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Population dynamics of seed and seedlings of *Albizia procera* (Roxb.) in Mizoram, India

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Abstract

Seed production, dispersal, germination, and seedling establishment are critical life phases in the trees. Understanding these processes is crucial to recognizing species composition and directional change in ecosystem restoration. This study aims to estimate seed production, dispersal, and fate of the seed population of *A. procera* (Roxb.) as well as to evaluate its seedling growth performance in relation to microclimates in the natural conditions. Seed production was estimated from 15 sampled trees for three years, and seed dispersal using circular sample plots. Additionally, seeds fall under the mother tree were estimated using seed traps. The mean seed production of *A. procera* was 145,352 seeds in 2022, 43,607 seeds in 2023, and 41,490 seeds in 2024 seed/plant and it significantly differed between years ($P < 0.001$) and among individual trees. Strong positive correlations were found between total seed production and tree characteristics such as number of branches, mean number of sub-sub-branches, inflorescences, crown height, and crown diameter. In contrast, a strong negative correlation was observed between seed dispersal and dispersal distance from the mother tree ($r = -0.908$ in 2022, $r = -0.927$ in 2023, and $r = -0.855$ in 2024). A majority of the seeds produced (55.02% in 2022, 54.25% in 2023 and 52.92 in 2024) fell under the mother tree while seeds disappearance decreased with increasing distance from the mother tree. Further, relative seedling growth rate was strongly influenced by soil temperature, moisture and relative humidity indicating their important role in the successful establishment of *A. procera* in natural conditions. The findings of this study may help in growth monitoring of *A. procera* and restoration of degraded land.

Keywords: *Albzia procera*, Seed Production and Dispersal, Dispersal Distance, Germination

1. Introduction

Albizia procera (Roxb.) (Family Fabaceae) is a fast growing, medium sized tree with an open canopy that can reach up to a height of 30 m^{1,2}. It is native to India, America, Pakistan and Australia³ and found in tropical countries such as Myanmar, Thailand, Bangladesh, Malaysia, Laos, Cambodia, Vietnam⁴, Nepal, Indonesia, China, Burma, Andaman, Kenya, South Africa and Uganda^{5,1}. Due to its varied adaptability and economic importance, *A. procera* is being planted in agroforestry systems including tea gardens reforestation, afforestation and social forestry programmes for restoration of degraded lands^{6,7}. Besides, the species is reported to have high medicinal properties^{8,9}. Additionally, it is extensively used for other purposes, such as its leaves are consumed as a vegetable² and its bark used as a fish poison^{5,10}. These extensive uses can impact the species status and reduce its distribution in its native area.

Seed production, dispersal, germination and seedling establishment are critical phases in the life of a tree^{11,12}. Understanding these processes is crucial to recognize species recruitment and directional change in ecosystem restoration¹¹. Seed production is considered a critical bottleneck of tree life cycle¹³ and its variation may affect regeneration and numerous biological phenomena including interaction between plant and animal, vegetation dynamics and nutrient cycle¹⁴. The seed production may be limited by various external factors such as adverse climate, pollination failure, predation of flowers, fruits and leaves, wind speed etc.¹⁵ and internal factors such as genetic condition, age and size of the tree^{16,17}. These factors could lead to seed production reduction and significantly impact seed dynamic, seedling recruitment, and population dynamics of given species. Seed dispersal is another important link in the reproductive cycle of a tree from the end of the adult plant to the beginning of the new plant. The distance to which the seeds get dispersed has important ecological significance. For example, seed dispersal can avoid high density-dependent mortality in close proximity to the parent plants¹⁸, while it can facilitate maintaining species diversity and may induce spatial accumulation of seeds and seedlings in pioneer trees¹⁹. Soil seed banks, on the other hand are influenced by seed production and dispersal and various governing factors that affect seed germination^{12,20}. The fate of the seeds after dispersal from parent plants can be influenced by several microclimatic and biotic factors²¹ and in turn primarily determine the future population structure. It is therefore of paramount importance to have a complete understanding of the population dynamics of a species right from seed production to the fate of its seed population. However, there are very limited studies in trees that deal with population dynamics of seed and seedlings.

A review of literature reveals that studies on seed production, dispersal, fate of seed and seedling population dynamics of *A. procera* is lacking or very limited. *A. procera* is a pioneer fast growing legume tree having hard seed coat and this property of seeds results in reduced germination in wild^{22,23} which may cause seedling population mosaic or heterogeneity in natural conditions^{24,25}. The results have shown that seed pre-treatments in *A. procera*^{6,23,26}, can bring seedling population homogeneity in nursery and plantations⁷. We hypothesized that seed production in *A. procera* is influenced by age and size of the tree and interannual variation in resource availability and therefore, it will vary between years and among individual tree species. The seedling growth would be influenced by seed dispersal distance and microclimatic variables governing on the sites. The aims of this study were to examine the life cycle strategies of *A. procera* in terms of seed production, implication of seed dispersal distance on the fate of seed and seedling population dynamics, and in relation to microclimatic variables. To achieve these aims, we conducted field experiments in *A. procera* to address the following questions: a) is there variations in seed production between years and among individual trees?, b) how do the tree traits affect its seed production?, (c) does the seed dispersal distance influence seed viability/germination and survival rate?, and (d) which microclimatic variables affect the seedling growth the most?. The findings of this study are expected to contribute to seed dynamics, dispersal and restoration of *A. procera* in the forests.

2. Material and Methods

2.1 Study Area

The study was carried out at Mizoram University (MZU) campus, located 15 km away from Aizawl city that encompasses roughly 980 acres of land and geographically located between 23°39'52"-23°48'43"N and 92°39'49"- 92°46'39"E (Fig. 1) and elevations ranging from 300 meters to 880 meters above sea level. However, the campus harbors represent tropical wet evergreen and semi-evergreen forests, e.g. small biodiversity park and protected forested water catchment reserve in the north. Several streams flow through the campus²⁷⁻²⁹. The forest included diversified plants species, where Wapongnungsang et al.²⁹ reported 384 plants belonging to 290 genera and 107 families and many grass species²⁷. The region receives an average annual rainfall of approximately 1,850 mm, influenced heavily by the southwest monsoon, with most precipitation occurring between May and September. The mean annual temperature is about 21.6 °C, with summer highs reaching 30 °C and winter lows ranging between 10 - 12 °C (Meteorological data of Mizoram, Aizawl, 2023).

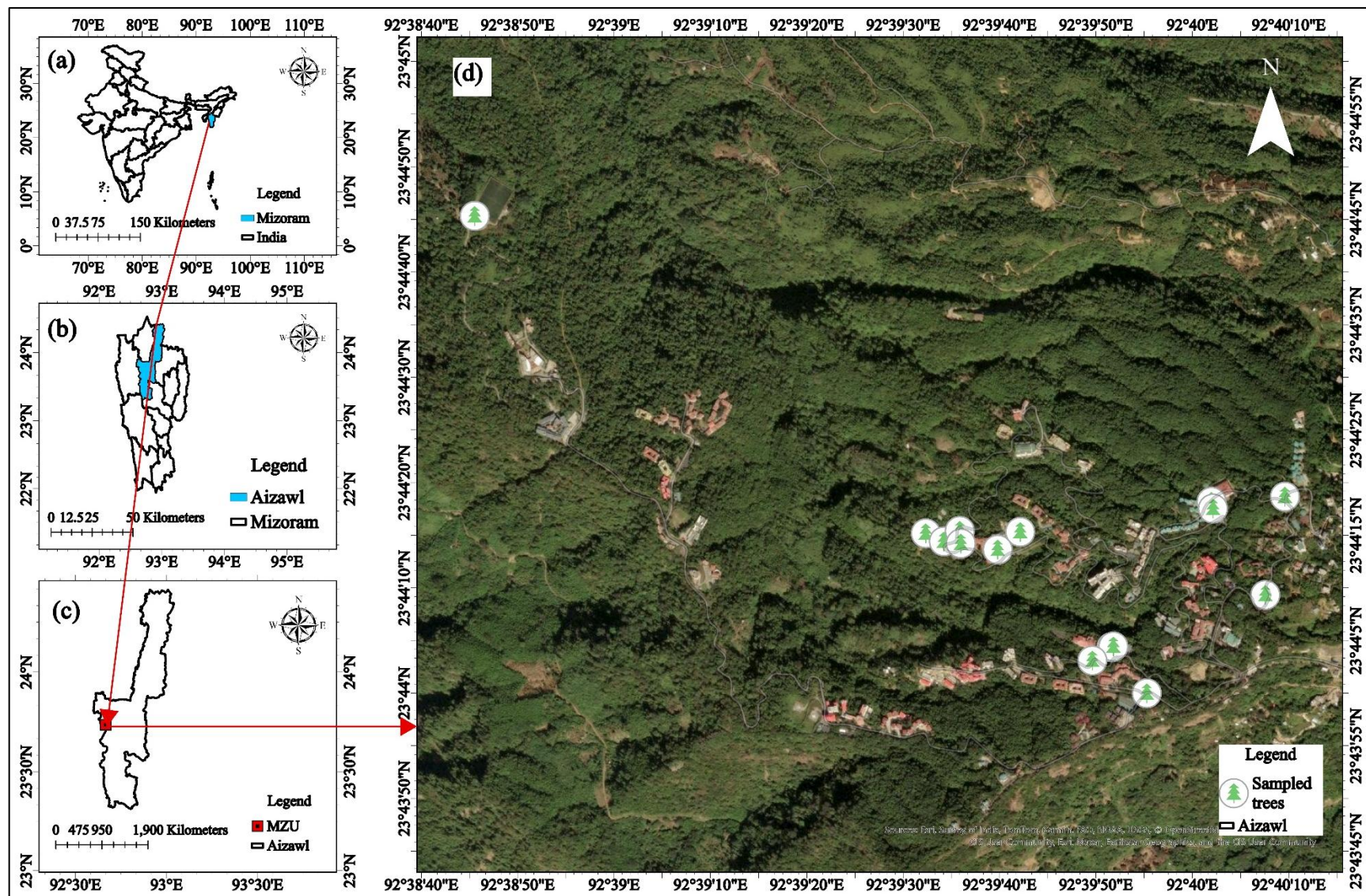
2.2 Data collection

2.2.1 Seeds production

The seeds production of *A. procera* was estimated from randomly selected 15 individual trees for three years (2022 to 2024). However, the seed production of each year was estimated by counting, number of branches, the average number of sub-branches, the average number of sub-sub-branches, the average number of inflorescences in sub-sub-branches and the average number of fruits per inflorescences before seed maturation and fall¹⁶. Additionally, in each tree, the mean number of inflorescences per sub-sub-branch was determined from 5-sub-sub-branches randomly (Formula 1). While the average number of fruits per inflorescence was calculated from a random selection of 10 random inflorescences. Conversely, the mean number of seeds per fruit were estimated from fifteen fruits (Fig. 2A). Furthermore, the number of seeds per kilogram was estimated using the average weight of 25 seeds (Fig. 2B) following the formula (2).

2.2.2 Seeds dispersal

To study the seed dispersal of *A. procera*, five individual fruiting trees were marked in the forest stand following the method suggested by Khan et al.³⁰. Additionally, the distance between marked trees was 100 meters and there is no adult trees from same species that were present between them. Each selected individual tree base was considered as a center, of which concentric circles of 2.5 meters circular increments were marked on the ground around the mother tree of *A. procera*, extending outside the crown radius as deliberated by Sahoo and Lalfakawma¹⁷. The first circle had a radius of a minimum of five meters and maximum was 25 meters. In the meantime, the seeds that fell under the tree crown were not considered as dispersed seeds. However, each selected individual tree was visited at three-days interval over 8-weeks during seed-fall season (Fig. 2C). All seeds collected within each marked circle were counted separately. Meanwhile, the number of seeds dispersed with distance from the mother tree was converted to square meter (m²) following formula (3) and the proportion of dispersed seeds relative to total seed production was calculated. Conversely, the number of seeds that fell under the tree crown and those dispersed at varying distance from the mother tree were recorded as percentages. The seeds damaged during dispersal were excluded from the analysis.



132

133 Fig. 1. Study area: a) India, b) Mizoram state, c) Aizawl district and Mizoram University location, and d) sampled trees.

2.2.3 Fate of seed populations in the soil

The fate of seed population in the soil was assessed, where the number of seeds disappearing (fraction) during the seed fall period was studied. Five seed traps sizing (1 m x 1 m with 30 cm depth) were placed randomly on the ground under the mother tree crown at the beginning of seeds fall (Fig. 3A). The seed traps were visited every five-days until completed seed shedding following the method described by Sahoo and Lalfakawma¹⁷ and de Sá Dechoum, et al.³¹. Simultaneously, during each visit, all seeds in the traps were counted, and seeds damaged (due to insects and rodents) were separated from undamaged ones. However, the difference between total produced seed and undamaged seeds that fell under the individual mother tree was estimated as the fraction of seeds loss during the seed fall period¹⁷.

To estimate the germination of healthy seed after fall and/or dispersal, the fate of undamaged seeds after dispersal was studied by sowing 20 seeds in plot sizing (1m x 1m) under the five sampled individual trees (Fig. 3B). Additionally, seed fate was assessed in relation to distance from the mother tree. Three 1 m² sample plots were randomly established within concentric circles at distances of 5, 15, 25, and 35 meters from the base of individual fruiting tree. In each sample plot, 20 seeds were marked with waterproof paint and placed to simulate the natural dispersal conditions, including seed handling by dispersal agents such as rodents, birds and others. Conversely, seeds fates were monitored at 7-days intervals over three months and the number of seeds that germinated, disappeared or rotted were recorded. Therefore, the number of seeds that disappeared (e.g. translocated or consumed by dispersal agents) or germinated was recorded.

2.2.4 Soil Seed Bank

The study on soil seed soil bank was conducted at the end of rainy season following the method described by Souza et al.³². Four sites were selected using stratified sampling²⁰, and from each site, five soil samples from area of (5 x 5 cm and 5 cm depth) were collected and bulked to estimate buried seed density. From each of the bulked sample 100 g of soil was weighed and washed gently using a jet of water (Fig. 2D) following the procedure and method described by Padonou et al.²⁰ to recover the seeds. The number of seeds found in the sample was then extrapolated to per square meter (m²).

2.2.5 Seedling growth performance in natural conditions and its relation to microclimate variables

To evaluate seedling growth performance and its relation to microclimatic variables, 10 quadrats (1m x 1m) were laid randomly in the forest near *A. procera* tree stand. All seedlings recruited from the dispersed seeds within quadrates were monitored for 14 months. The

seedlings height and stem collar diameter (SCD) were measured at two-weeks interval; seedlings height was measured using 30 cm ruler, while SCD measured using digital Vernier caliper (150 mm). Monthly increments in height and SCD were calculated along with relative growth. Microclimatic variables such as soil temperature, soil moisture, and humidity were recorded monthly throughout the study period. Soil temperature was measured using a stainless-steel dial thermometer, while soil moisture and relative humidity were measured using a digital soil moisture meter and hygrometer, respectively.

2.2.6 Population flux of *A. procera*

The life cycle of *A. procera* tree species is computed from the average of seed production, seeds dispersal and fate of seeds during seed-fall and post-seed fall, and soil seed bank over three years, as well seedling growth and mortality of 14 months. The mean seed production from 15 tree was estimated, along with seed dispersal and seed damage. Consequently, the seed disappeared percentage was calculated from the fate of undamaged seed at varying distances from the mother trees, which also included seed germinated and contribution to the soil seed bank. Moreover, seedling survival and mortality were monitored over 14 months to determine overall seedling survival rates.



Fig. 2. *A. procera* seed at different stages from seed development to soil bank formation: A) Fruits pod, B) Mature seeds, C) Seed in the fruit pod after fall from mother tree, and D) excavation of buried seeds using wet sieving technique.

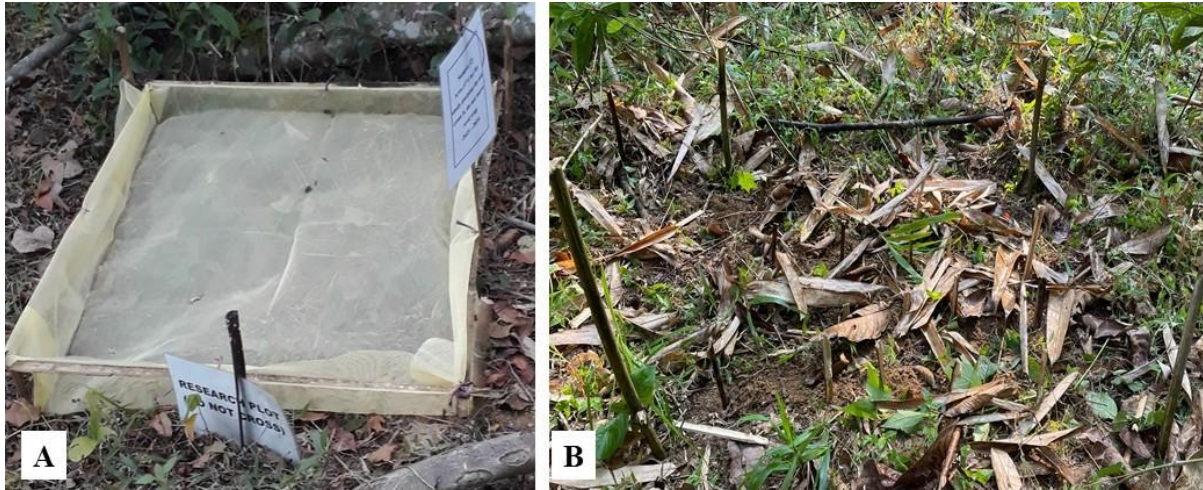


Fig. 3. A) Laying seed trap to collect the dispersed seed, B) Monitoring the fate of undamaged seed population (towards germination, disappearance and rotted seeds) from plots under the mother tree and at varying distance from the mother tree,

2.3 Data analysis

All field data on seed production, dispersal, fate of seed population, and seedling growth were compiled and organized into meaningful table for analysis. Data were summarized and expressed as mean and standard deviation (SD). The mean seed production for each year was computed, and seed germinated and disappeared was calculated using formula (4, 5 respectively) (17), as well as the percentage of seed that fell under the mother tree (UMT) *versus* those dispersed at varying distances from the mother tree were calculated following formula (6, 7)³³. The relationship between seed production and tree characteristics such as DBH, number of branches, number of inflorescences, crown height, crown diameter was examined. Additionally, the correlation between seed dispersal and dispersal distance were analyzed. Conversely, seedlings' height and SCD were processed and calculated their monthly means increment, and relative monthly growth rates as well as correlation between seedling parameters and microclimatic variables were also assessed. The seed population flux was computed from the mean seed production, mean seed damaged, mean seed dispersal, mean seed soil bank, and mean seed germinated percentage at varying distance from the mother tree. Moreover, statistical analysis including linear regression model, one-way ANOVA, and post-hoc Tukey and Fisher LSD test ($P < 0.05$) were examined to evaluate seed production variations among individual trees and between years as well as seeds dispersal. All data analysis were performed SPSS, Version 22.0, Jamovi (Version 2.5.6)³⁴, OriginPro 2025 and Microsoft Excel (Version 365).

2.4 Formula and equations

A. Total seed production = total number of branches $\times$ mean number of sub-branches in the main branch $\times$ mean number of sub-sub-branches per sub-branch $\times$ mean number of inflorescences per sub-sub-branches $\times$ mean number of fruits per inflorescence $\times$ mean number of seeds per fruit.(1).

B. Number of seeds in kg = $\frac{1000}{\text{Mean seeds weight}}$ (2).

C. Seeds density (seeds/m²) = $\frac{\text{Number of seed per sample plot (radius 2.5m)}}{\text{Area of sample plot}}$ (3)

D. Germination (%) = $\frac{\text{Number of seeds germinated}}{\text{total number of seeds sown or placed}} \times 100$ (4).

E. Disappeared or rotted seeds (%) = $\frac{\text{Number of seeds disappeared}}{\text{total number of seeds sown or placed}} \times 100$ (5).

F. Percentage of seeds fall under the mother tree or within distance from the mother tree = $\frac{\text{Number of seeds in one square meter under the mother tree or dispersed with distance}}{\text{Total number of seeds fall under the mother tree and dispersed with distance in one square meter}} \times 100$ (6).

G. Total seeds fall under the mother tree and disperse with distance from mother tree = $\frac{\text{Percentage of seeds fall under the tree or dispersed with distance}}{100} \times \text{Mean No. of seeds produced}$ (7).

3. Results

3.1 Seeds production, seed dispersal and soil seed bank

The mean seed production of *A. procera* significantly differed among individual trees ($P < 0.05$) (Fig. 4) and between years ($P < 0.001$) (Fig. 5). The mean seed production per individual tree was 145,352 in 2022, 43,607 in 2023, and 41,490 in 2024 (Table 1). The mean seed weight was 0.039 g with 25,654 seed per kilogram and significant difference between years (Table 1). A strong correlation was observed between seed production and tree traits such as DBH, number of branches, number of inflorescences, number of fruits, crown height, and crown diameter (Table 2). The seed soil bank is relatively low across the years, indicating low variability among sample plots and number of seed remaining in the soil (Table 1).

The results of seed dispersal revealed that the number of seeds per unit area decreased as the distance from the mother tree increased (Fig. 6), with significant difference between years and among individual trees ($P < 0.05$). Correlation analysis showed a strong negative relation between seed dispersed and distance from the mother tree (Pearson $r = -0.91$ in 2022, $r = -0.93$ in 2023, and $r = -0.86$ in 2024) (Fig. 6). Simultaneously, the density of seed per square

(m²) decreased with increasing the distance from the mother tree, with most seeds accumulated under or near the mother tree (Table 3). Further, 55.38% of total seed produced in 2022, 54.25% in 2023 and 52.92 in 2024 fell directly under the mother tree (Fig. 7). Conversely, the remaining seeds dispersed up to maximum distance of 22.50 meters in all years (Fig. 7).

Table 1. Inter-annual variations in seed production and soil seed bank formation by *A. procera* in Mizoram, northeast India

Variables	2022 (Mean±SD)	2023 (Mean±SD)	2024 (Mean±SD)	Sig.
Mean No. of infl./sub-branch	7.49 ± 1.74	4.43 ± 2.26	4.35 ± 1.93	0.00
Mean No. of fruit/infl.	13.21 ± 5.78	7.81 ± 2.71	7.40 ± 3.49	0.00
Mean No. of seeds/fruits	11.40 ± 1.45	9.40 ± 1.59	9.00 ± 1.44	0.00
Total seed production/tree	145,352	43,607	41,490	0.00
Soil seed bank (number m ²)	100 ± 0.44	120 ± 0.54	107 ± 0.45	0.92
Mean seed weight	0.04 ± 0.01	0.03 ± 0.01	0.04 ± 0.01	0.00

SD = standard deviation, infl. = inflorescences.

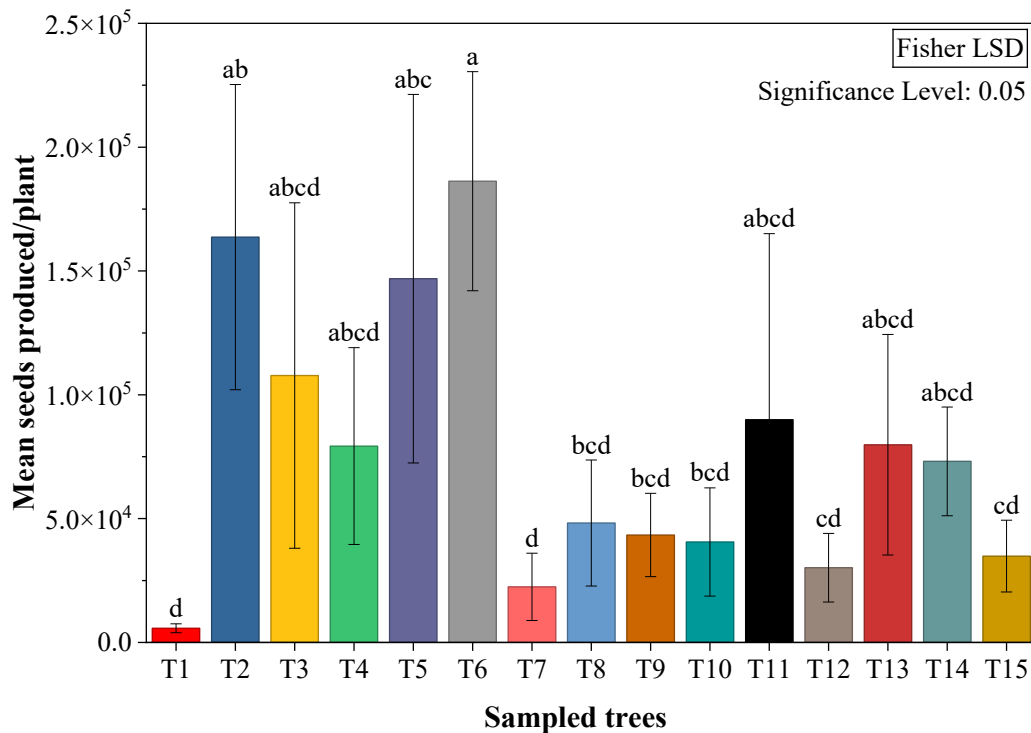


Fig. 4. Mean seed production of *A. procera* among individual trees over three years (2022 to 2024). The error bar shows the variation of seed production between years within population. The different alphabetic letters show significant variation of mean seed production between individual trees (where T1 to T15 are sampled trees).

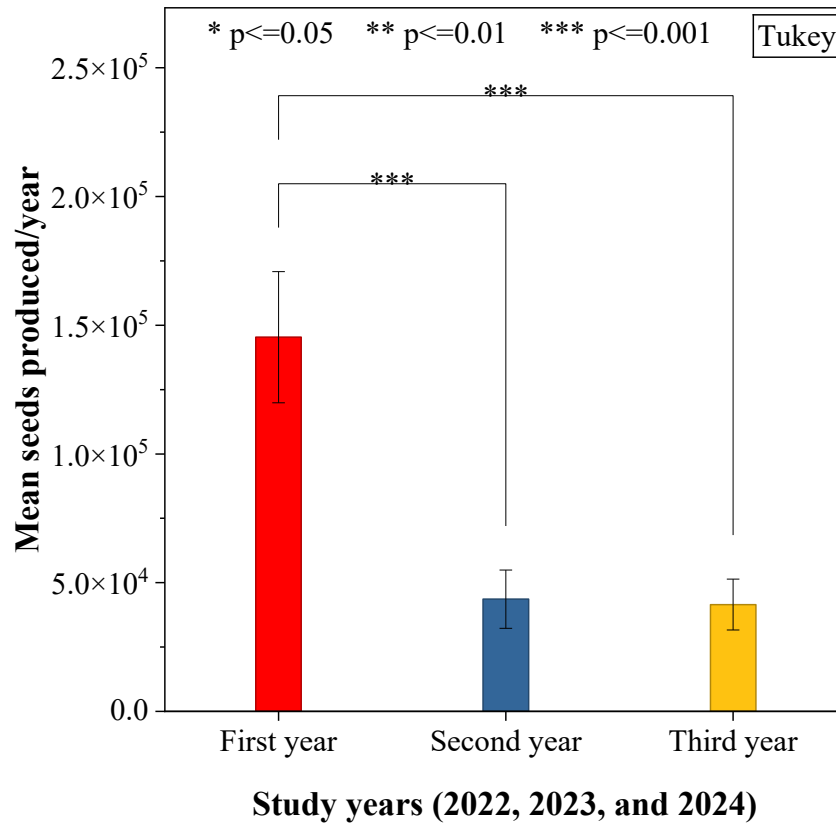


Fig. 5. *A. procera* mean seed production variation between study years.

Table 2. Correlation between mean seed production and tree characteristics

Variable	DBH	NB	MSB	MSSB	MI/SSB	MF/I	CH	CD	MSP
DBH	1								
NB	.22	1							
MSB	.32	-.43	1						
MSSB	.32	-.27	.46	1					
MI/SSB	.11	.26	.19	.03	1				
MF/I	.19	.06	.09	-.11	.58*	1			
CH	.51	.47	.11	.04	.60*	.56*	1		
CD	.50	.52*	.15	.05	.66**	.60*	.92**	1	
TSP	.40	.50	.26	.13	.80**	.66**	.87**	.89**	1

* and **. Correlation is significant at the 0.05 and 0.01 level respectively. DBH: diameter at breast height, NB: number of branches, MSB: mean no. of sub-branches, MSSB: mean no. of sub-sub-branches, MI/SSB: mean no of inflorescences per sub-sub-branches, MF/I: mean no of fruits per inflorescences, CH: crown height, CD: crown diameter, and MSP: mean seed produced

Table 3. Density of seeds (number/m²) under the mother tree (UMT) and with distance from mother tree

Distance from the mother tree (m)	No. of seed in 2022 (Mean ± SD)	No. of seed in 2023 (Mean ± SD)	No. of seed in 2024 (Mean ± SD)
UMT	126.4 ± 93.41	58.2 ± 39.98	55.00 ± 38.43
5.00	39.43 ± 17.23	17.70 ± 7.89	21.27 ± 14.49
7.50	23.41 ± 8.63	9.87 ± 2.86	7.62 ± 4.94
10.00	16.61 ± 6.41	8.27 ± 3.02	8.07 ± 2.61
12.50	9.63 ± 5.88	5.93 ± 2.91	5.66 ± 2.70
15.00	6.59 ± 5.13	3.42 ± 1.62	3.13 ± 1.44
17.50	3.41 ± 1.05	2.49 ± 1.31	2.11 ± 1.25
20.00	2.10 ± 0.75	0.91 ± 0.62	0.75 ± 0.54
22.50	0.65 ± 0.56	0.50 ± 0.69	0.33 ± 0.48

SD = standard deviation.

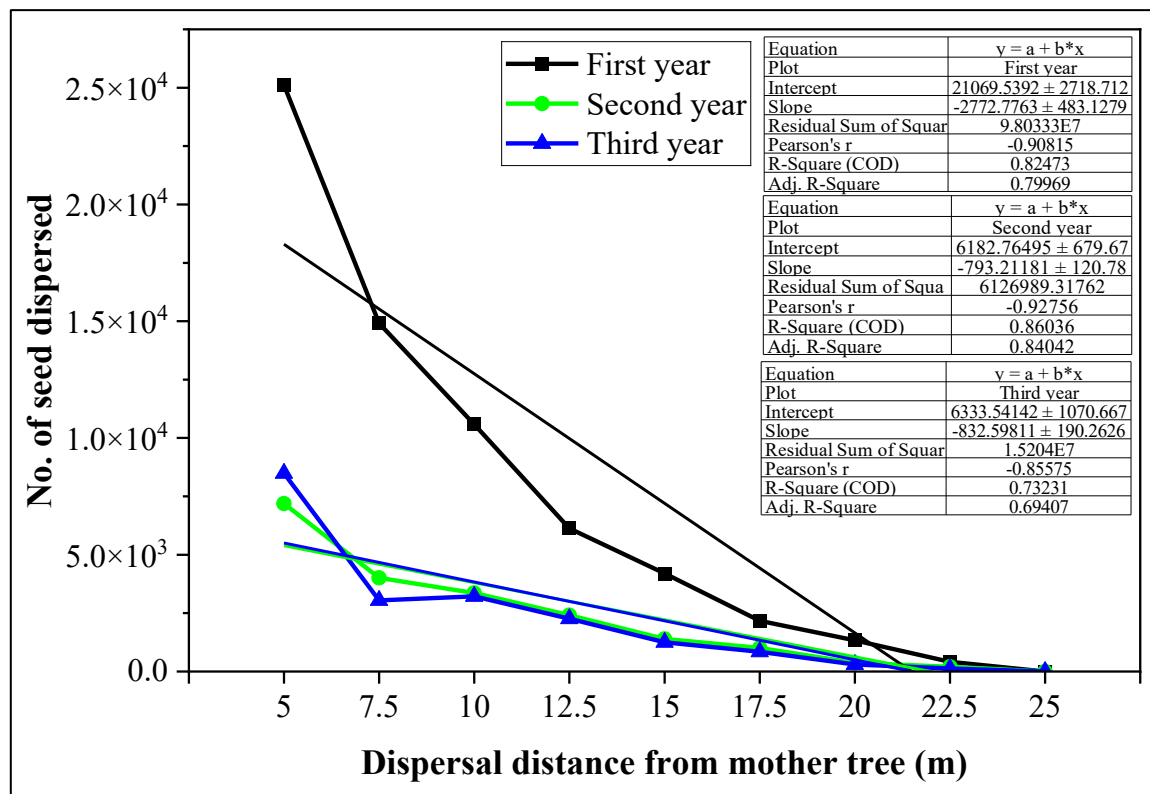


Fig. 6. Seed dispersal from the mother tree and linear model during study period

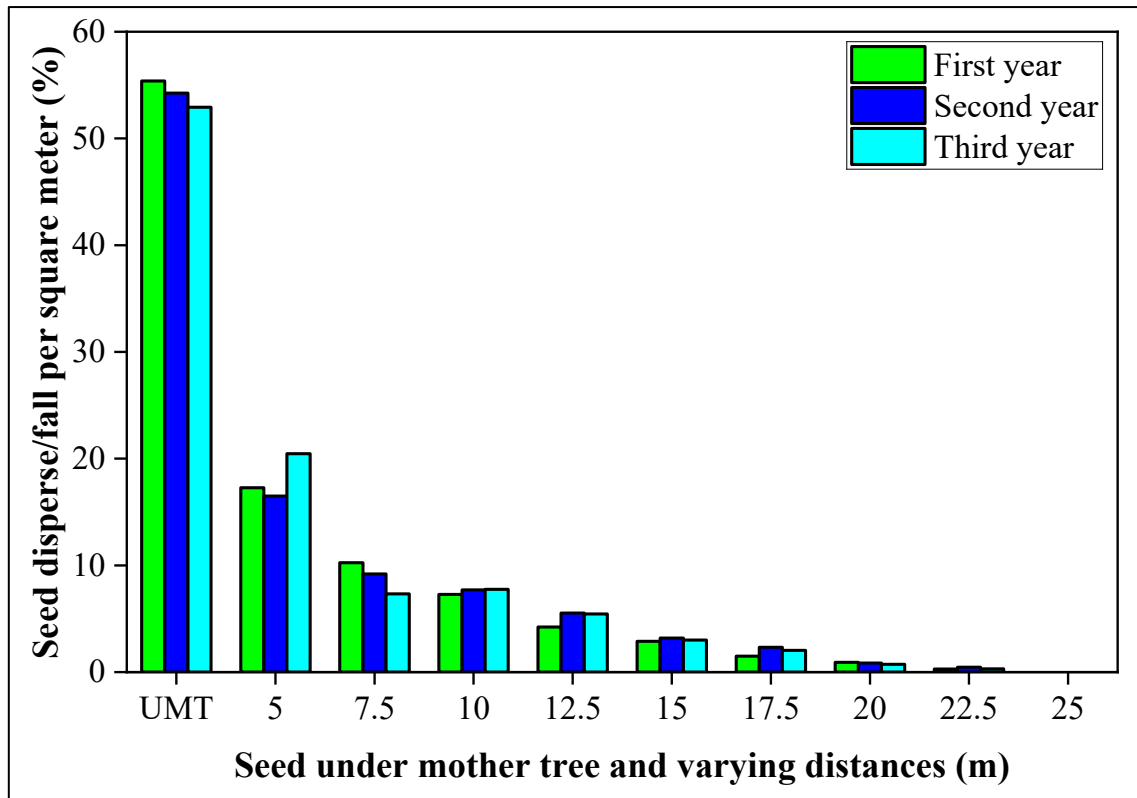


Fig. 7. The percentage of seeds fall under the mother tree (UMT) and dispersed with distance in square meter (m^2)

3.2 Fate of seed populations in the soil

During the seed-fall period, 97.40% of the seed that fell under the mother tree in 2022, 97.63% in 2023, and 97.15% in 2024 of *A. procera* were undamaged and viable. In mean time, 2.60% (2022), 2.37% (2023), and 2.85% (2024) of seeds were damaged during seed-fall season (Table 4). During the post-seed-fall, the fraction of seed disappeared was 56.6% in 2022 while decreased to 48% in 2023, and 49.80% in 2024. In contrast, the seed germination rates observed in natural forest conditions were moderate, ranging from 39.00%, 47.90% and 45.40% in 2022, 2023, and 2024 respectively, (Table 4).

3.3 Seed disappearance and germination in relation to distance from mother tree

The seed disappearance due to predation was higher near to the mother trees and decreased with increasing distance. Approximately 82.33% of the sown seeds had disappeared within a 5 meters circle while 67.33% disappeared at a distance of 35 meters from the mother tree (Fig. 8). Meanwhile, 17% and 32.67 % of sown seeds were germinated in the distance of 5 meters and 35 meters, respectively from the mother tree (Fig. 8).

3.4 Seedlings dynamics in the forest and its relation to microclimatic variables

A. procera seedling growth in the natural forest conditions during study period resulted in an average height and SCD of 22.50 cm and 3.25 mm respectively (Fig. 9). A significant

difference ($P < 0.05$) in seedling growth increments was observed between months in height and stem diameter (Fig. 10). The highest soil temperature was recorded in June (26.86 °C), while soil moisture in July (70.30%) (Fig. 11). A strong correlation was observed between relative seedling height and microclimatic variables such as soil temperature ($r = 0.60$), soil moisture ($r = 0.95$), and humidity ($r = 0.78$) (Table 5), and similarly these variables were positively correlated with seedling stem collar diameter but negatively correlated with soil pH (Table 5).

3.5 Population flux of *A. procera*

The population flux of *A. procera* integrates seed production, seed dispersal, seed soil bank, and seedlings recruitment over three years. Based on 15-sampled trees, the mean seed production over three years was 76,816 seeds/tree. Of these seeds 97.63% was fell beneath the mother tree and dispersed at varying distances. However, during post-seed-fall, we found that 73.44%, 25.50% and 1.06% of the seeds got disappeared, germinated and stored in soil bank respectively. Among the germinated seeds, only 46.07% developed into seedlings that survived for 14 months (Fig. 12). In contrast, the seedling continues with vigorous growth (height and diameter) during the rainy season while drop the leaves and stop shoot growth during dry season (Fig. 13).

Table 4. Fate of seed population during seed-fall period and post seed-fall period, expressed as fractions (%) of the total seed trapped (Mean $\pm$ SD).

Seeds conditions		First year (%)	Second year (%)	Third year (%)
Seed fall period	Undamaged	97.40 $\pm$ 1.76	97.63 $\pm$ 0.69	97.15 $\pm$ 0.50
	Insect-damaged	2.60 $\pm$ 1.76	2.37 $\pm$ 0.69	2.85 $\pm$ 0.50
Post-seed fall period	Disappeared	56.60 $\pm$ 2.39	48.00 $\pm$ 2.30	49.80 $\pm$ 1.90
	Rotten	4.40 $\pm$ 2.39	4.10 $\pm$ 2.30	4.80 $\pm$ 1.90
	Germinated	39.00 $\pm$ 2.39	47.90 $\pm$ 2.30	45.40 $\pm$ 1.90

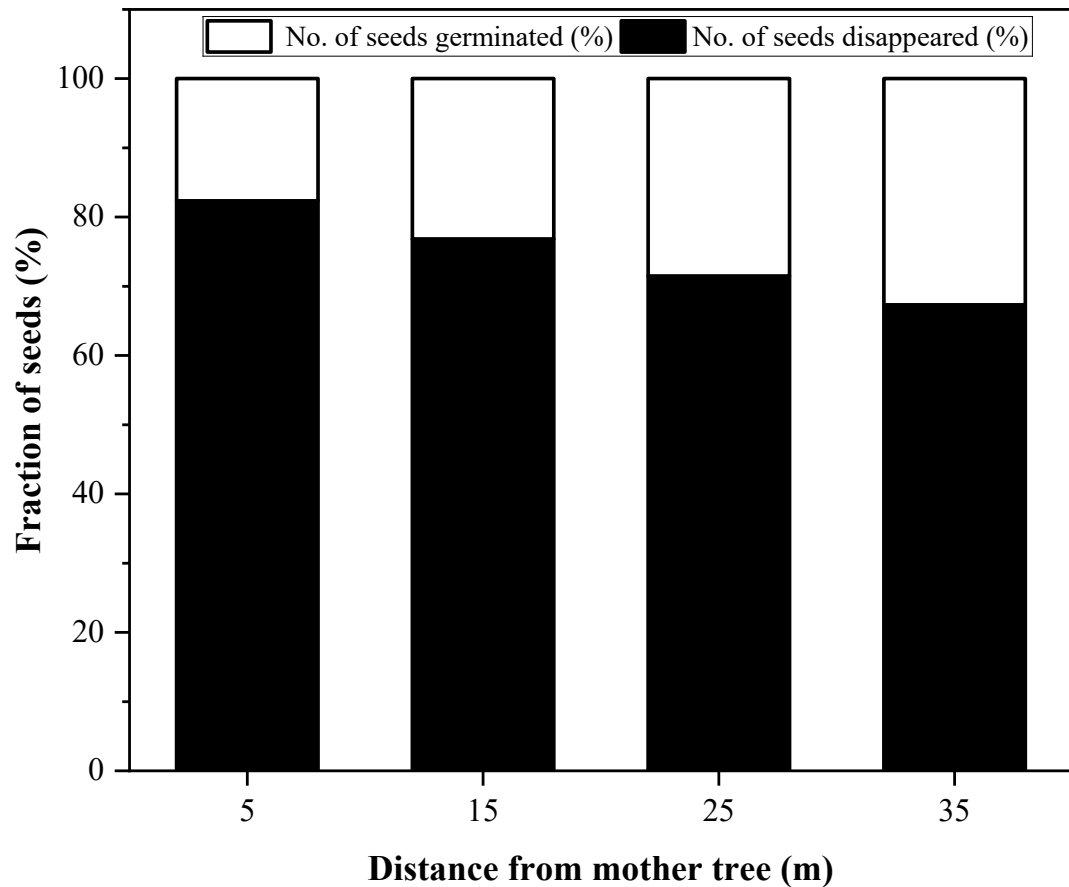


Fig. 8. Germination and disappearance of seeds of *A. procera* as influenced by distance from the mother tree

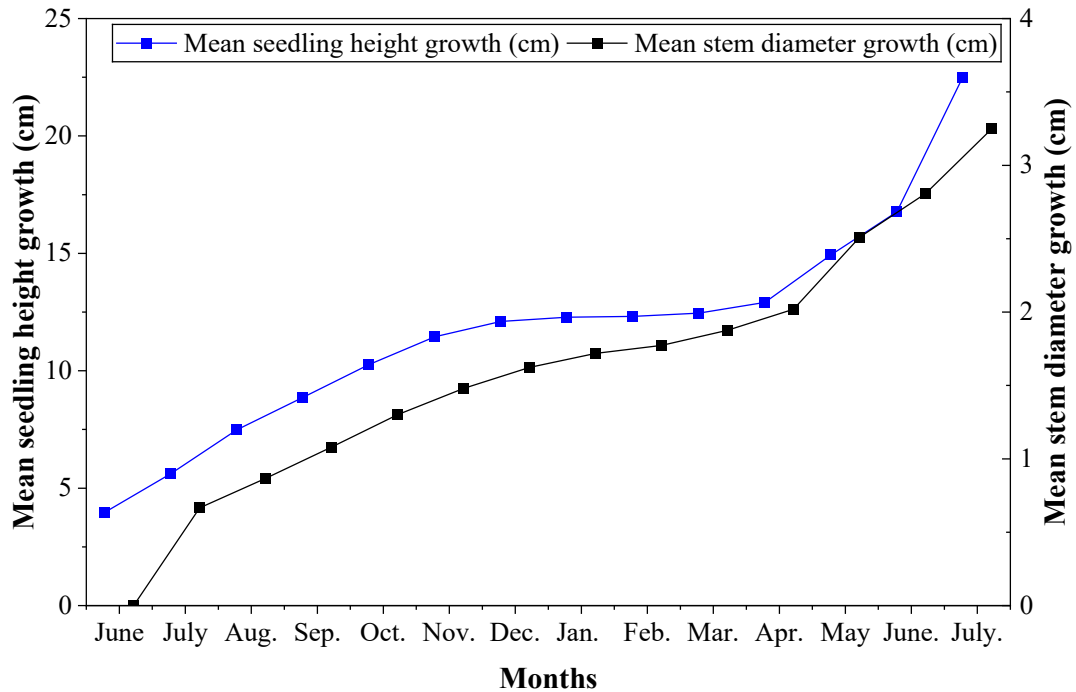


Fig. 9. Mean seedling growth performance in the natural forest conditions over study period.

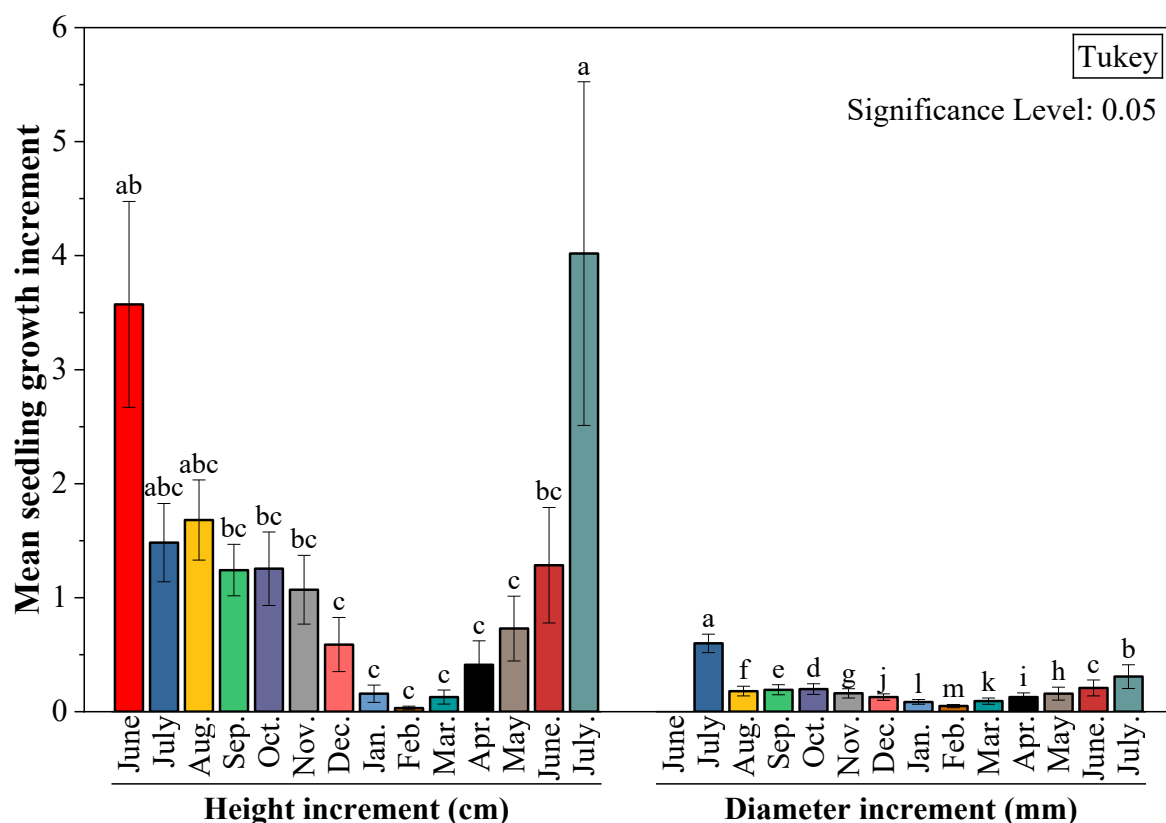


Fig. 10. Post-hoc Tukey test ($P < 0.05$) test for mean seedling height and stem diameter increments over study period. The different alphabetic letters show significant variation in seedling growth increments of height and stem diameter between months during study period.

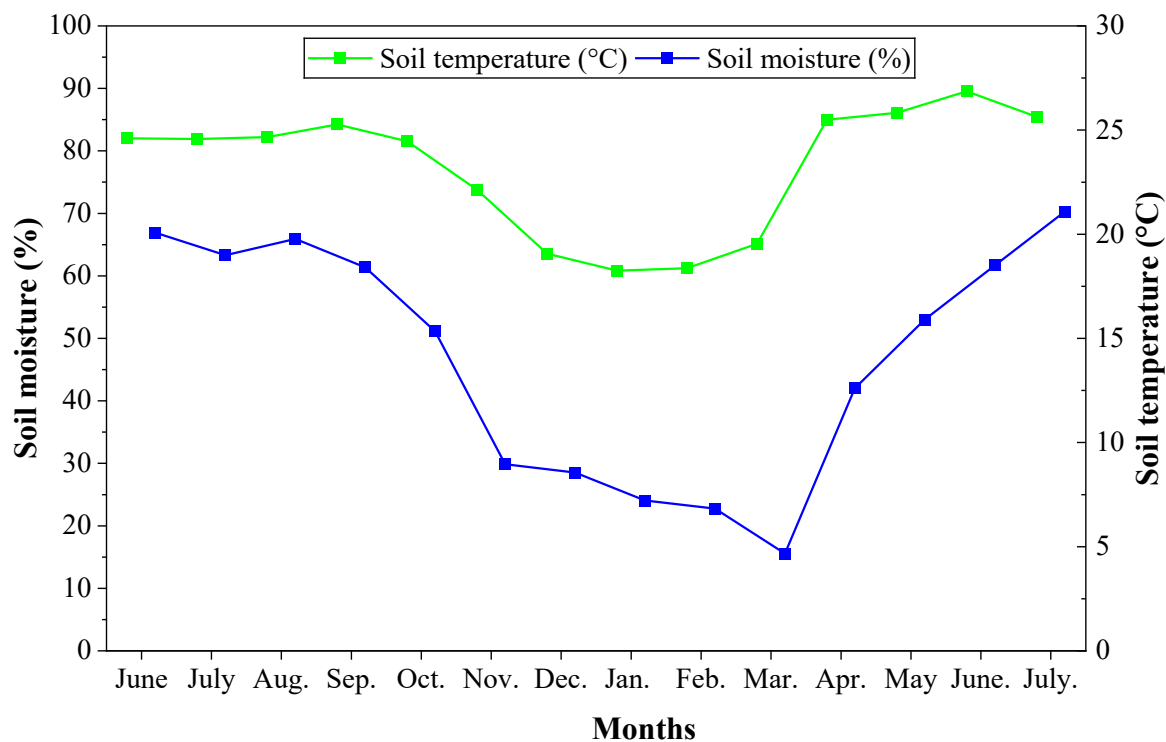


Fig. 11. Soil temperature and soil moisture in forest conditions during the study period

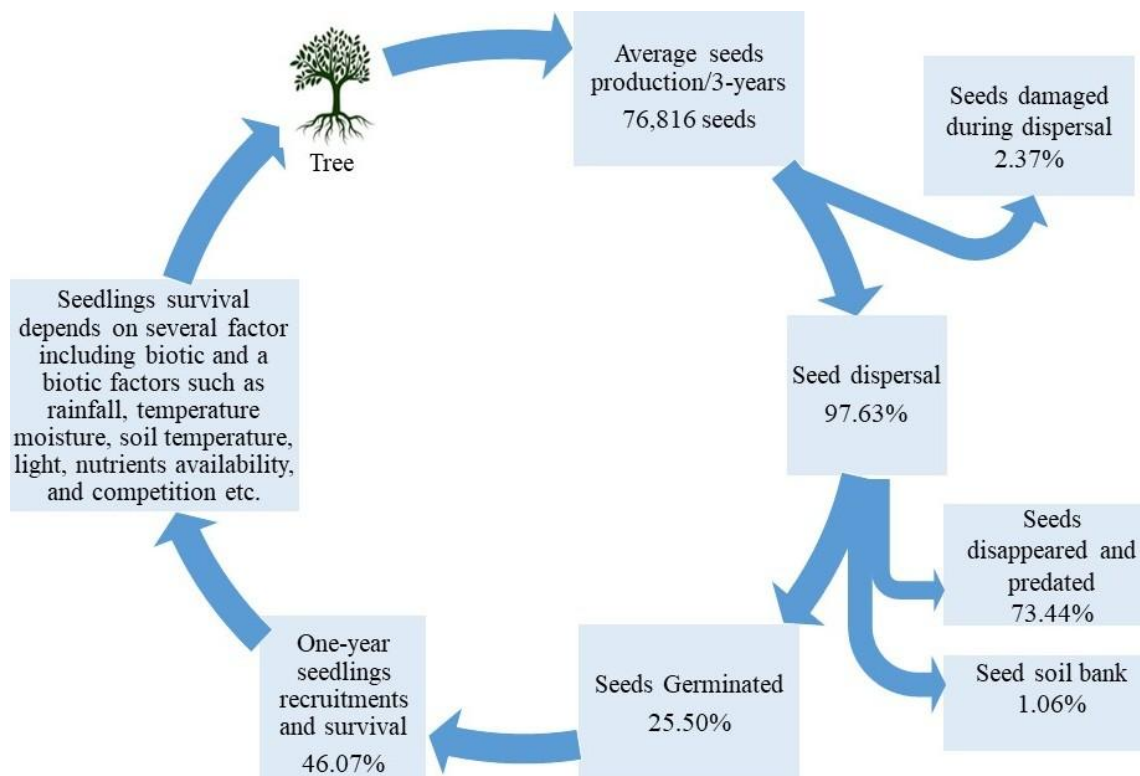


Fig. 12. *A. procera* population flux: average of 3 years seed production to seedling survival

Table 5. Correlation between seedlings parameters and microclimate variables

Variables	ST	SM	pH	H	RHG	RDG
Soil temperature (ST)	1.00					
Soil moisture (SM)	0.70**	1.00				
pH	- 0.22	- 0.44	1.00			
Humidity (H)	0.37	0.69**	- 0.26	1.00		
Relative height growth (RHG)	0.60*	0.95***	- 0.39	0.78**	1.00	
Relative diameter growth (RDG)	0.76**	0.87***	- 0.28	0.63*	0.85***	1.00

Note. * $p < .05$, ** $p < .01$, *** $p < .001$



Fig. 13. *A. procera* seedling growth performance in natural forest conditions: A) seedling during rainy season of the first year, B) Response of the seedling to dry winter season, and C) Seedling growth at the onset of rainy season.

4. Discussion

4.1 Seed population dynamics

A great year-wise variation was observed on the number of seeds produced by *A. procera* between years and among individual trees and similar variations was reported in other trees species^{11,14,16,17,35-37}. This variation was obviously related to the fruit loading of the species and the number of fruits bearing species in a given year. During 2022, seed production was significantly higher than 2023 and 2024, and this was obviously due to higher number of fruited branches and the number of fruits per sub-branch and the number of seeds per fruit (Table 1 and Fig. 5). On the other hand, the variation in seed production between years could be influenced by climatic factors and other genetic characteristics of tree. Many authors have suggested that seed production in a species will be influenced by several intrinsic and extrinsic factors during the flowering and seed setting period. For example, Iralu et al.¹² reported that the annual rainfall acts as a limited factor for seed production and seedling survival while^{17,38,16} explained that seed production of tree species can be influenced by a variety of factors such as availability of resources, pollination failure, predation on flower, fruits, climatic condition, plant age and size. We observed a strong correlation between mean seed production and tree characteristics such as DBH, number of branches, number of inflorescences, and crown cover. However, a strong positive correlation between mean seed production and tree morphological traits may partially reflect the estimation method used for seed production, which was based on multiplying these components. These findings also indicated that trees with large crown or more inflorescences are expected to produce more seeds. Similarly, these findings are in agreement with Khan et al.³⁰ who observed that dominant trees species with large crowns, which receive a lot of light, tend to produce an optimum number of seeds. Conversely, the higher seed production occurring in warmer year, meanwhile increased temperature negatively affects seedling establishment³⁹. Seed dispersal is the movement of seed from the mother tree by help of different dispersal agents. For successful tree regeneration, it is important that the seeds should disperse to a safe location where they can germinate, survive and translate into mature plants. Thus, it determines the seeds distribution and trees during natural regeneration process which can be influenced by several factors (e.g. biological and environmental). Though seeds dispersal in *A. procera* reached up to maximum of 22.50 meters from the mother tree and there were variations in seed dispersal distance between years and among individual trees, most of the seeds fell near the mother tree *via* explosion, while a small fraction of seeds was transported through to distance places by wind. These findings suggest that the seeds with capsules tend

to be exposed to secondary dispersal where wind moves it to another location. Seed dispersal, however, was highly restricted in this species, and for successful regeneration, the seeds need to be transported to far off places. Several studies observed that seeds from same mother tree with varying seed mass are influenced by dispersal distance and differ significantly among tree species sharing the same dispersal mode⁴⁰⁻⁴³. A strong negative correlation between number of seeds dispersed per unit area and dispersal distance suggests higher density-dependent mortality near the mother tree in this species. Similar findings have been observed by several authors for other trees species^{17,44}. Nathan et al.⁴⁵ argued that long-dispersal distance is more common in open terrestrial landscapes and driven by migratory animals and wind. While Chen et al.³⁵ and Kasi and Ramasubbu⁴⁶ indicated that tree species that dispersed their seed by gravity are aggregated around the parent tree.

The soil seed bank of *A. procera* was found to be transient type. Though the seeds of this species possess hard seed coats, they can germination in soil by weathering effects. Thus, *A. procera* does not form a persistent soil seed bank. Besides, the seed bank size was also low; on an average buried seed population was 100 seeds per square meter (m²) in species stand. However, soil seed bank nevertheless plays an important role in regeneration of tree species, and its size is determined by seed dispersal and seed characteristics, and its ability to remain viable during the unfavourable conditions. The prevailing microclimate such as low temperature and moisture can have a bearing on soil seed bank by limiting germination⁴⁷. Similarly, predation can reduce the seed soil bank in forest floor and may affect survival and mortality^{12,48}.

A majority of seeds were undamaged during seed fall were found disappeared during the post fall period, maybe due to predation, or dispersed by other secondary agents. However, the seed germination of trapped seeds during post-fall showed moderate germination of 39.0%, 47.9%, and 45.4% in 2022, 2023, and 2024 respectively (Table 4). While these rates indicate successful germination for a proportion of seeds in natural set up, the results were relatively lower compared to *A. procera* germination rate observed in nursery conditions which exceed 80 – 90%^{6,26}. These findings suggest that natural environmental constraints may significantly limit seed germination compared to controlled conditions. Similar findings have been reported by Sahoo and Lalfakawma¹⁷ for *Castanopsis tribuloides* in northeast India. Our results are also in agreement with Kasi and Ramasubbu⁴⁶ who observed that higher density of seeds near to adult tree act to intensify predation and competition.

4.2 Seed disappearance and germination in relation to distance from the mother tree

Seed disappearance in the present study was closely related to distance from the mother tree. The seeds that escape or disperse far off from the mother trees were found to be less predated than those which fell near the mother trees. Higher rate of predation and low survival near the mother tree were obviously due to density-dependent competition and predator preference, as also has been reported by several other workers^{16,17,33}. Additionally, our results revealed that with increased distance from the mother tree the seed germination percent increased while seed disappearance decreased, as also found by Souza et al.⁴⁹. We observed that the mean seed germination was poor (25.5%) (Fig. 8 and 12) compared to seed disappearance in their natural condition at varying distances from the mother tree and majority of seeds that still remained in capsule could not transform into successful seedlings due to unfavourable environmental conditions (Fig. 14). The results clearly demonstrate that the seeds will have a better chance of survival if they are dispersed far away from the parent plants and get favorable germination conditions.



Fig. 14. Seeds started germinating in it capsules but will die due to unfavorable environmental conditions

4.3 Seedling dynamics and its relation to microclimate variables

Seedling growth and survival are often influenced by a combination of environmental factors such as soil temperature, moisture, light availability, and relative humidity. In the present study, *A. procera* seedlings reached an average height of 22.5 cm and SCD of 3.25 mm over study period. A strong positive correlation was found between relative seedling height growth and other environmental factors such as soil moisture ($r = 0.95$), relative humidity ($r = 0.78$), and soil temperature ($r = 0.60$) as well as these factors positively correlated with relative diameter, indicating that these microclimatic variables play an important role in early-stage

seedling development under natural forest conditions. However, these findings are consistent with Musa and Sahoo²⁶, who reported that moisture availability and temperature significantly affect seedling performance of tropical species. While Bebre et al.⁵⁰ stated that multiple environmental factors in forests influence the seedling growth such as light, temperature, soil moisture, litter depth, intra and interspecific competition for various resources⁵⁰. Consequently, Greenwood et al.⁵¹ and Wieser et al.⁵² observed that higher soil temperature and moderate temperatures can improve physiological processes such as photosynthesis and nutrient uptake, leading to improved seedling establishment and growth. Johnson et al.⁵³ emphasized that mortality is often highest during early seedling stages, which further underscores the importance of the favorable microclimates during this critical stage. In our study, seedling mortality was relatively high compared to survival, with only 46.07 % of germinated seedlings surviving through the 14-month period. This aligns with findings from Brown⁵⁴ and Bebre et al.⁵⁰, who observed that forest microhabitats with variable light and moisture conditions often lead to differential survival outcomes among species. In the meantime, the presence of canopy gaps, for instance, has been shown to provide improved conditions for seedling recruitment and survival due to increased light availability and moderated competition. Additionally, the observed relationship between soil temperature and seedling growth supports earlier findings by Charru et al.⁵⁵ and Moore et al.⁵⁶, who demonstrated that warmer soil temperature, within a suitable range, can enhance seedling root activity and metabolic function. Awal⁵⁷ and Kharuk et al.⁵⁸ reported that soil temperature not only affects plant growth directly but also regulates microbial activity and nutrient cycling, which indirectly supports seedling vigor.

Finally, this study results confirm that microclimatic conditions at the forest floor particular soil temperature and moisture have a significant influence on the seedling dynamics of *A. procera* which highlights the need to consider fine-scale environmental variability in regeneration and restoration planning for this species.

Conclusion

Regeneration of *A. procera* was found affected by seed production, dispersal distance and the microclimates surrounding the forest floor. Seed production varied significantly between individual trees, and it was closely related to resource allocation in a given seed year. Seed dispersal in *A. procera* was by explosion resulting into majority of seeds falling under/near the mother trees. The species exhibited a density-dependent mortality as can be observed from higher seed disappearance/mortality near the mother plants than the fare-off distance. The size and persistence of soil seed bank was low while microclimates in soil seed

environment influenced the seedling growth performance. *A. procera* produced seeds in every year, however, the variability in seed production between years and among the individual trees was highly notable. The restricted seed dispersal was a hindrance to higher seedling survival. Therefore, reliance on natural regeneration may not be a suitable restoration strategy of this species. For continuity of life span, sufficient number of seed-bearing trees of this species in the natural conditions needs to be maintained.

Data availability statement

All data used/analyzed in this paper are available from corresponding author upon request

Ethical approval

The seeds used in this experiment were collected from the natural forests following the standard guidelines, and this research was carried out as per the local legislation and approval from the research ethical committee of Mizoram University, India.

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Competing interest

The authors declare no competing interest.

Authors' contribution

Faisal Ismail Musa: Conceptualization, data curation, formal analysis, investigation, methodology, software, validation, visualization, writing - original draft; Uttam Kumar Sahoo: Conceptualization, methodology, supervision, writing - review & editing; Ahmed Abdallah Adam Mohamed: Data curation, formal analysis, validation, visualization, writing - review & editing; Uttam Thangjam: Methodology, Review & editing; Mamta Chettri writing - Review & editing. All authors read and approved the final version for publication.

References

1. Hossen, K. & Kato-Noguchi, H. Evaluation of the Allelopathic Activity of *Albizia procera* (Roxb.) Benth. as a Potential Source of Bioherbicide to Control Weeds. International Journal of Plant Biology 13, 523–534 (2022).
<https://doi.org/10.3390/ijpb13040042>.

2. Srivastava, V., Kumar, V. S., Panwar, S., Deep, P., & Verma, S. A brief review on
phytopharmacological reports on *Albizia procera*. *Asian J. Pharm. Sci.* 6, 144-149
(2020).
3. Pachua, L., Lalhlenmawia, H. & Mazumder, B. Characteristics and composition of
Albizia procera (Roxb.) Benth gum. *Industrial Crops and Products* 40, 90–95 (2012).
<https://doi.org/10.1016/j.indcrop.2012.03.003>.
4. Shah, S. S., Aziz, Md. A., Mohamedkhair, A. K., Qasem, M. A. A., Hakeem, A. S.,
Nazal, M. K. & Yamani, Z. H. Preparation and characterization of manganese oxide
nanoparticles-coated *Albizia procera* derived carbon for electrochemical water
oxidation. *Journal of Materials Science Materials in Electronics* 30, 16087–16098
(2019). <https://doi.org/10.1007/s10854-019-01979-6>.
5. Rai, E., & Ansari, S. A. A protocol for recovery of whole plants through in vitro
shoots regeneration from leaflet explants of mature trees of *Albizia procera* (Roxb.)
Benth. *Indian Forester* 143, 487-498 (2017).
6. Azad, Md. S., Biswas, R. K. & Matin, Md. A. Seed germination of *Albizia procera*
(Roxb.) Benth. in Bangladesh: a basis for seed source variation and pre-sowing
treatment effect. *Forestry Studies in China* 14, 124–130
<https://doi.org/10.1007/s11632-012-0209-z> (2012).
7. Khurana, E. Influence of Seed Size on Seedling Growth of *Albizia procera* Under
Different Soil Water Levels. *Annals of Botany* 86, 1185–1192 (2000).
<https://doi.org/10.1006/anbo.2000.1288>
8. Bunluepuech, K., & Tewtrakul, S. Anti-HIV-1 integrase activity of Thai medicinal
plants in longevity preparations. *Sonklanakarin J of Sci and Tech.* 33, 693 (2011).
9. Khatoon, Mst. M., Khatun, Mst. H., Islam, Md. E. & Parvin, Mst. S. Analgesic,
antibacterial and central nervous system depressant activities of *Albizia procera*
leaves. *Asian Pacific Journal of Tropical Biomedicine* 4, 279–284 (2014).
<https://doi.org/10.12980/APJTB.4.2014C348>
10. Rai, E., Bouddha, S. & Ansari, S. A. Biochemical investigations during in vitro
adventitious shoot regeneration in leaflet explants from nodal segments of a mature
Albizia procera tree. *Journal of Forestry Research* 27, 699–705 (2015).
<https://doi.org/10.1007/s11676-015-0196-8>
11. Abiyu, A., Teketay, D., Glatzel, G. & Gratzner, G. Seed production, seed dispersal and
seedling establishment of two afro-montane tree species in and around a church forest:

- implications for forest restoration. *Forest Ecosystems* 3, (2016).
<https://doi.org/10.1186/s40663-016-0076-5>
12. Iralu, V., Barbhuyan, H. S. A., Upadhaya, K. Ecology of seed germination in threatened trees: A review. *Energy, Eco and Env.* 4, 189-210 (2019).
<https://doi.org/10.1007/s40974-019-00121-w>
13. Mattana, E., Fenu, G. & Bacchetta, G. Seed Production and in situ Germination of *Lamyropsis microcephala* (Asteraceae), a Threatened Mediterranean Mountain Species. *Arctic Antarctic and Alpine Research* 44, 343–349 (2012).
<https://doi.org/10.1657/1938-4246-44.3.343>
14. Wesolowski, T., Rowiński, P. & Maziarz, M. Interannual variation in tree seed production in a primeval temperate forest: does masting prevail? *European Journal of Forest Research* 134, 99–112 (2014).
<https://doi.org/10.1007/s10342-014-0836-0>
15. Kameswara, Rao, N., Dulloo, M. E., & Engels, J. M. A review of factors that influence the production of quality seed for long-term conservation in genebanks. *Genetic Resources and Crop Evolution* 64, 1061-1074 (2017).
<https://doi.org/10.1007/s10722-016-0425-9>
16. Barik, S. K., Tripathi, R. S., Pandey, H. N. & Rao, P. Tree regeneration in a subtropical humid forest: Effect of cultural disturbance on seed production, dispersal and germination. *Journal of Applied Ecology* 33, 1551 (1996).
<https://doi.org/10.2307/2404793>
17. Sahoo, U. K., & Lalfakawma, L. Population dynamics of *Castanopsis tribuloides* A. (DC) in an undisturbed and disturbed tropical forest stands of North-east India. *J of Exp Bio and Agri Sci.* 1, 454-463 (2013).
18. Herrero-Jáuregui, C., García-Fernández, C., Sist, P. L. J. & Casado, M. A. Recruitment dynamics of two low-density neotropical multiple-use tree species. *Plant Ecology* 212, 1501–1512 (2011).
<https://doi.org/10.1007/s11258-011-9924-0>
19. Howe, H. F., & Miriti, M. N. When seed dispersal matters. *BioScience.* 54, 651 (2004).
[https://doi.org/10.1641/0006-3568\(2004\)054](https://doi.org/10.1641/0006-3568(2004)054)
20. Padonou, E. A., Akakpo, B. A., Tchigossou, B., & Djossa B. (Methods of soil seed bank estimation: a literature review proposing further work in Africa. *iForest-Biogeosciences and Forestry* 15, 121 (2022). doi: <https://doi.org/10.3832/ifer3850-015>
21. Von Arx, G., Pannatier, E. G., Thimonier, A. & Rebetez, M. Microclimate in forests with varying leaf area index and soil moisture: potential implications for seedling

- establishment in a changing climate. *Journal of Ecology* 101, 1201–1213 (2013).
<https://doi.org/10.1111/1365-2745.12121>
22. Nongrum, A. & Kharlukhi, L. Effect of seed treatment for laboratory germination of *Albizia chinensis*. *Journal of Forestry Research* 24, 709–713 (2013).
<https://doi.org/10.1007/s11676-013-0408-z>
23. Sahoo, U. K. Effect of pretreatments on seed germination and seedling vigour of four different species of *Albizia*. *Seed Research* 35, 124–128 (2007).
24. Daibes, L. F., Pausas, J. G., Bonani, N., Nunes, J., Silveira, F. a O. & Fidelis, A. Fire and legume germination in a tropical savanna: ecological and historical factors. *Annals of Botany* 123, 1219–1229 (2019). <https://doi.org/10.1093/aob/mcz028>
25. Koutouan-Kontchoi, M. N., Phartyal, S. S., Rosbakh, S., Kouassi, E. K. & Poschlod, P. Seed dormancy and dormancy-breaking conditions of 12 West African woody species with high reforestation potential in the forest-savanna ecotone of Côte d’Ivoire. *Seed Science and Technology* 48, 101–116 (2020).
<https://doi.org/10.15258/sst.2020.48.1.12>
26. Musa, F. I. & Sahoo, U. K. Impact of pre-treatments on *Albizia procera* and *Albizia chinensis* seed germination and early growth performance in Nursery, Mizoram, India. *Forest Science and Technology* 21, 138–148 (2025).
<https://doi.org/10.1080/21580103.2025.2465604>
27. Sailo, L., Solanki, G. S. & Lalhruaizela, C. Avian Diversity in Mizoram University Campus, AIZAWL, Mizoram. *Science & Technology Journal* 7, 54–68 (2019).
<https://doi.org/10.22232/stj.2019.07.01.08>
28. Zothanpuui, J. H., Gouda, S., Parida, A. & Solanki, G. S. A study on diversity of mammalian species using camera traps and associated vegetation in Mizoram University Campus, Aizawl, Mizoram. *Journal of Threatened Taxa* 12, 17330–17339 (2020). <https://doi.org/10.11609/jott.6465.12.17.17330-17339>
29. Wapongnungsang, N., Ovung, E. Y. & Tripathi, S. Assessment of tree diversity in tropical moist deciduous forest of Mizoram University, Northeast India. *Journal of Applied and Natural Science* 13, 95–100 (2021).
<https://doi.org/10.31018/jans.v13i1.2436>
30. Khan, M. L., Bhuyan, P. & Tripathi, R. S. Effects of forest disturbance on fruit set, seed dispersal and predation of Rudraksh (*Elaeocarpus ganitrus* Roxb.) in northeast India. *Current Science* 88, 133–142 (2005).

31. De Sá Dechoum, M., Rejmánek, M., Castellani, T. T. & Zalba, S. Martin. Limited seed dispersal may explain differences in forest colonization by the Japanese raisin tree (*Hovenia dulcis* thunb.), an invasive alien tree in southern Brazil. *Tropical Conservation Science* 8, 610–622 (2015).
<https://doi.org/10.1177/194008291500800303>
32. Souza, M., Müller, V., Jr, Kurtz, C., Brunetto, G., Couto, R. R. & Comin, J. J. Weed Emergence in a Soil with Cover Crops in an Agroecological No-Tillage System. *Planta Daninha* 36, (2018). <https://doi.org/10.1590/S0100-8358201836010065>
33. Musa, F.I., Sahoo, U.K., Sarangi, P.K., Hrahsel, L., Upadhyaya, K. & Sundaram, S.R. Regeneration Ecology of *Lagerstroemia speciosa* (L.) Pers in the Eastern Himalayan Region of India. *Journal of Forest and Environmental Science* 41, 169-181 (2025).
<https://doi.org/10.7747/JFES.2025.41.2.169>
34. Fox, J., & Weisberg, S. *car*: Companion to Applied Regression. [R package]. Retrieved from <https://cran.r-project.org/package=car> (2023).
35. Chen, L., Wang, L., Baiketuerhan, Y., Zhang, C., Zhao, X. & Von Gadow, K. Seed dispersal and seedling recruitment of trees at different successional stages in a temperate forest in northeastern China. *Journal of Plant Ecology* 7, 337–346 (2014).
<https://doi.org/10.1093/jpe/rtt024>.
36. Calama, R. & Montero, G. Cone and seed production from stone pine (*Pinus pinea* L.) stands in Central Range (Spain). *European Journal of Forest Research* 126, 23–35 (2005). <https://doi.org/10.1007/s10342-005-0100-8>
37. Khan, M. L., Bhuyan, P., Shankar, U. & Todaria, N. P. Seed germination and seedling fitness in *Mesua ferrea* L. in relation to fruit size and seed number per fruit. *Acta Oecologica* 20, 599–606 (1999).
38. Owens, J. N. Constraints to seed production: temperate and tropical forest trees. *Tree Physiology* 15, 477–484 (1995). <https://doi.org/10.1093/treephys/15.7-8.477>
39. Ibáñez, I., Katz, D. S. W. & Lee, B. R. The contrasting effects of short-term climate change on the early recruitment of tree species. *Oecologia* 184, 701–713 (2017).
<https://doi.org/10.1007/s00442-017-3889-1>.
40. Jordano, P. What is long-distance dispersal? And a taxonomy of dispersal events. *Journal of Ecology* 105, 75–84 (2016). <https://doi.org/10.1111/1365-2745.12690>
41. Muller-Landau, H. C., Wright, S. J., Calderón, O., Condit, R. & Hubbell, S. P. Interspecific variation in primary seed dispersal in a tropical forest. *Journal of Ecology* 96, 653–667 (2008).

42. Vittoz, P. & Engler, R. Seed dispersal distances: a typology based on dispersal modes and plant traits. *Botanica Helvetica* 117, 109–124 (2007).
<https://doi.org/10.1007/s00035-007-0797-8>
43. Howe HF, Smallwood J. (1982). Ecology of Seed Dispersal. *Annual Review of Ecology and Syst.* 13:201–228. doi: <https://doi.org/10.1146/annurev.es.13.110182.001221>
44. Miranda, A., Vásquez, I. A., Becerra, P., Smith-Ramírez, C., Delpiano, C. A., Hernández-Moreno, A. & Altamirano, A. Traits of perch trees promote seed dispersal of endemic fleshy-fruit species in degraded areas of endangered Mediterranean ecosystems. *Journal of Arid Environments* 170, 103995 (2019).
<https://doi.org/10.1016/j.jaridenv.2019.103995>
45. Nathan, R., Schurr, F. M., Spiegel, O., Steinitz, O., Trakhtenbrot, A., Tsoar, A. Mechanisms of long-distance seed dispersal. *Trends in eco and evol.* 23(11):638–647 (2008).
46. Kasi, K. S. & Ramasubbu, R. Phenological patterns, fruit predation, and seed dispersal in two Endangered trees (*Elaeocarpus* spp.) of Southern Western Ghats, India. *Journal of Asia-Pacific Biodiversity* 14, 275–282 (2021).
<https://doi.org/10.1016/j.japb.2021.02.002>
47. Saatkamp, A., Affre, L., Dutoit, T. & Poschlod, P. Germination traits explain soil seed persistence across species: the case of Mediterranean annual plants in cereal fields. *Annals of Botany* 107, 415–426 (2011). <https://doi.org/10.1093/aob/mcq255>
48. Fenner M. (2017). Ecology of Seed Banks, in: Routledge eBooks. 507–528. doi: <https://doi.org/10.1201/9780203740071-19>
49. Souza, M. L., Silva, D. R. P., Fantecelle, L. B. & De Lemos Filho, J. P. Key factors affecting seed germination of *Copaifera langsdorffii*, a Neotropical tree. *Acta Botanica Brasilica* 29, 473–477 (2015). <https://doi.org/10.1590/0102-33062015abb0084>
50. Bebre, I., Riebl, H. & Annighöfer, P. Seedling Growth and Biomass Production under Different Light Availability Levels and Competition Types. *Forests* 12, 1376 (2021).
<https://doi.org/10.3390/f12101376>
51. Greenwood, S., Chen, J., Chen, C. & Jump, A. S. Temperature and sheltering determine patterns of seedling establishment in an advancing subtropical treeline. *Journal of Vegetation Science* 26, 711–721 (2015). <https://doi.org/10.1111/jvs.12269>
52. Wieser, G., Oberhuber, W., Walder, L., Spieler, D. & Gruber, A. Photosynthetic temperature adaptation of *Pinus cembra* within the timberline ecotone of the Central

- Austrian Alps. *Annals of Forest Science* 67, 201 (2010).
<https://doi.org/10.1051/forest/2009094>
53. Johnson, D. M., McCulloh, K. A. & Reinhardt, K. in *Tree physiology/Tree physiology* (Dordrecht) 65–87 (2011). doi:10.1007/978-94-007-1242-3_3
54. Brown, N. The implications of climate and gap microclimate for seedling growth conditions in a Bornean lowland rain forest. *J of Tropical Ecology*. 9:153–168. <https://doi.org/10.1017/s0266467400007136> (1993).
55. Charru, M., Seynave, I., Hervé, J.-C. & Bontemps, J.-D. Spatial patterns of historical growth changes in Norway spruce across western European mountains and the key effect of climate warming. *Trees* 28, 205–221 <https://doi.org/10.1007/s00468-013-0943-4> (2014).
56. Moore, C. E., Meacham-Hensold, K., Lemonnier, P., Slattery, R. A., Benjamin, C., Bernacchi, C. J., Lawson, T., & Cavanagh, A. P. The effect of increasing temperature on crop photosynthesis: from enzymes to ecosystems. *J of experimental botany*. 72(8):2822-2844. doi: <https://doi.org/10.1093/jxb/erab090> (2021).
57. Awal, M. Effects of changes in soil temperature on seedling emergence and phenological development in field-grown stands of peanut (*Arachis hypogaea*). *Environmental and Experimental Botany*. 47:101–113. [https://doi.org/10.1016/s0098-8472\(01\)00113-7](https://doi.org/10.1016/s0098-8472(01)00113-7) (2002).
58. Kharuk, V. I., Ranson, K. J., Im, S. T., & Vdovin, A. S. Spatial distribution and temporal dynamics of high-elevation forest stands in southern Siberia. *Global Ecol. Biogeography* 19:822–830. <https://doi.org/10.1111/j.1466-8238.2010.00555.x> (2010).