INNSPUB

International Journal of Biosciences | IJB |
ISSN: 2220-6655 (Print); 2222-5234 (Online)
Website: https://www.innspub.net
Email contact: info@innspub.net
Vol. 27, Issue: 6, p. 127-135, 2025

RESEARCH PAPER | OPEN ACCESS

Effect of flooding depth and harvest intensity on soil moisture dynamics and production of baobab (*Adansonia digitata*) seedlings

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Key words: Baobab seedlings, Soil moisture, Water management, Leaf harvesting

DOI: https://dx.doi.org/10.12692/ijb/27.6.127-135 Published: December 16, 2025

ABSTRACT

Baobab (*Adansonia digitata*) is widely used in African drylands for nutrition and income, but its sustainability is threatened by inconsistent natural regeneration and intensive leaf harvesting. This study assessed how flooding depth and harvest intensity influence growth, leave yield, and soil moisture dynamics in baobab seedlings under semi-arid conditions. A randomized complete block design was applied with three flooding depths (10 mm, 20 mm, and 30 mm) and two harvest intensities (25% and 50%) across 84 days after transplanting (DAT). Soil water content (SWC) significantly increased with flooding depth ($p < 0.05$), with 3 cm irrigation raising SWC by 36.7%, 80.6%, and 71.6% at 21, 64, and 84 DAT, respectively. Seedlings under 50% harvest intensity maintained 16-38% higher SWC than non-defoliated plants at early stages, indicating reduced water use. Plant height and leaf number were significantly influenced by both harvest intensity and flooding depth ($p < 0.05$); 25% harvest intensity increased height by 15-22% and leaf number by 9-24% compared to controls at early DAT. Seedlings under 3 cm flooding depth showed 11.8% shorter stems and 4.9-17.7% thinner stem diameters relative to 1 cm flooding depth, suggesting potential waterlogging stress. Fresh leaf yield was temporarily higher under 50% harvest intensity (11.9 g/plant) compared to 25% harvest intensity (3.5 g/plant) at 21 DAT, while dry yield remained unaffected, indicating a temporary compensatory growth response. These results suggest that moderate harvest intensity combined with appropriate flooding depth can enhance early seedling performance, but further studies are needed to evaluate long-term sustainability and resilience under fluctuating environmental conditions.

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INTRODUCTION

Baobab (*Adansonia digitata*) holds a central place in rural livelihoods throughout the African drylands, where it serves as both a nutritional and economical resources (Ofori and Addo, 2023; Owolodun and Merten, 2023). Its leaves, pulp and seeds contribute to food systems during periods when other crops are scarce (Asogwa *et al.*, 2021), and the tree is commonly integrated into farming landscapes because of its tolerance to heat and water scarcity (Kuyah *et al.*, 2023).

Leaves are harvested during the rainy season, dried and transformed into powders widely consumed in household diets (Asogwa *et al.*, 2021). They supply vitamins A and C, fibre, magnesium and zinc, making them valuable for nutrition and health (Ahmed *et al.*, 2024). The pulp is used in beverages and traditional recipes due to its binding and acidifying properties, and demand is steadily increasing in regional and international markets (Leakey *et al.*, 2022). Seeds are also incorporated into local sauces and are part of the cultural food practices of many communities (Oluyede *et al.*, 2024). Rising demand for baobab products, combined with climate variability and landscape change, is intensifying pressure on wild populations and reducing opportunities for natural regeneration. This growing vulnerability calls for greater attention to sustainable management to ensure continued access to its nutritional and economic benefits.

The urgency for more targeted recommendations is reinforced by the growing pressures on baobab populations. Natural regeneration is increasingly constrained by drought, land conversion, browsing and repeated leaf harvesting, especially near villages and agricultural fields. Young plants are highly sensitive to inconsistent soil moisture, which affects root establishment, nutrient uptake and early growth. Cutting intensity imposed on seedlings or juvenile trees may further compound stress, yet this practice is widespread because leaf biomass is a major source of food and income during the rainy season. As interest in baobab domestication expands, nurseries and field production systems require guidance on how to balance water supply and harvesting practices. Understanding how these factors work together is needed to refine recommendations for cultivation, stabilize yields of leaf biomass and reduce early mortality.

Several studies have already examined how to sustainably enhance baobab seedling performance. For instance, a greenhouse experiment on leaf phenology across different provenances showed that water availability strongly influences leaf flush and height growth, with seedlings adjusting leaf production based on moisture and photoperiod cues (Di Lucchio *et al.*, 2018). Research combining watering regimes and mycorrhizal inoculation revealed that daily watering significantly improved shoot height and seedling vigor compared to less frequent watering schedules (Ezekiel *et al.*, 2024). Earlier work on drought response found that baobab seedlings rely on conservative water use, storing water in their taproots and reducing transpiration under soil water deficit, which helps them survive periods of drought but constrains growth when water is limiting (Van den Bilcke *et al.*, 2013). Additionally, Zakari *et al.* (2025) found that moderate leaf harvesting led to taller seedlings, more leaves, and higher dry biomass, while heavier harvesting reduced overall performance. Higher harvest levels slightly increased surface soil moisture but did not translate into better growth (Zakari *et al.*, 2025). Despite this progress, there remains a gap in empirical knowledge on how varying flooding depths combined with controlled harvest intensity affect leaf yield, growth and soil moisture dynamics in baobab seedlings. This gap limits our ability to recommend optimal management for nursery cultivation or leaf-harvesting regimes under semi-arid conditions.

This study addresses these gaps by assessing how irrigation water depth and harvest intensity affect baobab seedling performance and soil moisture dynamics. Firstly, it evaluates how contrasting water levels affect soil moisture conditions at the root zone when plants are subjected to different cutting intensities. Secondly, it examines how these treatments shape key growth and yield indicators, including height, stem diameter, leaf production, fresh biomass and dry biomass.

By integrating plant responses and soil moisture behavior, the study aims to build a clearer understanding of how baobab seedlings cope with simultaneous water and harvesting pressures.

The outcomes are intended to guide nursery protocols and field management practices that support both regeneration and sustainable leaf harvesting. The findings also contribute to the broader knowledge on how drought-tolerant tree crops respond to combined abiotic and management factors, offering insights that will benefit ongoing domestication initiatives in dryland agroforestry systems.

MATERIALS AND METHODS

Site description

The study was carried out in Parakou, located in the Borgou region of northern Benin. The city lies near 9°21′ N and 2°37′ E at an altitude of roughly 350 m. Parakou covers about 441 km² and is organized into three administrative districts composed of multiple neighborhoods. It is positioned along the main north-south corridor linking Cotonou to northern Benin and neighboring countries, which shapes both its accessibility and its role as a regional agricultural hub. The surrounding landscape consists of a mixture of uplands and shallow valleys where smallholder farming, livestock rearing and tree-based systems coexist (Zohoun *et al.*, 2021).

Parakou has a tropical climate marked by the alternation of one rainy season and one dry season. Rainfall typically begins in May and continues until September, with an annual average close to 1200 mm (Yolou *et al.*, 2015). Temperatures remain relatively stable throughout the year and revolve around 26 to 27°C, with slightly warmer conditions from February to April. Humidity fluctuates with seasonal shifts and influences soil moisture availability during crop and tree growth cycles. This climatic pattern is characteristic of the transition zone between the humid south and the drier northern regions, making it suitable for experiments that require controlled water applications under real field conditions.

The soils in Parakou belong mainly to the tropical ferruginous group, shaped by prolonged weathering under alternating wet and dry phases (Zakari *et al.*, 2025). These soils are generally well drained, moderately fertile and often contain iron-rich concretions at shallow depths.

Study design

The experiment followed a completely randomized design to assess how flooding depth and harvest intensity affect growth, biomass production and soil moisture in baobab seedlings. Three blocks were established to account for spatial variation across the site. Each block contained 12 seedlings grown in containers, with two seedlings per container. Irrigation treatments were applied as three water depths of 1 cm, 2 cm and 3 cm. Within each block, four seedlings per irrigation level were kept as uncut controls, giving a total of 12 control plants across the three blocks (Fig. 1). The remaining seedlings in each flooding depth level were subjected to harvest intensity treatments. Harvest intensity was introduced as a second factor and applied to all non-control plants. Two harvest intensities were used: removal of 25 percent of total leaf biomass and removal of 50 percent of total leaf biomass.

Fig. 1. Schematic of one block of the experimental setup. H0, H25 and H50 represent 0, 25 and 50% leaf harvest intensities

Data collection

Soil moisture

Soil moisture was monitored weekly throughout the experiment from May to September 2023.

Measurements were taken using a handheld moisture probe inserted into the root zone of each container. The weekly schedule allowed the detection of short-term fluctuations linked to the different flooding depths. Readings were collected on the same day each week to maintain consistency across treatments and blocks.

Plant growth

Growth measurements began immediately after transplanting on 1 May 2023. Plant height, leaf number and stem diameter were recorded every 21 days until the end of the experiment. Height was measured using a tape measure, from the soil surface to the terminal growing point. Leaf number was determined by counting all fully expanded leaves on each seedling. Stem diameter was measured with a vernier caliper at two positions, the collar and 10 cm above it, to capture early structural development.

Leaf yield

Per Zakari *et al.* (2025), yields were determined after each harvest event. Fresh biomass was recorded by weighing all harvested leaves immediately after cutting using a precision balance.

For dry biomass, the leaves were placed in a drying oven at 70°C for 72 hours until a stable weight.

Data analysis

The raw data were first entered into an Excel spreadsheet, then imported into R software version 4.4.2 (R Foundation for Statistical Computing, 2024) for analysis. The Shapiro-Wilk test was applied to assess the distribution of each response variable, including soil moisture, plant height, leaf number, stem diameter, fresh biomass and dry biomass. When needed, non-normal variables were log-transformed prior to statistical testing. An analysis of variance (ANOVA) was performed to examine the effects of flooding depth and harvest intensity on all response variables. Post-hoc comparisons were conducted to assess differences among factor levels.

RESULTS

Variation in soil moisture content

The soil water content was significantly different among flooding depth at all DAT. As expected, SWC was 36.7, 80.6 and 71.6% higher under 3 cm flooding depth than 1 cm flooding depth at 21, 64 and 84 DAT, respectively ($p < 0.05$), while there was no significant difference between SWC under 2 cm and 1 cm flooding depths (Fig. 2A). The SWC was significantly affected by harvest intensity at all DAT. At 21 and 64 DAT, SWC was 16.2 and 38.5% higher under 50% harvest than no harvest ($p < 0.05$), with no significant difference between 25% harvest and no harvest (Fig. 1B). At 84 DAT however, SWC was 22.0 and 40.4% higher under 25% and 50% harvest than no harvest (Fig. 2B).

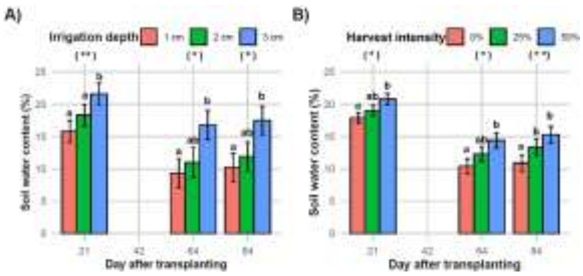

Fig. 2. Soil water content under varying flooding depth (A) and harvest intensity (B)

Letters "abc" represents the means separation with each date (a<b<c). The signs (*), (**) and (***) represent significant *p* values of <0.5, <0.1 and <0.01, respectively, while (ns) represent no significant effect.

Variation in growth parameters

The plant height was significantly different with flooding depth at all DAT, except for 42 DAT. The height was 11.8, 4.2 and 6.0% lower under 3 cm flooding depth than 1 cm flooding depth at 21, 64 and 84 DAT ($p < 0.05$), while there was no significant difference between plant heights under 2 cm and 1 cm flooding depth at (Fig. 3A). Plant height was significantly affected by harvest intensity at all DAT, except for 21 DAT. At 42, 64 and 84 DAT, plant height was 15.0, 22.2 and 16.8% higher under 25% harvest than no harvest ($p < 0.05$), respectively, with no significant increase between 25% and 50 % harvest (Fig. 3B).

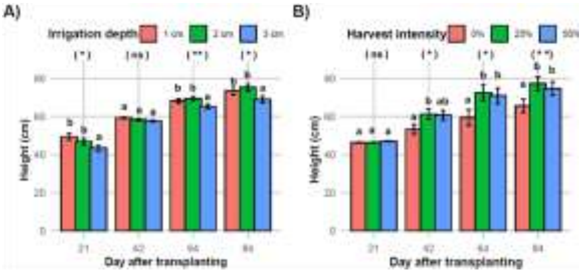

Fig. 3. Baobab seedlings plant height under varying flooding depth (A) and harvest intensity (B)

Letters “abc” represents the means separation with each date (a<b<c). The signs (*), (**) and (***) represent significant *p* values of <0.5, <0.1 and <0.01, respectively, while (ns) represent no significant effect.

The leaf number differed significantly with flooding depth at all DAT ($p < 0.05$). The highest leaf number was recorded under 3 cm flooding depth at 21, 42 and 64 DAT with a 6.9, 21.4 and 11.8% increase compared to 1 cm flooding depth (Fig. 4A). Oppositely, leaf number was 15.2% lower under 3 cm than 1 cm flooding depth at 84 DAT. Leaf number also varies significantly with harvest intensity at all DAT ($p < 0.05$). Leaf number was 24.0, 22.2 and 9.1% higher under 25% than no harvest, with no significant increase between 25% and 50% harvest (Fig. 4B). On the contrary, leaf number was 17.9% lower under 25% than no harvest at 84 DAT.

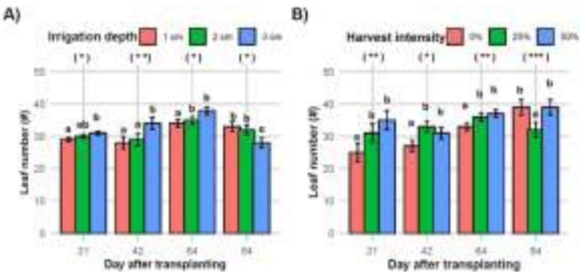

Fig. 4. Baobab seedlings leaf number under varying flooding depth (A) and harvest intensity (B)

Letters “abc” represents the means separation with each date (a<b<c). The signs (*), (**) and (***) represent significant *p* values of <0.5, <0.1 and <0.01, respectively, while (ns) represent no significant effect.

The stem diameter differed significantly with flooding depth at 21 and 84 DAT ($p < 0.05$). Stem diameter was 10.6 and 2.7% lower under 2 cm than 1 cm flooding depth at 21 and 84 DAT, respectively (Fig. 5A); and 17.7 and 4.9% lower under 3 cm than 1 cm flooding depth at the same dates. Stem diameter also varied significantly with harvest intensity at all DAT ($p < 0.05$). The stem diameter was 7.8, 15.0, 12.6 and 5.8% higher under 50% than no harvest, with no significant difference between 25% and no harvest (Fig. 5B).

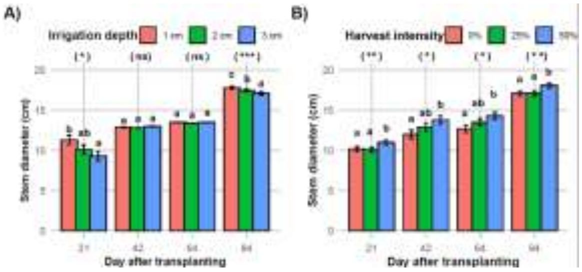

Fig. 5. Baobab seedlings stem diameter under varying flooding depth (A) and harvest intensity (B)

Letters “abc” represents the means separation with each date (a<b<c). The signs (*), (**) and (***) represent significant *p* values of <0.5, <0.1 and <0.01, respectively, while (ns) represent no significant effect.

Variation in leaf yield

The fresh and dry leaf yield were significantly affected by flooding depth at all DAT ($p < 0.05$). Fresh yield was 7.2 and 14.5% lower under 2 cm and 3 cm floodings depth than 1 cm flooding (Fig 6A). Oppositely, the fresh yield was 83.3, 28.7 and 31.3% higher under 2 cm than 1 cm flooding depth. Regarding dry leaf yield, they were 16.7 and 5.6% lower under 2 cm and 3 cm flooding depths compared to 1 cm flooding depth (Fig. 6C). On the contrary, the dry leaves yield was 12.5 and 23.5% higher under 2 cm than 1 cm flooding depth at 64 DAT; while it was 9.4 and 41.2% lower under 3 cm than 1 cm flooding depth.

The fresh leaf yield varied significantly with harvest intensity only at 21 DAT ($p < 0.05$). At this date, fresh yield was significantly higher under 50% harvest (11.9 g/plt) than 25% harvest (3.5 g/plt) (Fig. 6B). On the contrary, harvest intensity did not significantly affect dry yield at any date ($p > 0.05$; Fig. 6D).

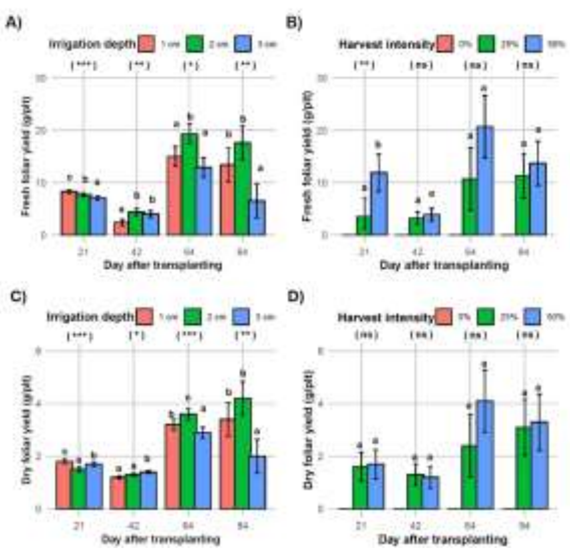

Fig. 6. Baobab fresh and dry leaf yield under varying flooding depth (A, C) and harvest intensity (B, D)

Letters "abc" represents the means separation with each date (a<b<c). The signs (*), (**) and (***) represent significant p values of <0.5, <0.1 and <0.01, respectively, while (ns) represent no significant effect.

DISCUSSION

Soil water content response to flooding depth and harvest intensity

We found that soil moisture did not linearly increase with flooding water depth. In fact, SWC was higher under the 3 cm flooding depth, while 2 cm flooding depth did not differ from 1 cm. This kind of pattern often arises when a moderate water input is insufficient to drive the wetting front deeper into the profile, leaving most of the applied water exposed to evaporation or rapid uptake, whereas a larger volume surpasses the threshold needed to fill deeper pore spaces. Similar observations have been reported in studies showing that infiltration efficiency and moisture retention increase only when irrigation exceeds a minimum hydraulic requirement (Wang *et al.*, 2024; Zhang *et al.*, 2024). Similarly, Sun *et al.* (2023) highlighted that shallow or moderate irrigation is quickly depleted by plants, while larger inputs alter the moisture profile more substantially.

The SWC was generally higher under 50% harvest than controls with no harvest, particularly during the early days of the plant. This indicates an immediate reduction in plant water extraction following canopy removal. This response is expected because reducing the leaf area reduces whole-plant transpiration demand, and it also alters the local microclimate so that soil evaporation and evaporative demand decline (Balducci *et al.*, 2020); thereby leaving more water in the root zone. Similar response has been reported on mango, by Hahn *et al.* (2022), where pruning practices reduced tree water use and supported water saving. This result is in line with Balducci *et al.* (2020), who also reported that harvest can improve tree water status and reduce transpiration under drought or reduced canopy scenarios.

Baobab seedlings growth response to flooding depth and harvest intensity

Lower plant height and thinner stems occurred under the 3 cm flooding compared with those under 1 cm flooding depth. This entails that high water supply sometimes constrained vegetative growth. Excess moisture likely reduced oxygen availability in the root zone, impairing root respiration and limiting water and nutrient uptake, and consequently inhibiting growth (Byeon *et al.*, 2024). Furthermore, plants may have shifted biomass allocation toward maintenance or root repair rather than outward growth when roots experienced stress, thereby limiting stem thickening and elongation. These responses are consistent with reports that tree crops exposed to waterlogging show reduced root hydraulic conductance and limited aboveground growth (Bhusal *et al.*, 2022; Byeon *et al.*, 2024). Bhusal *et al.* (2022) found that excess soil moisture in Quercus seedlings lowered root oxygen availability, which restricted water uptake and slowed height and stem expansion. Byeon *et al.* (2024) reported a similar pattern in Zelkova serrata, where prolonged saturated conditions decreased fine root activity, reduced leaf water transport, and eventually suppressed both height gain and stem diameter growth.

In our study, seedlings subjected to 25 percent harvest initially produced more leaves and grew taller than non-defoliated plants but had lesser leaves than non-defoliated plants at the later stage of the growing cycle. This highlights an initial compensatory growth response in such treatment. This early stimulation likely results from the plant reallocating stored carbohydrates and nutrients toward new shoots and leaves to restore photosynthetic capacity (Wang *et al.*, 2020). However, the advantage weakened by the later stage of the growing cycle, suggesting that repeated leaf removal gradually depleted resources and induced mild stress, thereby limiting further growth. This result contradicts evidence from broader tree-level studies, which suggests that harvest always reduces growth. For example, Wang *et al.* (2021) conducted a meta-analysis on defoliated trees across 40 species and found a net reduction in carbon assimilation and non-structural carbohydrate reserves after leaf loss, leading to declines in height and diameter. In the same line, Kosola *et al.* (2001) reported that repeated harvest depressed nitrogen uptake, reduced carbon allocation to shoots, and resulted in growth suppression in a long-term poplar field trial. The contrasting results between these studies and our study are likely due to differences in harvest intensity and frequency, species-specific recovery capacity, resource availability, and experiment duration.

Baobab seedlings leaf yield response to flooding depth and harvest intensity

Leaves yield (fresh and dry) responded inconsistently to flooding depth, with deeper watering (3 cm) sometimes reducing leaf yield compared to the lowest irrigation (1 cm), while at other dates moderate irrigation (2 cm) enhanced leaf accumulation. This observation suggests a non-linear relationship between water supply and leaf biomass. This could be attributed to the fact that excessive water may limit root oxygenation or cause nutrient leaching, while moderate irrigation provides sufficient moisture for photosynthesis without inducing stress. This result is in line with Zuazo *et al.* (2021) who reported that deficit irrigation in avocado trees maintained or improved leaf biomass and water-use efficiency at moderate watering levels, while excessive irrigation did not proportionally increase yield. Similarly, Chen *et al.* (2023) highlighted that regulated deficit irrigation in many species of woody crops show non-linear growth and yield responses to water, with moderate water supply sometimes outperforming both low and high extremes.

Fresh leaf yield was temporarily higher under 50% harvest compared to 25% or controls (at 21 DAT), but dry biomass yield remained unaffected over the cycle. This indicates a compensatory growth response in which harvest stimulated new leaf production but did not translate into a sustained biomass gain. Physiologically, the harvest likely triggered mobilization of carbohydrate reserves and increased allocation to leaf regrowth; however limited resource pools may have prevented this from resulting in higher dry mass accumulation. This result is in agreement with Ambebe *et al.* (2020) who reported that limited harvest under favorable nutrient conditions did not reduce *Gmelina arborea* leaf biomass. Similar observation has been reported for other tree crops, inlcuding *Populus tremuloides* (Erbilgin *et al.*, 2014), and *Robinia pseudoacacia* L. and *Amorpha fruticosa* L. (Wang *et al.*, 2020).

CONCLUSION

This study demonstrates that Adansonia digitata seedlings respond distinctly to flooding depth and harvest intensity, with moderate water supply and partial harvest producing the most favorable early growth responses. Growth indicators, including plant height, stem diameter, and leaf number, were initially enhanced under 25 % harvest and moderate irrigation (2 cm), while seedlings receiving the highest flooding depth (3 cm) showed reduced height and thinner stems.

Fresh leaf yield exhibited a temporary increase under 50 % harvest at early sampling (21 DAT), but dry biomass remained largely unaffected, highlighting a short-term compensatory growth response that did not translate into sustained biomass accumulation. Soil moisture content increased with both flooding depth and higher harvest, yet excessive water did not consistently enhance growth or leaf yield, suggesting non-linear plant-water interactions and potential limitations on root function under high moisture conditions.

A key limitation of this study is that seedlings were grown in containers under controlled nursery conditions, which may not fully replicate field environments. Despite this, the findings suggest that farmers should adopt moderate harvest and irrigation strategies to optimize early vegetative growth and leaf production while avoiding waterlogging stress. Future research should assess long-term effects of repeated harvest, the interaction with soil nutrient status, and field validation under varied climatic conditions to better inform sustainable management practices that reconcile leaf harvesting with seedling growth and conservation objectives.

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