and ensure that regeneration deficits are progressively corrected.

Any new trees planted through restoration or community initiatives will require sustained protection, watering, and monitoring, supported by government agencies, local authorities, and community groups. Safeguarding juvenile trees from livestock browsing, fire, and land-use pressures is essential to ensure survival through the vulnerable early stages.

The study confirms that the SEEA Species Account is a powerful tool for diagnosing ecological condition, identifying regeneration failure, and guiding evidence-based conservation policy. These results provide a strong foundation for a full-scale investigation into the regeneration capacity and future persistence of *Adansonia digitata* in Benin and across Africa.

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Competing interest

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