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Elephants in palm oil plantations), photo by Derek Storm

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Journal:

Saharjo BH, Nurhayati AD. 2006. Domination and composition structure change at hemic peat natural regeneration following burning; a case study in Pelalawan, Riau Province. Biodiversitas 7: 154-158. DOI: 10.13057/biodiv/d070213.

The usage of "et al." in long author lists will also be accepted:

Smith J, Jones M Jr, Houghton L et al. 1999. Future of health insurance. N Engl J Med 965: 325-329. DOI: 10.10007/s002149800025.

Book:

Rai MK, Carpinella C. 2006. Naturally Occurring Bioactive Compounds. Elsevier, Amsterdam.

Chapter in the book:

Webb CO, Cannon CH, Davies SJ. 2008. Ecological organization, biogeography, and the phylogenetic structure of rainforest tree communities. In: Carson W, Schnitzer S (eds.). Tropical Forest Community Ecology. Wiley-Blackwell, New York.

Abstract:

Assaeed AM. 2007. Seed production and dispersal of *Rhazya stricta*. 50th annual symposium of the International Association for Vegetation Science, Swansea, UK, 23-27 July 2007.

Proceeding:

Alikodra HS. 2000. Biodiversity for development of local autonomous government. In: Setyawan AD, Sutarno (eds.). Toward Mount Lawu National Park; Proceeding of National Seminary and Workshop on Biodiversity Conservation to Protect and Save Germplasm in Java Island. Universitas Sebelas Maret, Surakarta, 17-20 July 2000. [Indonesian]

Thesis, Dissertation:

Sugiyarto. 2004. Soil Macro-invertebrates Diversity and Inter-Cropping Plants Productivity in Agroforestry System based on Sengon. [Dissertation]. Universitas Brawijaya, Malang. [Indonesian]

Information from the internet:

Balagadde FK, Song H, Ozaki J, Collins CH, Barnet M, Arnold FH, Quake SR, You L. 2008. A synthetic *Escherichia coli* predator-prey ecosystem. Mol Syst Biol 4: 187. DOI: 10.1038/msb.2008.24. www.molecularsystembiology.com.

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Organic ameliorant and density arrangement affected the growth of *Calliandra calothyrsus* in nursery

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Abstract. *Sofyan FPM, Hartati W, Sudarmadji T, Syahrinudin. 2024. Organic ameliorant and density arrangement affected the growth of* Calliandra calothyrsus *in nursery. Asian J For 8: 107-114.* Seedling quality is crucial for forest stand development, but optimizing nursery conditions for specific species like *Calliandra calothyrsus* Meisn. needs further research. This study aims to investigate how organic ameliorants and seedling density affect *C. calothyrsus* seedling growth performance in nurseries. Three replicates of 4 levels of organic ameliorant (0%, 25%, 50%, and 100%) and 3 levels of seedling density (100, 25, and 16 seedling/m^2) were applied in a compatible arrangement with a factorial randomized design procedure. Each replication of treatment consisted of 30 seedlings for the assessment of the survival rate, diameter, height, and biomass accumulation. Ameliorant treatments and seedling density significantly influenced diameter, height, and biomass, whereas survival rate was unaffected by treatments. Only densities of 25 and 16 seedlings/m² met Indonesian quality standards (SNI 5006.2.2018) for field transplantation. This study demonstrates that improving the root environment through organic ameliorants and density management can enhance *C. calothyrsus* seedling growth in nurseries. This research offers insights for optimizing agroforestry seedling production. Identifying densities meeting national standards enhances reforestation success. The study lays the groundwork for future research on seedling quality and species-specific protocols in tropical agroforestry. Results can guide practitioners in producing high-quality seedlings, potentially improving reforestation efficiency and effectiveness.

Keywords: Biomass, energy crop, red calliandra, seedling growth, soil amendment

INTRODUCTION

Calliandra calothyrsus Meissn. (red caliandra) is a fast-growing woody shrub from the Fabaceae family, native to the tropical and subtropical Americas (Messi et al. 2020). It is locally used as fuelwood, plantation shade, and livestock forage or fodder. Since the 1970s, this species has been widely introduced and planted in agroforestry systems across approximately 30,000 hectares in Indonesia through a program by the Indonesian State Forest Corporation (Yudaputra 2020; Kosasih et al. 2022). The *C. calothyrsus* has high adaptability to local climatic conditions, especially at altitudes ranging from 250 to 1,800 meters above sea level (de Luna et al. 2020). It is readily found as a pioneer species in the forest successional stage (Binayao et al. 2021).

As a legume plant, *C. calothyrsus* can be utilized in revegetating post-mining land due to its ability to associate with Rhizobium and fix nitrogen from the air, improving soil nutrients. This allows it to cover the soil surface on rehabilitation land rapidly (Nyenda et al. 2020). Interestingly, *C. calothyrsus* has been reported as a promising energy crop, possessing a high heating value with low moisture content (Amirta et al. 2016, 2019; Yuliansyah et al. 2019). Its charcoal product also exhibits superior energy quality, with a calorific value of 7,200 kcal kg^{-1} (Saputra et al. 2022).

When cultivating *C. calothyrsus* for energy production, another benefit is the opportunity to plant it as a Short Rotation Coppice (SRC) crop due to its ability to regrow stems after harvesting (Haqiqi et al. 2018; Widyati et al. 2022). The harvested wood yield can reach 152 m^3 ha^{-1} or 76.3 tons ha^{-1} per year with a planting distance of 1×1 m^3 (Hendrati et al. 2020). These favorable characteristics have led to significant attention for *C. calothyrsus* as a promising biomass-based renewable energy feedstock, as instructed by the Government of Indonesia under Precedent Decree No.79/2014. Furthermore, Indonesia has announced the National Energy Policy, aiming to source 23% of total energy consumption in 2025 from renewable energy sectors (Bappenas 2020)

When developing large-scale plantations, producing high-quality, ready-to-plant seedlings is crucial. Providing appropriate growth media for seedlings in the nursery is one of the most essential factors. During seedling growth, the medium should contain sufficient water and oxygen to distribute to the plant roots (Krishnapillai et al. 2020). Organic fertilizers are also necessary to enrich nutrients in the media. Bokashi, a commercial organic substance frequently used as a substitute for chemical fertilizers, can improve soil fertility and restore its physical, chemical, and biological properties. It is commonly produced from agricultural wastes like straw, husk, and corn stalks, which are fermented by commercially effective microorganisms (EM-4) (Joshi et al. 2019).

An ameliorant like biochar, a carbon-rich solid material formed by low-oxygen combustion (pyrolysis) and utilized as a soil improvement agent (Mulinari et al. 2021), can improve soil quality (Dariah et al. 2019, 2021), increase soil retention of water and nutrients (Oni et al. 2019), increase pH and soil organic matter content (Cooper et al. 2020), boost nutrient usage efficiency (Hossain et al. 2020; Azman et al. 2023), and promote soil microorganism activity (Egamberdieva et al. 2021; Liu et al. 2021). Additionally, biochar application to soil reduced runoff by 25% and erosion by 16% (Gholamahmadi et al. 2023).The use of biochar has been widely observed to increase plant growth and production (Sarfraz et al. 2019; Dai et al. 2020; Zhang et al. 2021; Ji et al. 2022). Based on research conducted by Simiele et al. (2022) showed that biochar and/or compost applications improved growing medium physicochemical characteristics by increasing electrical conductivity, cation exchange capacity, and nutrient concentrations.

Implementing appropriate seedling density arrangements is also crucial to achieving the best conditions. According to Larijani et al. (2019), plant spacing is considered one of the significant management strategies to minimize space competition, which reduces the potential for diseases, especially during the rainy season. The adjustment of density or population is strongly related to the level of competition and growth factors of the plants.

Based on the above description, a study was conducted to determine the effect of providing soil amendments in the planting medium, as well as a polybag spacing treatment, on the growth of *C. calothyrsus* seedlings in the nursery to support its utilization as an energy crop.

MATERIALS AND METHODS

Study area

The research was carried out in the nursery of the Silviculture Laboratory, Faculty of Forestry, Universitas Mulawarman, East Kalimantan, Indonesia. It took six months to complete, with the last three months dedicated to growth observations.

Procedures

Seedling and media preparation

The selected seedlings of *C. calothyrsus* used in this study were three months old. The growing media applied in the research experiments was a combination of subsoil and organic ameliorants. The percentage of those growing media depended on the treatment generated from used experimental design. The subsoil was prepared at the Soil Sciences and Forest Nutrition Laboratory, Faculty of Forestry, Universitas Mulawarman. The organic ameliorant is made from a mixture of bokashi and biochar which has been enriched with 2% NPK fertilizer, with a bokashi:biochar ratio of 9:1 (v:v). This organic ameliorant is a product of the Forestry Faculty Silviculture Laboratory's Compost House.

Experimental design

The 3-month-old *C. calothyrsus* seedlings used in this study were transferred into polybags measuring 10×15 cm. These polybags were filled with four different levels of organic ameliorant (which then became treatment A). The other treatment is density per square meter (treatment B). Both treatments are made in three repetitions and consist of 30 units for each treatment dose. The observation units total 1,080 plants. The *C. calothyrsus* seedlings were grown on each treatment in a greenhouse for 6 months. Growth occurs under controlled water regimes, natural humidity, and temperature, and the plants were arranged in a randomized, complete design. The polybags were watered to prevent water stress (once a day, as required), and a suspended net was used to reduce exposure to sunlight.

The four treatments of soil ameliorant dose were 0%, 25%, 75%, and 100%. The three treatments of density were 100 seeds per square meter, 25 seeds per square meter, and 16 seeds per square meter. Table 1 states the factors of the experiment and their combination (level of organic ameliorant and seedling density).

Data analysis

Diameter, height, and biomass accumulation

From the beginning (T0) to the end of the experiment (T12), plant growth was monitored weekly by measuring the morphological traits. The major parameters observed in this study were the survival rate of seedlings, diameter, height, biomass potential, and seedling quality index. The temperature and humidity inside and outside the nursery were also measured. The calculation of the survival rate was done at the end of experiments using an equation as follows:

$$\text{Survival rate (\%)} = \frac{\textit{Accumulation of live seedlings}}{\textit{Total seedlings observed}}$$

The qualification of the ready-to-plant seedlings was evaluated based on the morphology of the *C. calothyrsus* seedlings, such as the height, root-shoot ratio, and seedling quality index. The aboveground (leaves and stems) and belowground (roots) dry weight, at time T12, were also determined after two days of drying in an oven at 80°C, and stem/root ratio (S/R ratio) was calculated in terms of dry weight. The root-shoot ratio was calculated according to an equation as follows:

$$\text{Root-shoot ratio} = \frac{\textit{Dry weight of shoot (g)}}{\textit{Dry weight of root (g)}}$$

The seedling quality index is a comparison between the total dry weight with seedlings' robustness and root-shoot ratio. This index can be the most important parameter since it can conclude the seedling quality based on the morphology and physiology characteristics of the observed seedlings. It was calculated using a Dickson''s index as follows (Grossnickle and MacDonald 2018):

$$\text{Seedling quality index} = \frac{\textit{Total dry weight (g)}}{\left(\frac{\textit{Height (cm)}}{\textit{Diameter (mm)}}\right) + \left(\frac{\textit{Dry weight of shoot (g)}}{\textit{Dry weight of root (g)}}\right)}$$

Table 1. Experiment used in this study

No	Treatment	Composition of organic ameliorant (%, w/w)	Density (seedlings/m^2)
1	A0B0	0	100
2	A1B0	25	100
3	A2B0	50	100
4	A3B0	100	100
5	A0B1	0	50
6	A1B1	25	50
7	A2B1	50	50
8	A3B1	100	50
9	A0B2	0	16
10	A1B2	25	16
11	A2B2	50	16
12	A3B2	100	16

All obtained data were then statistically analyzed by an F-test with significant levels of 0.05 and 0.01. The Analysis of Variance (ANOVA) followed by the Least Significant Difference (LSD) method was used.

RESULTS AND DISCUSSION

Survival rate

According to our observation, the growth of the *C. calothyrsus* seedlings revealed a survival rate higher than 93%. All the treatments showed a great contribution to the survival rate of the seedlings tested. For all treatments, the survival rate of seedlings was higher than 75%. However, the results of the statistical analysis demonstrated that the organic ameliorant additions did not affect the survival rate of *C. calothyrsus* in the nursery. The details of the survival rate can be seen in Table 2.

Plant diameter and height

The results of the ANOVA at a significant level of 0.05 showed that the dose of organic ameliorant (A) and density (B) had a significant contribution to the increase in diameter of the *C. calothyrsus* seedlings. The treatment of organic ameliorant loading producing the highest diameter was A1 (25% of organic ameliorant addition) with a different diameter value of 1.39 mm. On the other hand, the lowest diameter increase was obtained from A3 (100% organic ameliorant addition), with a gap in diameter value of 0.98 mm.

Conversely, the treatment of A0 (0% of organic ameliorant addition) showed the lowest height with a different value of 11.02 cm. The treatment of density revealed that the highest contribution to the plant height was obtained on B0 (100 seedlings/m^2) with a different value of 18.21 cm. On the other hand, B2 (16 seedlings/m^2) achieved the lowest height with a different value of 13.06 cm. The effect of ameliorant (A) and the effect of density arrangement (B) on the mean diameter and height increment can be seen in Tables 3 and 4.

Table 2. The measurement results of the survival rate of *Calliandra calothyrsus* seedlings

Treatment	Planted seedlings			Total	Live seedlings			Total	Survival rate (%)
	B0	B1	B2		B0	B1	B2		
A0U1	30	30	30	270	30	26	25	252	93.33
A0U2	30	30	30		30	28	25		
A0U3	30	30	30		30	30	28		
A1U1	30	30	30	270	30	28	30	265	98.15
A1U2	30	30	30		30	29	29		
A1U3	30	30	30		30	30	29		
A2U1	30	30	30	270	30	29	29	256	94.81
A2U2	30	30	30		30	30	26		
A2U3	30	30	30		30	28	24		
A3U1	30	30	30	270	29	29	29	261	96.67
A3U2	30	30	30		30	30	28		
A3U3	30	30	30		29	29	28		

Table 3. Effect ameliorant on the mean diameter and height increment of *C. calothyrsus* seedling during 6 month period of study (mean values followed by different letters are significant at $p<0.05$)

Treatment	Mean diameter increment (mm)	Mean height increment (cm)
A0	1.11^a	11.02^a
A1	1.39^b	19.91^c
A2	1.18^{ab}	16.13^b
A3	0.98^a	13.15^{ab}

Table 4. Effect of density arrangement on the mean diameter and height increment of *C. calothyrsus* seedling during 6 month period of study (mean values followed by different letters are significant at $p<0.05$)

Treatment	Mean diameter increment (mm)	Mean height increment (cm)
B0	1.31^b	18.21^b
B1	1.03^a	13.89^a
B2	1.16^{ab}	13.06^a

Table 5. Biomass potential of *Calliandra calothyrsus* seedlings under various treatment

Treatment	Dry weight (g)			Density (N/m²)	Biomass potential (g/m²)
	Root	Stem	Total		
A0B0	0.09	0.55	0.65	100	65.00
A1B0	0.22	1.05	1.27	100	127.00
A2B0	0.14	1.05	1.19	100	119.33
A3B0	0.11	0.67	0.78	100	78.33
A0B1	0.40	0.59	0.98	25	24.58
A1B1	0.95	1.85	2.80	25	69.92
A2B1	0.53	1.61	2.14	25	53.42
A3B1	0.36	0.64	1.00	25	25.08
A0B2	1.11	1.62	2.73	16	43.68
A1B2	0.78	1.52	2.30	16	36.80
A2B2	0.75	2.18	2.93	16	46.93
A3B2	0.38	0.83	1.22	16	19.47

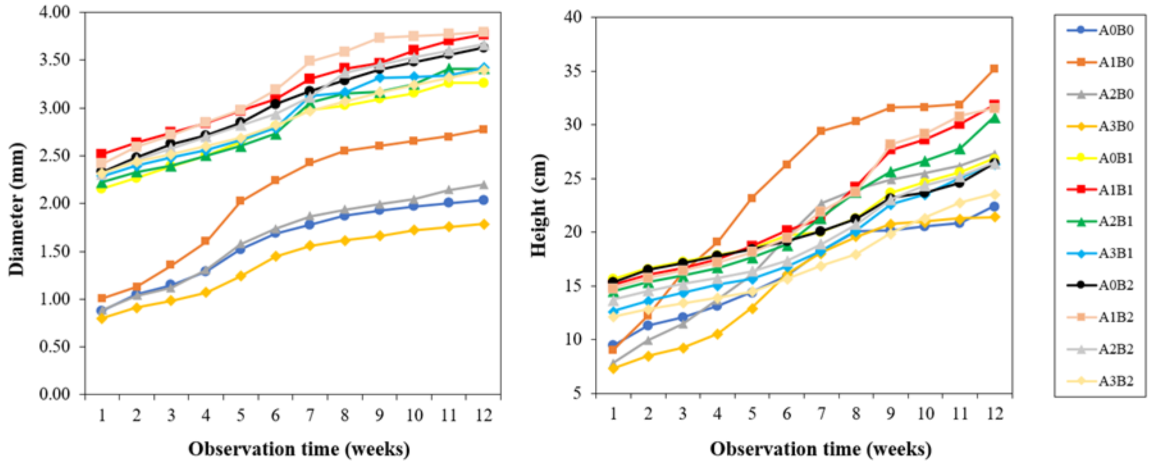

Figure 1. The diameter and height of *Calliandra calothyrsus* during the observation time used

Plant biomass

The results of the *C. calothyrsus* biomass calculation are shown in Table 5. It could be observed that after adding organic ameliorant at a concentration of 25%, the treatments of 100 seedlings/m² (A1B0) and 25 seedlings/m² (A1B1) showed their highest biomass production at 127.00 g/m² and 69.92 g/m², respectively. On the other hand, at the treatment of 16 seedlings/m², the highest biomass was produced by 50% of the organic ameliorant addition (A2B2) with a value of 46.93 g/m². It indicated that the use of the organic ameliorant concentration of 25% positively contributed to seedling growth, which could enhance biomass production compared to other concentrations used. The potential biomass results from each treatment can be seen in Table 5.

Quality index

One of the important indicators for the seedlings before they are planted is the quality index. Seedlings with a seedling quality index value of at least 0.9 had a high survival rate after being planted in the field (Posse et al. 2018). Based on the SNI 5006.2.2018 regarding the quality of seedlings for forest rehabilitation and forest plantations, the ideal height and diameter of *C. calothyrsus* seedlings were >30 cm and >4 mm, respectively. In this study, four *C. calothyrsus* seedlings possessed those qualifications. However, only two seedlings were evidently qualified according to the SNI standard. The first one was achieved by the treatments of A1BI (addition of 25% organic ameliorant with 25 seedlings/m²), with a quality index of 0.29 and a root-shoot ratio of 1.95. The second one was obtained from the A2B1 treatment (addition of 25% organic ameliorant with 16 seedlings/m²) with a quality index of 0.22 and a root-shoot ratio of 3.06.

Regarding the value of the quality index, most of the combinations of B1 (25 seedlings/m²) and B2 (16 seedlings/m²) met the qualification as ready-to-plant seedlings since they had values greater than 0.9. At the same time, the treatment of B0 (100 seedlings/m²) was not qualified since its value was still low. It was probably due to the fact that the used *C. calothyrsus* seedlings in B1 and B2 were considered seedlings at the age of three months when transferred to the new media. Hence, at the end of the measurement, they were six months old. It was different from the treatment of B0 in that the seedlings were still three months old at the end of the measurement. The details of the seedling quality index can be seen in Table 6.

Table 6. Seedling quality index of *Calliandra calothyrsus* seedlings under various treatment

Treatment	Height (cm)	Diameter (mm)	Dry weight (g)			Robustness	Root-shoot ratio	Quality index
			Stem + leave	Root	Total			
A0B0	29.33	2.63	0.55	0.09	0.65	11.15	5.93	0.04
A1B0	40.40	3.20	1.05	0.22	1.27	12.61	4.77	0.06
A2B0	42.80	2.71	1.05	0.14	1.19	15.77	7.33	0.05
A3B0	28.03	2.14	0.67	0.11	0.78	13.10	5.91	0.05
A0B1	23.80	3.41	0.59	0.40	0.98	6.97	1.48	0.11
A1B1	30.30	4.52	1.85	0.95	2.80	6.70	1.95	0.29
A2B1	31.77	4.06	1.61	0.53	2.14	7.82	3.06	0.22
A3B1	25.90	4.01	0.64	0.36	1.00	6.46	1.76	0.13
A0B2	26.93	4.61	1.62	1.11	2.73	5.84	1.47	0.35
A1B2	29.97	4.10	1.52	0.78	2.30	7.30	1.94	0.23
A2B2	27.23	4.23	2.18	0.75	2.93	6.44	2.89	0.34
A3B2	25.53	3.65	0.83	0.38	1.22	7.00	2.17	0.17

Table 7. The result of temperature measurements inside and outside the nursery

Observation time (weeks)	Inside nursery (ºC)				Outside nursery (ºC)			
	Morning*	Afternoon**	Evening***	Average	Morning*	Afternoon**	Evening***	Average
1	28.7	31.8	29.8	29.8	29.8	33.2	32.7	31.9
2	28.1	30.5	29.3	29.0	30.2	33.5	32.3	32.0
3	28.2	29.8	28.8	28.7	29.3	34.2	30.7	31.4
4	27.2	30.0	28.0	28.1	28.2	32.1	29.0	29.8
5	29.7	30.1	27.9	29.3	32.6	31.8	28.5	31.0
6	29.2	29.8	27.9	29.0	31.2	30.5	28.7	30.2
7	29.3	30.1	27.8	29.1	30.4	33.2	29.5	31.1
8	24.8	25.7	28.6	25.9	26.3	26.6	29.9	27.6
9	28.7	31.8	29.8	29.8	30.0	33.3	32.6	32.0
10	29.1	31.0	28.8	29.5	31.6	32.0	30.3	31.3
11	29.0	32.1	29.8	30.0	30.3	34.2	33.4	32.6
12	29.1	31.0	28.8	29.5	31.6	32.0	30.3	31.3
Average	28.4	30.3	28.8	29.0	30.1	32.2	30.7	31.0

Note: *measured at 8.00 a.m.; **measured at 0.00 p.m.; ***measured at 04.00 p.m.

Table 8. The result of humidity measurements inside and outside the nursery

Observation time (weeks)	Inside nursery (%)				Outside nursery (%)			
	Morning*	Afternoon**	Evening***	Average	Morning*	Afternoon**	Evening***	Average
1	80.1	66.7	72.0	73.0	69.6	71.4	72.6	71.2
2	86.3	67.0	74.3	75.9	79.3	71.7	70.3	73.8
3	85.4	71.7	83.4	80.2	73.3	75.9	77.7	75.6
4	95.6	79.6	88.6	87.9	92.7	76.3	86.1	85.0
5	83.9	73.4	84.4	80.6	75.9	68.0	84.0	76.0
6	87.4	79.0	86.9	84.4	77.0	72.4	83.3	77.6
7	86.0	74.7	82.4	81.0	77.1	68.0	80.3	75.1
8	74.9	69.3	81.7	75.3	68.6	66.9	85.1	73.5
9	79.7	64.3	72.7	72.2	76.9	67.0	71.4	71.8
10	83.6	69.1	76.1	76.3	81.4	70.4	77.9	76.6
11	81.9	60.9	70.4	71.0	76.4	63.1	65.7	68.4
12	81.6	67.7	72.7	74.0	80.3	68.1	74.6	74.3
Average	83.9	70.3	78.8	77.7	77.4	69.9	77.4	74.9

Note: *measured at 8.00 a.m.; **measured at 0.00 p.m.; ***measured at 04.00 p.m.

Temperature and humidity

The measurement of temperature and humidity has been conducted inside and outside the nursery, using a thermohygrometer for as long as twelve weeks every 8.00 a.m., 0.00 p.m., and 04.00 p.m. (see Tables 7 and 8). The results demonstrated that the average temperature obtained from those measurement times inside the nursery was 28.4°C, 30.3°C, and 28.8°C, respectively. The weekly average ranged from 25.9°C to 30.0°C. On the other hand, the temperatures outside the nursery were 30.1°C, 32.2°C, and 30.7°C, respectively.

According to the measurement of humidity during the twelve weeks of observation, it could be seen that the average humidity inside the nursery in the morning, afternoon, and evening was 83.9%, 70.3%, and 78.8%, respectively. Their weekly average ranged from 71.0% to 87.9%. Whereas, in the outside nursery, the humidity was 77.4%, 69.9%, and 77.4%, respectively. The results of the weekly measurement indicated ranges of humidity from 68.4% to 85.0%. The detailed measurement of temperature and humidity inside and outside the nursery can be seen in Table 7 and Table 8.

Discussion

The most important factors affecting the increase in seedling survival rate in the nursery are media and other environmental factors, including light, temperature, air humidity, and lighting duration (Syahrinudin et al. 2018). Data was analyzed by ANOVA to determine the effect of the addition of soil organic ameliorant in the media and seedling density in the nursery on the survival rate of the *C. calothyrsus* seedlings.

The treatment of density showed that the highest increase in diameter was reached by B0 (100 seedlings/m^2) with a different value of 1.31 mm. In comparison, the smallest diameter was produced by B1 (25 seedlings/m^2) with a different value of 1.03 mm. The significant value was also obtained from the statistical analysis of the measurement of the seedling height after being treated with a varied dose of organic ameliorant (A) and density (B). The treatment with the organic ameliorant addition obtained the highest increase in height at A1 (25% of the organic ameliorant addition) with a different value of 19.91 cm.

Similar to the increase in diameter, it could be seen that the application of a soil organic ameliorant with a concentration of 25% produced the greatest height compared to other concentrations. In line with the research conducted by Salsabila et al. (2023), the use of soil amendments such as compost and paclobutrazol can assist in maintaining the panicle weight and grain yield of rice plants, including the Sigupai Abdya and Tangse varieties, under environmental stress conditions in a Greenhouse through the nutrients present in the soil.

The treatment of the density arrangement also significantly affected the seedling height. It was due to the fact that the treatment of B0 placed the seedling closely compared to the treatments of B1 and B2, in which each seedling had a wider space. The density is related to the growth competition among seedlings, including the interception of light, air, and nutrients. The high density will increase the competition among seedlings. When the density of the seedling is low, the level of competition is also lower (Tataridas et al. 2022). This phenomenon was in accordance with the report of Bastos et al. (2020) that high density will enhance the plants' growth since they try to get more sunlight. As reported by Demisie and Tolessa (2018), Amalfitano et al. (2019), and Sopha (2020), planting distance and density significantly influence the weight and diameter of the bulbs.

The increase in plant height and diameter observed in this study can be attributed to the role of growth regulators, such as gibberellic acid, in promoting cell elongation and division (Chiranjeevi et al. 2018). Additionally, the application of organic ameliorant may have enhanced the availability of essential nutrients, leading to improved seedling growth (Alfandi et al. 2019).

According to Figure 1, it can be seen that the use of soil organic ameliorant at a concentration of 25% in all density treatments (A1B0, A1B1, and A1B2) resulted in better seedling height and growth compared to others. These results were in line with a study previously reported by Suita and Sudrajat (2018), which found that the relatively high compost composition (30%) in the seedling media could increase the survival rate (52%) and the growth of *Tamarindus indica* seedlings (89%), compared to the agricultural soil media. Seedling growth improvement by the incorporation of organic ameliorant (biochar) has also been reported (Syahrinudin et al. 2019, 2021).

The addition of soil amendments such as biochar, compost, and organic fertilizers plays a crucial role in plant growth and production. These amendment materials can help improve the physical properties of the soil and enhance its water-holding capacity, ensuring an adequate water supply for plants. Additionally, the increase in plant growth and yield is also attributed to the improvement of soil moisture conditions and the availability of sufficient nutrients. Overall, this supports plant growth and enhances crop yields (Sukartono et al. 2019).

According to research, some soil ameliorants can improve the survival and growth of seedlings in controlled situations, but when plants are moved to the field, their effectiveness may decrease (Nurida and Rachman 2020). Significant obstacles may arise from the availability and accessibility of the resources needed to produce soil supplements. The efficacy of the modifications may vary depending on the reliance on particular raw resources. Research has demonstrated, for example, that the effects of amendments like compost, charcoal, and mycorrhizal inoculants can vary based on their composition and source. Overall, soil supplements have shown promise in improving plant development; nevertheless, in order to achieve consistent and successful results, their field application requires careful consideration of local environmental conditions and material availability.

The utilization of bokashi as an organic ameliorant is targeted to improve the biomass accumulation in the topsoil (Iqbal et al. 2019). Thus, it will enhance the biological activities in the soil and also the water availability. Sufficient water in the soil will also increase nutrient absorption (Liang et al. 2018), which affects the better photosynthesis process to enhance the carbohydrate content for increased plant growth and fruit production.

The temperature range of 27.6°C to 32.6°C was obtained from the weekly average measurement. *C. calothyrsus* has been reported to grow better in daily temperatures from 24°C to 28°C (Kosasih et al. 2022). Another report informed the ability of *C. calothyrsus* grown in Majalengka, West Java, to adapt well in the temperature range of 22.6°C to 37.3°C (Widyati et al. 2022). Therefore, since this study revealed the temperature that is suitable for *C. calothyrsus* growth based on the literature published by those authors, it was also evidence that the nursery provided the optimum temperature conditions for the *C. calliandra* seedlings.

Finally, we concluded that our study on the effects of soil organic ameliorant addition and seedling density arrangement on *C. calothyrsus* seedlings yielded significant insights. The addition of organic ameliorants to the growth media and manipulation of planting density, both individually and in combination, significantly influenced seedling diameter and height. However, these treatments did not significantly affect seedling survival rates. The optimal treatment combination was found to be 25% organic ameliorant addition with a density of 100 seedlings/m² (A1B0), which resulted in the most substantial increases in both height and diameter.

Biomass potential was highest for the 25% organic ameliorant treatment (A1) when combined with densities of 100 seedlings/m² (B0) and 25 seedlings/m² (B1). Interestingly, the 50% organic ameliorant treatment (A2) showed high biomass productivity when combined with the lowest density of 16 seedlings/m² (B2). The nursery conditions, including temperature and humidity, were found to be optimal for *C. calothyrsus* seedling growth. Notably, the combination treatments A1B1 and A2B1 produced seedlings that met the quality standards set by SNI 5006.2.2018 for forest rehabilitation and industrial forest plantation purposes.

Future perspectives: Long-term studies: Conduct follow-up studies to assess the performance of these seedlings after out planting, evaluating their survival, growth, and productivity in various field conditions. Nutrient analysis: Investigate the specific nutrient contributions of the organic ameliorant and how they interact with native soil conditions to influence seedling growth. Microbial interactions: Explore the effects of organic ameliorants on soil microbial communities and their potential role in enhancing seedling growth and health. Organic ameliorant composition: Investigate the effects of different types and sources of organic ameliorants to identify the most effective and sustainable options.

These recommendations and future research directions aim to further optimize nursery practices for *C. calothyrsus* and potentially other species, contributing to more successful reforestation and agroforestry initiatives.

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REFERENCES

Alfandi, Wahyuni S, Nisa WW. 2019. Effect of *Rhizobium inoculum* and liquid organic fertilizer on growth and yield of peanut (*Arachis hypogaea* L.) CV. Takar-2. IOP Conf Ser: Earth Environ Sci 391: 012004. DOI: 10.1088/1755-1315/391/1/012004.

Amalfitano C, Golubkina NA, Del Vacchio L, Russo G, Cannoniero M, Somma S, Morano G, Cuciniello A, Caruso G. 2019. Yield, antioxidant components, oil content, and composition of Onion seeds are influenced by planting time and density. Plants 8 (8): 293. DOI: 10.3390/plants8080293.

Amirta R, Haqiqi MT, Saparwadi S, Septia E, Mujiasih D, Setiawan KA, Sekedang MA, Yuliansyah, Wijaya A, Setiyono B, Suwinarti W. 2019. Searching for potential wood biomass for green energy feedstock: A study in tropical swamp-peat forest of Kutai Kertanegara, Indonesia. Biodiversitas 20: 1516-1523. DOI: 10.13057/biodiv/d200605.

Amirta R, Yuliansyah, Angi EM, Ananto BR, Setiyono B, Haqiqi MT, Septiana HA, Lodong M, Oktavianto RN. 2016. Plant diversity and energy potency of community forestin East Kalimantan, Indonesia: Searching for fast growing wood species for energy production. Nusantara Biosci 8: 22-31. DOI: 10.13057/nusbiosci/n080106.

Azman NANMN, Inderakusumowati Md Khalid P, Aishah Saidina Amin N, Yamani Zakaria Z, Mohammad Zainol M, Ilham Z, Phaiboonsilpa, N, Asmadi M. 2023. Effects of biochar, compost, and composted biochar soil amendments on Okra plant growth. Mater Today: Proc. DOI: 10.1016/J.MATPR.2023.08.017.

Bastos LM, Carciochi W, Lollato RP, Jaenisch BR, Rezende CR, Schwalbert R, Vara Prasad PV, Zhang G, Fritz AK, Foster C, Wright Y, Young S, Bradley P, Ciampitti I A. 2020. Winter wheat yield response to plant density as a function of yield environment and tillering potential: A review and field studies. Front Plant Sci 11: 54. DOI: 10.3389/fpls.2020.00054.

Binayao NKD, de Luna CC, Limpiada AA. 2021. Evaluating the rehabilitation potential of Calliandra (*Calliandra calothyrsus* Meissn.) ibin degraded areas through landscape function analysis in Manolo Fortich, Bukidnon, Philippines. In: Ullah R, Sharma S, Inoue M, Asghar S, Shivakoti G (eds). Natural Resource Governance in Asia. Elsevier, Amsterdam. DOI: 10.1016/B978-0-323-85729-1.00010-4.

Chiranjeevi MR, Sneha MK, Hongal S, Muralidhara BM. 2018. Studies on foliar application of growth regulators and macro nutrients on seedling growth of aonla. Intl J Curr Microbiol Appl Sci 7: 3507-3510. DOI: 10.20546/ijcmas.2018.702.417.

Cooper J, Greenberg I, Ludwig B, Hippich L, Fischer D, Glaser B, Kaiser M. 2020. Effect of biochar and compost on soil properties and organic matter in aggregate size fractions under field conditions. Agric Ecosyst Environ 295: 106882. DOI: 10.1016/j.agee.2020.106882.

Dai Y, Zheng H, Jiang Z, Xing B. 2020. Combined effects of biochar properties and soil conditions on plant growth: A meta-analysis. Sci Total Environ 713: 136635. DOI: 10.1016/j.scitotenv.2020.136635.

Dariah A, Nurida NL, Jubaedah. 2019. Application of ameliorant for improving soil quality and chili (*Capsicum annum* L.) productivity on degraded acidic upland. IOP Conf Ser: Earth Environ Sci 393 (1): 012041. DOI: 10.1088/1755-1315/393/1/012041.

Dariah A, Nurida NL, Salma S, Nurjaya, Santi LP. 2021. The use of soil ameliorants to improve soil quality and crop productivity of degraded semi-arid upland in Gunung Kidul, Yogyakarta, Indonesia. IOP Conf Ser: Earth Environ Sci 648 (1): 012159. DOI: 10.1088/1755-1315/648/1/012159.

de Luna C, Calderon M, Cruz RV, Tolentino JrE, Carandang W. 2020. The economic value of *Calliandra calothyrsus* in watershed rehabilitation in Manolo Fortich, Bukidnon, Philippines. J Environ Sci Manag 2: 76-84. DOI: 10.47125/jesam/2020_sp2/06.

Demisie R, Tolessa K. 2018, Growth and bulb yield of onion (*Allium cepa* L.) in response to plant density and variety in Jimma, South Western Ethiopia. Adv Crop Sci Technol 6 (2): 357. DOI: 10.4172/2329-8863.1000357.

Egamberdieva D, Jabbarov Z, Arora NK, Wirth S, Bellingrath-Kimura SD. 2021. Biochar mitigates effects of pesticides on soil biological activities. Environ Sustain 4: 335-342. DOI: 10.1007/s42398-021-00190-w.

Gholamahmadi B, Simon J, Oscar GP, Sergio AP, Ana CB, Jan JB, Frank GAV. 2023. Biochar impacts on runoff and soil erosion by water: A systematic global scale meta-analysis. Sci Total Environ 871: 16860. DOI: 10.1016/j.scitotenv.2023.161860.

Government Regulation of the Republic of Indonesia. 2014. Government Regulation of the Republic of Indonesia No. 79 of 2014 Concerning the National Energy Policy. Jakarta. [Indonesian]

Grossnickle SC, MacDonald JE. 2018. Why seedlings grow: Influence of plant attributes. New For 49: 1-34. DOI: 10.1007/s11056-017-9606-4.

Haqiqi MT, Suwinarti W, Amirta R. 2018. Response surface methodology to simplify calculation of wood energy potency from tropical short rotation coppice species. IOP Conf Ser: Earth Environ Sci 144: 012041. DOI: 10.1088/1755-1315/144/1/012041.

Hendrati RL, Hidayati N, Nurrohmah SH. 2020. Biomass and coppicing ability of genetically improved *Calliandra calothyrsus* for wood-energy with different spacing. IOP Conf Ser: Earth Environ Sci 522: 012001. DOI: 10.1088/1755-1315/522/1/012001.

Hossain MZ, Bahar MM, Sarkar B, Donne SW, Ok YS, Palansooriya KN, Kirkham MB, Chowdhury S, Bolan N. 2020. Biochar and its importance on nutrient dynamics in soil and plant. Biochar 2: 379-420. DOI: 10.1007/s42773-020-00065-z.

Iqbal A, He L, Khan A, Wei S, Akhtar K, Ali I, Ullah S, Munsif F, Zhao Q, Jiang L. 2019. Organic manure coupled with inorganic fertilizer: An approach for the sustainable production of rice by improving soil properties and nitrogen use efficiency. Agronomy 9: 651. DOI: 10.3390/agronomy9100651.

Ji M, Wang X, Usman M, Liu F, Dan Y, Zhou L, Campanaro S, Luo G, Sang W. 2022. Effects of different feedstocks-based biochar on soil remediation: A review. Environ Pollut 294: 118655. DOI: 10.1016/J.ENVPOL.2021.118655.

Joshi H, Somduttand CP, Mundra SL. 2019. Role of Effective Microorganisms (EM) in sustainable agriculture. Intl J Curr Microbiol Appl Sci 8: 172-181. DOI: 10.20546/ijcmas.2019.803.024.

Kosasih I, Wu KT, Sipayung HN, Chen CT. 2022. Biochar application in *Calliandra calothyrsus* plantation management. Agrofor Syst 96: 115-127. DOI: 10.1007/s10457-021-00703-w.

Krishnapillai M, Young-Uhk S, Haase DL. 2020. Locally produced cocopeat growing media for container plant production. Tree Plant Notes 63 (1): 29-38.

Larijani MR, Asli-Ardeh EA, Kozegar E, Loni R. 2019. Evaluation of image processing technique in identifying rice blast disease in field conditions based on KNN algorithm improvement by K-means. Food Sci Nutr 7: 3922-3930. DOI: 10.1002/fsn3.1251.

Liang B, Ma C, Zhang Z, Wei Z, Gao T, Zhao Q, Ma F, Li C. 2018. Long-term exogenous application of melatonin improves nutrient uptake fluxes in apple plants under moderate drought stress. Environ Exp Bot 155: 650-661. DOI: 10.1016/j.envexpbot.2018.08.016.

Liu D, Ding Z, Ali EF, Kheir AMS, Eissa MA, Ibrahim OHM. 2021. Biochar and compost enhance soil quality and growth of roselle (*Hibiscus sabdariffa* L.) under saline conditions. Sci Rep 11 (1): 8739. DOI: 10.1038/s41598-021-88293-6.

Messi LM, Noté OP, Mbing JN, Lavedan P, Vedrenne M, Ouedraogo N, Carraz M, Bourgeade-Delmas S, Pegnyemb DE, Haddad M. 2020. Triterpenoid saponins from *Calliandra calothyrsus* Meisn. and their antiproliferative activity against two digestive carcinoma human cell lines. Fitoterapia 146: 104669. DOI: 10.1016/j.fitote.2020.104669.

Mulinari J, Junior FWR, de Oliveira CRS, da Silva Júnior AH, Scariot MA, Radünz LL, Mossi AJ. 2021. Biochar as a tool for the remediation of agricultural soils. In: Thapar Kapoor R, Treichel H and Shah MP (eds). Biochar and Its Application in Bioremediation. Springer Nature, Singapore. DOI: 10.1007/978-981-16-4059-9_13.

National Development Plan Council of Indonesia (Bappenas). 2020. Decree Number 11/2020. Strategic plan of Bappenas. year 2020–2024. [Indonesian]

Nurida NL, Rachman A. 2020. Amelioration of acid upland to increase soil productivity and soybean yield. AGRIVITA 42 (2): 350-359. DOI: 10.17503/agrivita.v42i2.1790.

Nyenda T, Gwenzi W, Gwata C, Jacobs SM. 2020. Leguminous tree species create islands of fertility and influence the understory vegetation on nickel-mine tailings of different ages. Ecol Eng 155: 105902. DOI: 10.1016/j.ecoleng.2020.105902.

Oni BA, Oziegbe O, Olawole OO. 2019. Significance of biochar application to the environment and economy. Ann Agric Sci 64: 222-236. DOI: 10.1016/J.AOAS.2019.12.006.

Posse RP, Valani F, Gonçalves AMS, Oliveira EC, Louzada JM, Quartezani WZ, Leite MCT. 2018. Growth and quality of yellow passion fruit seedlings produced under different irrigation depths. J Exp Agric Intl 22: 1-11. DOI: 10.9734/JEAI/2018/40948.

Salsabila YA, Nanda M, Cut NI. 2023. Response of soil conditioner and paclobutrazol in two rice varieties (*Oryza sativa* L.). Jurnal Ilmiah Mahasiswa Pertanian 8: 26-35. DOI: 10.17969/jimfp.v8i4.27554 [Indonesian]

Saputra NA, Darmawan S, Efiyanti L, Hendra D, Wibowo S, Santoso A, Komarayati S, Indrawan DA, Nawawi DS, Maddu A, Pari G. 2022. A novel mesoporous activated carbon derived from *Calliandra calothyrsus* via physical activation: Saturation and superheated. Energies 15: 6675. DOI: 10.3390/en15186675.

Sarfraz R, Hussain A, Sabir A, Ben Fekih I, Ditta A, Xing S. 2019. Role of biochar and plant growth promoting rhizobacteria to enhance soil carbon sequestration—a review. Environ Monit Assess 191 (4): 251. DOI: 10.1007/s10661-019-7400-9.

Simiele M, De Zio E, Montagnoli A, Terzaghi M, Chiatante D, Scippa GS, Trupiano D. 2022. Biochar and/or compost to enhance nursery-produced seedling performance: A potential tool for forest restoration programs. Forests 13: 550. DOI: 10.3390/f13040550.

Sopha GA. 2020. Influence of plant density, compost and biofertilizer on true shallot seed growth in alluvial soil. Indones J Agric Sci 21: 70-77. DOI: 10.21082/ijas.v.21.n2.2020.p.70-77.

Suita E, Sudrajat DJ. 2018. Growth of red sengon (*Albizia chinensis* (Osbeck) Merr.) seedlings on the molded seedling media and its comparison with polybag seedling. Jurnal Penelitian Kehutanan Wallacea 7: 141-149. DOI: 10.18330/jwallacea.2018.vol7iss2pp141-149. [Indonesian]

Sukartono, Suwardji, Azmi MK. 2019. The Influence of Irrigation System, Biochar, Biological Fertilizer, and Phytosan on the Growth, Yield, and Irrigation Efficiency for Sorghum Plants in Sandy Soil of Sub-Optimal Dry Land in North Lombok Regency. Sci Seminar Sci Technol. [Indonesian]

Syahrinudin, Hartati W, Sudarmadji T, Krisdianto N, Ibrahim. 2019. Biochar enriched with organic fertilizer improves the survival and growth rate of *Anthocepalus cadamba* seedlings planted on degraded spodosols. Biodiversitas 20: 3741-3750. DOI: 10.13057/biodiv/d201237.

Syahrinudin, Krisdianto N, Sudarmadji T, Ibrahim, Hartati W. 2021. Biochar application on spodosols soils promotes higher plant growth and survival rate. Adv Biol Sci Res 11: 364-368. DOI: 10.2991/absr.k.210408.060.

Syahrinudin, Wijaya A, Butarbutar T, Hartati W, Ibrahim, Sipayung M. 2018. Biochar produced by retort closed drum kiln promotes higher plant growth rate. Ulin J Trop For 2: 49-58. DOI: 10.32522/ujht.v2i1.1291. [Indonesian]

Tataridas A, Kanatas P, Chatzigeorgiou A, Zannopoulos S, Travlos I. 2022. Sustainable crop and weed management in the Era of the EU Green Deal: A survival guide. Agronomy 12 (3): 589. DOI: 10.3390/agronomy12030589.

Widyati E, Sutiyono, Darwo, Mindawati N, Yulianti M, Prameswari D, Abdulah L, Yuniarti K, Baral H. 2022. Optimum plant density and harvest age for maximizing productivity and minimizing competition in a *Calliandra* short-rotation-coppice plantation in West Java, Indonesia. For Sci Technol 18: 26-35. DOI: 10.1080/21580103.2022.2039305.

Yudaputra A. 2020. Modelling potential current distribution and future dispersal of an invasive species *Calliandra calothyrsus* in Bali Island, Indonesia. Biodiversitas 21: 674-682. DOI: 10.13057/biodiv/d210233.

Yuliansyah, Haqiqi MT, Septia E, Mujiasih D, Septiana HA, Setiawan KA, Setiyono B, Angi EM, Sari NM, Kusuma IW, Suwinarti W, Amirta R. 2019. Short Communication: Diversity of plant species growing during fallow period of shifting cultivation and potential of its biomass for sustainable energy production in Mahakam Ulu, East Kalimantan, Indonesia. Biodiversitas 20: 2236-2242. DOI: 10.13057/biodiv/d200818.

Zhang Y, Wang J, Feng Y. 2021. The effects of biochar addition on soil physicochemical properties: A review. CATENA 202: 105284. DOI: 10.1016/j.catena.2021.105284.

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Temporal dynamics of plant communities on Thirukudder Hill in Thiruparankundram, Madurai District, Tamil Nadu, India

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Abstract. *Palsamy P, Gayathrippriya S, Krishnan SG, Chinnakaruppan M, Premkumar M, Muthuvel U, Suresh K. 2024. Temporal dynamics of plant communities on Thirukudder Hill in Thiruparankundram, Madurai District, Tamil Nadu, India. Asian J For 8: 115-125.* The present investigation was conducted in Thirukudder Hill, situated in Thiruparankundram, Madurai District, Tamil Nadu, India, aimed to analyze plant community dynamics from December 2019, January, February, and March 2020, total of thirty-six (2×2 m) quadrats were randomly sampled to assess species distribution. The study investigation revealed significant diversity in frequency indices, ranging from 2.778 to 88.889. *Solanum nigrum* displayed the highest frequency (88.88) in December 2019, while 20 species like *Blepharis maderaspatana* and *Corchorus tridens* consistently exhibited lower values (2.778) across all seasons. Density patterns showed ecological dynamics, with *Cardiospermum helicacabum* having maximum density (24.11) in December 2019 and 18 species maintaining consistently low densities (0.028). Abundance fluctuations were observed, with *Chrysopogon orientalis* peaking in February 2020, while species like *Allmania nodiflora, Boerhavia diffusa, Chamaecrista mimosoides, Vachellia leucophloea, Corchorus aestuans, Asparagus racemosus* etc., showed minimal abundance (1.00) throughout all study seasons. *Canthium coromandelicum* displayed the highest Importance Value Index (IVI) in February 2020 (48.698), while *V. leucophloea* recorded the lowest (0.002), indicating varied impacts on community structure. In Shannon's Index, *C. orientalis* exhibited a higher value (0.14) in February 2020, contrasting with *C. tridens* and *Vicoa indica*, which showed lower index values (0.001). These findings illustrate the dynamic nature of plant communities in Thirukudder Hill, emphasizing the temporal variability and structural significance of key plant species in shaping the local ecosystem's composition and diversity over the study period. The study highlights how the presence and interactions of specific plant species can lead to substantial changes in the ecosystem's structure, affecting everything from soil composition to the availability of resources for other organisms. By analyzing these temporal changes, the study offers significant insights into the resilience and adaptability of plant communities amid environmental variations. This contributes to a deeper comprehension of ecosystem dynamics and aids in shaping conservation strategies.

Keywords: Plant community, seasonal variations, species distribution, temporal dynamics, Thirukudder Hill

INTRODUCTION

According to the FAO (2020), a forest is characterized as an area of land greater than 0.5 hectares, with trees exceeding 5 meters in height and having a canopy cover of more than 10% or with trees that have the potential to reach these dimensions naturally. Forests are vital ecosystems, serving as essential habitats for various species and offering numerous ecosystem services (Brockerhoff et al. 2017). Vegetation plays a key role in shaping long-term human settlement patterns due to its impact on the environment and resources available for human use. Plant communities change their floristic composition and structure over relatively short periods, responding to both biotic factors, such as interactions with other species, and abiotic factors, including climate, soil conditions, and water availability. These changes in plant assemblages and species diversity significantly influence the nature and absorbance capabilities of forests, affecting everything from local microclimates to the overall health and stability of ecosystems. Thus, understanding vegetation dynamics is crucial for sustainable human development and environmental conservation (Khan et al. 2020). A good knowledge of plant communities is essential for conserving the natural heritage and developing sustainable landscape management strategies (Nuta and Niculescu 2019). Thus, phytosociological surveys provide relevant data on plant communities and verify possible relationships between species (Silva et al. 2002). In addition, these studies define ecological values of varied environments mainly for conserving species diversity considering the different spatial scales (Gomes et al. 2011). To assess the temporal dynamics and predict future trends of plant communities, examining the type of vegetation, their composition and structure, the patterns of species association, and notably, the key factors contributing to their destruction are identified as the fundamental components of community studies (Shimwell 1971; Mueller-Dombios and Ellenberg 1974).

A thorough examination of a community within a specific area can result in a classification system for the different vegetation types. By adhering to fundamental approaches, modern ecologists have resolved numerous issues within their focus areas and have implemented methods responsive to environmental changes and plant adaptations. The evolutionary traits of plants reflect their response to shifting environmental conditions. Stand-level attributes can depict the state of the forest, encapsulating community interactions, prevailing trends, dominance, and diversity. According to a recent study by Hansen et al. (2021), the relentless demand for land and resources driven by global population growth has significantly altered forest ecosystems worldwide. This growing pressure has led to widespread deforestation, disrupting forest growth patterns and contributing to changes in global climatic conditions. The study underscores the rapid pace at which forests are removed for agriculture, urban expansion, and building infrastructure. These actions endanger biodiversity and diminish the essential ecological benefits that forests offer. One critical service is carbon sequestration, where forests absorb carbon dioxide from the air, aiding climate change mitigation. They also regulate water cycles, ensuring the availability of clean water for various ecosystems and human use. The loss of these essential services due to deforestation can have far-reaching impacts on both the environment and human societies. The essential services forests provide, such as carbon sequestration, water regulation, soil conservation, and biodiversity support, are crucial for maintaining ecological balance and supporting human livelihoods. The recognition and detailed examination of plant communities within a specific region are crucial for their comprehensive understanding and management. This involves identifying and analyzing these communities from various ecological, geographical, taxonomic, and dynamic perspectives. Such an approach is invaluable in scientific research and practical applications, providing insights into ecosystem dynamics, species interactions, and environmental health. Therefore, the systematic study and description of plant communities play a pivotal role in ecological research and the sustainable management of natural resources. Such comprehensive studies help understand the intricate relationships within ecosystems, guide conservation efforts, and inform sustainable land-use practices. This holistic approach ensures that ecological integrity and biodiversity are preserved, benefiting future generations. The current study aims to analyze the plant diversity of Thirukudder Hill in Thiruparankundram, located in the Madurai District of Tamil Nadu, India.

MATERIALS AND METHODS:

Study area: Thirukudder Hill

The present investigation focused on Thirukudder Hill, positioned at Latitude 9.88875º and Longitude 78.075294º, within Thiruparankundram of Madurai District, Tamil Nadu, India (Figure 1). The experimental site is situated in the south-eastern part of Thiruparankundram; this study area is distinguished by notable landmarks such as the Arulmigu Kattikulam Soottokkole Mayandi Swamy Temple at the foothill in the north and the Mottaiyarasu Temple located to the north and the study periods revealed a stable temperature regime, with mean monthly minimum and maximum temperatures hovering around 22ºC and 40ºC, respectively. The study region experiences an annual rainfall ranging from 535 to 800 mm, significantly influencing its distinctive ecological profile. These climatic and geographic features underscore the ecological uniqueness of Thirukudder Hill, making it an ideal location for studying local biodiversity and ecosystem dynamics. The temples and natural settings provide a rich backdrop for understanding the interplay between human activities and environmental sustainability.

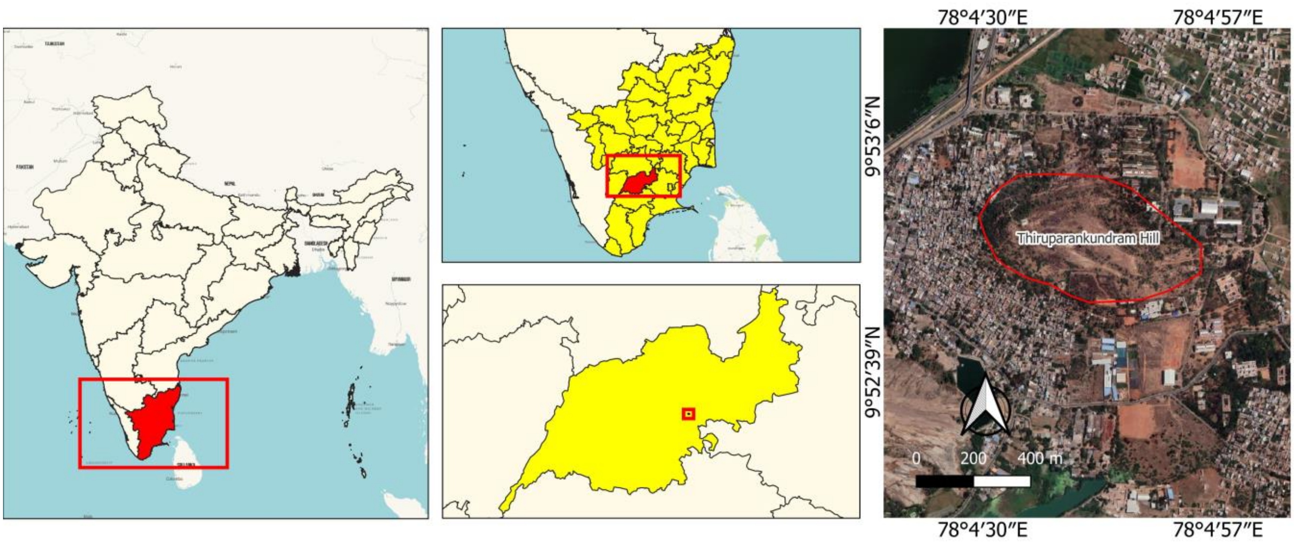

Figure 1. Depicts the geographical details of Thirukudder Hill in Thiruparankundram of Madurai District, Tamil Nadu, India

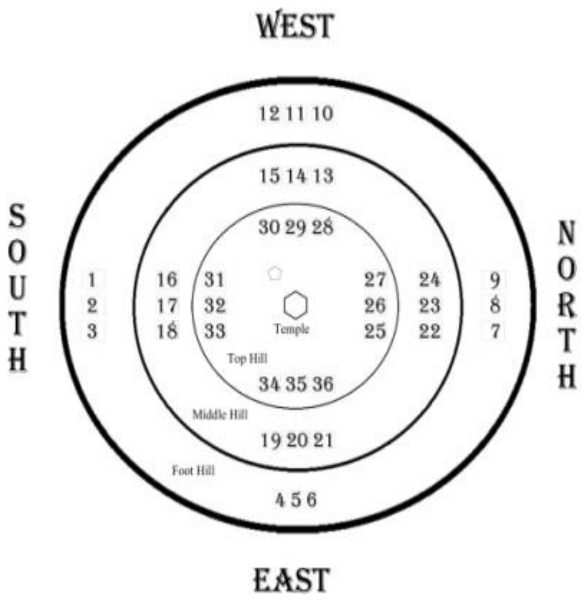

Figure 2. Layout of plant diversity analyzed sites

Field methods

A comprehensive plant community analysis was undertaken during December 2019, January, February, and March 2020. The study utilized the species-area curve method described by Shailaja and Sudha (2001) to accurately determine the appropriate size of the quadrats for the sampling site. In total, 36 quadrats (2×2m) were initially selected randomly; however, their final placement around the temple center may appear systematic due to specific environmental or cultural considerations (Figure 2) within the study area to capture a representative sample of the herbaceous vegetation and tree/shrub seedlings present. The collected data was meticulously analyzed using well-established ecological methods. Frequency, density, and abundance of plant species were calculated according to Magurran (1988), while the basal area of the trees was determined using the formula πr^2. The Importance Value Index (IVI), which provides insight into the ecological significance of each species, was calculated using the Curtis (1959) method. Additionally, the diversity of the plant community was assessed using Shannon's Index, as proposed by Shannon and Weiner (1963). All the formulas are provided below.

Frequency (presence of a species in several samples or plots) (%) = Number of quadrats in which species occur X 100 / Total number of quadrats studied

Density (number of individuals of a species per unit area) = Total number of individuals of a species in all quadrats/ Total number of quadrats studied

Abundance (total number of individuals of a species in a given area) = Total number of individuals of a species in all quadrats/Total number of quadrats in which the species occurred

Basal area (cross-sectional area of a tree trunk or multiple tree trunks at breast height) = $\pi r2$

Where, r = Average diameter ÷ 2, $\pi = 22 / 7$

IVI = Relative Frequency (frequency of a species relative to the total frequency of all species) + Relative density (density of a species relative to the total density of all species) + Relative Basal area (a species' basal area relative to all species' total basal area).

Shannon's Index (H) = $\sum$ pi log pi
Where: pi is the decimal ratio of individuals of a species to the total number of individuals overall.

The collected plant specimens were exactly identified based on their vegetative and reproductive characteristics using authoritative standard regional floras by Gamble and Fischer (1915-1935), Nair and Henry (1983), Henry et al. (1989), and Matthew (1991). These comprehensive references ensured accurate identification. Voucher specimens were then carefully deposited in the Post Graduate and Research Department of Botany at Saraswathi Narayanan College (SN-MH) in Madurai, Tamil Nadu, India, providing a valuable resource for future study and verification.

RESULTS AND DISCUSSION

During the study periods, a significant and comprehensive plant community assessment was conducted in Thirukudder Hill, as detailed in Tables 1 through 4. In December 2019, the diversity analysis recorded 83 plant species. This was followed by 67 species in January 2020, 45 in February 2020, and 50 in March 2020. This extensive assessment involved surveying various plant species, analyzing their distribution patterns, and understanding the ecological dynamics in diverse habitats on the hill studied. The data collected provides valuable insights into the biodiversity and health of the plant community in this region. The result data highlights the seasonal variations in plant species diversity, indicating a significant decrease in species counts from December to February, followed by a slight increase in March. These fluctuations suggest that certain species may be more prevalent during specific times of the year, potentially due to changes in environmental conditions such as temperature, rainfall, and sunlight availability.

The variation in frequency indices, ranging from 2.778 to 88.889, signifies considerable diversity in the distribution of plant species within the study area. In December 2019, *Solanum nigrum* exhibited the highest frequency at 88.888%, indicating its dominance. On the other hand, 20 species, *Blepharis maderaspatana*, *Corchorus tridens*, and several other species, consistently displayed low-frequency values of 2.778% throughout all study periods, underscoring their less prominent presence. These variations reflect the species' different ecological roles and competitive abilities, further evidenced by their varying density patterns. For instance, *Cardiospermum helicacabum* showed the highest density, reaching 24.111 in December 2019. In contrast, *Cucumis maderaspatanus* and other species maintained low densities of 0.0722 across all study periods. This disparity highlights the complex ecological dynamics and interactions among the species within the habitat, as illustrated in Figures 3 and 4. The data suggests a thriving ecosystem with dominant species and a variety of less abundant ones, each contributing to the biodiversity and ecological balance of the area.

Abundance trends revealed notable fluctuations, with *Chrysopogon orientalis* exhibiting a higher range in January 2020. Conversely, *Allmania nodiflora*, *Boerhavia diffusa*, *Chamaecrista mimosoides*, *Vachellia leucophloea*, *Corchorus aestuans*, *Asparagus racemosus* etc., were displayed minimal abundance (1.00), reflecting a limited existence and ecological contribution (Figure 5). The Importance Value Index (IVI) emerged as a valuable parameter for assessing ecological significance; *Canthium coromandelicum* exhibited the highest IVI value (48.698) in December 2019, representing its major contribution to the overall plant community structure. The *V. leucophloea* recorded the lowest IVI value (0.002) during the same month (Figure 6), suggesting a lesser impact on ecological composition.

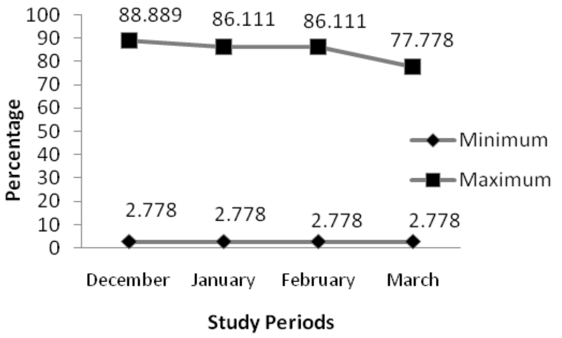

Figure 3. Distribution of species frequencies

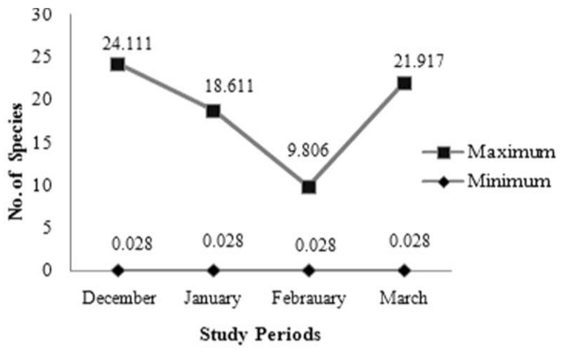

Figure 4. Distribution of species density

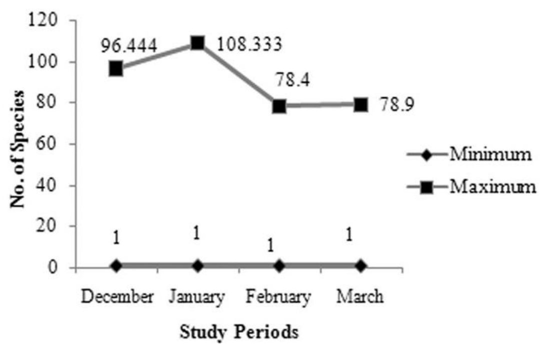

Figure 5. Distribution of species abundance

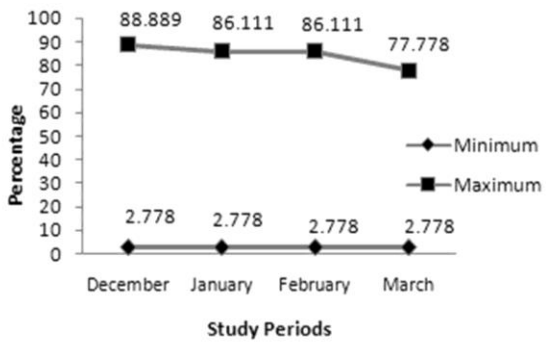

Figure 6. Distribution of species IVI

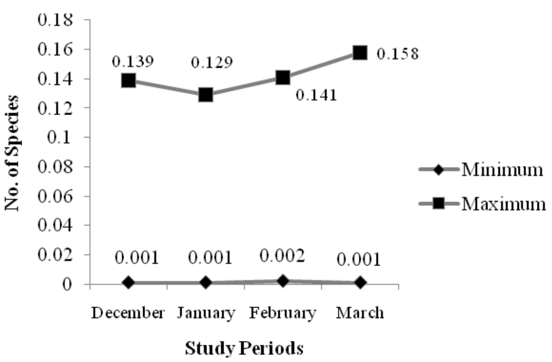

Figure 7. Shannon's Index

Shannon's Index, a comprehensive measure of biodiversity, revealed intriguing patterns in the study. The maximum Shannon's Index value was observed in *C. orientalis* (0.158) during the study period of March 2020, underscoring its significant role in enhancing overall species diversity within the studied ecosystem (Figure 7). This high value suggests a balanced distribution of species and a rich community structure. Conversely, *C. tridens* and *Vicoa indica* exhibited the minimum Shannon's Index value (0.001) across all study seasons, indicating a stark contrast in species evenness and richness and highlighting areas of lower biodiversity and potential ecological stress. These findings underscore the importance of monitoring biodiversity indices for ecosystem health.

Table 1. Plant diversity assessment in Thirukkuder Hill, Madurai District, Tamil Nadu, India (December 2019)

Botanical name	Frequency	Density	Abundance	IVI	Shannon's Index
Abrus precatorius L.	8.333	0.083	1.000	0.663	0.002
Acalypha indica L.	2.778	0.028	1.000	0.344	0.001
Achyranthes aspera L.	66.667	3.056	4.583	7.242	0.040
Albizia lebbeck (L.) Benth.	38.889	0.528	1.357	3.013	0.010
Allmania nodiflora (L.) R. Br. ex Wight	2.778	0.028	1.000	0.264	0.001
Alysicarpus monilifer (L.) DC.	30.556	0.722	2.364	4.686	0.013
Andrographis echioides (L.) Nees	13.889	0.333	2.400	1.265	0.007
Asparagus recemosus Willd.	8.333	0.083	1.000	0.834	0.002
Azima tetracantha Lam.	19.444	2.167	11.143	3.397	0.031
Barleria buxifolia L.	19.444	1.417	7.286	2.647	0.022
B. noctiflora L.f.	8.333	0.083	1.000	0.727	0.002
Blepharis integrifolia (L.f.) E.Mey. & Drège ex Schinz	13.889	0.194	1.400	1.774	0.004
B. maderaspatensis (L.) B. Heyne ex Roth	8.333	0.083	1.000	3.521	0.002
Boerhavia diffusa L.	11.111	0.111	1.000	0.968	0.003
Calotropis gigantea (L.) W.T. Aiton	5.556	0.083	1.500	0.463	0.002
Canthium coromandelicum (Burm.f.) Alston	2.778	0.028	1.000	48.698	0.001
Capparis zeylanica L.	30.556	5.278	17.273	7.223	0.059
Cardiospermum helicacabum L.	25.000	24.111	96.444	26.094	0.139
Catunaregam spinosa (Thunb.) Tirveng.	2.778	0.028	1.000	0.264	0.001
Chamaecrista mimosoides (L.) Greene	11.111	0.111	1.000	0.995	0.003
Chrysopogon orientalis (Desv.) A. Camus	83.333	10.556	12.667	15.809	0.091
Cissus quadrangularis L.	50.000	1.667	3.333	4.782	0.025
Cleome viscosa L.	16.667	0.778	4.667	1.851	0.014
Commelina benghalensis L.	11.111	0.417	3.750	1.116	0.008
C. erecta L.	5.556	0.139	2.500	0.487	0.003
C. longifolia Lam.	30.556	1.750	5.727	3.684	0.026
Corchorus aestuans L.	2.778	0.028	1.000	0.236	0.001
C. tridens L.	2.778	0.028	1.000	0.236	0.001
Crotalaria angulata Mill.	11.111	0.167	1.500	0.897	0.004
Cucumis maderaspatanus L.	2.778	0.028	1.000	0.524	0.001
Cyanthillium cinereum (L.) H. Rob.	72.222	12.278	17.000	16.895	0.100
Cymbopogon caesius (Hook. & Arn.) Stapf	25.000	0.417	1.667	18.211	0.008
Cynodon barberi Rang. & Tadul.	8.333	0.556	6.667	1.254	0.011
Dalbergia coromandeliana Prain.	25.000	0.278	1.111	7.246	0.006
Datura metel L.	2.778	0.028	1.000	0.456	0.001
Dichrostachys cinerea (L.) Wight & Arn.	2.778	0.028	1.000	0.396	0.001
Drimia indica (Roxb.) Jessop	11.111	0.167	1.500	0.885	0.004
Elytraria acaulis (L.fil) Lindau	33.333	0.722	2.167	2.808	0.013
Euphorbia antiquorum L.	8.333	0.194	2.333	0.733	0.004
E. hirta L.	2.778	0.028	1.000	4.833	0.001
Evolvulus alsinoides (L.) L.	2.778	0.028	1.000	0.236	0.001
Hibiscus micranthus L.f.	30.556	0.667	2.182	2.581	0.012
Holoptelea integrifolia (Roxb) Planch.	13.889	0.139	1.000	1.124	0.003
Hypertelis cerviana (L.) Thulin	33.333	0.444	1.333	2.526	0.009
Indigofera aspalathoides Vahl ex DC.	2.778	0.028	1.000	0.396	0.001
Jasminum angustifolium (L.) Willd.	36.111	2.083	5.769	4.388	0.030
Jatropha gossypiifolia L.	2.778	0.111	4.000	10.304	0.003
Leucas aspera (willd.) Link	11.111	0.111	1.000	0.920	0.003
Mesosphaerum suaveolens (L.) Kuntze	19.444	0.194	1.000	1.398	0.004
Microstachys chamaelea (L.) Mull. Arg.	27.778	3.278	11.800	5.029	0.042
Neltuma juliflora (Sw.) Raf.	13.889	0.361	2.600	1.254	0.007
Ocimum americanum L.	2.778	0.028	1.000	0.300	0.001
Oldenlandia umbellata L.	2.778	0.028	1.000	0.264	0.001
Opuntia monacanthos (Willd.) Haw.	11.111	1.167	10.500	1.964	0.019
Ouret lanata (L.) Kuntze	11.111	0.222	2.000	0.941	0.005
Parthenium hysterophorus L.	30.556	0.861	2.818	2.764	0.015
Passiflora foetida L.	5.556	0.056	1.000	0.400	0.002
Pavonia zeylanica (L.) Cav.	44.444	1.917	4.313	4.696	0.028
Pergularia daemia (Forssk.) Chiov.	2.778	0.028	1.000	0.216	0.001
Perotis indica (L.) Kuntze	27.778	0.944	3.400	2.708	0.016
Phyllanthus amarus Schumach. & Thonn.	16.667	0.222	1.333	1.275	0.005
P. maderaspatensis L.	19.444	0.361	1.857	1.621	0.007
Pigea enneasperma (L.) P.I. Forst.	38.889	1.639	4.214	4.128	0.025
Polycarpaea corymbosa (L.) Lam.	5.556	0.056	1.000	0.499	0.002
Polygala arvensis Willd.	27.778	3.500	12.600	5.263	0.044
Rhynchosia minima (L.) DC.	27.778	1.139	4.100	2.877	0.019
Rivea hypocrateriformis (Desr) Choisy	2.778	0.056	2.000	0.232	0.002
Rostellularia mollissima (Nees) Nees	63.889	4.417	6.913	8.414	0.052
R. obtusa Nees	8.333	0.083	1.000	0.686	0.002
Ruellia patula Jacq.	8.333	0.139	1.667	0.709	0.003
R. prostrata Poir.	27.778	1.111	4.000	2.881	0.018
Sida acuta Burm. f.	63.889	9.194	14.391	13.270	0.084
S. cordata (Burm.f.) Borss.Waalk.	13.889	0.306	2.200	1.174	0.006
Solanum nigrum L.	88.889	9.611	10.813	15.245	0.086
Spermacoce articularis L.f	44.444	5.611	12.625	8.415	0.061
Striga densiflora (Benth.) Benth.	2.778	0.028	1.000	4.833	0.001
Tephrosia purpurea (L.) Pers.	13.889	0.250	1.800	1.407	0.005
Trigastrotheca pentaphylla (L.) Thulin	2.778	0.028	1.000	0.300	0.001
Turnera subulata Sm.	2.778	0.028	1.000	0.344	0.001
Vachellia leucophloea (Roxb.) Maslin, Seigler & Ebinger	5.556	0.111	2.000	0.504	0.003
Vicoa indica (L.) DC.	52.778	2.889	5.474	6.186	0.038
Waltheria indica L.	25.00	0.694	2.778	2.255	0.013
Xenostegia tridentata (L.) D.F. Austin & Staples	5.556	0.139	2.500	0.547	0.003

Table 2. Plant diversity assessment in Thirukkuder Hill, Madurai District, Tamil Nadu, India (January 2020)

Botanical name	**Frequency**	**Density**	**Abundance**	**IVI**	**Shannon's Index**
Achyranthes aspera L.	5.556	0.056	1.000	0.624	0.002
Ageratum conyzoides L.	2.778	0.389	14.000	0.788	0.009
Allmania nodiflora (L.) R. Br.ex Wight	61.111	4.056	6.636	9.236	0.052
Alysicarpus monilifer (L.) DC.	2.778	0.028	1.000	0.333	0.001
Andrographis echioides (L.) Nees	50.000	1.278	2.556	5.658	0.022
Asparagus racemosus Willd.	8.333	0.083	1.000	0.854	0.002
Atalantia monophylla DC.	2.778	0.028	1.000	1.314	0.001
Azadirachta indica A. Juss.	2.778	0.083	3.000	1.366	0.002
Azima tetracantha Lam.	5.556	0.056	1.000	4.215	0.002
Barleria buxifolia L.	2.778	0.111	4.000	0.934	0.003
B. noctiflora L.f.	8.333	0.194	2.333	1.230	0.005
Benkara malabarica (Lam.) Tirveng.	2.778	0.194	7.000	0.889	0.005
Blepharis integrifolia (L.f.) E.Mey. & Drège ex Schinz	25.000	2.611	10.444	4.653	0.038
B. maderaspatana (L.) B. Heyne ex Roth	8.333	1.361	16.333	2.065	0.023
Boerhavia diffusa L.	5.556	0.056	1.000	1.060	0.002
Capparis zeylanica L.	5.556	0.056	1.000	0.624	0.002
Celosia polygonoides Retz.	5.556	0.139	2.500	0.659	0.004
Chamaecrista mimosoides (L.) Greene	27.778	5.028	18.100	7.143	0.060
Chrysopogon orientalis (Desv.) A. Camus	16.667	18.056	108.333	18.587	0.128
Cissus quadrangularis L.	8.333	0.167	2.000	1.017	0.004
Cleome viscosa L.	5.556	0.194	3.500	0.731	0.005
Commelina benghalensis L.	13.889	0.611	4.400	1.897	0.012
Corchorus aestuans L.	2.778	0.028	1.000	0.333	0.001
Croton bonplandianus Baill.	2.778	0.056	2.000	0.323	0.002
Cucumis maderaspatanus L.	2.778	0.028	1.000	0.333	0.001
Cyanthillium cinereum (L.) H. Rob.	11.111	0.417	3.750	1.488	0.009
Cymbopogon caesius (Hook. & Arn.) Stapf	5.556	0.056	1.000	22.525	0.002
Cynodon barberi Rang. & Tadul.	2.778	0.222	8.000	0.632	0.005
Dalbergia coromandeliana Prain	11.111	0.222	2.000	37.305	0.005
Drimia indica (Roxb.) Jessop	5.556	0.083	1.500	0.868	0.002
Euphorbia antiquorum L.	2.778	0.028	1.000	0.856	0.001
Evolvulus alsinoides (L.) L.	75.000	10.389	13.852	16.268	0.096
Flueggea leucopyrus Willd.	2.778	0.028	1.000	0.529	0.001
Gymnosporia montana (Roth) Benth.	8.333	0.139	1.667	14.928	0.004
Hibiscus micranthus L.f.	16.667	0.556	3.333	2.015	0.011
Holoptelea integrifolia (Roxb) Planch.	2.778	0.028	1.000	0.333	0.001
Indigofera aspalathoides Vahl ex DC.	33.333	1.250	3.750	4.361	0.022
Jasminum angustifolium (L.) Willd.	13.889	0.250	1.800	1.516	0.006
Jatropha glandulifera Roxb.	2.778	0.028	1.000	5.567	0.001
Leucas aspera (Willd.) Link	36.111	2.417	6.692	5.512	0.036
Microstachys chamaelea (L.) Mull. Arg.	38.889	3.111	8.000	6.369	0.043
Neltuma juliflora (Sw.) Raf.	8.333	0.083	1.000	0.854	0.002
Ocimum americanum L.	30.556	0.722	2.364	3.440	0.014
Oldenlandia umbellata L.	25.000	1.722	6.889	3.835	0.028
Ouret lanata (L.) Kuntze	38.889	2.528	6.500	5.822	0.037
Pavonia zeylanica (L.) Cav.	13.889	0.611	4.400	1.855	0.012
Pergularia daemia (Forssk.) Chiov.	2.778	0.028	1.000	0.384	0.001
Perotis indica (L.) Kuntze	2.778	0.194	7.000	0.685	0.005
Phyllanthus maderaspatensis L.	25.000	0.806	3.222	2.968	0.015
Polycarpaea corymbosa (L.) Lam.	8.333	0.306	3.667	1.109	0.007
Rhynchosia minima (L.) DC.	2.778	0.028	1.000	0.384	0.001
Rivea hypocrateriformis (Desr) Choisy	38.889	2.500	6.429	5.742	0.037
Rostellularia mollissima (Nees) Nees	33.333	4.806	14.417	7.478	0.059
R. obtusa Nees	55.556	2.500	4.500	7.268	0.037
Sida acuta Burm. f.	8.333	0.667	8.000	1.389	0.013
S. cordata (Burm.f.) Borss. Waalk.	30.556	1.306	4.273	3.963	0.022
Solanum nigrum L.	2.778	0.028	1.000	0.333	0.001
Spermacoce articularis L.f	27.778	2.833	10.200	5.187	0.040
*Tephrosia purpurea (*L.) Pers.	86.111	11.472	13.323	18.360	0.101
Tridax procumbens L.	2.778	0.028	1.000	0.333	0.001
Trigastrotheca pentaphylla (L.) Thulin	27.778	4.806	17.300	6.927	0.059
Turnera subulata Sm.	2.778	0.028	1.000	8.671	0.001
Vachellia leucophloea (Roxb.) Maslin, Seigler & Ebinger	5.556	0.056	1.000	0.944	0.002
Vicoa indica (L.) DC.	2.778	0.083	3.000	0.349	0.002
Waltheria indica L.	75.000	18.611	24.815	24.060	0.129
Xenostegia tridentata (L.) D.F. Austin & Staples	33.333	1.306	3.917	4.167	0.022
Zornia diphylla (L.) Pers.	2.778	0.028	1.000	0.733	0.001

Table 3. Plant diversity assessment in Thirukkuder Hill, Madurai District, Tamil Nadu, India (February 2020)

Botanical name	Frequency	Density	Abundance	IVI	Shannon's Index
Allmania nodiflora (L.) R. Br. ex Wight	58.333	3.194	5.476	20.478	0.078
Andrographis echioides (L.) Nees	33.333	0.472	1.417	9.005	0.019
Asparagus racemosus Willd.	5.556	0.056	1.000	1.538	0.003
Barleria buxifolia L.	8.333	0.139	1.667	2.417	0.007
B. noctiflora L.f.	8.333	0.139	1.667	2.417	0.007
Boerhavia diffusa L.	5.556	0.056	1.000	1.713	0.003
Calotropis gigantea (L.) W.T. Aiton	5.556	0.222	4.000	1.830	0.011
Canthium coromandelicum (Burm.f.) Alston	2.778	0.028	1.000	0.772	0.002
Capparis zeylanica L.	5.556	0.056	1.000	1.579	0.003
Cardiospermum halicacabum L.	2.778	0.028	1.000	0.937	0.002
Cissus quadrangularis L.	8.333	0.194	2.333	2.516	0.010
Cleome viscosa L.	8.333	0.139	1.667	2.302	0.007
Commelina benghalensis L.	19.444	0.889	4.571	6.526	0.032
Cyanthillium cinereum (L.) H. Rob.	22.222	0.667	3.000	6.703	0.025
Cymbopogon caesius (Hook.f. & Arn.) Stapf	2.778	0.028	1.000	26.821	0.002
Dalbergia coromandeliana Prain	11.111	0.167	1.500	22.770	0.008
Elytraria acaulis (L.f.) Lindau	2.778	0.028	1.000	0.748	0.002
Evolvulus alsinoides (L.) L.	36.111	4.111	11.385	17.014	0.091
Gymnosporia montana (Roth) Benth.	8.333	0.083	1.000	17.631	0.005
Holoptelea integrifolia (Roxb) Planch.	5.556	0.056	1.000	1.713	0.003
Indigofera aspalathoides Vahl ex DC.	2.778	0.056	2.000	9.396	0.003
Jasminum angustifolium (L.) Willd.	8.333	0.111	1.333	2.650	0.006
Jatropha glandulifera Roxb.	2.778	0.028	1.000	8.663	0.002
Leucas aspera (Willd.) Link	16.667	0.944	5.667	5.980	0.033
Microstachys chamaelea (L.) Mull. Arg.	27.778	1.389	5.000	9.499	0.044
Neltuma juliflora (Sw.) Raf.	8.333	0.083	1.000	2.303	0.005
Ocimum americanum L.	22.222	0.889	4.000	7.214	0.032
Oldenlandia umbellata L.	5.556	0.056	1.000	1.464	0.003
Ouret lanata (L.) Kuntze	27.778	0.944	3.400	8.612	0.033
Pavonia zeylanica (L.) Cav.	13.889	0.444	3.200	4.270	0.019
Phyllanthus maderaspatensis L.	5.556	0.056	1.000	1.475	0.003
Rhynchosia minima (L.) DC.	19.444	2.306	11.857	9.349	0.063
Rivea hypocrateriformis (Desr) Choisy	5.556	0.083	1.500	3.084	0.005
Rostellularia mollissima (Nees) Nees	38.889	2.639	6.786	14.691	0.069
R. obtusa Nees	30.556	2.083	6.818	11.613	0.058
Sida acuta Burm. f.	13.889	0.750	5.400	4.881	0.028
S. cordata (Burm.f.) Borss. Waalk.	27.778	0.972	3.500	8.645	0.034
Spermacoce articularis L.f	33.333	3.000	9.000	14.886	0.074
Tephrosia purpurea (L.) Pers.	86.111	8.417	9.774	37.798	0.132
Trigastrotheca pentaphylla (L.) Thulin	16.667	2.139	12.833	8.346	0.060
Turnera subulata Sm.	2.778	0.028	1.000	16.198	0.002
Vachellia leucophloea (Roxb.) Maslin, Seigler & Ebinger	2.778	0.028	1.000	0.937	0.002
Vicoa indica (L.) DC.	2.778	0.028	1.000	0.748	0.002
Waltheria indica L.	75.000	9.806	13.074	37.975	0.140
Xenostegia tridentata (L.) D.F. Austin & Staples	27.778	0.694	2.500	8.081	0.026

Discussion

Diversity analysis in vegetation ecology plays a crucial role in assessing how human activities impact the variety and abundance of plant species. This is an important method for measuring the influence of human actions on the overall diversity and composition of plant communities in ecosystems. Ecological studies not only help us comprehend the interaction between vegetation and the environment but they are also required for monitoring global climate change responses (Davis et al. 2021). It has long been the goal of ecological studies to disentangle the dynamics that underlie the spatiotemporal distribution of biodiversity (Rossi et al. 2021) and further functions of the ecosystem (Jiménez-Alfaro et al. 2018; Peters et al. 2019). Specific drivers of contemporary environments drive both biodiversity and ecosystem functions. The vegetation in any area is shaped over time through complex interactions with biotic and abiotic factors. These factors include topography, changes in land use, soil conditions, climate variations, competition among species, and herbivory. They collectively impact the composition, diversity, and spatial arrangement of plants. Competition for resources and interactions with other organisms are particularly significant biotic factors influencing the distribution of plant communities. Such interactions can directly dictate the presence or absence of specific species within a particular geographical area (Gebrehiwot et al. 2019).

Table 4. Plant diversity assessment in Thirukkuder Hill, Madurai District, Tamil Nadu, India (March 2020)

Botanical name	Frequency	Density	Abundance	IVI	Shannon's Index
Achyranthes aspera L.	2.778	0.056	2.000	0.500	0.002
Allmania nodiflora (L.) R. Br. ex Wight	50.000	2.722	5.444	10.645	0.054
Alysicarpus monilifer (L.) DC.	2.778	0.028	1.000	0.499	0.001
Andrographis echioides (L.) Nees	19.444	0.222	1.143	3.084	0.008
Atalantia monophylla DC.	8.333	0.139	1.667	29.637	0.005
Barleria noctiflora L.f.	2.778	0.056	2.000	3.315	0.002
Blepharis integrifolia (L.f.) E. Mey. & Drège ex Schinz	2.778	0.194	7.000	0.695	0.007
B. maderaspatensis (L.) B. Heyne ex Roth	22.222	1.917	8.625	5.730	0.042
Boerhavia diffusa L.	2.778	0.028	1.000	0.759	0.001
Calotropis gigantea (L.) W.T. Aiton	2.778	0.028	1.000	0.607	0.001
Capparis zeylanica L.	2.778	0.028	1.000	0.461	0.001
Celosia polygonoides Retz.	16.667	1.028	6.167	3.745	0.027
Chamaecrista mimosoides (L.) Greene	8.333	1.111	13.333	2.698	0.028
Chrysopogon orientalis (Desv.) A. Camus	27.778	21.917	78.900	34.793	0.158
Commelina benghalensis L.	13.889	0.806	5.800	3.086	0.022
C. longifolia Lam.	5.556	0.417	7.500	1.527	0.013
Corchorus aestuans L.	2.778	0.083	3.000	0.626	0.003
C. tridens L.	2.778	0.056	2.000	0.500	0.002
Cyanthillium cinereum (L.) H. Rob.	13.889	0.472	3.400	2.608	0.014
Dalbergia coromandeliana Prain.	8.333	0.222	2.667	23.145	0.008
Euphorbia antiquorum L.	2.778	0.028	1.000	7.823	0.001
Evolvulus alsinoides (L.) L.	30.556	2.972	9.727	8.292	0.058
Gymnosporia montana (Roth) Benth.	2.778	0.028	1.000	21.220	0.001
Hibiscus micranthus L.f.	5.556	0.194	3.500	1.069	0.007
Holoptelea integrifolia (Roxb) Planch.	2.778	0.028	1.000	0.607	0.001
Indigofera aspalathoides Vahl ex DC.	13.889	0.361	2.600	2.738	0.012
Jasminum angustifolium (L.) Willd.	5.556	0.056	1.000	14.904	0.002
Leucas aspera (willd.) Link	5.556	0.194	3.500	1.106	0.007
Mesosphaerum suaveolens (L.) Kuntze	2.778	0.028	1.000	0.607	0.001
Microstachys chamaelea (L.) Mull. Arg.	11.111	0.528	4.750	2.284	0.016
Neltuma juliflora (Sw.) Raf.	13.889	0.194	1.400	2.286	0.007
Ocimum americanum L.	11.111	0.389	3.500	2.097	0.012
Oldenlandia umbellata L.	5.556	0.111	2.000	0.969	0.004
Ouret lanata (L.) Kuntze	22.222	1.028	4.625	4.512	0.027
Pavonia zeylanica (L.) Cav.	13.889	0.500	3.600	2.656	0.015
Phyllanthus maderaspatensis L.	5.556	0.083	1.500	0.876	0.003
Rhynchosia minima (L.) DC.	44.444	5.472	12.313	13.674	0.086
Rivea hypocrateriformis (Desr.) Choisy	8.333	0.111	1.333	1.594	0.004
Rostellularia mollissima (Nees) Nees	38.889	5.167	13.286	12.543	0.083
R. obtusa Nees	27.778	3.194	11.500	8.295	0.061
Sida acuta Burm. f.	11.111	1.972	17.750	4.324	0.043
S.cordata (Burm.f.) Borss. Waalk.	22.222	0.722	3.250	4.117	0.020
Spermacoce articularis L.f	16.667	0.750	4.500	3.404	0.021
Tephrosia purpurea (L.) Pers.	77.778	5.278	6.786	17.987	0.084
Trigastrotheca pentaphylla (L.) Thulin	16.667	1.750	10.500	4.708	0.040
Vachellia leucophloea (Roxb.) Maslin, Seigler & Ebinger	5.556	0.056	1.000	0.960	0.002
V. nilotica (L.) P.J.H. Hurter & Mabb.	2.778	0.028	1.000	0.759	0.001
Vicoa indica (L.) DC.	2.778	0.028	1.000	0.434	0.001
Waltheria indica L.	75.000	8.000	10.667	21.427	0.107
Xenostegia tridentata (L.) D.F. Austin & Staples	19.444	0.306	1.571	3.070	0.010

As reported by Kefalew et al. (2022), the study's results indicate that environmental aspects like altitude and slope variations, soil properties such as total nitrogen content and organic matter levels, and disturbances within the ecosystem influence the current makeup and variety of plant species. Tree layer diversity can impact herb layer diversity by influencing resource availability and environmental variables important to herb plants. At the same time, there have been reports of relationships between herb and tree layer diversity. In the last several decades, studies of environmental changes have emerged more rapidly than other studies because to effects of these environmental changes have been intensified by recent anthropogenic activities (Alig et al. 2002). It also revealed that the indicator species of each plant community were linked to a particular set of environmental gradients. A region’s forest communities evolve through time, but altitude, slope, latitude, aspect, precipitation, and humidity all have a part in their development and composition (Paudel et al. 2018). Ecosystems respond to simultaneous environmental changes affecting community diversity and distribution (Reich 2009). In each microhabitat type, specialist plant communities thrive and are composed of specific taxa that have adapted to the unique environmental conditions of that particular microhabitat (De Paula et al. 2020). Aboveground and underground communities work together to control whole-ecosystem processes and reactions to environmental changes (Geisen et al. 2022).

Packiaraj et al. (2023) conducted an extensive study on the biodiversity of Thirukudder Hills and discovered a remarkable abundance of plant species. On the other hand, the vegetation within a forest is strongly affected by the local microclimate. Their research highlighted that the significant variation in altitude and the region's diverse soil composition, climate, and microclimates likely contribute to this rich flora. The varying altitudes create unique ecological niches, while the diverse soil types provide different nutrients and conditions favorable for various plant species. Additionally, the climate and microclimates offer a range of temperature and moisture conditions that support a wide array of plant life, leading to a highly diverse and thriving plant community (Jiren et al. 2020). The present study shows that the plant community undergoes fluctuations across different study seasons, showing variations from one season to another. December tends to exhibit consistently the greatest diversity within this community. This research also notes abundant trees and shrubs alongside herbaceous plants. Climate plays a crucial role in determining the makeup of the plant community, while temporal factors also strongly influence its configuration. These periodic changes in vegetation complexity underscore how species respond to evolving environmental conditions, impacting their distribution within the community. As environmental conditions fluctuate, plant species successively replace one another, leading to species composition and distribution variations across ecological gradients. Other studies (Desalegn 2002; Shaheen et al. 2011; Khan et al. 2012) have also found a relationship between plant communities and environmental gradients. The maintaining of biodiversity is critical for environmental conditions to persist. The experimental hill findings illustrate the dynamic nature of plant communities, emphasizing the temporal variability and structural significance of key plant species in shaping the local ecosystem over the study periods. Understanding individual plant species' ecological dynamics is essential because certain species' high frequency, density, and abundance values impact community structure. The landscape is transforming both locally and globally, largely influenced by human activities and the effects of climate change (Sax and Gaines 2003). This study highlighted significant challenges during the observation periods, notably excessive grazing, over-browsing by domestic animals, and deforestation, which have emerged as primary concerns affecting vegetation composition. Furthermore, this study underscores the encroachment of settlement areas into study sites driven by population growth, posing an additional threat to the area under investigation. Uncontrolled grazing in open areas diminishes the diversity and abundance of herbaceous species, accentuating strain on ecosystems; grazing pressure can severely threaten plant biodiversity (Mayer et al. 2009) and species composition. This led to biodiversity loss, drought, ecological imbalance, and environmental degradation (Mewded et al. 2019; Birhanu et al. 2021). Due to increased demand for land, forested areas are converted into agricultural land, industrial belts, and urban areas, leading to loss of habitat as well as habitat fragmentation for both flora and fauna (Van Doorn-Hoekveld et al. 2016). We need to ascertain whatever biodiversity is left in these already stressed habitats for their much-needed preservation to maintain the stability of the ecosystem.

The impacts caused by human activities, such as deforestation and the introduction of alien species, have had major consequences for the local ecosystem in the Thirukudder Hills, leading to a decline in species richness and density from undisturbed to disturbed areas. Despite research documenting these changes, the region faces major challenges in preserving its unique vegetation, leaving Madurai's ecosystem increasingly threatened. Moreover, the varying physical conditions of the study area, specific climatic conditions, and biogeographical position mean that researchers' attention could be more extensive. Therefore, to maintain the diverse and dynamic plant communities of Thirukudder Hills, it is essential to implement informed conservation and management strategies, which can only be developed through extensive research and understanding. These strategies must be tailored to the study area's specific ecological requirements and aim to mitigate ongoing threats while promoting sustainable practices. Future research efforts should focus on comprehensive species mapping, detailing their localized distributions across different zones within the study area. This approach will facilitate a deeper understanding of their ecological roles and structural contributions to the ecosystem. By identifying key areas requiring conservation interventions, such research endeavors will be instrumental in guiding targeted conservation measures. Addressing the current experimental site's conservation challenges demands proactive and scientifically grounded efforts. By investing in robust research and strategic conservation initiatives, we can aspire to preserve this invaluable natural habitat's ecological integrity and biodiversity for generations.

In conclusion, the investigation at Thirukudder Hill in Madurai District revealed an intriguing story of plant community dynamics. The study meticulously recorded fluctuations across various ecological indices and uncovered distinct patterns in species distribution, shedding light on the complex interplay among plant species within this ecosystem. The study habitat's rich species diversity, temporal variability, and key plant species' structural importance emerged as prominent themes. However, the current study also emphasized significant challenges posed by human activities. Deforestation driven by agricultural expansion and urban settlements, along with degradation from selective logging and forest thinning, emerged as major threats to the study area's ecological integrity. As a result, recognizing such an indication might be used to manage species in a range of microhabitats with varying soil types and climatic conditions. Assessing the abiotic and biotic variables that drive the ecosystem dynamics is one of the main goals nowadays, mainly due to the continuous process of climate change and anthropogenic impacts. These findings highlight the dynamic nature of plant communities and underscore the urgency of understanding these dynamics for effective conservation and management strategies. Understanding is crucial for preserving biodiversity and maintaining the ecological balance in this unique habitat. By acknowledging and addressing the impacts of human activities, we can protect these plant communities and uphold their critical roles within the broader ecosystem. These efforts are essential for ensuring the environmental health of Thirukudder Hill, thereby securing its resources and biodiversity for future generations.

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REFERENCES

Alig RJ, Adams DM, McCarl BA. 2002. Projecting impacts of global climate change on the US forest and agriculture sectors and carbon budgets. For Ecol Manag 169: 3-14. DOI: 10.1016/S0378-1127(02)00290-6.

Birhanu T, Mohammed AS, Mekonnen AB. 2021. Floristic composition, structure and regeneration status of woody plants in church forests of Dangila, Northwestern Ethiopia. Cogent Food Agric 7 (1): 1911438. DOI: 10.1080/23311932.2021.1911438.

Brockerhoff EG, Barbaro L, Castagneyrol B, Forrester DI, Gardiner B, González-Olabarria JR, Lyver POB, Meurisse N, Oxbrough A, Taki H, Thompson ID, van der Plas F, Jactel H. 2017. Forest biodiversity, ecosystem functioning and the provision of ecosystem services. Biodivers Conserv 26: 3005-3035. DOI: 10.1007/s10531-017-1453-2.

Curtis JT. 1959. The vegetation of Wisconism: An ordination of Plant communities. University of Wisconsin Press Madison, Wisconsin.

Davis E, Trant A, Hermanutz L, Way RG, Lewkowicz AG, Collier LS, Cuerrier A, Whitaker D. 2021. Plant–environment interactions in the Low Arctic Torngat Mountains of Labrador. Ecosystems 24: 1038-1058. DOI: 10.1007/s10021-020-00577-6.

De Paula LFA, Colmenares-Trejos SL, Negreiros D, Rosado BHP, de Mattos EA, de Bello F, Porembski S, Silveira FAO. 2020. High plant taxonomic beta diversity and functional and phylogenetic convergence between two Neotropical inselbergs. Plant Ecol Divers 13: 61-73. DOI: 10.1080/17550874.2019.1673846.

Desalegn W. 2002. Plant Communities and Diversity Along Altitudinal Gradients from Lake Abaya to Chencha Highland. [Ph.D Thesis]. Addis Ababa University, Addis Abababa, Ethiopia.

FAO. 2020. Global Forest Assessment (FRA) 2020: Terms and Definitions. Forest Resources Assessment Working Paper 188, Rome.

Gamble JS, Fischer CSC. 1915-1935. Flora of the Presidency of Madras, Vols I–III. Adlard and Son Ltd, London. DOI: 10.5962/bhl.title.21628.

Gebrehiwot K, Woldu Z, Fekadu M, Teferi E, Desalegn T, Demissew S. 2019. Classification and ordination of plant communities in Abune Yosef mountain range, Ethiopia. Acta Ecol Sinica 40 (5): 398-411. DOI: 10.1016/j.chnaes.2019.12.001.

Geisen S, Heinen R, Andreou B, van Lent T, ten Hooven FC, Thakur MP. 2022. Contrasting effects of soil microbial interactions on growth–defence relationships between early-and midsuccessional plant communities. New Phytol 233: 1345–1357. DOI: 10.1111/nph.17609.

Gomes L, Lenza E, Maracahipes L, Marimon BS, Oliveira EA. 2011. Comparacoes floristicas e estruturais entre duas comunidades lenhosas de cerrado típico e cerrado rupestre, Mato Grosso, Brasil. Acta Bot Bras 25 (4): 865-875. DOI: 10.1590/S0102-33062011000400013.

Hansen M, Potapov PV, Moore R, Hancher M, Turubanova SA, Tyukavina A, Thau D, Stehman SV, Goetz SJ, Loveland TR, Kommareddy A, Egorov A, Chini L, Justice CO, Townshend JRG, Kommareddy A. 2021. High-resolution global maps of 21st century forest cover change. Science 342 (6160): 850-853. DOI: 10.1126/science.1244693.

Henry AN, Chitra V, Balakrishnan NP. 1989. Flora of Tamil Nadu, India, Ser 1. Vol 3. Botanical Survey of India, Coimbatore.

Jiménez-Alfaro B, Girardello M, Chytrý M, Svenning JC, Willner W, Gégout JC, Agrillo E, Campos JA, Jandt U, Kącki Z, Šilc U, Slezák M, Tichý L, Tsiripidis I, Turtureanu PD, Ujházyová M, Wohlgemuth T. 2018. History and environment shape species pools and community diversity in European beech forests. Nat Ecol Evol 2: 483-490. DOI: 10.1038/s41559-017-0462-6.

Jiren TS, Hanspach J, Schultner J, Fischer J, Bergsten A, Senbeta F, Hylander K, Dorresteijn I. 2020. Reconciling food security and biodiversity conservation: Participatory scenario planning in southwestern Ethiopia. Ecol Soc 25 (3): 24. DOI: 10.5751/ES-11681-250324.

Kefalew A, Soromessa T, Demissew S. 2022. Plant diversity and community analysis of Sele-Nono forest, Southwest Ethiopia: implication for conservation planning. Bot Stud 63: 23. DOI: 10.1186/s40529-022-00353-w.

Khan A, Ahmed M, Ahmed F, Saeed R, Siddiqui F. 2020. Vegetation of highly disturbed conifer forests around Murree, Pakistan. Turk J Biodivers 3 (2): 43-53. DOI: 10.38059/biodiversity.708154.

Khan SM, Page S, Ahmad H, Shaheen H, Harper D. 2012. Vegetation dynamics in the Western Himalayas, diversity indices and climate change. Sci Technol Dev 31: 232-243.

Magurran A. 1988. Ecological Diversity and its Measurement. Princeton University Press, New Jersey. DOI: 10.1007/978-94-015-7358-0.

Matthew KM. 1991. An Excursion Flora of Central Tamil Nadu, India. Oxford and IBH, New Delhi.

Mayer R, Kaufmann R, Vorhauser K, Erschbamer B. 2009. Effects of grazing exclusion on species composition in high-altitude grasslands of the Central Alps. Basic Appl Ecol 10: 447-455. DOI: 10.1016/j.baae.2008.10.004.

Mewded B, Negash M, Awas T. 2019. Woody species composition, structure and environmental determinants in a moist evergreen Afromontane forest, southern Ethiopia. J For Res 31: 1173-1186. DOI: 10. 1007/ s11676- 019- 00894-0.

Mueller-Dombios D, Ellenberg H. 1974. Aims and Methods of Vegetation Ecology. John Wiley and sons. Inc. New York.

Nair NC, Henry AN. 1983. Flora of Tamil Nadu, India, Ser. 1, Vol I. Botanical Survey of India, Coimbatore.

Nuta IS, Niculescu M. 2019. Phytosociology, distribution and ecology of a Willow Community with False Tamarisk from the Lotru Valley (Romanian Carpathians). Not Bot Horti Agrobot Cluj-Napoca 47 (3): 621-628. DOI: 10.15835/nbha47311400.

Packiaraj P, Ramar R, Premkumar M, Suresh K, Gopala Krishnan S. 2023. A Preliminary Survey of Angiospermic Diversity of Thirukudder Hills in Madurai District, Tamil Nadu, India. Univers J Plant Sci 10 (2): 39-49. DOI: 10.13189/ujps.2023.100201.

Paudel PK, Sipos J, Brodie JF. 2018. Threatened species richness along a Himalayan elevational gradient: Quantifying the influences of human population density, range size, and geometric constraints. BMC Ecol 18: 6. DOI: 10.1186/s12898-018-0162-3.

Peters MK, Hemp A, Appelhans T. 2019. Climate–land-use interactions shape tropical mountain biodiversity and ecosystem functions. Nature 568: 88-92. DOI: 10.1038/s41586-019-1048-z.

Reich PB. 2009. Elevated CO_2 reduces losses of plant diversity caused by nitrogen deposition. Science 326: 1399-1402. DOI: 10.1126/science.1178820.

Rossi C, Kneubühler M, Schütz M, Schaepman ME, Haller RM, Risch AC. 2021. Remote sensing of spectral diversity: A new methodological approach to account for spatio-temporal dissimilarities between plant communities. Ecol Indic 130: 108106. DOI: 10.1016/j.ecolind.2021.108106.

Sax DF, Gaines SD. 2003. Species diversity: From global decreases to local increases. Trends Ecol Evol 18: 561-566. DOI: 10.1016/S0169-5347(03)00224-6.

Shaheen H, Khan SM, Harper DM, Ullah Z, Allem Qureshi R. 2011. Species diversity, community structure, and distribution patterns in western Himalayan alpine pastures of Kashmir, Pakistan. Mount Res Dev 31: 153-159. DOI: 10.1659/MRD-JOURNAL-D-10-00091.1.

Shailaja R, Sudha P. 2001. Biomass Studies; Field Methods for Monitoring Biomass. Oxford & IBH Publishing Co. Pvt. Ltd. New Delhi.

Shannon CE, Wiener W. 1963. The Mathematical Theory of Communication. University of Illinois Press, Urbana, IL.

Shimwell DW. 1971. Description of Classification of Vegetation. Sedgewick and Jackson, London.

Silva LO, Costa DA, Santo Filho KE, Ferreira HD, Brandao D. 2002. Levantamento florístico e fitossociologico em duas areas de cerrado sensu stricto no Parque Estadual da Serra de Caldas Novas, Goias. Acta Bot Bras 16 (1): 43-53. DOI: 10.1590/S0102-33062002000100006.

Van Doorn-Hoekveld WJ, Goytia SB, Suykens C, Homewood S, Thuillier T, Manson C, Van Rijswick HF. 2016. Distributional effects of flood risk management - a cross-country comparison of pre-flood compensation. Ecol Soc 21: 26. DOI: 10.5751/ES-08648-210426.

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Phytosociology and carbon sequestration potential of tropical forest landscape: A case from Northwest Chittagong, Bangladesh

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Abstract. *Chowdhury MIH, Rakib MH. 2024. Phytosociology and carbon sequestration potential of tropical forest landscape: A case from Northwest Chittagong, Bangladesh. Asian J For 8: 126-135.* This study evaluates the carbon sequestration potential of tree species within Sheikh Russel Aviary and Eco-Park, Bangladesh, emphasizing its contribution to carbon storage and biodiversity. Conducted in 2023, 781 individual trees from 27 families of 35 species were assessed across 18 plots (26×26 meters each) using a Randomized Block Design (RBD) to account for altitudinal variation (top, middle, bottom zones, total of 54 samples from 18 plots). Carbon sequestration was measured through allometric equations, while soil Organic Carbon (OC) was determined using the Loss on Ignition (LOI) method. Phytosociological parameters, such as species composition and height class, were analyzed to assess carbon storage. Results indicated that 44.3% of trees fell within the significant height class (12.1-17 m) for carbon sequestration, with *Acacia auriculiformis*, *Tectona grandis*, and *Gmelina arborea* sequestering 18.95, 13.18, and 3.67 tons/ha of carbon, respectively. The average biomass was 102.774 tons/ha, and carbon sequestration averaged 51.387 tons/ha. Soil organic carbon averaged 1.46%, with soil moisture content at 18.73%, indicating favorable growing conditions. Statistical analyses, including ANOVA, confirmed significant differences in carbon sequestration across altitudinal zones. Comparison with similar studies demonstrated that the park's carbon storage capacity is comparable to other hilly forests in Bangladesh. This research highlights the park’s role in climate mitigation and suggests adaptive management for enhancing carbon storage and biodiversity. Future studies should include understory vegetation and refined allometric models for a more comprehensive evaluation of its ecological potential.

Keywords: *Acacia auriculiformis,* allometric model, carbon sequestration, Eco-Park, importance value index

INTRODUCTION

Carbon sequestration is a vital ecosystem service that mitigates climate change by capturing and storing atmospheric carbon dioxide in vegetation, soils, and oceans. Forest ecosystems, particularly in tropical regions, play a crucial role in carbon storage, contributing significantly to global efforts to reduce greenhouse gas emissions (Talukdar et al. 2020). Bangladesh, a country rich in biodiversity, faces significant challenges in forest conservation. Besides its importance for biodiversity, forests in Bangladesh are also essential in term of carbon sequestration to mitigate climate change. The country’s forests are a critical component of global carbon cycles, storing an estimated 251.8 million Mg of carbon, with nearly half of this stored in the mangrove forests alone. Along with hill forests, they provide high potential for carbon conservation through REDD+ (Reducing Emissions from Deforestation and Forest Degradation) (Simon et al. 2018). However, deforestation and forest degradation due to overpopulation, shifting cultivation, and agricultural expansion pose serious threats to these ecosystems (Wabnitz et al. 2018).

In tropical developing countries like Bangladesh, REDD+ is becoming an increasingly important mechanism for conserving forests and protecting biodiversity, as in the case of the Sheikh Russel Aviary and Eco-Park which is situated in Rangunia Upazila, Chittagong, Bangladesh. This conservation area is an example of remarkable site that integrates ecological conservation with public recreation. Spanning 210 hectares, this park was established in 2001 to honor Sheikh Russel, the youngest son of Bangabandhu Sheikh Mujibur Rahman. Inaugurated by Prime Minister Sheikh Hasina, the park has since become a popular destination for tourists, especially nature and bird enthusiasts (Zhou 2018). Managed by the Chittagong South Forest Division, its unique features (Schnell et al. 2014), including hill forests, artificial plantations, and a ropeway cable car, attract visitors year-round, making it an ideal spot for ecotourism. The park’s strategic location, close to the Chittagong-Kaptai Highway, Karnafuly Paper Mill, and Kaptai hydroelectric project (Simiele et al. 2022), enhances its accessibility and significance.

The objectives of the Sheikh Russel Aviary and Eco-Park establishment are multifaceted. The park aims to conserve biodiversity, promote natural beauty, and create ecotourism opportunities for public recreation. Additionally, it seeks to establish an educational and research center to enhance knowledge about forest resources and wildlife. Public awareness campaigns within the park focus on the importance of conserving natural forest resources and wildlife, further emphasizing its role in environmental education. the park is dedicated to biodiversity conservation, offering a sanctuary for various bird species, including those that are endangered. The park also serves as a rehabilitation center for injured birds, providing them with proper care and treatment (Zukswert et al. 2023).

Phytosociology, the study of plant communities and their relationships, offers valuable insights into the ecological structure and carbon storage potential of forests. By analyzing species composition, abundance, and spatial distribution, phytosociological assessments help identify key species contributing to carbon sequestration (Mukul et al. 2014). Understanding the capacity of different tree species and forest stands to sequester carbon is essential for informing conservation and sustainable land management practices. Baseline estimates of carbon in forest ecosystems are crucial for the success of these projects. For instance, the hill forests in Bangladesh have a carbon density of 115.56 Mg/ha, while mangrove forests and Sal forests have carbon densities of 98.9 Mg/ha and 153.9 Mg/ha, respectively (Uddin et al. 2020; Teets et al. 2023). These figures highlight the significant role that Bangladesh's forests play in global carbon sequestration efforts. In the context of Sheikh Russel Aviary and Eco-Park, phytosociology provides a detailed understanding of the park's capacity to act as a carbon sink, emphasizing the importance of local biodiversity for climate change mitigation.

The Sheikh Russel Aviary and Eco-Park, with its diverse ecosystems, offers a unique opportunity to study the interplay between biodiversity conservation and carbon sequestration. The park's efforts to protect endangered bird species and rehabilitate injured birds contribute to the overall health of the ecosystem (Rolkier 2021), which in turn enhances its capacity for carbon storage (Rahman et al. 2022). Moreover, the park's focus on public education and awareness is crucial for fostering a deeper understanding of the importance of forest conservation in the fight against climate change. It is not only just a recreational site but also a vital ecological reserve that plays a significant role in biodiversity conservation, carbon sequestration (Talukdar et al. 2020), and environmental education. Research conducted in this park can provide valuable insights into the effectiveness of conservation strategies in Bangladesh, contributing to global efforts to mitigate climate change and preserve natural resources for future generations.

The aim of this study is to assess the phytosociological status and carbon sequestration potentials in Sheikh Russel Aviary and Eco-Park. Specifically, the research seeks to examine the diversity of tree species within the park, quantify the total carbon sequestration by these species, and explore the relationship between carbon sequestration potential and tree species diversity. Additionally, the study will measure soil moisture content and soil organic carbon to discover how tree species diversity and altitudinal variation influence carbon storage and soil properties (Rakib et al. 2024). By analyzing tree species distribution and biomass across different altitudes, the research aims to identify which species contribute the most to carbon sequestration (Ouimette et al. 2019). The hypothesis is that higher tree species diversity will positively correlate with greater carbon sequestration potential, and altitude will significantly impact both soil moisture content and organic carbon levels (NOAA 2019). The study also aims to identify the five species with the highest Importance Value Index (IVI) to determine their critical role in carbon capture. These insights will contribute to understanding how biodiversity enhances carbon sequestration and will provide valuable data for improving sustainable forest management practices.

MATERIALS AND METHODS

Study area and period

Sheikh Russel Aviary and Eco-Park is located in Nischintapur Mouza, Kudala Beat, under the Rangunia Range of the Chittagong South Forest Division, Bangladesh (Figure 1). The park spans 210 hectares, positioned between 22°18'–22°37' N and 91°58'-92°08' E (Rahman et al. 2022). Approximately 35 km east of Chittagong City, Aviary Park is easily accessible via the Chittagong-Kaptai Highway, near Chandraghona, the Karnafuly paper mill, and the Kaptai hydroelectric project. The park's hilly terrain, ranging from 50 to 350 meters in altitude (Mukul et al. 2014), offers a valuable landscape for studying carbon sequestration, Soil Moisture Content (SMC), and Organic Carbon (OC) across elevation zones, where altitude influences vegetation and soil properties (Moeys 2018). Climate conditions are subtropical, with annual precipitation of approximately 3000 mm and an average temperature of 26°C.

Research design

The study followed a Randomized Block Design (RBD), which was adopted to ensure the randomness and representativeness of the data collected. This design helps minimize environmental and soil variability across different parts of the study area, improving the reliability of the results (Mamun et al. 2022). The study area was divided into nine blocks based on altitude, which was further categorized into three plots within each block. These plots were labeled as Top, Middle, and Bottom zones to reflect the altitude at which they were located on the hills (Hossain et al. 2020; Uddin et al. 2020; Islam et al. 2022). This division allowed for an in-depth analysis of the effects of altitude on SMC, OC, and carbon sequestration potential (CSP). The quadratic sampling method was used to determine plot sizes, which were fixed at 26 meters by 26 meters for uniformity and to facilitate comparable data collection across all plots. This method is commonly used in ecological studies to assess the density and distribution of trees and soil properties within a specified area (Mamun et al. 2022) within each plot, detailed measurements of SMC and OC were recorded, enabling the analysis of carbon storage potential at different altitudes (Metzger et al. 2021). The data gathered from the different soil layers (Top and Bottom) within each block provide insights into the potential for sustainable forest management in similar hilly regions of Bangladesh (Figure 1).

Vegetation data collection

Soil data collection

In this study, a total of 18 plots were selected from nine blocks across the study area, ensuring a representative sample from different altitudinal zones (Mason et al. 2022a). Soil samples were collected from each plot at two depths: 0-15 cm and 15-35 cm. For each plot, soil samples were collected from two layers: surface soil (0-15 cm) and subsoil (15-35 cm). The rationale for selecting these depth intervals stems from their critical role in nutrient cycling and carbon storage. Surface soils generally contain higher concentrations of organic matter due to the accumulation of plant litter, while subsoil layers play a key role in long-term carbon sequestration. This sampling design aimed to assess variations in soil Organic Carbon (OC) and other soil properties (Zhang et al. 2014; Thong et al. 2020), such as Soil Moisture Content (SMC), across both the top to bottom portions of the hills. Collecting soil from these depths allows for a comprehensive understanding of the vertical distribution of OC and how it is influenced by environmental factors such as elevation, slope, and vegetation cover. The depth differentiation is essential for understanding how OC and SMC change with soil depth (Mason et al. 2022b), a factor that can significantly influence soil fertility, carbon storage capacity, and overall ecosystem functioning.

After collection, soil samples were prepared for analysis. The organic carbon content of the soil was determined using the Loss on Ignition (LOI) methodology via dry it at oven (112°C) till it reaches at constant weight after that burned it at furnace at 65°C for two and half hours the each 5 gram of dry soil sample and measures the log of ignition through equation mention in data analysis section properly (Shivanna 2022), a well-established technique for estimating OC in soil samples (Mamun et al. 2022). The LOI method involves heating soil samples to high temperatures to burn off organic matter, which can then be quantified by measuring the weight loss of the soil sample (Siarudin et al. 2021). This method is particularly useful in studies of soil carbon dynamics as it provides a reliable estimate of OC, especially in forest soils where organic matter content can vary significantly with depth and topography.

The determination of OC in this study followed a series of carefully controlled laboratory procedures (Shiferaw et al. 2022). First, the soil samples were placed in washed silica crucibles, which were pre-dried in an oven at 105°C for 20 minutes to remove any residual moisture. After drying, the soil samples were finely ground to ensure homogeneity, a crucial step for accurate OC measurements (Sharma et al. 2021). A 5-grams sample of the ground soil was weighed and placed in a silica crucible, which was then transferred to an electric furnace. The furnace was heated to 850°C, a temperature high enough to burn off the organic matter in the soil. The samples were kept in the furnace for three hours to ensure complete combustion of organic materials. After the combustion process, the crucibles were removed from the furnace and placed in a desiccator to cool. Cooling the samples in a desiccator is important as it prevents moisture from the air from being absorbed by the soil samples, which could alter the weight measurements. Once cooled, the crucibles were reweighed using an electric balance (Sharma et al. 2021), and the percentage Loss on Ignition (LOI) was calculated based on the weight difference before and after combustion. LOI represents the amount of organic matter that was burned off during the heating process and is a proxy for OC. The LOI values were then used to estimate the percentage of OC in each soil sample, which was expressed relative to the weight of the oven-dry soil.

Analysis of vegetation biomass and carbons

Tree Above-Ground Biomass (TAGB) was calculated using the formula provided by Mahmood et al. (2020). This formula estimates AGB based on tree diameter at breast height (D), tree height (H), and wood density (W). The formula is expressed as:

$$AGB = -6.6937 + 0.809 \times \ln (D^2 \times H \times W)$$

Where: Ln represents the natural logarithm. The diameter (D) is squared and multiplied by height (H) and wood density (W) to estimate the biomass in logarithmic terms. The constants (-6.6937 and 0.809) are derived from empirical data and calibrated the model to better fit the biomass data (Mahmood et al. 2020).

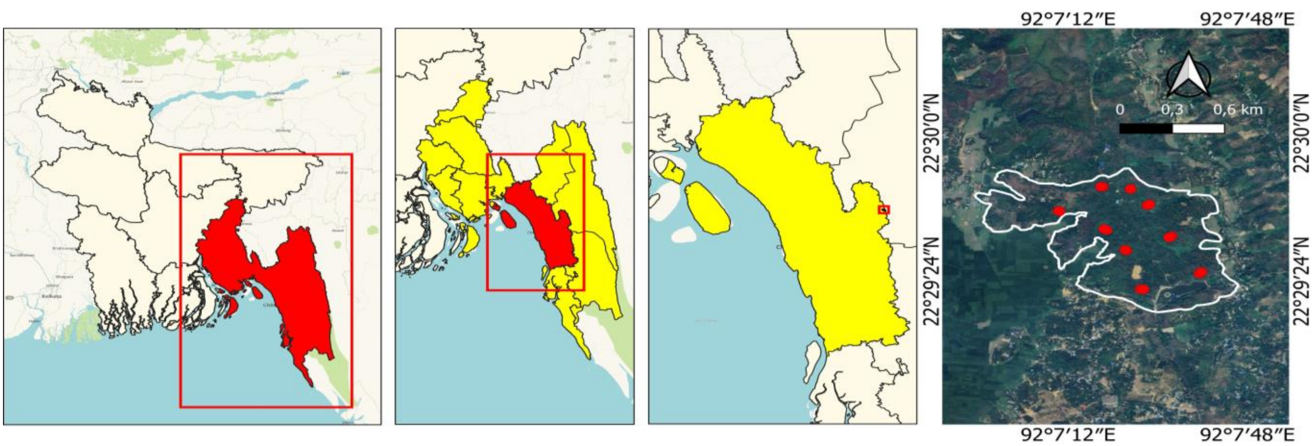

Figure 1. Map of study area showing sampling blocks in Sheikh Russel Aviary and Eco-Park, Bangladesh

Below-Ground Tree Biomass (BGTB) was estimated by applying a root-to-shoot ratio of 0.26 to the TAGB. This ratio, based on studies by Islam et al. (2016) and Hale et al. (2019), reflects the typical proportion of biomass found in the roots compared to the above-ground parts of the tree (Sharmake et al. 2023):

BGB = AGB × 0.26

To find the Total Tree Biomass (TTB), both The Above-Ground Biomass (TAGB) and Below-Ground Biomass (BGTB) are summed:

TTB = AGB + BGB

Carbon Sequestration Potential (CSP) was calculated as 50% of the Total Tree Biomass (TTB). This estimation reflects the portion of biomass that is converted to carbon and stored in the environment (Pearson et al. 2005; Islam et al. 2016):

CSP = TTB × 50%

Analysis of soil organic carbon

Soil Organic Carbon (OC) content was calculated with the formula (Seid 2022):

OC = 0.476 × (%LOI-108)

The subtraction of 108 from %LOI (percentage loss on ignition) adjusts for the residual inorganic matter, and the factor 0.476 converts the loss into an estimate of organic carbon content.

Statistical analysis

All collected data were analyzed using ANOVA (Analysis of Variance) to identify significant differences in soil Organic Carbon (OC) and Soil Moisture Content (SMC) between the top and bottom soil layers and among plots at different altitudes. Pairwise comparisons were conducted using the Tukey HSD test to detect specific differences between blocks (Mamun et al. 2022). Correlation analysis was performed to examine the relationship between OC and SMC. Results were visualized using ggplot2 in R, and ggboxplot was used to represent the distribution of SMC and OC across the study area, including pairwise comparisons between soil layers (Lovett et al. 2018).

RESULTS AND DISCUSSION

Phytosociological status

Acacia auriculiformis, Gmelina arborea, and *Tectona grandis* were three dominant species with the highest Importance Value Index (IVI), Relative Density (RD), Relative Dominance (RDo), and Relative Frequency (RF) (Table 1). Among the species, *A. auriculiformis* exhibited the highest IVI, exceeding 60%, which indicates its significant role in the forest's structure and composition. Both *G. arborea* and *T. grandis* had lower IVI values, suggesting they play a less prominent role in the forest. In terms of RD, *A. auriculiformis* and *T. grandis* showed comparable percentages, with both exhibiting high relative densities, whereas *G. arborea* had a notably lower RD. On the other hand, *T. grandis* displayed the highest RF among the species, indicating that it is more widely distributed throughout the sampled forest plots. The patterns of these forest parameters reveal that while *A. auriculiformis* dominates in terms of importance and density, *T. grandis* is more consistently distributed across the area.

In addition to its role in carbon sequestration, the diversity of tree species and families within the park supports a wide range of ecological processes and services. These include habitat provision for various wildlife species, soil stabilization, water regulation, and nutrient cycling. The presence of species from different families also indicates a resilient ecosystem capable of withstanding environmental changes and disturbances (Talukdar et al. 2020; Yousefiard et al. 2024). However, the study also points to the need for ongoing monitoring and management to maintain and enhance the ecological health of the park. This includes efforts to protect and promote the growth of young trees, manage invasive species (Sahoo et al. 2019), and ensure sustainable tourism practices. The high IVI values of certain species suggest that they are particularly well-suited to the local conditions and may be prioritized in future afforestation and conservation efforts (Siddique et al. 2024). Overall, the study provides a comprehensive overview of the tree species composition and structure within Sheikh Russel Aviary and Eco-Park, highlighting its significant role in carbon sequestration and biodiversity conservation.

Soil moisture content and soil organic carbon across varying depths

The comparison of Soil Moisture Content (SMC) between the top and bottom soil layers showed no significant differences, as indicated by the ANOVA test ($p=0.54$) (Figure 2.A). The mean SMC values were relatively similar between the two layers, with the top layer showing a mean value of approximately 17%, while the bottom layer demonstrated a slightly higher median value, although the difference was not statistically significant. The variability in moisture content, as observed through the scatter plot, was somewhat greater in the bottom layer, with some outliers indicating higher moisture retention at deeper soil levels (Kreiselmeier et al. 2020). This suggests that moisture distribution across soil depths is relatively uniform, with no clear stratification between the top and bottom layers.

The soil Organic Carbon (OC) was also assessed for both the top and bottom layers (Figure 2.B). The results showed no significant difference between the layers ($p =0.44$). However, the bottom layer exhibited higher variability in OC content compared to the top layer (Singh et al. 2018), as indicated by a broader interquartile range and several higher data points in the scatter plot. The median OC content in the top layer was approximately 1.5%, whereas the bottom layer's median was slightly higher, at around 2%. Although the difference was not statistically significant, the broader spread of OC values in the bottom layer suggests greater heterogeneity in organic matter accumulation at deeper soil depths.

Tree biomass and carbon estimation

The *A. auriculiformis* exhibited the highest total biomass, with an Above-Ground Biomass (AGB) of 29.49 t/ha (Table 2) and a Below-Ground Biomass (BGB) of 7.51 t/ha. This resulted in a Total Tree Biomass (TTB) of 34.89 t/ha, which was the highest among the species studied. The *T. grandis* ranked second, with a AGB of 11.05 t/ha and a BGB of 7.17 t/ha, contributing to a TTB of 25.23 t/ha. The *G. arborea* followed with a AGB of 9.41 t/ha and a BGB of 2 t/ha, leading to a TTB of 9.37 t/ha. These three species are the major contributors to the overall biomass in the study area (Table 2).

Species such as *Artocarpus heterophyllus* and *Terminalia arjuna* exhibited lower biomass levels, with TTB values of 4.38 t/ha and 3.50 t/ha, respectively as sample results showed (Chowdhury and Das 2024) where field study conducted in 2019 at Sheikh Russel Aviary and Eco-Park. The remaining species, including *Artocarpus chama*, *Syzygium cumini*, *Terminalia bellerica*, *Grewia nervosa*, and *Protium serratum*, had relatively smaller contributions to the total biomass, ranging between 1.98 t/ha and 3.23 t/ha.

Carbon sequestration potential (CSP)

The carbon sequestration potential (CSP) reflects the ability of these tree species to capture and store carbon. The *A. auriculiformis* demonstrated the highest CSP at 18.95 t/ha, aligning with its highest biomass values (Table 2). Similarly, *T. grandis* had a CSP of 13.18 t/ha (Karmakar et al. 2019), and *G. arborea* had 3.67 t/ha which is low from (Rudgers et al. 2022; Chowdhury and Das 2024). These three species stand out for their superior ability to sequester carbon (Talukdar et al. 2020), making them vital contributors to mitigating climate change impacts within the forest ecosystem. Lower CSP values were observed for *A. heterophyllus* (2.19 t/ha), *T. arjuna* (1.75 t/ha), and *A. chama* (1.62 t/ha). The remaining species had even lower CSP values, ranging from 0.99 t/ha (*P. serratum*) to 1.35 t/ha (*S. cumini*), reflecting their smaller role in carbon sequestration due to lower biomass accumulation. In summary the data suggests that tree species such as *A. auriculiformis*, *T. grandis*, and *G. arborea* not only dominate in terms of biomass but also hold significant potential for carbon sequestration (Islam et al. 2016, 2020). These findings highlight the importance of preserving and promoting such species in forest management and conservation efforts for maximizing carbon capture in the ecosystem (Hale et al. 2019).

Table 1. Relative frequency (RF), relative density (RD), relative dominance (RDo), and Importance Value Index (IVI) of trees

Species name	Family Name	RD (%)	RF (%)	RDo (%)	IVI
Acacia auriculiformis A. Cunn.	Mimosaceae	21.25	8.79	32.09	62.14
Tectona grandis L.f.	Verbenaceae	17.67	9.21	17.14	44.01
Gmelina arborea Roxb.	Verbenaceae	11.27	8.37	10.90	30.54
Artocarpus heterophyllus Lam.	Moraceae	7.04	2.93	5.57	15.54
Terminalia arjuna (Roxb.ex DC.)	Combretaceae	4.74	2.93	3.72	11.39
Artocarpus chama Buch.-Ham.	Moraceae	3.33	5.02	2.84	11.19
Syzygium cumini (L.) Skeels	Myrtaceae	3.46	5.02	1.81	10.29
Terminalia bellerica (Gaertn.)	Combretaceae	2.94	3.35	2.81	9.10
Grewia nervosa (Lour.) Panigr.	Tiliaceae	2.56	3.77	2.70	9.03
Protium serratum (Wall. Ex Coelbr.) Engl.	Burseraceae	2.30	2.93	1.71	6.95

Table 2. Total biomass and carbon sequestration potential of top 9 tree species based on relative density

Species	Biomass (kg)	AGB (t/ha)	BGB (t/ha)	TTB (t/ha)	CSP (t/ha)
Acacia auriculiformis A. Cunn.	167	29.49	7.51	34.89	18.95
Tectona grandis L.f.	139	11.05	7.17	25.23	13.18
Gmelina arborea Roxb.	90	9.41	2.00	9.37	3.67
Artocarpus heterophyllus Lam.	55	3.48	0.90	4.38	2.19
Terminalia arjuna (Roxb.ex DC.)	37	2.78	0.72	3.50	1.75
Artocarpus chama Buch.-Ham.	23	2.57	0.67	3.23	1.62
Syzygium cumini (L.) Skeels	26	2.15	0.56	2.71	1.35
Terminalia bellerica (Gaertn.)	13	1.85	0.48	2.34	1.17
Grewia nervosa (Lour.) Panigr.	20	1.78	0.46	2.24	1.12
Protium serratum (Wall. Ex Coelbr.) Engl.	18	1.57	0.41	1.98	0.99

Note: The table presents data on Biomass (kg), Above-Ground Biomass (AGB) in tons per hectare (t/ha), Below-Ground Biomass (BGB) in tons per hectare (t/ha), Total Tree Biomass (TTB) in tons per hectare (t/ha), and Carbon Sequestration Potential (CSP) in tons per hectare (t/ha)

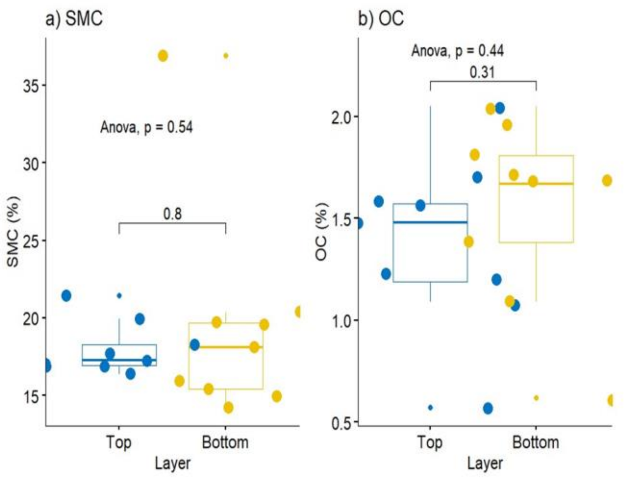

Figure 2. A. Soil moisture content across different layers of the hill in Sheikh Russel Aviary and Ecopark, Bangladesh; B. Organic carbon across different layers of the hill in Sheikh Russel Aviary and Ecopark, Bangladesh. For Soil Moisture Content (SMC) and Organic Carbon (OC), "top" refers to the soil layer at a depth of 0-15 cm, and "bottom" refers to the soil layer at a depth of 15-35 cm.

Soil carbon potential, soil moisture, and soil organic carbon across blocks

This study assessed the Carbon Sequestration Potential (CSP), Soil Moisture Content (SMC), and soil Organic Carbon (OC) across different blocks, with data collected at two distinct soil depths: Top (0-15 cm) and Bottom (15-35 cm). CSP, expressed in tons per hectare (t/ha), represents the soil's capacity to capture and store carbon dioxide (CO_2), which is essential for mitigating climate change by reducing atmospheric CO_2 concentrations (IPCC et al. 2019). Higher CSP values are crucial for long-term carbon storage, playing a key role in regulating global temperatures and supporting environmental sustainability (Islam et al. 2016).

The study found significant variations in CSP across different blocks, which were differentiated into three zones: top, middle and bottom (Harris and Gibbs 2021). At the top layer, Block 3 had the highest CSP (2.68 t/ha), a 141.4% higher compared to Block 5 (Table 3), which recorded the lowest value (1.09 t/ha). The middle layer showed the greatest variability (Hasan et al. 2021), with Block 2 having the highest CSP (4.55 t/ha), marking a 342% increase over Block 4 (Figure 3), which had the lowest CSP (1.03 t/ha). In the bottom layer, CSP was highest in Block 1 (2.74 t/ha), closely followed by Block 3 (2.82 t/ha), while Block 8 had the lowest value (1.43 t/ha), a difference of 94% between the highest and lowest blocks (Islam et al. 2022).

Soil Moisture Content (SMC) exhibited significant differences between different soil layers through different blocks. In the top layer, Block 2 recorded the highest SMC (21.45%), which was 30.8% greater than the lowest value in Block 1 (16.39%). The Bottom layer had the most pronounced variation (Henry et al .2021), with Block 6 showing the highest SMC (36.92%), more than double that of Block 8 (14.19%), a difference of 160%. Block 2 had the lowest Bottom-layer SMC (14.97%), 59.5% lower than Block 6, indicating substantial moisture retention differences across the study area.

Soil Organic Carbon (OC) levels also varied notably across soil layers and blocks. In the Top layer, Block 5 exhibited the highest OC (2.05%), which was 79.8% higher than Block 1 (0.57%). For the Bottom layer, Block 7 had the highest OC (2.05%), while Block 4 recorded the lowest OC (0.62%), resulting in a 230% difference. These variations in OC reflect differences in soil fertility and organic matter content across the blocks, influencing plant growth and carbon sequestration. The results revealed considerable variability in CSP, SMC, and OC across the study area. CSP values ranged from 1.03 to 4.55 t/ha, highlighting the differences in carbon storage capacity across different blocks (Hossain and Moniruzzaman 2021). Block 2 stood out with the highest CSP in the Middle layer (4.55 t/ha), indicating its superior ability to sequester carbon compared to other blocks, while Block 4 had the lowest CSP values overall. SMC also varied substantially between the Top and Bottom layers (Table 3), with Block 6 recording the highest Bottom-layer SMC (36.92%), suggesting better moisture retention in deeper soil layers, which could support more robust root systems and improve nutrient cycling. OC levels varied significantly as well (Hossain et al. 2015, 2020), with Block 5 exhibiting the highest Top-layer OC (2.05%) and Block 4 showing the lowest Bottom-layer OC (0.62%), indicating differences in soil organic matter content and fertility.

In summary, the findings from this study show that CSP, SMC, and OC exhibit high spatial and vertical variability across blocks and soil depths. Block 2 displayed the highest CSP in the Middle layer, Block 6 demonstrated significantly higher moisture content in the Bottom layer (Hossain et al. 2020), and Block 5 had elevated organic carbon in both Top and Bottom layers. This variability highlights the need for site-specific management strategies to optimize carbon sequestration, moisture retention, and overall soil health. Recognizing these spatial and vertical differences in soil properties is critical for developing effective forest management and conservation practices that maximize carbon capture and improve soil conditions across different regions.

Discussion

The study at Sheikh Russel Aviary and Eco-Park offers a comprehensive assessment of carbon sequestration potential, revealing the critical contributions of certain tree species to the park's ecological balance and carbon storage capacity. The *A. auriculiformis*, *T. grandis*, and other key species are highlighted for their substantial carbon sequestration rates, ranging from 17.95 to 1.35 t/ha (Zukswert et al. 2023). These findings underscore the significant role that targeted species selection plays in enhancing the carbon sink capacity of reforestation and afforestation projects, particularly in tropical regions like Bangladesh. The selection of *A. auriculiformis* and *T. grandis* as focal species in this study is particularly noteworthy given their well-documented growth rates and resilience in a variety of environmental conditions. The *A. auriculiformis*, for instance (Zhang et al. 2023), is recognized for its rapid growth and adaptability to poor soil conditions, making it a suitable candidate for areas in need of quick green cover and carbon sequestration. Also, the Mimosaceae has an excellent nitrogen-fixing ability which contributes to soil enrichment (Ahirwal et al. 2021a,b; Akhtar et al. 2022), indirectly supporting the growth of other plant species and enhancing overall forest productivity (French et al. 2023b). The *T. grandis*, commonly known as teak, is another fast-growing species that is valued not only for its timber but also for its significant carbon storage potential (Urcuqui-Bustamante et al. 2023). Its deep-rooting system helps stabilize soil (Aziz and Paul 2015; Aryal et al. 2020), reducing erosion, and maintaining soil moisture levels (Tables 2 and 3), which are critical for sustaining forest ecosystems in the long term. The presence of species like *G. arborea* and *A. heterophyllus*, which contribute to both carbon storage and biodiversity, adds an additional layer of ecological value to the park (French et al. 2023a). The *G. arborea*, for example (BFD 2017, 2020a), is known for its fast growth and ability to thrive in a variety of soil types, making it an excellent choice for reforestation projects aimed at both carbon sequestration and habitat restoration (Barna et al. 2011). Its wood is also used for various purposes, contributing to the local economy (Teets et al. 2023). The *A. heterophyllus*, or jackfruit (Table 1, Figure 2), not only sequesters carbon but also supports local food security by providing a nutritious fruit that is a staple in the region. The dual benefits of these species highlight the importance of integrating multifunctional trees into reforestation efforts to achieve both environmental and socio-economic goals (Mason et al. 2022a). The *T. arjuna*, another species highlighted in the study, plays a unique role in the ecosystem (Figure 3) due to its medicinal properties and its ability to support a diverse range of wildlife. Traditionally used in Ayurvedic medicine (Mason et al. 2022b), *T. arjuna* is valued for its therapeutic properties, which include the treatment of heart conditions. Its presence in the park not only contributes to carbon sequestration but also supports the conservation of traditional knowledge and practices (Fuss et al. 2019). Additionally, its role in providing habitat for various bird and insect species enhances the park's biodiversity (Jacob et al. 2024), making it a vital component of the ecosystem. The study also provides critical insights into the soil characteristics within the park (Banik et al. 2018; BFD 2020), which are essential for understanding the broader dynamics of carbon storage and ecosystem health (Bricker 2013). The soil Organic Carbon (OC) content (Mason et al. 2022b), averaging 1.46%, indicates a relatively healthy soil profile that is capable of supporting robust plant growth (Figures 3.A-B). OC is a key indicator of soil fertility and plays (Figure 2) a vital role in the global carbon cycle (Zhou et al. 2018) by acting as both a source and a sink for atmospheric carbon dioxide. The relatively high soil moisture content, averaging 18.73% (Gogoi and Sahoo 2018; Gogoi et al. 2021; Ghale et al. 2022), further supports the growth of the park's vegetation, contributing to a dense canopy that enhances the park's overall carbon sequestration potential (Ouimette et al. 2019).

However, the study acknowledges several limitations that could impact the accuracy and comprehensiveness of its findings. The exclusion of understory vegetation and soil carbon measurements, for instance, represents a significant gap in the assessment of the park's total carbon sequestration potential. Understory vegetation, while often overlooked, plays a crucial role in the carbon cycle by contributing to biomass and supporting nutrient cycling within the forest ecosystem (Chowdhury et al. 2023, 2024). Similarly, soil carbon is a critical component of the carbon cycle (Figure 3.B) that, if not fully accounted for, can lead to an underestimation of the ecosystem's true carbon storage capacity. Future studies should aim to include these factors to provide a more complete picture of the park's role in carbon sequestration (Fuss et al. 2019).

Table 3. Carbon sequestration potential, soil moisture content (%), and soil organic carbon (%) status from selected blocks of the study area

	CSP(t/ha)			SMC (%)		OC (%)	
	Top	**Middle**	**Bottom**	**Top**	**Bottom**	**Top**	**Bottom**
Block 1	1.11	1.17	2.74	16.39	19.57	0.57	1.67
Block 2	1.72	4.55	2.47	21.45	14.97	1.57	1.81
Block 3	2.68	1.51	2.82	16.94	18.12	1.71	1.71
Block 4	2.33	1.03	1.51	16.83	15.45	1.24	0.62
Block 5	1.09	1.60	1.54	17.08	20.37	2.05	1.95
Block 6	1.49	1.05	1.77	17.71	36.92	1.57	1.67
Block 7	1.61	1.89	1.94	19.97	19.71	1.48	2.05
Block 8	2.24	1.37	1.43	18.27	14.19	1.09	1.09
Block 9	1.99	2.06	2.70	17.28	15.98	1.19	1.38

Note: In the context of Carbon Sequestration Potential (CSP), the terms "top," "middle," and "bottom" refer to different zones of the hill. For Soil Moisture Content (SMC) and Organic Carbon (OC), "top" refers to the soil layer at a depth of 0-15 cm, while "bottom" refers to the soil layer at a depth of 15-35 cm

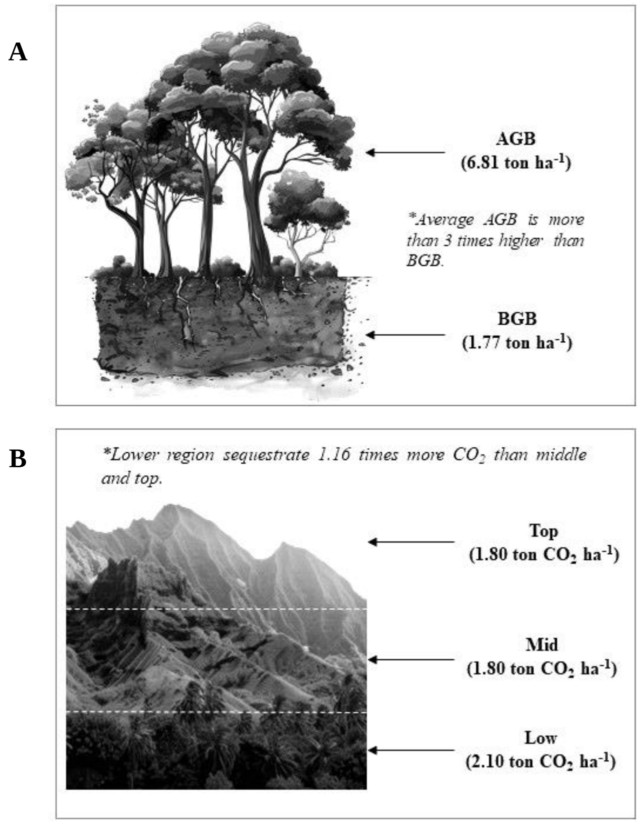

Figure 3. The figure illustrates: A. The average biomass of ten tree, and B. The carbon sequestration potential of hill at top, middle and bottoma of Sheikh Russel Aviary and Ecopark, Bangladesh

Moreover, the study's reliance on allometric equations for estimating carbon sequestration introduces potential uncertainties. While these equations are widely used in ecological research, they are often based on generalized models that may not fully capture the growth patterns and biomass accumulation of specific species (Lovett et al. 2018). This highlights the need for more field-based measurements to validate and refine the estimates provided by allometric models (Chowdhury et al. 2023). Additionally, the focus on carbon sequestration, while important, should be balanced with the consideration of other ecosystem services provided by the park. Biodiversity conservation, water regulation (Costello et al. 2016; Das et al. 2023), and soil protection are equally critical components of ecosystem health that should be integrated into park management and conservation strategies (Nath et al. 2019; Rakib et al. 2024). While the study offers valuable insights into the carbon sequestration potential of key tree species within Sheikh Russel Aviary and Eco-Park, it also emphasizes the need for a more holistic approach to understanding and managing the park's ecological contributions. Integrating a broader range of species (French et al. 2023b), accounting for understory vegetation and soil carbon, and considering the full spectrum of ecosystem services will be crucial for developing sustainable management practices. These practices should aim to balance the dual goals of carbon sequestration and biodiversity conservation, ensuring the long-term health and resilience of the park's ecosystem in the face of ongoing environmental challenges.

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REFERENCES

Ahirwal J, Nath A, Brahma B, Deb S, Sahoo UK, Nath AJ. 2021a. Patterns and driving factors of biomass carbon and soil organic carbon stock in the Indian Himalayan region. Sci Total Environ 770: 145292. DOI: 10.1016/j.scitotenv.2021.145292.

Ahirwal J, Saha P, Nath A, Nath AJ, Deb S, Sahoo UK. 2021b. Forest litter dynamics and environment patterms in the Indian Himalayan region. For Ecol Manag 499:119612. DOI: 10.1016/j.foreco.2020.119612.

Akhtar N, Uddin MK, Tan Y. 2022. Remote sensing-based changes in the Ukhia Forest, Bangladesh. GeoJournal 87 (5): 4269-4287. DOI: 10.1007/s10708-021-10494-3.

Aryal JP, Sapkota TB, Rahut DB, Jat ML. 2020. Agricultural Sustainability under emerging climatic variability: Role of climate smart agriculture and relevant policies in India. Intl J Innov Sustain Dev 14 (2): 219-245. DOI: 10.1504/IJISD.2020.106243.

Aziz A, Paul A. 2015. Bangladesh Sundarbans: Present status of the environment and biota. Diversity 7 (3): 242-269. DOI: 10.3390/d7030242.

BFD. 2017. Natural Mangrove Forest (Sundarbans). Bangladesh National Portal: Forest Department, Government of the People's Republic of Bangladesh. Government Database. http://www.bforest.gov.bd/site/page/19d63ffe-01e1-4351-b85b-3b60811b87f7/-.

BFD. 2020. Tree and Forest Resources of Bangladesh: Report on the Bangladesh Forest Inventory (Assessment No. GCP/BGD/058/USA). Forest Department, Ministry of Environment, Forest and Climate Change, Government of the People's Republic of Bangladesh, Dhaka, Bangladesh. http://bfis.bforest.gov.bd/bfi/.

Banik B, Deb D, Deb S, Datta BK. 2018. Assessment of biomass and carbon stock in sal (*Shorea robusta* Gaertn.) forests under two management regimes in Tripura, northeast India. J For Environ Sci 34 (3): 209-223. DOI: 10.7747/JFES.2018.34.3.209.

Barna C, Epure M, Vasilescu R. 2011. Ecotourism – conservation of the natural and cultural heritage. Rev Appl Soc-Econ Res 1 (1): 87-96.

Bricker K. 2013. The International Ecotourism Society. 11. CFSR. (1979). Global Weather Data for SWAT.

Chowdhury MIH, Das C. 2024. Carbon sequestration potentials for conservation of Sheikh Russel Aviary and Eco-Park, Rangunia, Chittagong. J Environ Sci Econ 3 (2): 90-101. DOI: 10.56556/jescae.v3i2.940.

Chowdhury MIH, Rakib MH, Das C. 2023. Intra and interspecific relation of tree species aspects of seed biometry, phenology, seed dispersion, and germination. J Agric Sustain Environ 2 (2): 57-69. DOI: 10.56556/jase.v2i2.877.

Chowdhury MIH, Rakib MH, Das C, Hossain Z. 2024. Tree species germination: A comprehensive meta-analysis and its implications for pre-sowing treatment in Bangladesh. J Soil Plant Environ 3 (1): 24-40. DOI: 10.56946/jspae.v3i1.397.

Costello L, Piazza M, Iqbal Z, Nur Siddiqui B, Akhter M, Siddiqui R, Henry M. 2016. Experiences in Field Missions to Locate the Plots of the 2005 National Forest Assessment (NFA) of Bangladesh (Assessment No. GCP/GD/058/USAID). Bangladesh Forest Department (BFD) and Food and Agriculture Organization of the

United Nations (FAO), Dhaka, Bangladesh. http://bfis.bforest.gov.bd/library/wp-content/uploads/2018/12/38.pdf.
Das S, Nama A, Deb S, Sahoo UK. 2023. Soil quality, carbon stock and climate change mitigation potential of Dipterocarp natural and planted forests of Tripura, Northeast India. Vegetos 36: 1105-1118. DOI: 10.1007/s42535-022-00515-y.
French KL, Vadeboncoeur MA, Asbjornsen H, Fraver S, Kenefic LS, Moore DB, Wason JW. 2023a. Resistance of mature red spruce trees to an experimental extreme drought. Theor Exp Plant Physiol 35: 31-49. DOI: 10.1007/s40626-023-00267-3.
French KL, Vadeboncoeur MA, Asbjornsen H, Fraver S, Kenefice LS, Moore DB, Wason JW. 2023b. Temporary thinning shock effects in previously shaded red spruce. Can J For Res 35: 31-49. DOI: 10.1139/cjfr-2022-0227.
Fuss CB, Lovett GM, Goodale CL, Ollinger SV, Lang AK, Ouimette AP. 2019. Retention of Nitrate-N in mineral soil organic matter in different forest age classes. Ecosystems 22 (6): 1280-1294. DOI: 10.1007/s10021-018-0328-z.
Ghale B, Mitra E, Sodhi HS, Verma AK, Kumar S. 2022. Carbon sequestration potential of agroforestry systems and its potential in climate change mitigation. Water Air Soil Pollut 233: 228. DOI: 10.1007/s11270-022-05689-4.
Gogoi A, Ahirwal J, Sahoo UK. 2021. Plant biodiversity and carbon sequestration potential of the planted forest in Brahmaputra flood plains. J Environ Manag 280: 111671. DOI: 10.1016/j.jenvman.2020.111671.
Gogoi A, Sahoo UK. 2018. Impact of anthropogenic disturbance on species diversity and vegetation structure of a lowland tropical rainforest of eastern Himalaya, India. J Mt Sci 15 (11): 2453-2465. DOI: 10.1007/s11629-017-4713-4.
Hale RP, Wilson C, Bomer E. 2019. Seasonal variability of forces controlling sedimentation in the Sundarbans National Forest, Bangladesh. Front Earth Sci 7: 00211. DOI: 10.3389/feart.2019.00211.
Harris N, Gibbs D. 2021. Forests absorb twice as much carbon as they emit each year. World Resources Institute, Washington DC. https://www.wri.org/insights/forests-absorb-twice-much-carbon-they-emit-each-year.
Hasan ME, Zhang L, Mahmood R, Guo H, Li G. 2021. Modeling of forest ecosystem degradation due to anthropogenic stress: The case of Rohingya Influx into the Cox’s Bazar–Teknaf Peninsula of Bangladesh. Environments 8 (11): 121. DOI: 10.3390/environments8110121.
Henry M, Iqbal Z, Johnson K et al. 2021. A multi-purpose National Forest Inventory in Bangladesh: Design, operation a lisation and key results. For Ecosyst 8: 12. DOI: 10.1186/s40663-021-00284-1.
Hossain F, Moniruzzaman M. 2021. Environmental change detection through remote sensing technique: A study of Rohingya refugee camp area (Ukhia and Teknaf Sub-district), Cox’s Bazar, Bangladesh. Environ Chall 2: 100024. DOI: 10.1016/j.envc.2021.100024.
Hossain MA, Hossain MK, Alam MS, Uddin MM. 2015. Composition and diversity of tree species in Kamalachari Natural Forest of Chittagong South Forest Division, Bangladesh. J For Environ Sci 31 (3): 192-201. DOI: 10.7747/JFES.2015.31.3.192.
Hossain MK, Alim A, Hossen S, Hossain A, Rahman A. 2020. Diversity and conservation status of tree species in Hazarikhil Wildlife Sanctuary (HWS) of Chittagong, Bangladesh. Geol Ecol Landsc 4 (4): 298-305. DOI: 10.1080/24749508.2019.1694131.
IPCC, Sato A, Vitullo M, Gschwantner T. 2019. Intergovernmental Panel on Climate Change 2014. Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Vol 4. IPCC, Geneva, Switzerland.
Islam I, Cui S, Hoque MZ, Abdullah HM, Tonny KF, Ahmed M, Ferdush J, Xu L, Ding S. 2022. Dynamics of tree outside forest land cover development and ecosystem carbon storage change in Eastern Coastal Zone, Bangladesh. Land 11 (1): 76. DOI: 10.3390/land11010076.
Islam KN, Rahman MM, Jashimuddin M, Islam K, Zhang Y. 2020. Impact of co-management on tree diversity and carbon sequestration in protected areas: Experiences from Bangladesh. Trees for People 2: 100033. DOI: 10.1016/j.tfp.2020.100033.
Islam MS, Tusher TR, Kabir MH, Hassan MR, Khan MNH. 2016. Carbon storage and sequestration potentiality of tree species in Madhupur Sal forest of Bangladesh. Bangladesh J Environ Sci 30: 33-39.
Jacob D, Ukpong E, Jacob I, Bassey E, Atabo L. 2024. A survey of butterfly species at the University of Uyo Main Campus, Nigeria. Sci Rep Life Sci 5 (1): 49-66. DOI: 10.5281/zenodo.11080923
Karmakar D, Ghosh T, Padhy PK. 2019. Effects of air pollution on carbon sequestration potential in two tropical forests of West Bengal, India. Ecol Indic 98: 377-388. DOI: 10.1016/j.ecolind.2018.11.014.
Kreiselmeier J, Chandrasekhar P, Weninger T, Schwen A, Julich S, Feger KH, Schwärzel K. 2020. Temporal variations of the hydraulic conductivity characteristic under conventional and conservation tillage, Geoderma 362: 114127. DOI: 10.1016/j.geoderma.2019.114127.
Lovett GM, Goodale SV, Ollinger C, Fuss Ouimette A, G, Likens. 2018. Nutrient retention during ecosystem succession: A revised conceptual model. Front Ecol Environ 16 (9): 532-538. DOI: 10.1002/fee.1949.
Mahmood H, Siddique MRH, Islam SMZ, Abdullah SMR, Matieu H, Iqbal MZ, Akhter M. 2020. Applicability of semi-destructive method to derive allometric model for estimating aboveground biomass and carbon stock in the Hill zone of Bangladesh. J For Res 31 (4): 1235-1245. DOI: 10.1007/s11676-019-00881-5.
Mamun AA, Hossain MK, Hossain MA. 2022. Ecological restoration through natural regeneration in Chunati Wildlife Sanctuary – a protected area of South-East Bangladesh. Ecofeminism Clim Chang 3 (1): 41-55. DOI: 10.1108/efcc-06-2020-0019.
Mason RE, Craine JM, Lany NK, Jonard M, Ollinger S, Groffman PM, Fulweiler RW, Angerer J, Read QD, Reich PB, Templer PH, Elmore AJ. 2022a. Evidence, causes, and consequences of declining nitrogen availability in terrestrial ecosystems. Science 376: eabh3767. DOI: 10.1126/science.abh3767.
Mason RE, Craine JM, Lany NK, Jonard M, Ollinger SV, Groffman PM, Fulweiler RW, Angerer J, Read QD, Reich PB, Templer PH, Elmore AJ. 2022b. Explanations for nitrogen decline—Response. Science 376: 1170-1170. DOI: 10.1126/science.abq8690.
Metzger JC, Filipzik J, Michalzik B, Hildebrandt A. 2021. Stemflow infiltration hotspots create soil microsites near tree stems in an unmanaged mixed beech forest. Front For Glob Chang 4: 701293. DOI: 10.3389/ffgc.2021.701293.
Moeys J. 2018. Soil texture: Functions for Soil Texture Plot, Classification and Transformation, R package version 1.5.1 [code]. https://CRAN.R-project.org/package-soil-texture.
Mukul SA, Biswas SR, Uddin MB, Alamgir M, Khan NA, Islam S, Chowdhury MSH, Rana P, Rahman SA. 2014. A new estimate of carbon for Bangladesh forest ecosystems with their spatial distribution and REDD+ implications. Intl J Res Land-use Sustain 1 (1): 33-41. DOI: 10.13140/RG.2.1.4864.2166.
Nath AJ, Tiwari BK, Silesh GW, Sahoo UK, Brahma B, Deb S, Devi NB, Das AK, Reang D, Chaturvedi SS, Tripathi OP, Das DJ, Gupta A. 2019. Allometric models for estimation of forest biomass in north east India. Forestry 10: 103. DOI: 10.3390/f10020103.
Ouimette AP, Ollinger LC, Lepine RB, Stephens RJ, Rowe MA, Vadeboncoeur SJ, Tumber-Davila, EA, Hobbie. 2019. Accounting for carbon flux to mycorrhizal fungi may resolve discrepancies in forest carbon budgets. Ecosystems 23: 715-729. DOI: 10.1007/s10021-019-00440-3.
Rahman MH, Roy B, Chowdhury GM, Hasan A, Saimun MSR. 2022. Medicinal plant sources and traditional healthcare practices of forest-dependent communities in and around Chunati Wildlife Sanctuary in southeastern Bangladesh. Environ Sustain 5 (2): 207-241. DOI: 10.1007/S42398-022-00230-z.
Rakib MH, Chowdhury MIH, Das C, Hossain T, Tanvir MSSI. 2024. Wildlife ecological spectrum: Unveiling alpha (α), beta (β), and gamma (γ) diversity of the Kaptai National Park, Bangladesh. Preprint. DOI: 10.21203/rs.3.rs-4668666/v1.
Rolkier G. 2021. Current Status of Nile lechwe in Gambella National Park. Scientific Reports in Life Sciences, 2(3), 18–24. DOI: 10.22034/srls.2021.245822
Rudgers JA, Fox S, Porras-Alfaro A, Herrera J, Reazin C, Kent DR, Souza L, Chung YA, Jumpponen A. 2022. Biogeography of root-associated fungi in foundation grasses of North American plains. J Biogeogr 49: 22-37. DOI: 10.1111/jbi.14260.
Sahoo UK, Singh SL, Gogoi A, Kenye A, Sahoo SS. 2019. Active and passive soil organic carbon pools as affected by different land use types in Mizoram, Northeast India. PLoS ONE 14 (7): e0219969. DOI: 10.1371/journal.pone.0219969.
Schnell S, Altrell D, Ståhl G, Kleinn C. 2014. The contribution of trees outside forests to national tree biomass and carbon stocks—A comparative study across three continents. Environ Monit Assess 187 (1): 4197. DOI: 10.1007/s10661-014-4197-4.
Siddique MRH, Hossain M, Manzoor Rashid AZM, Khan NA, Shuvo SN, Hassan MZ. 2024. Evaluating co-management in the Sundarbans

mangrove forest of Bangladesh: success and limitations from local forest users' perspectives. Ecol Soc 29 (2): 8. DOI: 10.5751/ES-14905-290208.

Simiele M, De Zio E, Montagnoli A, Terzaghi M, Chiatante D, Scippa GS, Trupiano D. 2022. Biochar and/or compost to enhance nursery-produced seedling performance: A potential tool for forest restoration programs. Forests 13 (4): 550. DOI: 10.3390/f13040550.

Simon LN, Mbua RL, Roger E. 2018. Estimation of carbon stock in Bimbia Bonadikombo coastal community forest, south west region, Cameroon: An implication for climate change mitigation. Intl J Sci Res Manag 6 (10): FE-2018-99-110. DOI: 10.18535/ijsrm/v6i10.fe02.

Singh SL, Sahoo UK, Kenye A, Gogoi A. 2018. Assessment of growth, carbon stock and sequestration potential of oil palm plantations in Mizoram, northeast India. J Environ Prot 9: 912-931. DOI: 10.4236/jep.2018.99057.

Seid YM. 2022. Biomass and soil carbon stocks of selected agroforestry practice and cultivated land, in Tehuledere District. Preprint. DOI: 10.21203/rs.3.rs-1935909/v1.

Sharmake MA, Sultan K, Hussain R, Rehman A, Hussain A. 2023. Decadal impacts of climate change on rainfed agriculture community in Western Somaliland, Africa. Sustainability 15 (1): 421. DOI: 10.3390/su15010421.

Sharma S, Rana VS, Prasad H, Lakra J, Sharma U. 2021. Appraisal of carbon capture, storage, and utilization through fruit crops. Front Environ Sci 9: 700768. DOI: 10.3389/fenvs.2021.700768.

Shiferaw H, Kassawmar T, Zeleke G. 2022. Above and belowground woody-biomass and carbon stock estimations at Kunzila watershed, Northwest Ethiopia. Trees for People 7: 100204. DOI: 10.1016/j.tfp.2022.100204.

Shivanna K. 2022. Climate change and its impact on biodiversity and human welfare. Proc Indian Natl Sci Acad 88: 160-171. DOI: 10.1007/s43538-022-00073-6.

Siarudin M, Rahman SA, Artati Y, Indrajaya Y, Narulita S, Ardha MJ, Larjavaara M. 2021. Carbon sequestration potential of agroforestry systems in degraded landscapes in West Java, Indonesia. Forests 12 (6): 714. DOI: 10.3390/f12060714.

Talukdar NR, Ahmed R, Choudhury P, Barbhuiya NA. 2020. Assessment of forest health status using a forest fragmentation approach: A study in Patharia Hills Reserve Forest, northeast India. Model Earth Syst Environ 6 (1): 27-37. DOI: 10.1007/s40808-019-00652-5.

Teets AA, S Bailey K, Hufkens SV, Ollinger C, Schädel B, Seyednasrollah AD, Richardson. 2023. Early spring onset increases carbon uptake more than late fall senescence: Modeling future phenological change in a US northern deciduous forest. Oecologia 201: 241-257. DOI: 10.1007/s00442-022-05296-4.

Thong P, Sahoo UK, Thangjam U, Pebam R. 2020. Pattern of forest recovery and carbon stock following shifting cultivation in Manipur, northeast India. PLoS ONE 15 (10): e0239906. DOI: 10.1371/journal.pone.0239906.

Uddin M, Chowdhury FI, Hossain MK. 2020. Assessment of tree species diversity, composition and structure of Medha Kachhapia National Park, Cox's Bazar, Bangladesh. Asian J for 4 (1): 15-21. DOI: 10.13057/asianjfor/r040104.

Urcuqui-Bustamante AM, Selfa TL, Jones KW, Ashcraft CM, Asbjornsen H, Jones KW, Manson RH, Mayer A. 2023. Using science-based role-play simulations to inform payment for hydrological services program design in Mexico. Environ Sci Policy 139: 71-82. DOI: 10.1016/j.envsci.2022.10.016.

Wabnitz CCC, Cisneros-Montemayor AM, Hanich Q, Ota Y. 2018. Ecotourism, climate change and reef fish consumption in Palau: Benefits, trade-offs and adaptation strategies. Mar Policy 88: 323-332. DOI: 10.1016/j.marpol.2017.07.022.

Yousefiard K, Naderi M, Ansari A, Kazemi A. 2024. Evaluation of the effects of oak forest changes on Persian Squirrel (*Sciurus anomalus*) habitat selection. Sci Rep Life Sci 5 (3): 37-47. DOI: 10.5281/zenodo.13777746

Zhang H, Yuan W, Dong W, Liu S. 2014. Seasonal patterns of litterfall in forest ecosystem worldwide. Ecol Complex 431: 240-247. DOI: 10.1016/j.ecocom.2014.01.003.

Zhang Z, Zhang L, Hang Creed IF, Blanco JA, Wei X, Sun G, Asbjornsen H, Bishop K. 2023. Forest water-use efficiency: Effects of climate change and management on the coupling of carbon and water processes. For Ecol Manag 534: 120853. DOI: 10.1016/j.foreco.2023.120853.

Zukswert J, Vadeboncoeur MA, Yanai RD. 2023. Responses of stomatal density and carbon isotope composition of sugar maple and yellow birch foliage to N, P, and $CaSiO_3$ fertilization. Tree Physiol 44: tpad142. DOI: 10.1093/treephys/tpad142.

Zhou Z, Ollinger SV, Lepine LC. 2018. Landscape variation in canopy nitrogen and carbon assimilation in a temperate mixed forest. Oecologia 188 (2): 595-606. DOI: 10.1007/s00442-018-4223-2.

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Phenology, diversity, community characteristics, and regeneration status of an endangered tree, *Aquilaria malaccensis* in homegarden of Tripura, Northeast India

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Abstract. *Chowdhury BD, Debnath A, Debnath B. 2024. Phenology, diversity, community characteristics, and regeneration status of an endangered tree,* Aquilaria malaccensis *in homegarden of Tripura, Northeast India. Asian J For 8: 136-146.* The present study was conducted in 90 tropical homegarden (HG) from 18 selected villages in Northeast India for the assessment of various ecological parameters of the agarwood (*Aquilaria malaccensis*) agroecosystem. Vegetation was studied using the quadrat method. Our result shows that all the HGs are important sources of forest genetic repositories. Phenological observation showed initiation of the reproductive phases is strongly correlated with the monsoon period in the state. The result also bared a total of 207 plant species to 186 genera, and 98 families were recorded. The *A. malaccensis* is accounting 100% frequency, and 823 individual ha^{-1} of the total tree density of 1635 ha^{-1}. The *A. malaccensis* contributed 26.17 m^2/ha of total basal area of woody species 89.59 m^2/ha. The ecological indices showed that the distribution of various woody species in homegardens is even and consistent. In different woody species, the Important Value Index (IVI) of *A. malaccensis* was the highest, followed by *Areca catechu*, *Mangifera indica,* and *Litchi chinensis.* The findings also showed that Poaceae is the dominant herbaceous family with 18 species, followed by Asteraceae and Areceae. The population structure of agarwood trees showed good regeneration status. The result clearly showed that the homegardens of NE India could serve as a valuable tool for the on-farm conservation of *A. malaccensis* and other associated commercially important plants' genetic diversity in this region. Sustainable uses and declaration of the agarwood tree as an agricultural crop could help to conserve these critically endangered taxa and promote the rural economy.

Keywords: Agarwood tree, agroforestry, essential oil, homegardens, North East India

INTRODUCTION

Tropical forests are the most diverse terrestrial ecosystems in the world, and also the hub of most of the global biodiversity hotspots identified worldwide (Sloan et al. 2014). Tropical forests, despite covering just 7% of the terrestrial surface globally, are home to more than half of the world's species. Moreover, over 90% of biodiversity resources are concentrated within human-influenced landforms in tropical regions (Garrity 2004). However, due to human activities, tropical forests are experiencing deforestation and forest degradation, leading to biodiversity loss (Talbot 2010). Therefore, to achieve forest sustainability, biodiversity conservation is essential. The evaluation can be performed using non-parametric units like diversity indices, which have become increasingly reputable over time (Yam and Tripathi 2016). The impact of this loss of biodiversity can be seen in changes in phenological events, interactions between species, distributions of species, morphological characteristics, and primary producer biomass (Beaumont et al. 2011). Research has shown that human-dominated landscapes are crucial for biodiversity conservation and livelihood sustainability (Endale et al. 2016; Gachuiri et al. 2017).

The occurrence of phenological events can be attributed to the way plant species adapt to the particular abiotic conditions present in their habitat (Wang et al. 2015; Paul et al. 2018), and therefore, these phenological events are sensitive to climate change (Hoffmann and Sgro 2011). Tree phenological events play a crucial role in providing early indications of how plants respond to climate change within the forest ecosystem (Montgomery et al. 2020). The shifting climate patterns can lead to alter in the timing of flowering and fruiting of individual plants as well as at the community level, influencing the way different species interact with each other. These changes can have far-reaching effects on the capacity of ecosystems to absorb carbon and on the reproductive processes of trees (Hazarika et al. 2023). Such changes will significantly affect ecosystem processes, and in this way, their services have made a significant impact on various communities and populations at different levels of space (Morisette et al. 2009). Hence, it is crucial to understand the alterations in natural phenophases of plants across various regions (Stucky et al. 2018).

The *A. malaccensis* is a valuable and endangered evergreen tree species that grows quickly and is native to the sub-tropical tropical rainforests of Northeast India (Rahman et al. 2011; Borogayary et al. 2018). It is recognized for its fragrant wood, which is used in the production of perfumes, incense, and traditional medicines and is a well-known commodity (Rasool and Mohamed

2016). The agar tree, which is indigenous and native to India and Southeast Asia, is the main source of agarwood (Hazarika et al. 2023). India is rich in biodiversity, hosting three significant species of *Aquilaria*, namely *A. malaccensis* Lam, *A. khasiana* Hall, and *A. macrophylla* Miq. (Mir et al. 2017). However, *A. malaccensis* is the most important and widely cultivated species, as it produces the highest quality agarwood (Saikia and Khan 2014). In recent years, agarwood has become an important income source for rural communities in North East India and other parts of the world (Rasool and Mohamed 2016). However, overexploitation and habitat loss have led to a decline in agarwood production, threatening the livelihoods of many communities (Borah et al. 2019).

Smallholder communities are increasingly recognized for maintaining plantations outside of forests (Betemariyam et al. 2020). These plantations can take various forms, but they all involve many trees being established through planting and/or seeding (Henry et al. 2009). Homegardens, which are traditional agroecosystems, are typically located near human habitations and carefully managed to fulfill daily needs. They support the distinct and occasionally rare genetic diversity found in crop plants and their wild counterparts (Saikia and Khan 2014). Homegardens have attracted considerable interest from ethnobotanists and other researchers due to their impact on preserving biodiversity, ecological and socio-economic objectives, sustaining local communities livelihoods, and potential for maintaining soil health (Saikia and Khan 2014). Agar-based HGs also support the intercropping of other tree species, which uplifts the socio-economic condition of small farmholders (Nath et al. 2024). Home gardens are rich in plant diversity, hosting a wide range of both crop and non-crop species due to diverse needs and traditional practices of local communities and the availability of species based on climate and edaphic factors (Coomes and Ban 2004). HGs provide repositories of genetic resources and biodiversity, which helps to improve agricultural crops. They also conserve rare species and preserve traditional knowledge to a greater extent (Ouinsavi and Sokpon 2008). Saikia et al. (2012) reported that the home gardens of upper Assam have high plant diversity and significant potential for conserving species with great economic value.

Tripura, a small hilly state in the Northeastern Region of India, falls within the 9B-North-East Hills biogeographic zone (Champion and Seth 1968). The area is situated within the Indo-Burma hotspot region (Champion and Seth 1968) and is part of the Indo-Burma hotspot region (Debbarma et al. 2015; Debnath and Debnath 2017). The Tropic of Cancer intersects Tripura throughout the state, making tropical forests prevalent in this state, which is characterized by considerable plant and animal diversity (Lodh and Agarwal 2016; Das and Datta 2018). Agarwood is a valuable and highly sought-after wood. Despite the potential benefits, the establishment of agarwood oil production in plantations has been hindered by the uncertainties surrounding its production process. Nevertheless, due to its significant commercial prospects, positive efforts are currently underway to cultivate agarwood trees in various regions around the world, including Tripura and adjoining areas in Northeast India (Assam), and South and Southeast Asia. In Tripura, agarwood is extensively grown in the home gardens of the North Tripura District. However, no report is available on agarwood-based HGs from Tripura, Northeast India. Therefore, the present study aimed to achieve the following objectives: (i) behavioral changes in major phenological events of the agarwood tree, (ii) species diversity and population structure using various ecological indices, (iii) regeneration status of *Aquilaria malaccensis* (critically endangered tree) in the selected HGs.

MATERIALS AND METHODS

Study sites

The study was conducted in the north district of Tripura (especially two major blocks: Ramnagar and Kadamtala), Northeast India (Latitude – 23°36′26″ - 24º34′22″ N & Longitude- 91°52′20″ - 92º51′00″ E) through randomly selected home gardens, covering an area of 1422.19 km^2 (Figure 1). The altitude ranges from 50-80 masl. The district is mainly plain in the north, while towards the south and east, it is undulating till a hilly peak. The region is bounded by the states Mizoram and Assam in the east, while the Dhalai and Unakoti Districts surround the west side. In the extreme north and south sides, the area is internationally bounded by Bangladesh. The population density of North Tripura Districts is 394 people per square kilometer (Census of India 2011). The Bengali Hindu community is known for its rich cultural activities, while the Bengali Muslim community maintains home gardens of various sizes. The economy of these study locations is mainly agar-based homegardens.

Temperature and precipitation data for the study sites were obtained from the NASA Data Access Viewer (nasa.gov). During the study period, Figure 2 illustrates the average monthly rainfall and temperature patterns. The climate is defined by monsoons, exhibiting pronounced seasonal fluctuations in temperature and precipitation. Winter sets in from November to February, bringing about comparatively lower temperatures (ranging from 8 to 17°C) and markedly reduced precipitation. The onset of the rainy season occurs in late April, marked by sporadic showers. The precipitation intensifies during the months of June and July and lasts until October. During the summer, the temperature ranges from 32 to 38°C. The annual average rainfall of North districts is 2,430 mm. June through August typically receive the majority of the annual rainfall, accounting for about 65% of the total.

Phenological observation

A total of 110 individual *A. malaccensis* (>30 cm diameter at the breast with clearly visible) trees were selected and properly tagged with uniform numbers throughout the seven sites of two selected blocks of North Tripura. Observations were made at monthly intervals from May 2020 to April 2022 for flowering and fruiting phenophases. Leafing phenophases were excluded because it is an evergreen species. However, maximum leaf bud and leaf senescence were observed. Binocular observations were made to check the overlapping of events and tree branches.

Sampling design and data collection

An extensive field survey was conducted in 90 randomly selected home gardens from 18 villages of North District of Tripura during 2020-2023 for phenology and vegetation analysis. The study began with a preliminary survey to collect information about agarwood cultivation areas in the district. After that, six villages were randomly selected from the central agarwood cultivation areas. Subsequently, 90 homegardens were chosen from these villages, approximately five homegardens on average in each village. In each quadrat, we meticulously documented the number of trees exceeding 30 cm in diameter at ground level for every species, along with their respective girth measurements. Furthermore, we meticulously recorded the traits and quantities of all seedlings (less than 40 cm in height), saplings, and coppices (greater than 40 cm in height and less than 30 cm in diameter at ground level) for both indigenous and exotic species (Bharathi and Prasad 2015). In order to study the vegetation in each homegarden, we utilized the quadrat method and ensured that at least 30% of the area was covered. Next, a total of 90 randomly placed 10×10 m quadrats to assess the distribution of all stand trees. Additionally, within each of these quadrats, one 5×5 m quadrat was designated for studying shrubs, while two 1×1 m quadrats were specifically allocated for examining herbaceous plants in each homegarden. Saplings and seedlings of *A. malaccensis* Lam were assessed using 5×5 m quadrats for saplings and 1×1 m quadrats for seedlings. These quadrats were randomly distributed within 10×10 m quadrats on the survey site. This approach was taken to thoroughly examine the population structure and assess the status of regeneration for *A. malaccensis* Lam. To conduct a comprehensive analysis of saplings and seedlings, a total of 90 quadrats were carefully laid out for saplings, while 180 quadrats were meticulously set up for seedlings. We took precise measurements of the circumference at breast height (1.37 m) to ensure an accurate determination of the trees' basal area; basal area (m^2/ha) determined the relative dominance of a tree species. The studied plant samples were identified with the help of various floras (Kanjilal et al. 1940; Deb 1981, 1983; Chowdhury 2005) and various published literature and articles. Then, the preliminary identification was confirmed by the Plant Taxonomy Laboratory, Department of Botany, Tripura University, and Dr. Kaushik Majumder.

Data analysis

The field data was compiled and analyzed to understand the status of phytosociological characteristics. The following parameters were considered: Family Relative Density (FRDe%), Family Relative Diversity (FRDi%), Family Importance Value (FIV), Density (D), Relative Density (RD%), Frequency (F), Relative Frequency (RF%), Relative Abundance (RA%), Basal Area (BA), Dominance (DO), Relative Dominance (RDO), and Importance Value Index (IVI). The detailed methods and equations are listed in Table 1. However, calculating floral diversity indices is listed in Table 2. The Species Diversity Index (SDI) starts from one when there is only one individual in one species, and the value reaches the maximum with the increase in species number (Odum 1971). All the data were assessed, and then the phytosociological characters such as Relative density (RD), Relative Frequency (RF), Basal Area (BA), Relative Dominance (RDO), Importance Value Index (IVI) were analyzed numerically and graphically using MS Excel 2013; different biodiversity indices viz. Simpson (D′), Shannon (H), Evenness (E), Brillouin (HB), Menhinick (M), Margalef (R), Fisher-alpha (S), Berger-Parker (B) were evaluated by the Software Past 4.03.

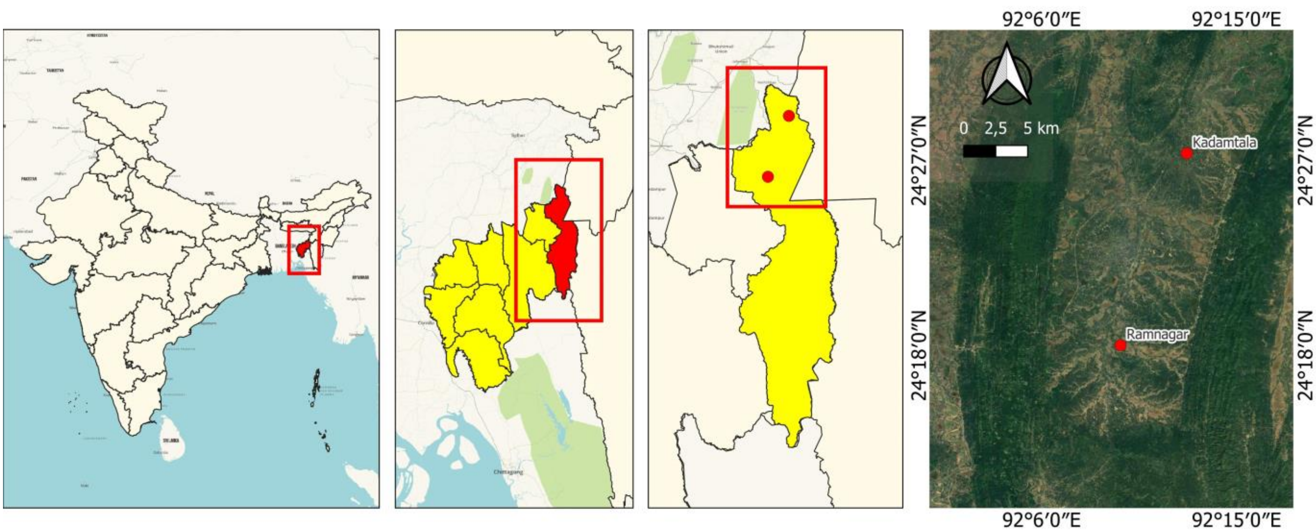

Figure 1. Map of Ramnagar and Kadamtala Blocks of North Tripura, Tripura, Northeast India, showing the locations of the study sites

Table 1. Summary of equations used for calculating plant sociological characteristics

Parameters	**Formula**	**Sources**
Family Relative Density (FRDe)	$FRDe = \frac{Number\ of\ individuals\ in\ a\ family}{Total\ number\ of\ individuals} \times 100$	Mori et al. (1983)
Family Relative Diversity (FRDi)	$FRDi = \frac{Number\ of\ species\ in\ a\ family}{Total\ no\ of\ species} \times 100$	Rahman et al. (2011)
Family Importance Value (FIV)	$FIV = FRDe + FRDi$	Rahman et al. (2011)
Density (D)	$\mathrm{D} = \frac{\text{Total number of individuals of a species in all quadrates}}{\text{Total number of quadrates studied}}$	Muller-Dombois and Ellenberg (1974)
Relative Density (RD)	$\mathrm{RD} = \frac{\text{Density of species}}{\text{Sum of the density of all species}} \times 100$	Kelbessa and Demissew (2014)
Frequency (F)	$F = \frac{\text{Total number of quadrates in which species occur}}{\text{Total number of quadrates studied}} \times 100$	Shukla and Chandel (2000)
Relative Frequency (RF)	$\mathrm{RF} = \frac{\text{Frequency of species}}{\text{Sum of frequency of all species}} \times 100$	Kelbessa and Demissew (2014)
Basal Area (BA)	$\mathrm{BA} = \frac{\pi d^2}{4}$	EWNHS (1996)
Dominance (DO)	$\mathrm{DO} = \frac{\text{Basal area of species}}{\text{area of quadrates in hectare}}$	Kelbessa and Demissew (2014)
Relative Dominance (RDO)	$\mathrm{RDO} = \frac{\text{Dominance of species}}{\text{Sum of dominance of all species}} \times 100$	Kelbessa and Demissew (2014)
Importance Value Index (IVI)	$IVI = RD + RF + RDO$	EFAP (1994)

Table 2. List of equations for accessing different biodiversity indices

Biodiversity Indices	**Formula**	**Sources**
Dominance (D)	$\mathrm{D} = \sum_{i=1}^{n} Pi^2$	Magurran (1988)
Simpson (D′)	$D' = 1 - D$	Magurran (1988)
Shannon (H)	$\mathrm{H} = \sum_{i=1}^{n} Pi^2 \ln(Pi)$	Michael (1990)
Evenness (E) / Equitability (J)	$E = \frac{\mathrm{H}}{\ln(S)}$	Pielou (1966)
Brillouin (HB)	$HB = \frac{\ln(N) - \sum_{i=1}^{n} \ln(ni)}{N}$	Brillouin (1962)
Menhinick (M)	$M = \frac{\mathrm{S}}{\sqrt{\mathrm{N}}}$	Menhinick (1964)
Margalef (R)	$\mathrm{R} = \frac{(\mathrm{S} - 1)}{\ln(N)}$	Margalef (1958)
Fisher_alpha (S)	$S = a \times \ln(1 + \frac{n}{a})$	Fisher et al. (1943)
Berger-Parker (B)	$B = Nmax - N$	Berger and Parker (1970)

The rejuvenation status of *A. malaccensis* tree was thoroughly scrutinized by precisely considering the abundance of delicate seedlings, growing saplings, and towering adult trees. "Good regeneration" indicates a healthy status when there are more seedlings than saplings and adults. "Fair regeneration" occurs when there are more or less seedlings than saplings or adults. "Poor regeneration" is determined when the species only survives as saplings or seedlings, regardless of the numbers in comparison to the adult population. "No regeneration" indicates that the species only exists in adult form. Finally, "new regeneration" signifies that the species only has seedlings or saplings and no adult trees (Bharathi and Prasad 2015).

RESULTS AND DISCUSSION

Flowering of agarwood trees was observed first in about February-March and occurred in the period from March to July. The duration of flowering phenophase was ranged between 35-75 days during the study period. Flowering in *A. malaccensis* was clearly influenced by the edaphic and climatic conditions like temperature, rainfall, etc. Whereas the fruiting phenophase duration ranged between April to late August, the highest fruiting was observed in May, June, and May in the years 2020-2021, 2021-2022, and 2022-2023 respectively. The unripe fruits were found to last a maximum of 45-50 days. The one-month lagging trend in fruiting was found through the three years of observation correlated with only rainfall was significant (Figure 2).

We have recorded a total of 207 plant species belonging to 186 genera and 98 families, with 108 herbs, 45 shrubs, and 54 tree species. The diversity of woody species is particularly notable, with the family Myrtaceae contributing the highest number of species (Table 3). Other families that add to the diversity of woody species are Rutaceae, Euphorbiaceae, Meliaceae, Papilionaceae, Lauraceae, and Lamiaceae, each with three species. The family Malvaceae is the most diverse in terms of shrub species, contributing five different species. Other families that add to the diversity of shrub species are Lamiaceae, Papilionaceae, and Solanaceae, each with four species. When it comes to herbaceous species diversity, the Poaceae family dominates with 18 different species, followed by Asteraceae with 13 species. Overall, the home gardens of North Tripura are an incredible resource for plant diversity, with a wide variety of species and families represented. The girth classes (30-90 cm) of all woody taxa together show similar shapes to the Agarwood tree, indicating a stable population structure (Figure 3), except for the ≥90 cm class. It may be the result of the selective felling of agarwood trees after a certain age to produce agarwood oil.

The present finding also revealed that agarwood, a tropical tree species, is the most dominant tree in the studied region, accounting for 100% of the frequency and 823.33 individuals ha^{-1} of the total tree density of 1,635 ha^{-1}. The *A. malaccensis* contributed almost half of the relative density (50.36), and the rest of the RD (49.64) were from 53 associated woody tree species (Table 3). This finding indicates a trend of mixed silviculture practices in the home gardens of North Tripura. The *A. malaccensis* was found to have the highest importance value index (IVI) of 93.53, followed by *Areca catechu* (30.14), *Mangifera indica* (20.55), *Artocarpus heterophyllus* (13.32), and *L. chinensis* (10.73) (Table 4). The number of individuals associated with woody taxa in all the study sites shows a similar pattern of different height classes to the agarwood tree alone (Figure 3).

The study also revealed that the HG's total basal area was 89.59 m^2/ha. Among the woody species observed, *A. malaccensis* had the highest basal area contribution of 26.17 m^2/ha, followed by *M. indica*, *A. heterophyllus*, and *L. chinensis* contributing 7.91 m^2/ha. 7.14 m^2/ha and 6.32 m^2/ha, respectively (Table 3).

Species diversity indices play a crucial role in assessing the health and structure of a forest ecosystem. Various diversity indices were enumerated in this study to determine the richness of the forest, which are listed in Table 4**.** According to Sobuj and Rahman (2011), the H' index value is higher for an ecosystem with rich species diversity, whereas an ecosystem with lower species diversity has a lower value. In the present study, the dominance value (d) and the evenness index (E) recorded for tree species were 0.33 and 0.78, respectively. These values indicate that the distribution of woody species in the home gardens is even. The evenness value of shrubs (0.94) and herbs (0.95) also shows their high diversity in the homogeneous. A higher evenness value suggests that the species distribution is more consistent (Sarkar and Devi 2014).

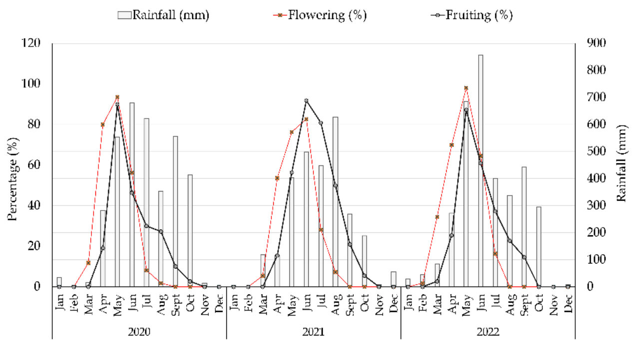

Figure 2. Relationship between monthly rainfall with *A. malaccensis* plant flowering and fruiting in monthly intervals from 2020 to 2022 [POWER | Data Access Viewer (nasa.gov)]

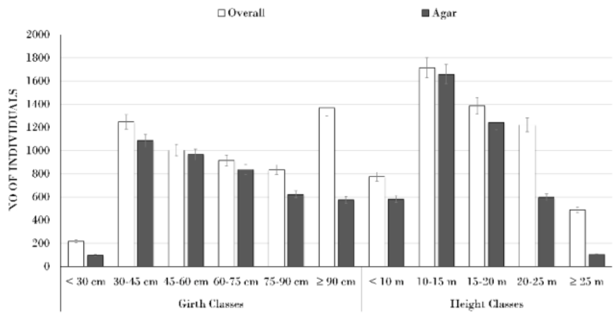

Figure 3. Comparison of individuals based on their girth and height classes between agarwood plants and other associated tree species

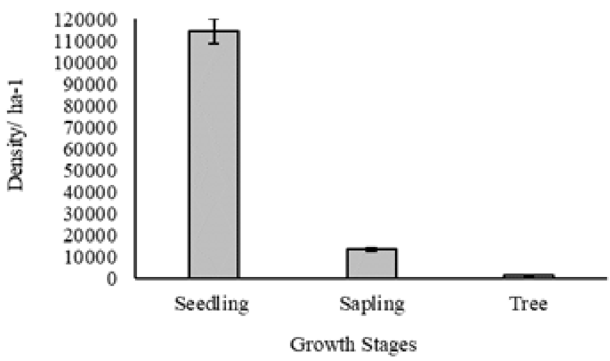

Figure 4. Seedling, sapling, and tree density ha^{-1} of agarwood in the studied home gardens of North Tripura, India

Table 3. Inventory of woody tree species in the studied homegardens and their different sociological values

Family name	Species name	Flowering period	Fruiting period	No. of species in family (Ns)	Total ind.	D	RD	F	RF	BA (sq.m)	DO (sq.m/ha)	RDO	IVI
Thymelaeaceae	*Aquilaria malaccensis* Lam.	Jul-Aug	Nov-Dec	1	741	8.23	50.36	100.00	13.95	23.56	26.17	29.22	93.53
Rutaceae	*Aegle marmelos* (L.) Correa	Mar-May	Mar-Jun	3	8	0.08	0.51	8.33	1.16	0.61	0.67	0.75	2.42
	Citrus ×limon (L.) Burm.f.	Jun-Jul, Sep-Oct, Jan-Feb	TY		5	0.05	0.31	5.00	0.70	0.06	0.07	0.08	1.08
	Citrus maxima (Burm.) Merr.	Mar-May	Jul-Sep		12	0.13	0.82	13.33	1.86	0.82	0.91	1.01	3.69
Apocynaceae	*Alstonia scholaris* (L.) R. Br.	Oct-Nov	Jan-Jun	1	8	0.08	0.51	8.33	1.16	0.14	0.16	0.17	1.85
Anacardiaceae	*Mangifera indica* L.	Jan-Mar	Mar-Jul	2	63	0.70	4.28	53.33	7.44	7.12	7.91	8.83	20.55
	Spondias pinnata (L. f.) Kurtz.	Apr-May	Jun-Aug		9	0.10	0.61	10.00	1.40	0.80	0.89	0.99	3.00
Annonaceae	*Annona cherimola* Mill.	Jun-Jul	Nov-Jan	1	6	0.07	0.41	6.67	0.93	0.06	0.07	0.08	1.41
Euphorbiaceae	*Antidesma acuminatum* Wight.	Jun-Jul	Dec-Jan	3	6	0.07	0.41	6.67	0.93	0.09	0.10	0.11	1.45
	Emblica officinales Gaertn.	Mar-May	Aug-Dec		12	0.13	0.82	13.33	1.86	0.11	0.12	0.14	2.81
	Hevea brasiliensis (Willd. ex A. Juss.) Müll. Arg.	Mar-Apr	Jun-Jul		9	0.10	0.61	3.33	0.47	0.18	0.20	0.22	1.30
Meliaceae	*Azadirachta indica* A. Juss.	Mar-Apr	May-Jun	3	11	0.12	0.71	11.67	1.63	0.50	0.56	0.63	2.97
	Toona ciliata M.Roem.	Jan-Mar	Mar-May		5	0.05	0.31	3.33	0.47	0.54	0.60	0.67	1.44
	Swietenia mahagoni (L.) Jacq.	Apr-May	Oct-Jan		2	0.02	0.10	1.67	0.23	0.04	0.05	0.05	0.39
Arecaceae	*Areca catechu* L.	Mar-Aug	Nov-May	2	209	2.32	14.17	88.33	12.33	2.94	3.27	3.65	30.14
	Cocos nucifera L.	TY	TY		21	0.23	1.43	23.33	3.26	3.60	4.00	4.46	9.14
Moraceae	*Artocarpus chaplasha* Roxb.	Jan-Mar	Apr-Jun	2	8	0.08	0.51	8.33	1.16	1.27	1.41	1.58	3.25
	Artocarpus heterophyllus Lam.	Mar-Apr	Jun-Aug		24	0.27	1.63	26.67	3.72	6.42	7.14	7.97	13.32
Oxalidaceae	*Averrhoa bilimbi* L.	Feb-Apr	May-Oct	2	17	0.18	1.12	18.33	2.56	0.31	0.34	0.38	4.06
	Averrhoa carambola L.	Jul-Aug	Oct-Jan		3	0.03	0.20	3.33	0.47	0.25	0.28	0.31	0.98
Phyllanthaceae	*Baccaurea motleyana* (Müll. Arg.) Müll. Arg.	NA	NA	2	3	0.03	0.20	3.33	0.47	0.05	0.06	0.06	0.73
	Breynia vitis-idaea (Burm. f.) C.E.C. Fisch.	Oct-Nov	Nov-Dec		5	0.05	0.31	5.00	0.70	0.34	0.38	0.43	1.43
Papilionaceae	*Butea monosperma* (Lamk.) Tanbert.	Jan-Mar	Feb-Apr	3	8	0.08	0.51	8.33	1.16	0.83	0.92	1.03	2.70
	Dalbergia sissoo Roxb.ex DC	Mar-May	May-Jul		2	0.02	0.10	1.67	0.23	0.15	0.17	0.19	0.52
	Sesbania grandiflora (L.) Poir.	Oct-Nov	Jan-Feb		14	0.15	0.92	15.00	2.09	1.52	1.69	1.89	4.90
Bombacaceae	*Ceiba pentandra* (L.) Gaertn.	Jan-Apr	Jun-Aug	1	5	0.05	0.31	5.00	0.70	0.99	1.10	1.22	2.23
Lauraceae	*Cinnamomum glanduliferum* (Wall.) Meisn.	Mar-May	Jul-Sep	3	3	0.03	0.20	3.33	0.47	0.48	0.54	0.60	1.27
	Cinnamomum tamala (Buch.-Ham.) T.Nees & Eberm.	Mar-Apr	May-Jul		9	0.10	0.61	10.00	1.40	1.66	1.84	2.05	4.06
	Cinnamomum zeylanicum Blume.	Mar-Apr	Jul-Nov		17	0.18	1.12	18.33	2.56	0.99	1.10	1.23	4.91
Fabaceae	*Pterocarpus santalinus* L.f.	Feb-Aug	Sep-Jan	1	6	0.07	0.41	6.67	0.93	0.35	0.39	0.44	1.78
Dilleniaceae	*Dillenia indica* L.	Jul-Aug	Aug-Apr	1	6	0.07	0.41	6.67	0.93	0.76	0.84	0.94	2.28
Dipterocarpaceae	*Dipterocarpus turbinatus* C.F.Gaertn.	Mar-Apr	Apr-May	1	20	0.22	1.33	15.00	2.09	1.80	1.99	2.23	5.64
Elaeocarpaceae	*Elaeocarpus serratus* L.	Mar-Jun	Jul-Oct	1	11	0.12	0.71	11.67	1.63	0.46	0.51	0.57	2.91
Lamiaceae	*Gmelina arborea* Roxb.	Feb-Apr	May-Jun	3	26	0.28	1.73	18.33	2.56	2.92	3.25	3.63	7.92
	Tectona grandis L.	Jun-Sep	Nov-Jan		30	0.33	2.04	21.67	3.02	2.53	2.81	3.14	8.20
	Vitex peduncularis Wall. ex Schauer	Mar-Apr	Apr-Jun		6	0.07	0.41	6.67	0.93	0.16	0.17	0.19	1.53

Myristicaceae	*Knema angustifolia* (Roxb.) Warb.	Nov-Feb	NA	1	5	0.05	0.31	5.00	0.70	0.13	0.15	0.17	1.17
Lythraceae	*Langerstroemia speciosa* (L.) Pers.	Apr-Jun	Jun-Aug	1	8	0.08	0.51	8.33	1.16	0.31	0.34	0.38	2.06
Sapindaceae	*Litchi chinensis* Sonn.	Feb-Mar	Apr-Jun	2	17	0.18	1.12	18.33	2.56	5.68	6.32	7.05	10.73
	Sapindus mukrossi Gaertn.	May-Jun	Oct-Nov		2	0.02	0.10	1.67	0.23	0.07	0.07	0.08	0.42
Sabiaceae	*Meliosma simplicifolia* (Roxb.) Walp.	Apr-Jun	May-Jul	1	9	0.10	0.61	10.00	1.40	1.29	1.43	1.60	3.60
Calophyllaceae	*Mesua ferrea* L.	Apr-Jun	Jul-Sep	1	6	0.07	0.41	6.67	0.93	0.45	0.50	0.56	1.90
Myrtaceae	*Metrosideros robusta* A.Cunn.	Nov-Jan	Feb-Apr	4	8	0.08	0.51	8.33	1.16	0.45	0.50	0.56	2.23
	Psidium guajava L.	Jun-Jul	Jul-Sep		11	0.12	0.71	11.67	1.63	0.18	0.21	0.23	2.57
	Syzygium cumini (L.) Skeels	Feb-Mar	Mar-Jul		8	0.08	0.51	8.33	1.16	0.75	0.84	0.94	2.61
	Syzygium jambos (L.) Alston.	Feb-Apr	Jun-Jul		8	0.08	0.51	8.33	1.16	1.08	1.20	1.34	3.02
Malvaceae	*Microcos paniculata* L.	Mar-May, Jul-Sep	Jul-Sep	1	6	0.07	0.41	6.67	0.93	0.15	0.17	0.19	1.53
Moringaceae	*Moringa oleifera* Lamk.	Jun-Jul	Jul-Sep	1	12	0.13	0.82	13.33	1.86	1.45	1.61	1.79	4.47
Rubiaceae	*Nauclea sessilifolia* Roxb.	Aug-Dec	Oct-Apr	1	5	0.05	0.31	5.00	0.70	0.65	0.73	0.81	1.81
Santalaceae	*Santalum album* L.	Jul-Oct	Dec-Mar	1	6	0.07	0.41	6.67	0.93	0.37	0.41	0.46	1.80
Caesalpinaceae	*Saraca asoca* (Roxb.) de Wilde	Mar-May	Jun-Jul	2	5	0.05	0.31	5.00	0.70	1.43	1.59	1.78	2.78
	Tamarindus indica L.	May-Jun	Dec-Jan		5	0.05	0.31	5.00	0.70	0.15	0.16	0.18	1.19
Combretaceae	*Terminalia arjuna* (Roxb.) Wight & Arn.	Apr-May	Feb-May	1	2	0.02	0.10	1.67	0.23	0.13	0.15	0.16	0.50
Rhamnaceae	*Ziziphus mauritiana* Lam.	Jul-Nov	Jan-Mar	1	14	0.15	0.92	16.67	2.33	0.48	0.54	0.60	3.84
	Total			54	1472	16.35	100.00	716.67	100.00	80.63	89.59	100.00	300.00

Note: D: Density, RD: Relative Density, F: Frequency, RF: Relative Frequency, BA: Basal Area, DO: Dominance, RDO: Relative Dominance, IVI: Importance Value Index. TY: Throughout the year. *Total number of trees recorded in 0.9 ha (90 quadrants each 10×10 m) = 1472

Table 4. Phytosociological attributes of the standing tree, shrub, and herbaceous species in the HGs of North Tripura, India

Indices	Tree	Shrub	Herb
Individuals (Avg.)	16.35	36.16	70.84
Number of genera	48	40	98
Number of families	32	23	43
Dominance (d)	0.33	0.09	0.05
Simpson (d′)	0.67	0.91	0.95
Shannon (H)	1.50	2.57	3.27
Evenness(E)/Equitability(J)	0.78	0.94	0.95
Brillouin (H_B)	1.12	2.09	2.73
Menhinick (M)	1.75	2.59	3.89
Margalef (R)	2.18	4.05	7.45
Fisher_alpha (S)	5.98	10.85	24.88
Berger-Parker (B)	0.51	0.15	0.10

Population structure and regeneration status

The density of mature agarwood trees with a diameter at a breast height (≥30 cm) was found to be 823±52.05 individuals ha^{-1} in the home gardens studied. However, the number of agarwood saplings and seedlings per hectare was 13,314±649.36 and 114,500±1374.38, respectively. The population structure of agarwood in the studied home gardens displayed a promising regeneration status, with the density of seedlings exceeding that of saplings and mature trees. This trend, where seedlings were more abundant than saplings and mature trees, is an encouraging sign for the future sustainability of the agarwood species (Figure 4). The seedling survivability rate ranged between 8.78-11.63 and was highest found in the Kadamtala Block of North Tripura, especially in the Fulbari, Laxminagar, and Saraspur sites.

Discussion

According to phenological changes over each year, it was observed that *A. malaccensis* showed a seasonal pattern of flowering and fruiting. The one-month-lag pattern in fruiting was similar to the study by Borogayary et al. (2018), which could be influenced by the major environmental and climatic factors, i.e., temperature and rainfall. The initiation of fruiting during the rainy season clearly indicates the close relationship between the average rainfall and the fruiting of the agarwood tree. This phenomenon evolved to ensure dispersal and seed germination by utilizing the soil water and seedling establishment of recalcitrant seeds of agarwood trees. This systematic seed germinating strategy was commonly found in tropical trees.

The agarwood tree is a valuable plant frequently grown in home gardens alongside other important crops in the sites. Our study has revealed that the homegardens in North Tripura, particularly in Panisagar and Kadamtala Blocks, are extremely rich in plant diversity. Due to different management practices and preferences of farm owners, the variation in woody stand richness is observed (Wade et al. 2010; Birhane et al. 2020). A high IVI value suggests that farmers intend to intensively manage agarwood trees on their farmlands to increase economic success. Additionally, a diverse range of fruit-producing and timber trees as associated species in the mixed culture shows the various benefits provided by the farms, which aligns with observations from other parts of India (Saikia and Khan 2014; George and Christopher 2019). The presence of fruit-yielding (*M. indica*, *A. heterophyllus*, *L. chinensis*, and *Cocos nucifera*) and timber-yielding (*Tectona grandis*, *Gmelina arborea*, *Dipterocarpus turbinatus*, and *Artocarpus chaplasha*) tree species indicates the farmer's intention to diversify their income source. The variety of tree species found on farmland depends on the supply needs of the owner. The noteworthy use of resources supplied by associated tree species is studied by analyzing the functional diversity. It is worth noting that the home garden owners we visited tended to allocate more land, particularly from the dense areas, for areca nut cultivation. Despite the remarkable diversity in these home gardens, there is a possibility that the commercialization of areca nut may lead to a reduction in the diversity of other surrounding species in home gardens in the future.

Our study unveiled a rich tapestry of species thriving in agarwood-based small-scale agriculture, a testament to the farmers' pivotal role in shaping this diversity. A total of 54 tree species, spanning 32 families, were documented in these small-scale farms, a qualitative reflection of the farmers' diverse choices in catering to their needs. The same findings have been reported in the agroforestry systems of Ghana and Costa Rica for coffee (*Coffea arabica*) and cocoa (*Theobroma cacao*), respectively (Asigbaase et al. 2019; de Sousa et al. 2019). Similar observations have also been made in home gardens across different regions of India, highlighting their varying conservation significance (Das and Das 2005; Vibhuti et al. 2019).

The potential of the home garden as a repository for genetic diversity is one element of high floral diversity (Saikia and Khan 2012). Overall, the data indicates that the Poaceae family has the highest number of species (18), followed by Asteraceae (13) and Araceae (8). This diversity is often associated with the amount of rainfall and the nutrient status of the site (Hartshorn 1980). Despite the rich species diversity, the high similarity index between study locations suggests a shared cultural influence among household owners, shaping the flora composition in these areas.

Although tree density (1635 individuals ha^{-1}) and the tree species' basal area (89.59 m^2 ha^{-1}) in home gardens of North Tripura was higher than the recorded tree density in home gardens of Kerala (238-319 ha^{-1}) and Assam (1535 ha^{-1}) (Kumar et al. 1994; Das and Das 2005), the significance of this finding lies in the potential of these home gardens to support ecosystem services. The higher density of tree species in the homegardens of North Tripura may be because of the choice of the farmholder for cultivating all possible species of common domestic uses. The tree density noted in this study is similar to that described by Saikia and Khan (2014) in the selected homegardens of Assam and also by Nath et al. (2020) in Barak Valley in the Karimganj District of Assam. The use of diversity indices is important for quantifying community diversity and describing its numerical structure. In tropical forests of the Indian subcontinent, the Shannon–Wiener diversity index is generally high, ranging from 0.81 to 4.1 (Bhuyan et al. 2003). This index signifies a similar structure of home gardens in the upper Assam and tropical forests of the Indian subcontinent. Generally, there is an inverse relationship between species diversity and concentration dominance (Joshi and Behera 1991). The Shannon diversity in our study (0.76-2.25) is similar to that found in smallholder agroforestry farms in Ethiopia (1.75-2.29) (Jegora et al. 2019; Birhane et al. 2020) and India (0.99-3.99) (Saikia and Khan 2016; Vibhuti et al. 2019). However, the evenness index of this study (0.38-0.59) was less than the values (0.76-0.90) reported in homegardens in Ethiopia (Jegora et al. 2019). This suggests that smallholder homegardens contribute to and enhance positive benefits of the ecosystem, which would then need to be obtained from natural forests. Therefore, the intervention of human impacts in forests has been reduced for extracting NTFP products by agarwood-based smallholder farms.

Compared to other products of homegardens, agarwood has a potentially immense commercial value. This potentiality depends on the maturity of the tree, the quantity of resinous wood produced, and the degree of infection. The production of resinous agarwood is considered a defense strategy by the tree against microbial infection or wounds caused by borer-insect or natural injury. In North Tripura, traditional growers commonly promote rapid agarwood formation by artificially wounding tree trunks through pin-hole nailing or making big holes. Various edaphic and genetic factors of individual trees, along with age and periodic growth variations, also play a crucial role in the induction of oleo-resinous blackwood (Ng et al. 1997). While an individual *A. malaccensis* tree provides a one-time income to the family, using intercropping can make agarwood a more desirable cash crop in the region's home gardens. The successful natural regeneration of the species depends on the population structure, which is characterized by seed production, germination, and the establishment of seedlings and saplings. The presence of a sufficient number of young plants indicates good regeneration despite competition from surrounding vegetation (Bhuyan et al. 2003). A species' ability to regenerate demonstrates its suitability to the environment. The characteristics of specific areas and local environmental conditions also affect tree regeneration from seeds (Schulte and Marshall 1983). Variations in seedling survival rates in different home gardens are primarily due to varying levels of disturbances. The higher survival rates during the rainy season may be attributed to favorable growing conditions and increased availability of soil moisture and nutrients resulting from rapid leaf litter decomposition (Khumbongmayum 2004).

In conclusion, the homegardens of North Tripura are known for their remarkable diversity of plant species, many of which hold significant economic potential. Among these, *A. malaccensis* stands out as a particularly valuable and sought-after commodity. However, due to its limited availability but highly demanded, agarwood is at high risk of extinction and requires careful conservation and management to ensure its continued existence. Fortunately, the results of recent studies have shown that agarwood has displayed good natural regeneration and population status in the homegardens of North Tripura. This suggests that homegardens could serve as a valuable tool for the conservation of agarwood and other associated plant species, sparking interest in the potential economic benefits of conservation efforts. In addition, the associated woody plants that grow alongside agarwood in these homegardens provide smallholder farmers with additional benefits, such as sources of wood, fruits, and firewood, without requiring any extra care or effort. Based on these findings, agarwood could be cultivated in home gardens in other parts of Northeast India, potentially boosting the rural economy. Our findings also strongly support that the declaration of *A. malaccensis* as a cultivated species will be an effective conservation tool for this critically endangered taxa. By promoting the conservation and management of agarwood, we can help ensure the continued prosperity and sustainability of the region's homegardens while providing much-needed economic opportunities for local farmers.

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REFERENCES

Asigbaase M, Sjogersten S, Lomax BH, Dawoe E. 2019. Tree diversity and its ecological importance are valued in organic and conventional cocoa agroforests in Ghana. Plos One 14: e0210557. DOI: 10.1371/journal.pone.0210557.

Beaumont L, Pitman A, Perkins S, Zimmermann N, Yoccoz N, Thuiller W. 2011. Impacts of climate change on the world's most exceptional ecoregions. Proc Natl Acad Sci 108: 2306-2311. DOI: 10.1073/pnas.1007217108.

Berger WH, Parker FL. 1970. Diversity of planktonic Foraminifera in deep-sea sediments. Science 168: 1345-1347. DOI: 10.1126/science.168.3937.1345.

Betemariyam M, Negash M, Worku A. 2020. Comparative analysis of carbon stocks in homegarden and adjacent coffee based agroforestry systems in Ethiopia. Small-scale For 19 (3): 319-334. DOI: 10.1007/s11842-020-09439-4.

Bharathi S, Prasad AD. 2015. Regeneration status of tree composition in the sacred groves of Mercara, Central Western Ghats. Eur J Exp Biol 5 (10): 29-40.

Bhuyan P, Khan ML, Tripathi RS. 2003. Tree diversity and population structure in undisturbed and human-impacted stands of tropical wet evergreen forest in Arunachal Pradesh, Eastern Himalayas, India. Biodivers Conserv 12: 1753-1773. DOI: 10.1023/A:1023619017786.

Birhane E, Ahmed S, Hailemariam M, Negash M, Rannestad MM, Norgrove L. 2020. Carbon stock and woody species diversity in homegarden agroforestry along an elevation gradient in southern Ethiopia. Agrofor Syst 94: 1099-1110. DOI: 10.1007/s10457-019-00475-4.

Borah JR, Evans KL, Edwards DP. 2019. Quantifying carbon stocks in shifting cultivation landscapes under divergent management scenarios relevant to REDD+. Ecol Appl 28 (6): 1581-1593. DOI: 10.1002/eap.1764.

Borogayary B, Das AK, Nath AJ. 2018. Vegetative and reproductive phenology of *Aquilaria malaccensis* Lam. (agarwood) in Cachar District, Assam, India. J Threat Taxa 10 (8): 12064-12072. DOI: 10.11609/jott.3825.10.8.12064-12072.

Brillouin L. 1962. Science and Information Theory. 2nd Edition., Academic Press, New York.

Census of India. 2011. Provisional Population Totals Figures at a Glance, Tripura. www.tripurainfo.com/info/ATripura/census11.htm

Champion HG, Seth SK. 1968. A Revised Survey of Forest Types of India. Manager of Publications, New Delhi.

Chowdhury S. 2005. Assam's flora – Present Status of Vascular Plants. Assam Science Technology and Environment Council, Guwahati, Assam.

Coomes OT, Ban N. 2004. Cultivated plant species diversity in homegardens of an Amazonian peasant village in Northeastern Peru. Econ Bot 58: 420-434. DOI: 10.1663/0013-0001(2004)058[0420:CPSDIH]2.0.CO;2.

Das D, Datta BK. 2018. An assessment of plant diversity in home gardens of Reang Community of Tripura. Pleione 12 (2): 208-222. DOI: 10.26679/Pleione.12.2.2018.208-222.

Das T, Das AK. 2005. Inventorying plant biodiversity in home gardens: A case study in Barak Valley, Assam, North East India. Curr Sci 89: 155-163.

de Sousa K, van Zonneveld M, Holmgren M, Kindt R, Ordoñez JC. 2019. The future of coffee and cocoa agroforestry in a warmer Mesoamerica. Sci Rep 9: 8828. DOI: 10.1038/s41598-019-45491-7.

Deb DB. 1981. The Flora of Tripura State, Vol. I. Today and Tomorrow' Printers and Publishers, New Delhi, India.

Deb DB. 1983. The Flora of Tripura State, Vol. II. Today and Tomorrow' Printers and Publishers, New Delhi, India.

Debbarma J, Deb D, Deb S. 2015. Tree diversity and sociocultural significance of homegardens in the Baramura range, Tripura, North-East India. For Trees Livelihoods 25 (1): 33-40. DOI: 10.1080/14728028.2015.1076357.

Debnath A, Debnath B. 2017. Diversity, invasion status and usages of alien plant species in Northeastern Hilly State of Tripura: A confluence of Indo-Barman Hotspot. Am J Plant Sci 8: 212-235. DOI: 10.4236/ajps.2017.82017.

EFAP. 1994. Ethiopian Forestry Action Program. (EFAP), Addis Ababa.

Endale Y, Derero A, Argaw M, Muthuri C. 2016. Farmland tree species diversity and spatial distribution pattern in semi-arid East Shewa, Ethiopia. For Trees Livelihoods 26: 199-214. DOI: 10.1080/14728028.2016.1266971.

EWNHS. 1996. Important bird areas of Ethiopia: A first inventory. Ethiopian Wildlife and Natural History Society (EWNHS), Addis Ababa, Ethiopia. In: Fichtl R, Adi A (eds). Honeybee Flora of Ethiopia. Margraf, Verlag, Germany.

Fisher R, Corbet A, Williams C. 1943. The relation between the number of species and the number of individuals in a random sample of an animal population. J Anim Ecol 12: 42-58. DOI: 10.2307/1411.

Gachuiri AN, Carsan S, Karanja E, Makui P, Nyaguthii A, Carsan S, Karanja E. 2017. Diversity and importance of local fodder tree and shrub resources in mixed farming systems of central Kenya. For Trees Livelihoods 26: 143-155. DOI: 10.1080/14728028.2017.1316216.

Garrity D. 2004. Agroforestry and the achievement of the millennium development goals. Agrofor Syst 61: 5-17. DOI: 10.1023/B:AGFO.0000028986.37502.7c.

George MV, Christopher G. 2019. Structure, diversity and utilization of plant species in tribal homegardens of Kerala, India. Agrofor Syst 94: 297-307. DOI: 10.1007/s10457-019-00393-5.

Hartshorn GS. 1980. Neotropical forest dynamics. Biotropica 12 (2): 23-30. DOI: 10.2307/2388152.

Hazarika A, Deka, JR, Nath PC, Sileshi GW, Nath AJ, Giri K, Das AK. 2023. Modelling habitat suitability of the critically endangered agarwood (*Aquilaria malaccensis*) in the Indian East Himalayan region. Biodivers Conserv 32: 4787-4803. DOI: 10.1007/s10531-023-02727-3.

Henry M, Tittonell P, Manlay RJ, Bemoux M, Albrecht A, Vanlauwe B. 2009. Biodiversity, carbon stocks and sequestration potential in aboveground biomass in smallholder farming systems of western Kenya. Agric Ecosyst Environ 129 (1-3): 238-252. DOI: 10.1016/j.agee.2008.09.006.

Hoffmann AA, Sgro CM. 2011. Climate change and evolutionary adaptation. Nature 470: 479-485. DOI: 10.1038/nature09670.

Jegora T, Asfaw Z, Anjulo A. 2019. Woody species diversity and management in home- garden agroforestry: The case of Shashemene District, Ethiopia. Intl J For Res 2019: 3697047. DOI: 10.1155/2019/3697047.

Joshi SK, Behera N. 1991. Qualitative analysis of vegetation from a mixed tropical forests of Orissa, India. Indian For 117: 200-206.

Kanjilal UN, Kanjilal PC, De RN et al. 1940. Flora of Assam, Vol. 4. Assam Govt. Govt. Press, Shillong, India.

Kelbessa E, Demissew S. 2014. Diversity of vascular plant taxa of the flora of Ethiopia and Eritrea. Ethiop J Biol Sci 13: 37-45.

Khumbongmayum AD. 2004. Studies on Plant Diversity and Regeneration of a Few Tree Species in the Sacred Groves of Manipur. [Ph.D. thesis]. Department of Botany, Northeastern Hill University, Shillong.

Kumar BM, George SJ, Chinnamani S. 1994. Diversity, structure, and standing stock of wood in the homegardens of Kerala in Peninsular India. Agroforest Syst 25: 243-262. DOI: 10.1007/BF00707463.

Lodh R, Agarwala BK. 2016. Rapid assessment of diversity and conservation of butterflies in Rowa Wildlife Sanctuary: An Indo-Burmese hotspot - Tripura, N.E. India. Trop Ecol 57 (2): 231-242.

Magurran AE. 1988. Ecological Diversity and Its Measurements. Princeton University Press, Princeton, NJ. DOI: 10.1007/978-94-015-7358-0.

Margalef R. 1958. Temporal succession and spatial heterogeneity in phytoplankton. In: Buzzati-Traverso (eds). Perspectives in Marine Biology. University of California Press, Berkeley. DOI: 10.1525/9780520350281-024.

Menhinick EF. 1964. A comparison of some species-individuals diversity indices applied to samples of field insects. Ecology 45: 859-861. DOI: 10.2307/1934933.

Michael P. 1990. Ecological Methods for Field and Laboratory Investigation. Tata Mc Graw Hill Publishing Co., Ltd., New Delhi, India.

Mir AH, Roy DK, Upadhaya K. 2017. Taxonomy, recollection and conservation implications of *Aquilaria khasiana* (Thymelaeaceae): An endemic and threatened species of India. Rheedea 27 (2): 85-89. DOI: 10.22244/rheedea.2017.27.2.14.

Montgomery RA, Rice KE, Stefanski A, Rich RL, Reich PB. 2020. Phenological responses of temperate and boreal trees to warming depend on ambient spring temperatures, leaf habit, and geographic range. Proc Natl Acad Sci 117 (19): 10397-10405. DOI: 10.1073/pnas.1917508117.

Mori SA, Boom BM, de Carvalino AM. 1983. Ecological importance of Myrtaceae in an eastern Brazilian wet forest. Biotropica 15 (1): 68-70. DOI: 10.2307/2388002.

Morisette J, Richardson A, Knapp A, Graham E, Abnatzoglou J, Wilson B, Breshears D, Henebry G, Hanes J, Liang L. 2009. Tracking the rhythm of the seasons in the face of global change: Phenological research in the 21st century. Front Ecol Environ 7: 253-260. DOI: 10.1890/070217.

Muller-Dombois D, Ellenberg H. 1974. Aims and Methods of Vegetation Ecology. Wiley, New York.

Nath PC, Nath AJ, Sileshi GW, Das AK. 2020. Stand structure and functional attributes of agarwood (*Aquilaria malaccensis* Lam.) based smallholder farms in Northeast India. Trees For People 2: 100027. DOI: 10.1016/j.tfp.2020.100027.

Nath PC, Sileshi GW, Majumdar K, Nath AJ, Das AK. 2024. Allometric scaling of above and below ground biomass of the critically endangered agarwood (*Aquilaria malaccensis* Lam.) in homegardens. Agroforest Syst 98: 1591-1604. DOI: 10.1007/s10457-024-01030-6.

Ng LT, Chang YS, Kadir AA. 1997. A review on agar (gaharu) producing *Aquilaria* species. J Trop For Prod. 2: 272-285.

Odum EP. 1971. Fundamentals of Ecology. W. B. Saunders Co., Philadelphia, USA.

Ouinsavi C, Sokpon N. 2008. Traditional agroforestry systems as tools for conservation of genetic resources of *Milicia excelsa* Welw. C.C. Berg in Benin. Agroforest Syst 74: 17-26. DOI: 10.1007/s10457-008-9109-6.

Paul A, Khan ML, Das AK. 2018. Phenological characteristics of *Rhododendron* species in temperate mixed broad-leaved forests of Arunachal Himalaya, India. J For Environ Sci 34: 435-450. DOI: 10.7747/JFES.2018.34.6.435.

Pielou EC. 1966. Species-diversity and pattern-diversity in the study of ecological succession. J Theor Biol 10 (2): 370-383. DOI: 10.1016/0022-5193(66)90133-0.

Rahman MH, Khan MASA, Roy B, Fardusi MJ. 2011. Assessment of natural regeneration status and diversity of tree species in the biodiversity conservation areas of Northeastern Bangladesh. J For Res 22 (4): 551-559. DOI: 10.1007/s11676-011-0198-0.

Rasool S, Mohamed R. 2016. Understanding agarwood formation and its challenges. In: Mohamed R (eds). Agarwood. Springer, Singapore. DOI: 10.1007/978-981-10-0833-7.

Saikia P, Choudhury BI, Khan ML. 2012. Floristic composition and plant utilization pattern in homegardens of Upper Assam, India. Trop Ecol 53: 105-118.

Saikia P, Khan ML. 2012. Seedling survival and growth of *Aquilaria malaccensis* in different microclimatic conditions of northeast India. J For Res 23: 569-574. DOI: 10.1007/s11676-012-0296-7.

Saikia P, Khan ML. 2014. Ecological features of cultivated stands of *Aquilaria malaccensis* Lam (Thymelaeaceae)- a vulnerable tropical tree species in Assamese homegardens. Intl J For Res 2014: 140926. DOI: 10.1155/2014/140926.

Saikia P, Khan ML. 2016. Tree species diversity and its population and regeneration status in homegardens of upper Assam, Northeast India. J For Environ Sci 32 (2): 129-139. DOI: 10.7747/JFES.2016.32.2.129.

Sarkar M, Devi A. 2014. Assessment of diversity, population structure and regeneration status of tree species in Hollongapar Gibbon Wildlife Sanctuary, Assam, Northeast India. Trop Plant Res 1 (2): 26-36.

Schulte PJ, Marshall PE. 1983. Growth and water relations of black locust and Pine seedlings exposed to controlled water stress. Can J For Res 13: 334-338. DOI: 10.1139/x83-047.

Shukla R, Chandal PS. 2000. Plant Ecology and Soil Science (9th ed.). S. Chand and Company Limited, New Delhi, India.

Sloan S, Jenkins CN, Joppa LN, Gaveau DLA Laurance WF. 2014. Remaining natural vegetation in the global biodiversity hotspots. Biol Conserv 177: 12-24. DOI: 10.1016/j.biocon.2014.05.027.

Sobuj NA, Rahman M. 2011. Comparison of plant diversity of natural forest and plantations of Rema-Kalenga wildlife sanctuary of Bangladesh. J For Sci 27 (3): 127-134.

Stucky BJ, Guralnick R, Deck J, Denny EG, Bolmgren K, Walls R. 2018. The plant phenology ontology: A new informatics resource for large-scale integration of plant phenology data. Front Plant Sci 9: 00517. DOI: 10.3389/fpls.2018.00517.

Talbot JD. 2010. Carbon and Biodiversity Relationships in Tropical Forests. Mult Benefits Ser 4.

Vibhuti V, Bargali K, Bargali SA. 2019. Species composition, diversity and traditional uses of homegarden in Kumaon Himalaya, India. Indian J Agric Sci 89: 47-50. DOI: 10.56093/ijas.v89i9.93479.

Wade AS, Asase A, Hadley P, Mason J, Ofori-Frimpong K, Preece D, Spring N, Norris K. 2010. Management strategies for maximizing carbon storage and tree species diversity in cocoa-growing landscapes. Agric Ecosyst Environ 138: 324-334. DOI: 10.1016/j.agee.2010.06.007.

Wang H, Liu D, Lin H, Montenegro A, Zhu X. 2015. NDVI and vegetation phenology dynamics under the influence of sunshine duration on the Tibetan plateau. Intl J Climatol 35: 687-698. DOI: 10.1002/joc.4013.

Yam G, Tripathi OM. 2016. Tree diversity and community characteristics in Talle Wildlife Sanctuary, Arunachal Pradesh, Eastern Himalaya, India. J Asia-Pac Biodivers 9: 160-165. DOI: 10.1016/j.japb.2016.03.002.

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Identifying the factors that influence the decision of farmers in the Imam Sahib District of Kunduz Province, Afghanistan to plant trees

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Abstract. *Omerkhil N, Ahmad L, Khurram S. 2024. Identifying the factors that influence the decision of farmers in the Imam Sahib District of Kunduz Province, Afghanistan to plant trees. Asian J For 8: 147-157.* For years, agroforestry has been employed as a sustainable management approach to enhance and provide services and products traditionally obtained from natural forests. This study focuses to analyze the factors that influence farmers' farm tree planting decisions. We focused on the Imam Sahib District of Kunduz Province, Afghanistan and collected data from 160 households in 32 villages, and within each village, five farmer families randomly selected for a face-to-face interview and data collection using a randomized snowball sampling strategy. A binary logistic regression model was developed using the acquired data to identify the features influencing farmers' tree-planting decisions. The findings reveal that several variables affect the propensity of tree planting and the intensity of agroforestry technology. These factors include the income of the head of farmer households, availability of irrigated farmland, large cropping land, and prior tree planting experience. Conversely, factors such as education, limited access to planting materials, large family size, availability of tree seedlings, and age of the head of the households, loan, and insurance facilities can influence farmers' decisions and adaptation practices. So far, education plays an important role in strengthening farmers' understanding of the limits, opportunities, and needs of new technologies in the form of short-term training. This might mitigate the unfavorable relationship between the age of the family head and willingness to use agroforestry practices on their farmland. These findings, particularly the potential of education to improve farmers' adoption of agroforestry practices, can help strengthen the National Agroforestry Policy to promote tree planting among the farmers, achieve targets for tree coverage, and reduce pressure on natural forests in Kunduz and other provinces and countries with similar situations.

Keywords: Agroforestry, binary logistic regression, farmland, household

INTRODUCTION

The escalating demand for forest products, such as wood fuel, poles, furniture, and materials for housing and development, has driven significant deforestation in developing nations.This trend reflects a concerning reliance on these resources (Kulindwa 2016; Brockhaus et al. 2021). Large and small-scale agriculture and the harvesting of trees for fuel wood and timber are the main culprits in the worldwide loss of natural forest cover (Adesina et al. 2000; Brockhaus et al. 2021). Conversely, agroforestry is an age-old practice integrating trees with crop and livestock production systems (Kulindwa 2016; Brockhaus et al. 2021). Agroforestry now seen as a crucial approach to providing forest functions and products previously obtained from natural forests (Kulindwa 2016). The system aims to diversify and sustain production for enhanced benefits to land users, comprising social-economical, ecological, and environmental benefits (Ashraf et al. 2018). Even though various circumstances, such as the worsening economic situation in many developing countries, have led to the rising interest in combining trees with crops and animals' production system, there are still significant challenges to doing so successfully (Akinnifesi et al. 2008). Growing interest in farming systems, population pressure leading to scarcity and degradation of land, increased tropical deforestation, and intercropping and environmental issues since the 1970s, the benefits of this management system are becoming more apparent (Akinnifesi et al. 2008; Basamba et al. 2016; Kulindwa 2016; Magugu et al. 2018).

Tree planting is becoming an increasingly appealing choice, especially for smallholder farmers involved in low-investment agriculture and low-technology agricultural systems that generally combine a mix of subsistence and market output (Kulindwa 2016; Ashraf et al. 2018). Agroforestry has expanded rapidly on small farms facing forest scarcity, as these systems reduce the cost of tree production through integrated crop and livestock farming (Ficko and Boncina 2013). Agroforestry, is the deliberate integration of planting trees and shrubs with cultivated plants along with livestock production (training) systems in agricultural areas. This is a novel technique that utilized to offer economic, social, and environmental potential (Tremblay et al. 2014; NEPA 2019), evolving as part of intensive ecologically-based farmland management focused on sustainable resource consumption and providing cost-effective alternatives within given economic, social, and environmental settings (Basamba et al. 2016; Magugu et al. 2018). Increasing agricultural productivity and diversity and generating items like fuelwood, construction materials, food, medicine, and fodder, tree plantation on the farmlands has the capacity and potential to decrease food shortage and poverty and may be put to effective use in food safety and poverty decline globally (Neupane et al. 2002; Magugu et al. 2018). Planted trees in agriculture farms are anticipated to supply forest products that were previously obtained from natural forest ecosystems (Lambert and Ozioma 2011). Agroforestry provides opportunities to achieve various goals, such as creating a suitable small-scale climate for high-value plants and appropriate ecological processes, especially for sustainable agricultural land use (Magugu et al. 2018). The deliberate integration of crops in to the trees and shrubs with the animal production system is a suitable framework for water and soil protection and conservation at a reasonable price compared to traditional methods of trace (Neupane et al. 2002), and the functions of forest ecosystems are significantly improved by planting industrial fast-growth trees (Basamba et al. 2016).

High population pressure and an increased demand for food have caused in the degradation and deforestation of huge natural forest cover areas in Afghanistan, resulting in a loss in natural forest products (Groninger and John 2014; FAO 2018). Recent assessments indicate that out of the total land area of Afghanistan (652,860 km^2), only 2.1% is covered by natural forests, and the remaining natural forests have poor tree cover (Reddy and Saranya 2017; Shalizi et al. 2018; FAO 2018; NEPA 2019; Omerkhil et al. 2020). The last four decades of conflict in Afghanistan have caused a decline in forestland cover, likely to continue due to over-exploitation, deforestation, climate change, and developing activities (FAO 2018; Omerkhil et al. 2020; Khurram et al. 2024). To protect natural forest concerns, the lack of industrial and fuel wood, timber and non-timber forest products, has necessitated the implementation of serious measures to protect and preserve the remaining forests. These measures have led to limited timber and wood extraction, reducing forest production (Reddy and Saranya 2017). The fuel and industrial wood production in agriculture farmlands through the planting of fast-growing trees such as *Amygdalus communis*, *Fraxinus xanthoxyloides*, *Eucalyptus globulus*, *Elaeagnus angustifolia*, *Morus alba*, *Platanus orientalis*, *Populus alba*, *Robinia pseudoacacia*, *Prunus armeniaca* and *Salix aemophyla*, both in the form of woodlot and agroforestry system has the potential as a partial solution to the increasing wood shortage (FAO 2003; Groninger and John 2014; Omerkhil et al. 2020).

The Afghanistan forestry policy recognizes agroforestry for the provision of poles, timber, firewood, and even non-wood products like fruits (NEPA 2019) to aid communities, farmers, entrepreneurs, and institutions in agroforestry development. The policy also includes provisions for strengthening the capacity of government agencies, private suppliers, Community-Based Organizations (CBOs), and Non-Governmental Organizations (NGOs), to offer advisory and extension services (NEPA 2019; Omerkhil et al. 2020). There has been no study to identify the factors influencing the enhancfement of the adoption of agroforestry technologies in Afghanistan, particularly in northeastern region. Even though the Ministry of Agriculture, Irrigation and Livestock (MAIL), and National Environmental Protection Agency (NEPA) of Afghanistan have been involved in the widespread extension of these on-farm technologies, particularly in North Eastern Afghanistan, as well as the Imam Sahib district (FAO 2003; MAIL 2019; NEPA 2019). Considering that "adaptation of new technology" is a local event that can differ with time and geographical location (Ali and Erenstein 2017), it is always possible that a need to develop a realistic perception of adaptation practices by farmers worldwide is necessary to negotiate the acceptance of new technology in agriculture farm positively. There is a compelling need to design agroforestry research that determine unique, localized factors that influence farmers' farm tree planning decisions because of agroforestry importance and associated activities for the livelihoods of rural areas and the overall socio-economic development of Afghanistan. This can be achieved through estimating the farmers' decision while considering the area's demographic, socio-economic, and natural factors, as their combined interaction often determines a farmer's choice and adaptation for tree plantation. Therefore, this study aims to evaluate the influence of socio-demographic, economic, and natural factors on the decision of farmers to plant or not to plant trees on their farmlands in the conflict-stricken Imam Sahib District of Kunduz Province, Afghanistan. Previous studies generally address agroforestry in broader contexts or other regions; this study employs a binary logistic regression model to pinpoint precise local factors, such as income levels, land availability, irrigation, and past tree-planting experience that uniquely affect tree-planting decisions in a highly vulnerable and under-researched area. Additionally, this study provides targeted policy recommendations that align with Afghanistan's National Agroforestry Policy, which has not been widely discussed or evaluated in prior research.

MATERIALS AND METHODS

Study site description

This study focused on Imam Sahib District of Kunduz Province, Afghanistan. Kunduz has more than 1.1 million population distributed in a total geographical area of 7,666.7 kilometers square in six official and three temporary districts, of which 88% is foot-plains and 12% is semi-mountainous or mountainous terrain with an average elevation of 405 meters above sea level (Sadiq et al. 2019). Among them, 25.11% of the geographical area of this province, which is 193,983 hectares, is allocated to agricultural lands (FAO 2012). Owing to its unique natural topography and a pattern of different geographical landscape, that presents exceptional socio-demographic and economic dynamics as the context of this study. The Imam Sahib District is further extended into the 189 major and minor villages (CSO 2017). Around its total land area of 25.11% is cultivable and grown 35 different crops (USAID 2017), whereas 74% of the cultivated farmland area is concentrated in four southeastern and northern districts in the foot plain near the center of Kunduz and Amu River basin (FAO 2012; CSO 2017). The rest geographical area of these districts is not suitable for agricultural crop cultivation but is only used for livestock rearing due to the raised slope and mountainous terrain (Sadiq et al. 2019). Producing both rain-fed and irrigated vegetables, cereal, oil seed, cotton, and fruit crops, Kunduz serves as the region's food basket (Sadiq et al. 2019; MAIL 2019). Due to the short growing season in mountainous terrain, only one agrarian crop is cultivated annually at higher elevations, while in plain areas, two crops can grow (Aich and Khoshbeen 2016). Agroforestry and livestock are other important sources of revenue for farmer households in this district. An average the monthly income of households in the study region is around 23,353 Afghani (333. 61 $), (MAIL 2019).

Imam Sahib District is one of the largest districts in Kunduz Province located in the coordinates of N 37° 12′ 68″ and E 68° 46′ 21″ in the northeast of the country, with a mean altitude of 365 meters above sea level. Dasht-i-Archi and Qalizal Districts of Kunduz Province surround Imam Sahib to the southeast and west, Tajikistan to the north, and Kunduz center to the south (Figure 1). The total geographical space of Imam Sahib District is 1,610 km^2 which is spread to 189 major and minor villages across the region (FAO 2012; CSO 2017). Imam Sahib is also distinctive in undulating topography with plain, river valleys, hills, and mountains. The total population of this district in 2019 was state to be 288,603 individuals, with men 163,824 and females 124,779, spread in uneven proportions as the province's second-largest and most populous district. Livestock rearing and agriculture are the main sources of income for dwellers, and around 70% of its people are engaged in farm activities and livestock raising (CSO 2017; MAIL 2019). According to Copen climate classification, its climate is a local steppe and rain deficient (Belda et al. 2014), with a mean annual temperature of 17.1°C. The coldest months are January and February, at 3.4°C, and July and August, the hottest months of the year, with an average temperature of 30.2°C (Belda et al. 2014; WMO 2018).

Imam Sahib District has 2,600 km^2 of Tigai and riparian forest near the bank of Amu River and foothill. This forest is home to various tree species, including reeds (*Phragmites australis*) grass, *Tamarix* spp., willows (*Salix* spp.), and a strip of *Pistaci* and *Elaegnus* spp. (Groninger and John 2014; Moheb et al. 2016; FAO 2016). Based on the ecological importance and scarcity of this forest ecosystem in Afghanistan, the central government has declared the Imam Sahib riparian forest a protected forest to preserve its functioning and ecological values for future generations (UNEP 2013; Aich and Khoshbeen 2016).

Sampling and data collection

The targeted population of present study was all Imam Sahib District farmers who leave a conflict-stricken rural area of Afghanistan and predominantly practiced agroforestry and dispersed across 189 minor and major villages. Out of 189 villages of the district, 32 villages, and within each village, five farmer families randomly selected for a face-to-face interview and data collection using a randomized snowball sampling strategy. A pre-tested questionnaire, including a consent criterion at the beginning, ensuring that respondents were fully aware and participated voluntarily, produced an aggregate of 160 farmer families from 32 villages. In-person interviews with key informants were among the other forms of data collecting used in the research, focus group discussion, field visits, and observation to acquire information about farmers' on-farm tree planting aims, and subsequently, the variables inducing their on- farm tree-growing decisions.

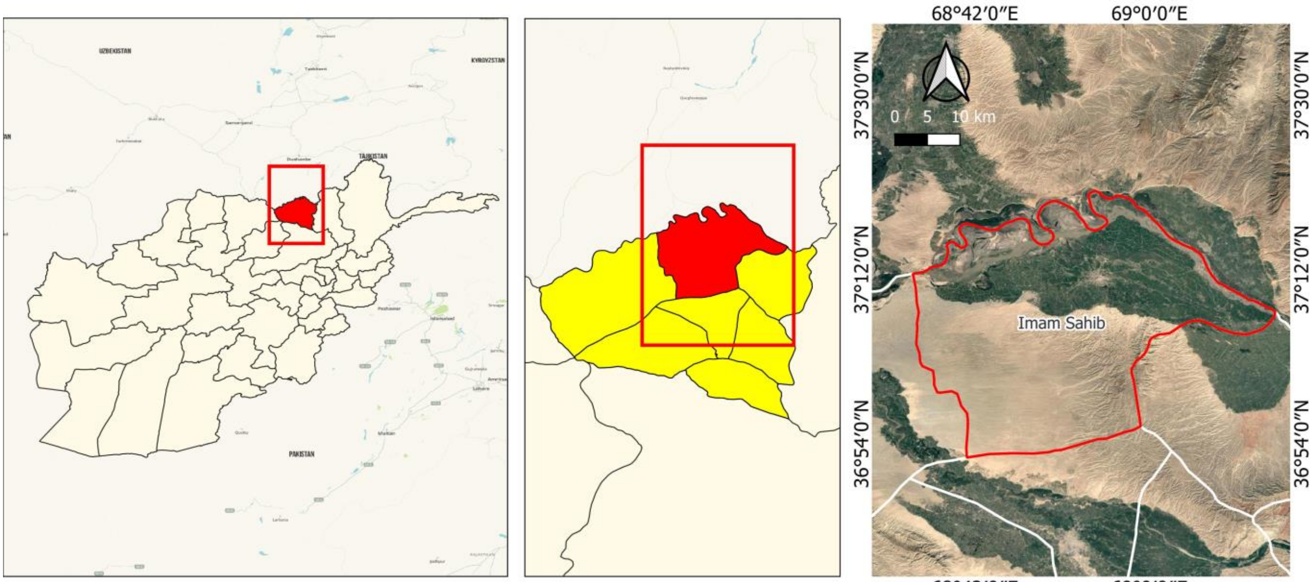

Figure 1. Study site map in Imam Sahib District, Kunduz, Afghanistan

Table 1. Explanation of variables considered in statistical analysis of binary logistic regression model for the present study

Parameter name	Acronym	Coding	Descriptions	References
Age	V1	≥ 45 years old = 1, else = 0 (dummy)	Age of family head in years	Ashraf et al. (2018)
Education	V2	1 up to high school, else = 0 (dummy)	Household head formal education level in years	Suyanto et al. (2005)
Family size	V3	1 = ≥ 8 member, else = 0 (dummy)	Number of members in the family	Ficko and Boncina (2013)
Seed facility	V4	1= Yes, 0 = No (dummy)	Seed adequacy and availability to the farmers	Brockhaus et al. (2021)
Irrigated land	V5	1= Yes, 0 = No (dummy)	Irrigated farmland ownership of farmers	Dhiman (2012)
Monthly income	V6	1 if > 15000 AFGs, else = 0 (dummy)	Monthly income of farmers	Jara-Rojas et al. (2020)
Agriculture land	V7	In hectare (continues)	Total cultivated land of farmers	Gebru et al. (2019)
Tree planting experiences	V8	In years (continues)	On-farm tree planting experience of farmers	Ashraf et al. (2018)
Scientific technique applied	V9	1= Yes, 0 = No (dummy)	The scientific technique used for tree plantations by farmers	Jara-Rojas et al. (2020)
Loan availability	V10	1= Yes, 0 = No (dummy)	Awareness about loan facilities and availability	Thangata and Alavalapati (2003)
Insurance awareness	V11	Yes = 1, No = 0 (dummy)	Household awareness related to crop insurance facilities	Place et al. (2012)
Institutional support	V12	1= Yes, 0 = No (dummy)	Institutional support for tree plantations of farmers	Gebru et al. (2019)
Tree harvesting right	V13	1= Yes, 0 = No (dummy)	Farmers rights for trees harvesting and its transportation to the market	Ashraf et al. (2018)
Awareness of the tree plantation program	V14	1= Yes, 0 = No (dummy)	Farmers' awareness about tree plantation programs	Saha et al. (2018)

For primary data collection, a semi-structured pre-tested questionnaire (open and closed-ended) and key squalor interviews were used to confirm the adequacy and precision of the data and information acquired while preventing uncertainty in the questionnaire and key informant interviews, previously from field visits and observations a pilot survey was done to verify the interviewers' feedbacks. The questions comprised the farmer's household socio-demographic and economic status, crops and tree cultivation practices, current land use, institutional and other supporting factors, resource endowment, and main problems for farm activities; the details of these variables characterized in Table 1. Face-to-face interviews, focus group discussions, and field surveys conducted during March and April 2022 by the researchers' in native languages (Pashto and Dari) to confirm that the interviewer understood the designed questions. Where possible, we spoke with the heads of farmer households directly; if that was not possible, we spoke with the next-most senior member of farmer households. On average, each interview completed in 30 minutes, and the researchers used a questionnaire sheet to note the respondents' answers. Supplementary informant group discussions with farmers and field visits helped raise this study to comprehensively understand numerous socio-demographic, economic, and natural factors and constraints on the farm's tree plantations.

Model specification and data analysis

Adopting and implementing new activities is a long process that includes information processing and deciding to enhance farmers' utilization of their own productive resources (Saha et al. 2018). Ultimately, the decision making of whether or not to adopt new technology on their farmlands will be made after the heads of farmer households go through a series of phases of introspection and experimentation designed to increase their knowledge and technical understanding of the benefits and drawbacks of doing so (Saha et al. 2018; Shin et al. 2020). The age and education level of the family head and family sizes, the amount of land available, the number of available workers, the gender distribution within the household, the availability of transportation, the proximity to the market, the availability of planting materials, and the availability of supporting services like loan and insurance facilities, institutional support, and extension services can all have an impact on a farmer household's final decision (Ashraf et al. 2018; Saha et al. 2018). External determinants include things like product pricing and even government laws, in contrast, internal ones include the scat-redness of land pieces, land quality, proximity to irrigation facilities, and other natural and environmental conditions (Thangata and Alavalapati 2003; Suyanto et al. 2005; Place et al. 2012).

Considering these factors, it was determined that the farmers' decision-making and adoption of on-farm tree planting by the farmer households can be characterized using the binary logistic regression statistical model. This statistical model aims to measure the predicted influence of a set of descriptive characteristics on a dichotomous outcome (in this case, the likelihood of a farmer deciding to plant trees on their acreage) based on the values of independent variables. This study's dependent variable is whether farmers have adopted tree-planting practices, and it is given a value of one (1) if, farmers have adopted tree planting and a value of zero (0) otherwise. Statistical trials were done by the maximum likelihood technique using SPSS 22, to estimate the assigned parameters of the model. Some contextual variables for the present study were regressed with the dependent variable *Y* to quantify the influencing factors (β_i).

The equation (population model) to be estimate based on the following explanatory variables is as follows:

E(*Y*) = β_0 + β_1*V1 + β_2*V2 + β_3*V3 + β_4* V4 ++ β_8*V5 + β_6*V6 + β_5* V7 + + β_7*V8 + β_9* V12 + β_{10}*V10 + β_{11}*V11 + β_{12}*V13 + β_{13}*V14 + ε

Where, β_is are population parameters and ε is an error term of the model to be estimated.

The selection of variables shown in Table 1 is based on the author's knowledge and different promises of agricultural decision-making. It illustrates the explanatory variables in detail involved in the population model. This model hypothesizes that the explanatory factors reflect the tree planting adaptation choice (Thangata and Alavalapati 2003; Suyanto et al. 2005; Place et al. 2012). The continuous explanatory variables, except the dichotomous V7 and V8 variables converted to dummy variables. The dummy variables categorized based on the available sample data and the Interviewers' replies specific to the variables. The elder head of the farmer's household has greater skills in managing a family, so V1 is reflected as a dummy variable due to their high family administration experience (beyond 45 years was judged to achieve the experiences). As a result, they will implement any new technology in farms with risk management capability and aversion (Buyinza and Wambede 2008; Place et al. 2012; Ashraf et al. 2018). Since individuals with a grade 12 (high school) education level are more able to study, enjoy, and comprehend tree planting, the education level was transformed into a dummy variable as suggested by (Neupane et al. 2002; Sidibe 2005). Due to the high illiteracy rate among Afghan farmers, they cultivate and grow trees on their farmlands based on their experiences in tree plantation and contacts with their neighbor farmers. It was expected that a farmer with a (high school) education level, who knows very little about tree plantation and agriculture would have a similar capacity to enjoy, study, and comprehend tree planting. A family with eight or more individuals considered a big family and a dummy variable.

The independent variables V1 (household head age) and V3 (family size) describe the agricultural labor source. The education level of the farmer's household heads (V2) is a personal feature that aids decision-making (Sidibe 2005; Saha et al. 2018). V4 denotes insufficient nearby seed sources, V7 denotes the entire cultivated land area, and V5 denotes farmland with irrigation facilities. Both variables define on-farm tree plantation choice of farmers, whether to grow annual crops. The total monthly income of the farmer's household (V6) is associated with farmers' potential to invest in agricultural and farm activities, consisting of tree plantations (Place et al. 2012; Ashraf et al. 2018). V8 is (on-farm tree planting experiences in a year), and V9 describes applying the scientific technique for tree plantation and crops. V11 and V10 illustrate farmers' awareness of the insurance and loan facilities and availability (Zomer et al. 2007; Ashraf et al. 2018). At the same time, V12 and V13 represent farmers' institutional support and tree harvesting right, whereas V14 represents awareness of the tree plantation program (Buyinza and Wambede 2008; Ashraf et al. 2018). The odds ratios Exp (b) (exponents of variable) for each parameter were investigated to determine the influence of dependent variables on explanatory factors, and the Nagelkerke-R^2 statistic was used to estimate the model adequacy. The strength of the relationship was measured using Percent Concordant, Tau-a, and c-statistics, and Somer's-D statistic. The binary logistic regression statistic model was used to examine the Lemeshow and Hosmer goodness of fit (GOF) test. The acquired primary data was coded and analyzed using statistical software for social sciences (SPSS. 22).

RESULTS AND DISCUSSION

Socio-demographic status of sample farmers

Across Imam Sahib District, the living status of farmers was poor, with farmers living in small houses constructed from local materials, as observed during the survey. Most households depended on firewood for cooking and small solar panels for light. The distribution of respondents according to their age classes is shown in Table 2. The majority of Imam Sahib people (36.04%) were within 31-40 years, followed by age class of 16-30 years (31.31%), up to 15 years old (16.37%), 41-50 years (14.56%), while the age class above 65 years representing (1.37%) of the total population. Males consist (59.08%) of its population and females (40.91%). This implies that the population of this district was relatively young compared to the national level and actively involved in farming activities. According to Kinyili et al. (2020), as the age of the family head increases, so does the adoption of tree planting since younger farmers are more ready to take risks and have a long-term planning horizon than the elder family heads of farmers. The percentage of males is somewhat greater than that of females; this benefits agroforestry technology development.

Family size and dependency ratio

Imam Sahib District farmers followed a joint family culture, so the farmland could not be divided among the offspring. The large family concept has been prevalent for the generations due to the resource intactness and stringent livelihood options requiring a high labor force, and this indicates that farmer's households with a higher number of family members were further willing to adopt new on-farm activities like on-farm tree planting technologies related to those families with fewer family members. However, nowadays, the nuclear family concept is also in practice (19.37%,) respectively having a family size of up to four members (Table 2). The proportion of families mainly consisting of more than 12 members was very high (46.86%). There was a discrepancy between the results of this study and those of Ficko and Boncina (2013), and Shin et al. (2020), who found that farmers' larger family sizes were associated with greater adoption of on-farm tree planting. These results showed that a family with more members had a significant consequence, and they confirmed that there is a large number of working-age and active labor force in the population.

Household education level

Education is essential for human resource development, encompassing better health, nutrition, improved socio-economic opportunities, and a more pleasant and beneficial natural environment. The educational situation clearly shows society's awareness and likely future growth (Buyinza and Wambede 2008; Kinyili et al. 2020; Shin et al. 2020; and Brockhaus et al. 2021). The farmers' household-head education status analysis and their counterpart showed that illiteracy level was higher with a very small proportion of heads of household and their counterpart with education more than high school. The reason for the low education level among the head of the household was primarily not economic but rather geographical location and non-availability of school, as interviewers reported during the survey (Table 2). Respondents reported that the non-existence of road infrastructure and the very typical and hazardous footpaths on the hilly terrains were also factors responsible for low education. The children's educational status was also investigated during the survey. It was observed that although people of this district were aware of the merits of education, socio-economic and geographic constraints still forced most farmer families to withdraw their kids from school and get involved in farm and domestic activities. During the survey and field observations, it was observed that there were some farmers' families whose kids were totally involved in domestic and farm activities. The non-attendance of school by children was chiefly due to the non-availabilities of the schools near the villages or the involvement of kids in some socio-economic activities; these domestic duties, in the case of male children, included mainly the livestock rearing and in the case of female children, household affairs, in addition, observed during the survey. The results of this study are quite in line with the studies conducted by Faham et al. (2008), Dhiman (2012), Ficko and Boncina (2013), and Gebru et al. (2019).

Land holding size of farmers

Landholding overall and irrigated land are the most significant factors for rural households, especially once agriculture is the main profession. The proportion of households possessing a land area of more than 1 hectare was high (52.5%) in the region (Table 2), followed by 1-4 hectare (38.75%) and 4-8 hectare (8.75%). Therefore, the size of a farmer's property seems to be a significant factor in the farmer's selection for tree planting. This study's evaluation is consistent with the findings of other investigations (Lönnstedt 2012; Gebru et al. 2019; Shin et al. 2020); they reported that if all other circumstances remain constant, on-farm tree planting would rise if a farmer has enough farmland to produce enough food to sustain his family members, unlike a farmer with a tiny landholding.

Availability of loan and insurance facility

Loan and insurance availabilities are the main components of agriculture. Table 2 shows the proportion of households having awareness and access to agriculture loans and crop insurance facilities. Almost all households in the region (73.75%) were unaware of loan and crop insurance facilities. Farmers with access to many funding sources and loans are more likely to involve tree-planting practices on their farm than those without such options. According to the findings of Raina et al. (2011), Saha et al. (2018), and Jara-Rojas et al. (2020), loan availability and credit facility is a major problem in future on-farm tree planting.

Table 2. Socio-demographic descriptions of farmer's households living in the study region

Parameter	Frequency	Percentage (%)
Age (in years)		
Up to 15 years old	218	16.37
16-30 years old	417	31.31
31- 40 years old	480	36.04
41-50 years old	194	14.56
Above 65 years old	23	1.73
Gender		
Male	787	59.08
Female	545	40.91
Family size		
1-4	31	19.37
4-8	54	33.75
8-12	75	46.86
Education level		
Illiterate	870	64.26
Primary	176	13.61
Intermediate	132	10.20
Graduate	100	7.73
B.Sc.	29	2.24
Above B.Sc.	25	1.93
Agriculture land area (in hectare)		
>1	84	52.5
1-4	62	38.75
4-8	14	8.75
Family head awareness about loan and insurance facilities		
Yes	42	26.25
No	118	73.75

Table 3. Concise statistics of surveyed households' characteristics (N=160)

Variable name	Adopters		Non- adopters	
	Mean	**Standard division**	**Mean**	**Standard division**
Age of family head (in years)	43.38	11.38	12.10	43.38
Education level of HH (in years)	8.15	6.04	5.12	6.00
Family size of HH	6.11	2.89	2.88	7.13
Secondary occupation of HH	4.6	3.18	2.76	3.61
Agricultural land (in ha)	0.15	6	1.97	2.10
Irrigated land (in ha)	16.45	19.66	5.99	3.89
Tree planting experience of HH (in years)	75%	N=160	N=160	47%
Off-farm income HH	24.92	38.36	18.39	12.92
Total number of trees planted	-	-	-	20%
Income from planted trees	2	0.97	1.02	3
Awareness of HH about loan and insurance facilities	3	1.01	0.80	2

Table 4. Evaluated standard errors, coefficients, and other descriptive statistics of the binary logistic regression model

Variable name	Standard error (p-value)	Coefficient (b)	Upper CI	Lower CI	Probability (Odds ratio)	Exp (β)
CONSTANT	4.30 (0.62)	-2.62	3.99	-8.52	8.00	0.11
V1	3.15 (0.37)	-2.81	2.70	-7.75	7.00	0.08
V2	4.48 (0.06)	-9.54	0.05	-19.59	0.18	0.00
V3	2.90 (0.03)	-3.74	1.99	-9.93	4.00	0.04
V7	0.18 (0.05)	0.40	0.69	0.03	7.50	1.53
V6	4.60 (0.02)	11.08	18.36	1.79	4.30	38,852.10
V5	2.33 (0.04)	5.05	8.75	0.62	146.5	0.89
V8	0.32 (0.03)	0.63	0.91	0.09	5.30	1.90
V4	1.96 (0.07)	-4.19	0.13	-7.61	5.00	0.05
V11	8.39 (0.81)	3.15	18.43	-12.47	7.20	18.63
V10	6.32 (0.74)	1.35	17.05	-11.79	9.00	4.76

Note: Concordant Percent = 99.0 Somers' Tau-a = 0.163, D = 0.98, c = 0.99, Lemeshow and Hosmer Goodness-of-Fit Test = 0.51 (p = 0.99), Nagelkerke-R^2 = 0.84

Factors determining farmer's decision to plant trees

Table 3 presents the summary statistics of a few key attributes of adopters and non-adopters farmer households of Imam Sahib District of Kunduz Province. The information concerning these essential features is not supplied entirely for non-project and project heads of households since the changes in certain variables within the project and non-project farmers' households were considerably varied. On average, the adopter and non-adopter farmer's families were fairly varied in terms of the economic and socio-demographic features of the family head, such as education level, age, secondary profession, family size, irrigated farmland, and income from other sources. For instance, the average family size in terms of family members was 2.88 for non-adopters and 6.11 for adopters. The variation was significant at the 0.05% probability level; the results of current study are quite in harmony with the evaluation of Tefera and Lerra (2016), Saha et al. (2018), Gebru et al. (2019), Jara-Rojas et al. (2020), and Kinyili et al. (2020), who led the research that found, overall family size had a substantial influence. Similarly, the secondary occupation of heads of household was an average of 4.6 for adopters and 2.76 for non-adopters. The variation was highly significant at 0.05% probability level. Apart from a relatively higher household head age similarity among the non-adopters and adopters, both farmers' families had non-parallel cultural structures (Table 3). The proportion of farmers' households that adopted on-farm tree plantation was 90%, and non-adopted households were less than 10% of 160 sampled farmers' households. The field observation also confirmed this statistic. However, on-farms tree planting intensity is varied extremely, with the majority of farmers' households' heads having low to moderate on-farm tree planting activities on their farms; these evaluations conform to the results of Lönnstedt (2012), Basamba et al. (2016), Ashraf et al. (2018), Kinyili et al. (2020), and Brockhaus et al. (2021). According to their findings, farmers less likely to plant trees on their property are more likely to have a negative outlook on the potential benefits of other cultivable crop yields, water availability, soil health, and biodiversity.

The descriptive statistics illustrate that more on-farm tree planting being carried out among the farmers with the highest education level, and education level boosts the adaptation of more on-farm tree plantations in the farmlands. The farmers' households, with higher monthly income and more irrigated and agricultural land ownership follow this on-farm technology. When comparing farmers with different family sizes, those who adopted the practice had more family members, who helped around the house and on the farm. This means large family size provides an abundant labor supply with many members. On the other hand, small families with few numbers of family members are not liable to espouse tree plantations on their farmland for the reason of labor deficiencies. The results reported by Adesina et al. (2000), Akinnifesi et al. (2008), Faham et al. (2008), Cosmas et al. (2012), and Dhiman (2012), confirm the evaluation of this study as they described, on-farm tree planting adoption decision of farmers household was significantly influenced by the farmers' family size and household head education level. Tree planting adopters had more experience in agroforestry and general farming than non-adopters did. The results further indicated that the income from planted trees for adopters (2) was higher than non-adopters (1.02) on average. This demonstrates that farmers who benefit economically from their on-farm trees plantation are more inclined and are agree to adopt agroforestry practices. As family monthly income is one of the essential components in deciding the households' choice of on-farm tree planting, our findings are in concord with the evaluations of Sharma et al. (2009), Tremblay et al. (2014), and Kinyili et al. (2020), that the farmers' monthly income needs to adopt trees. With a rise in per capita income, a family's chances of becoming middle class raise dramatically. Table 2 summary statistics also show that agroforestry adopters were more likely to be aware of loan and crop insurance facilities than non-adopters. It suggesting that easy access to credit and knowledge of loan availabilities and insurance facilities are major motivators for the introduction of innovative farming practices, such as tree planting systems on farmland area (Lambert and Ozioma 2011; Magugu et al. 2018).

Analytical modeling of the binary logistic regression equation

A binary logistic regression model was used with the help of maximum likelihood estimation of parameters to investigate and measure the association between the explanatory factors and dependent variables that influence farmers' choice to accept tree planting on their farmlands. The evaluated variables show the adaptation manners of the farmer households. These variables include the farmers' family size, household head formal education level, age of family head, monthly income of the family, agriculture land, irrigated farm size, crop cultivation and tree planting experiences, seed facilities, awareness about loan and insurance facilities, and institutional support. According to the results of the significant likelihood ratio test, the estimated models that include both constant and explanatory factors provide a better fit to the data for the farmers than the models that include just the constant variables. Lemeshow and Hosmer's goodness-of-fit test yielded a small p-value, and Nagalkere's R^2 was very near to 1, indicating that the model was adequate. On the other hand, the highest relationship between expected likelihoods and acquired answers, i.e., the ratio of concordances, proposes that the assessed adopted model had an excellent descriptive ability. The area under the receiver functional trait curve, which confirms the power of the model shown by c, is also close to 1, the same finding is reported by Akinnifesi et al. (2008), Basamba et al. (2016), and Ashraf et al. (2018). Even though many of the coefficients in the model are statistically insignificant when considered separately, the investigation reveals a correlation between the log of odds of reflected explanatory variables and, by extension, the odds and likelihood of accepting on-farm tree planting practices. All the critical factors show the predicted symptoms, and the accepted theory of how the environment affects farmers' acceptance rate holds. Validating the current knowledge of how farmers' circumstances influence their accepting behaviors, all the significant factors show the expected symptoms. Insignificant coefficients and signs for family size and age suggest that these factors have no significant role in determining whether or not trees are planted on a farm (Table 4).

The monthly income of the family (V6), the area of agricultural land owned by farmer households (V7), irrigated cropping land area (V5), and the farmers' household head on-farm tree-planting experience (V8) are the most significant factors that are influencing on-farm tree planting adoption decision at the 0.05 confidence level. The model shows that, after adjusting for other factors, the monthly income of farmer's families, agricultural land area ownership, on-farm tree planting experience, and irrigated farmland size all positively influence the adoption of new on-farm technology. In probability terms, each of these estimated variables are more than 50% important. The odds ratio indicates that farmers household head monthly income has the highest contribution role to the implementation of tree planting on agricultural land, followed by the area of irrigated land in general and specifically by the number of family members, agricultural land without irrigation facilities, and the tree planting experience of the head of the farming household. The studies conducted by Ashraf et al. (2018), Magugu et al. (2018), and Saha et al. (2018) have practical implications for agricultural researchers, policymakers, and professionals, empowering them to make informed decisions and apply the knowledge in their work. The number of factors, including production goods, consumption goods, family income, and technical skills and knowledge in tree planting experience, which govern a farmer's risk, are all intertwined with the monthly income the farmer's family receives, which decides the risk. This evaluation is also in harmony with the reports of Lambert and Ozioma (2011), Lambert and Ozioma (2011), Tremblay et al. (2014), Tefera and Lerra (2016), and Kulindwa (2016), who illustrated farmers' monthly income matters for their adoption of on-farm trees plantation, and a rise in income per person greatly raises the household's chances of doing so. These factors, in combination, simplify the farmers' on-farm tree planting decisions and adoption.

Given the current resource mix and environmental conditions, the projected outcomes highlight that irrigated farmland is associated with greater incomes, quality of life, and adopting innovative creativities, such as on-farm tree planting. That is to say, farmers with high-quality farmland may choose between planting trees on their property and growing a variety of cash crops that will provide them with the income and food they need to improve their standard of living. Farmers in the higher income bracket are more likely to adopt on-farm tree planting activities due to their greater financial resources and willingness to take on greater levels of risk (Lönnstedt 2012; Ficko and Boncina 2013; Gebru et al. 2019; Kinyili et al. 2020). When farmers adopt a new on farm activity, their circumstances also make it possible to take risks, which they do. The formal education level of household heads and the availability and adequacy of tree saplings are only weakly related to farmers' on-farm tree planting adoption decisions at a 10% significance level. This district's low and similar formal education level makes the feeble relationship between the education level and on-farm tree planting adoption, possibly due to the parallel education status across the entire region.

According to the assessment of the current study, farmers with higher education levels may perceive the risk of compromising food security or monthly income as too great if they adopt on-farm tree planting technology. The assessment of this study confirmed by the studies of Cosmas et al. (2012), Dhiman (2012), Kinyili et al. (2020), and Brockhaus et al. (2021). One barrier to the widespread use of new on-farm technology is the high price of planting stock, directly correlated with the ease with which one may get tree seedlings. The result reported by Ghadim and Pannell (1999), Ashraf et al. (2018), and Kinyili et al. (2020), who evaluated that the accessibility of tree seedlings is associated with it cost of the labor force of farmers' household and land ownership. The farmers on farm tree planting decision is determined by several factors, including land and labor, or a combination of the two, as well as education level, ease of access to planting stocks, and the cost of planting stocks. The main determining factors for planters to adopt trees on their farms, due to their considerable variability, loan information (V10) and awareness of insurance facilities (V11) cannot be used as explanatory factors for adaptation. We speculate that this diversity is due to a critical need for more distribution to promote these services among the farmers in the area due to poor awareness of farmers and governmental organizations.

The results of the current study's model analysis, combined with the theory and constants from previous research, indicate that the variable V1 in the evaluated statistic model strongly correlates adversely with the practice of on-farm tree planting activities. There is a negative correlation between the age of household head and the number of trees planted on agricultural land by the farmers. This may be because of young farmers are more willing to take risks and have a long-term planning horizon than those with a high age level. This evaluation is in agreement with the findings from various studies conducted by Suyanto et al. (2005), Sharma et al. (2009), Tremblay et al. (2014) Saha et al. (2018), and Kinyili et al. (2020). Their results indicate that younger farmers' heads are more eager to embrace new technology, and they are more equipped to harvest crops, fruit, and vegetables than their more senior counterparts. This is because younger family heads are more ready to take risks than elder people are, and fewer trees are planted as the average age of a household's head rises. A farmer's household is less likely to embrace cutting-edge farming methods if its members have large families. It was hypothesized that bigger families would utilize more of their property to provide for their members' needs. In contrast, smaller families could do so with a minor portion of their farmlands and may devote the remaining farmland areas to the agroforestry system. Kinyili et al. (2020) research notes that many relatives have no noticeable impact. There was no positive significant statistical relationship between the availability of agricultural insurance and loans and measures of wealth or risk tolerance. This might be because of the low diversity of loan facilities among the families of the farmers in this area and the poor performance of the loan agencies responsible for delivering these services. Loan, and credit facility, and availability were shown to be a significant problem in future tree planting following the advice that confidence intervals were computed for the variables of investigated parameters in the logistic regression statistical regression model, as confirmed by Agresti (1996); Ashraf et al. (2018), Kinyili et al. (2020). This allowed us to assess model parameters' influence, extent, and significance. There are 95% confidence intervals for all of the examined critical parameters in the model utilized in this investigation. The data highlight the verified impacts on the adoption of these factors, and the tight confidence ranges double confirm this.

In conclusion, an increasing demand for forest non-timber products and the harvesting of trees for fuel wood and timber for housing and development activities (Adesina et al. 2000; Brockhaus et al. 2021), including large and small-scale agriculture are the main causes of natural forest cover losses that led to extensive deforestation in developing nations (Kulindwa 2016; Brockhaus et al. 2021). This study was set to examine the factors influencing the tree-planting horizons of farmers to adopt agroforestry technology. A binary logistic regression statistic model was proposed to assess the influencing factors on the decision of 160 regional farmers from 32 villages of the northern-east of Afghanistan agro-ecological region. The finding of this study highlighted that several variables affect both the choice to plant trees and the intensity of agroforestry technology. The empirical results deemed the high income of the farmer's household head, the availability of irrigated land, the amount of cropping land, and the farmers' previous experience with tree planting on their own farms are the most influencing factors to adopt plantings of trees on their farmland.

On the other hand, factors such as education, limited access to planting materials, large family size, availability of tree seedlings, age of family head, and insurance and loan facilities influenced farmers' decisions and adaptation practices towards tree planting. However, short-term training is critical driver in helping farmers understand modern innovation's possibilities, challenges, and requirements. Further, these influencing factors may need to evolve over time following the course of agroforestry adaptation practices and society to help reduce the age bias towards agroforestry adoption that has been seen to date. Sustainable techniques such as agroforestry must spread widely, and social media may play an important role. The urgency and importance of increasing data sets to approve other impactful strategies, such as improving the service offerings of loan and insurance organizations, cannot be overstated. Policy support is critical to successfully implementing this technology as it develops and becomes popular. Furthermore, as biophysical circumstances vary among the regions in Afghanistan. This study also calls for more investigation into the design of tree-planting incentives for farmers in various agro-ecological zones properly, on rain-fed hill terrain agriculture. Meanwhile, this portion of the agricultural land area is insufficiently explored.

The findings of this study might benefit policymakers in Afghanistan and other developing nation facing equivalent challenges, to strengthen the National Agroforestry Policy for creating a massive people's movement to achieve national tree cover targets and minimize the present pressure on existing natural forests and may provide insights into the policies that can be implemented to reduce deforestation and increase farm forest products. The government should develop policies and create programs and networks for farmers, researchers, extension agents, and stakeholders to share information and knowledge on agroforestry and crop management and incentivize farmers to adopt agroforestry practices through financial and technical support for tree planting, establishment of agroforestry demonstration plots, and training programs for farmers. Allocation of more fund towards research and development in agroforestry, and crop management for sustainable land use, food security, and safety, and climate change adoption measure, to ensure the long term and sustainable uses of land and other natural resources to protect biodiversity, ecosystem functions, and services. Such policies and partnerships can help bridge the gap between research and practice and facilitate the development and adoption of innovative technologies and practices. This study has highlighted the need and opportunity for further research in on-farm tree plantation and socio-demographic dimensions, and may provide a basis to modify the existing framework and policies in the various developing and under developed countries.

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REFERENCES

Adesina AA, Mbila D, Nkamleu GB, Endamana D. 2000. Econometric analysis of the determinants of adoption of alley farming by the farmers in the forest zone of southern Cameroon. Agric Econ Syst Environ 80 (3): 255-265. DOI: 10.1016/S0167-8809(00)00152-3.

Agresti A. 1996. An Introduction to Categorical Data Analysis. John Wiley and Sons, New York.

Aich V, Khoshbeen AJ. 2016. Afghanistan: Climate Change Science Perspectives. National Environmental Protection Agency (NEPA) and UN Environment, Kabul.

Akinnifesi FK, Chirwa PW, Ajayi OC, Sileshi G, Matakala P, Kwesiga FR, Harawa H, Makumba W. 2008. Contributions of agroforestry research to livelihood of smallholder farmers in southern Africa: Taking stock of the adaptation, adoption and impact of fertilizer tree options. Agric J 3 (1): 58-75.

Ali A, Erenstein O. 2017. Assessing farmer use of climate change adaptation practices and impacts on food security and poverty in Pakistan. Clim Risk Manag 1 (2): 35-48. DOI: 10.1016/j.crm.2016.12.001.

Ashraf J, Rajiv P, Jong WD, Nagar B. 2018. Factors influencing farmers'' decisions to plant trees on their farms in Uttar Pradesh, India. J For Environ Sci 2 (3): 256-267. DOI: 10.1007/s11842-015-9289-7.

Basamba TA, Mayanja C, Kiiza B, Nakileza B, Matsiko F, Nyende P, Kukunda EB, Tumushabe A, Ssekabira K. 2016. Enhancing adoption of agroforestry in the eastern agro-ecological zone of Uganda. Intl J Ecol Sci Environ Eng 3 (1): 20-31.

Belda M, Haltanová E, Holenke T, Kavlová J. 2014. Climate classification revisited: From Koëppen to Trewartha. Clim Res 59: 1-13. DOI: 10.3354/cr01204.

Brockhaus M, Gregoria , Djoudi H, Moleiono M, Pham TT, Wong GY. 2021. The forest fontier in the global south: Climate change policies and the promise of development and equity. Ambio 1 (2): 346-351. DOI: 10.1007/s13280-021-01602-1.

Buyinza M, Wambede N. 2008. Extension for agroforestry technology adoption: Mixed intercropping of crotalaria (*Crotalaria grahamiana*) and maize (*Zea mays* L.) in Kabale District, Uganda. Environ Res J 2 (3): 131-137.

Cosmas P, Christopher G, Chaarles K, Vincent TM. 2012. A review of agro forestry technologies adoption among smallholder farmers in Zimbabwe. J Sustain Dev Stud 1 (1): 68-92.

CSO. 2017. Socio-Demographic and Economic Survey. Survey Report of Central Statistic Organization, Kabul, Afghanistan.

Dhiman CR. 2012. Transforming rural Uttar Pradesh through integrating tree culture on farm land: A case study of WIMCO''s Poplar Programme. Lucknow Manag Assoc Conv J 8 (1): 85-98.

Faham E, Rezvanfar A, Shamekhi T. 2008 Analysis of factors influencing motivation of villagers' participation in activities of social forestry (the case study of West Mazandaran). Am J Agric Biol Sci 3 (2): 451-456. DOI: 10.3844/ajabssp.2008.451.456.

FAO. 2003. Trees and Bushes of Afghanistan. Rome Italy.

FAO. 2012. Country Profile – Afghanistan. FAO Aquastat Report, Version 2012. Rome, Italy.

FAO. 2016. Land Cover Atlas of the Islamic Republic of Afghanistan. FAO, Kabul, Afghanistan.

FAO. 2018. 15 Years in Afghanistan a Special Report: 2003-2018. Rome.

Ficko A, Boncina A. 2013. Probabilistic typology of management decision making in private forest properties. For Policy Econ 27: 34-43. DOI: 10.1016/j.forpol.2012.11.001.

Gebru BM, Wang SW, Kim SJ, Lee WK. 2019. Socio-ecological niche and factors affecting agroforestry practice adoption in different agro-ecologies of southern Tigray, Ethiopia. Sustainability 11 (13): 729. DOI: 10.3390/su11133729.

Ghadim AKA, Pannell DJ. 1999. A conceptual framework of adoption of an agricultural innovation. J Intl Assoc Agric Econ 21 (2): 145-154. DOI: 10.1111/j.1574-0862.1999.tb00590.x.

Groninger, John W. 2014. Forestry and Forestry education in Afghanistan. J For 104 (8): 426-430. DOI: 10.1093/jof/104.8.426.

Jara-Rojas R, Russy S, Roco L, Fleming-Muñoz D, Engler A. 2020. Factors affecting the adoption of agroforestry practices: Insights from silvopastoral systems of Colombia. Forests 11: 684. DOI: 10.3390/f11060648.

Khurram S, Shalizi MN, Bashari M, Akamani K, Groninger JW. 2024. Barriers and opportunities regarding community-based forest

management in Afghanistan: considerations for fragile states. Environ Conserv 51 (1): 6-16. DOI: 10.1017/S0376892923000280.
Kinyili BM, Ndunda E, Kitur E. 2020. Socio-economic and institutional factors influencing adoption of agroforestry in arid and semi-arid (ASALs) areas of Sub Saharan Africa. Intl J For Hortic 6 (1): 8-18. DOI: 10.20431/2454-9487.0601002.
Kulindwa YJ. 2016. Key factors that influence households' tree planting behavior. Nat Resour Forum 40 (1-2): 37-50. DOI: 10.1111/1477-8947.12088.
Lambert O, Ozioma AF. 2011. Adoption of improved agroforestry technologies among contact farmers in Imo State, Nigeria. Asian J Agric Rural Dev 2 (1): 1-9.
Lönnstedt L. 2012. Small Scale forest owners' responsibilities: Results from a Swedish Case Study. Small-scale For 11 (3): 407-416. DOI: 10.1007/s11842-011-9187-6.
Magugu JW, Feng S, Ototo G. 2018. Socio-economic factors affecting agro-forestry technology adoption in Nyando, Kenya. J Water Land Dev 39 (1): 83-91. DOI: 10.2478/jwld-2018-0062.
Ministry of Agriculture Irrigation and Livestock (MAIL). 2019. Resettlement due Diligence Report AFG: Panj Amu River Basin Sector Projects. Ministry of Agriculture Irrigation and Livestock, Kabul, Afghanistan.
Moheb Z, Jahid N, Noori H. 2016. Bactrian Deer (*Cervus elaphus bactrianus*) still exist in Afghanistan. DSG Newsl 28: 5-12.
NEPA. 2019. Afghanistan' Afghanistan''s sixth National Report to The United Nation''s Convention on Biological Diversity. National Environmental Protection Agency Kabul, Afghanistan.
Neupane RP, Sharma KR, Thapa GB. 2002. Adoption of agroforestry in the hills of Nepal: A logistic regression analysis. Agric Syst 72 (3): 177-196. DOI: 10.1016/S0308-521X (01)00066-X.
Omerkhil N, Chand T, Valente D, Alatalo JM, Pandey R. 2020. Climate change vulnerability and adaptation strategies for smallholder farmers in Yangi Qala District, Takhar, Afghanistan. Ecol Indic 110: 105863. DOI: 10.1016/j.ecolind.2019.105863.
Place F, Ajayi OC, Torquebiau E, Detlefsen G, Gauthier M, Buttoud G. 2012. Improved Policies for Facilitating the Adoption of Agroforestry. In: Kaonga ML (eds). Agroforestry for Biodiversity and Ecosystem Services: Science and Practice. IntTechOpen, Rijeka. DOI: 10.5772/34524.
Raina R, Hara SS, Hara V, Irland LC. 2011. Twenty-first century forest plantations: Development of agroforestry in Haryana. J Resour Energy Dev 8 (2): 67-74. DOI: 10.3233/RED-120084.
Reddy CS, Saranya KRL. 2017. Earth observation data for assessment of nationwide land cover and long-term deforestation in Afghanistan. Glob Planet Chang 155: 155-164. DOI: 10.1016/j.gloplacha.2017.07.005.
Sadiq GA, Omerkhil N, Zada KA, Safdary AJ. 2019. Evaluation of growth and yield performance of five cucumbers (*Cucumis sativus* L.) genotypes; Case study Kunduz Province, Afghanistan. Intl J Adv Educ Res 4 (6): 22-28.
Saha S, Sharmin A, Biswas R, Ashaduzzaman MD. 2018. Farmers' Perception and Adoption of Agroforestry Practices in Faridpur District of Bangladesh. Intl J Environ Agric Biotechnol 3 (6): 1987-1994. DOI: 10.22161/ijeab/3.6.5.
Shalizi MN, Khurram S, Groninger JW, Ruffner CM, Burney OT. 2018. Indigenous knowledge and stand characteristics of a threatened tree species in a highly insecure area: Chilgoza pine in Afghanistan. For Ecol Manag 413: 1-8. DOI: 10.1016/j.foreco.2018.01.053.
Sharma SK, Sudhir C, Sharma SK, Kaur B, Arya ID. 2009. Opportunities and major constraint''s in agroforestry systems of western UP: A vital role of Star Paper Mills, Saharanpur (UP) – India. Agric Biol J N Am 1 (3): 343-349. DOI: 10.5251/abjna.2010.1.3.343.349.
Shin S, Soe KT, Lee H, Kim TH, Lee S, Park MS. 2020. A systematic map of agroforestry research focusing on ecosystem services in the Asia-Pacific Region. Forests 11: 368. DOI: 10.3390/f11040368.
Sidibe M. 2005. Farm-level adoption of soil and water conservation techniques in northern Burkina Faso. Agric Water Manag 71 (3): 211-224. DOI: 10.1016/j.agwat.2004.09.002.
Suyanto S, Permana RP, Khususiyah N, Joshi N. 2005. Land tenure, Agroforestry Adoption, and reduction of fire hazard in a forest zone: A case study from Lampung, Sumatra, Indonesia. Agrofor Syst 65: 1-11. DOI: 10.1007/s10457-004-1413-1.
Tefera SA, Lerra MD. 2016. Determinants of farmers decision making for plant *Eucalyptus* trees in Market District, North Willow, Ethiopia. Res Hum Soc Sci 6 (13): 123-146.
Thangata PH, Alavalapati JRR. 2003. Agroforestry adoption in southern Malawi: The case of mixed intercropping of *Gliricida sepium* and maize. Agric Syst 78 (1): 57-71. DOI: 10.1016/S0308-521X(03)00032-5.
Tremblay S, Lucotte M, Revert JP, Davidson R, Mertens F, Passos JS, Romana CA. 2014. Agroforestry systems as a profitable alternative to slash and burn practices in small-scale agriculture of the Brazilian Amazon. Agrofor Syst 89: 193-204. DOI: 10.1007/s10457-014-9753-y.
UNEP. 2013. Afghanistan Post-Conflict Environmental Assessment; First Published in Switzerland by the United Nations Environment Programme. First published in Switzerland by the University of Notre Dame Afghanistan Notre Dame Global Adaptation Index. http://index.gain.org/country/afghanistan
USAID. 2017. Kunduz Province profile. College of Agriculture and Environmental Sciences. International Programs ip. ucdavis. edu. USAID report, 2017, http:// Afghanag.ucdavis. edu/ Afghanistan-province-agriculture profile.
WMO. 2018. The State of the Global Climate in 2018 (World Meteorological Organization), DOI: 10.1029/2018GL079362.
Zomer RJ, Bossio DA, Trabucco A, Yuanjie L, Gupta DC, Singh VP. 2007. Trees and Water: Smallholder Agroforestry on Irrigated lands in Northern India. IWMI Research Report 122 International Water Management Institute, Colombo Sri Lanka.

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Contribution of deadwood and forest soil to carbon sequestration in Chitwan National Park, Nepal

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Abstract. *Lamichhane U, Ghimire P. 2024. Contribution of deadwood and forest soil to carbon sequestration in Chitwan National Park, Nepal. Asian J For 8: 158-164.* Deadwood and forest soil are essential components of forest ecosystems, significantly contributing to carbon (C) sequestration and climate change mitigation. This study evaluated the condition of deadwood in Chitwan National Park (CNP) and assessed the carbon sequestration potential of both deadwood and forest soil. Using the line transect method, we assessed standing and fallen deadwood, along with soil analysis. Soil samples were collected by incremental depth (0-15 and 16-30 cm). Deadwood classes were categorized into three density classes—sound, intermediate, and rotten—based on wood hardness. The study found that the total volume and biomass of deadwood were 24.66 m^3 ha^{-1} and 12.84 t ha^{-1}, respectively, with a total carbon stock of 6.43 t ha^{-1}. Carbon stock was primarily concentrated in the intermediate class for both standing (40.57%) and fallen deadwood (43.01%). A significant difference was found between total carbon stocks in standing and fallen deadwood ($p<0.003$) in CNP forest. Total soil organic carbon (SOC) in CNP was measured at 69.64 t ha^{-1} up to a 30 cm soil depth. An independent t-test revealed a significant difference in average SOC between the two soil layers ($p<0.001$). Thus, the development and implementation of regional plans for deadwood management are necessary in Chitwan National Park.

Keywords: Carbon sink, climate change, deadwood carbon, forest ecosystem, soil organic carbon

Abbreviations: C: Carbon, CNP: Chitwan National Park, CO_2: Carbon dioxide, GHGs: Greenhouse gases, SOC: Soil organic carbon

INTRODUCTION

There is a global consensus that climate change is a real and rapidly advancing threat in this century, with world temperatures increasing by 0.11°C per decade since 1850 (IPCC 2023). Since 1982, this warming rate has accelerated to 0.20°C per decade, with widespread agreement that an increase above 2°C could trigger runaway climate change, severely impacting weather systems and biodiversity (USGCRP 2017; IPCC 2023). Forests play a crucial role in the global carbon (C) cycle, storing a significant proportion of atmospheric C. In forest ecosystems, biomass C and soil C are key components of C storage (Lal et al. 2015; Ghimire 2022). Depending on management practices, forests can either act as C sinks or sources. Notably, green forests have been identified as a cost-effective solution for C sequestration, aiding in the mitigation of global warming (Gren and Aklilu 2016; Raihan et al. 2019). In this context, Nepal's forests are of particular importance, and quantifying C stored across various pools contributes to global management efforts.

Deadwood, including fallen trees, branches, fragmented wood, stumps, and standing dead trees (snags), represents an essential component of forest ecosystems (Neumann et al. 2023; Stokland and Alfredsen 2024). Historically, deadwood was often misperceived as a vector for tree diseases, insect infestations, and forest fires (Kafle et al. 2019; Paletto et al. 2021; Seibold et al. 2021). However, recent studies on nutrient cycling and global warming emphasize that deadwood is critical to ecosystem biodiversity, stability, and balance (Blonska et al. 2017; Paletto et al. 2021; Neumann et al. 2023). Numerous studies have highlighted the vital role of deadwood in C storage, nutrient cycling, energy flow, and soil fertility improvement, among other benefits (Kafle et al. 2019; Seibold et al. 2021).

Soils also represent a vital C sink, significantly contributing to climate change mitigation (Lal et al. 2015; Blonska et al. 2019). Soil C sequestration captures atmospheric carbon dioxide (CO_2) and stores it as organic matter, which plays a critical role in reducing atmospheric CO_2 levels (Lal et al. 2015; Ghimire et al. 2018). In addition to offsetting anthropogenic emissions, soil C sequestration strengthens terrestrial C sinks. Globally, soil is the largest reservoir of terrestrial organic C, containing three times more C than the atmosphere and 3.8 times more than the biotic pool (Lal et al. 2015; Boubehziz et al. 2024). Consequently, soil organic carbon (SOC) stocks have a vital role in mitigating climate change as a key component of the terrestrial C cycle.

The global forest C reservoir is larger than that in the atmosphere (Lal et al. 2015; IPCC 2023). Soils worldwide contain approximately 1,500 billion tonnes of organic C, making them the second-largest active C sink after oceans, which store around 4,000 billion tonnes. Soil stores more C than vegetation (560 billion tonnes) and the atmosphere (760 billion tonnes) combined (Kafle et al. 2019; Mo et al. 2023). Thus, forestry initiatives have significant potential for reducing net greenhouse gas emissions by preventing C release from standing forests, enhancing soil management, or promoting natural regeneration of degraded areas. Deadwood is increasingly recognized as critical in C stock conservation (Seibold et al. 2015; Kafle et al. 2019; Liu and Fan 2023). For example, deadwood in the USA stores 14% of the nation's total forest C pool (Woodall et al. 2008). In Nepal's forests, out of the total C stock, tree components (live, dead standing, deadwood, and below-ground biomass), forest soils, and litter and debris account for 61.53, 37.80, and 0.67%, respectively (DFRS 2016). Kafle et al. (2019) reported 10.741 t ha^{-1} of total C stock in dead wood in Parsa National Park, Nepal. According to, Subedi et al. (2015), forests in Nepal's Chitwan-Annapurna Landscape (CHAL) region have a total C stock of 540.1 million tCO_2e with an average of 725.9 tCO2e ha^{-1}. Of the various carbon pools, the live C pool stored above and below ground is 399.6 tCO_2e ha^{-1}, the soil is also an important pool of C with an average of 320.3 tCO_2e ha^{-1}. Thus, deadwood contributes to sustainable forest management and mitigates climate change due to its C storage capacity (Senhofa et al. 2020; Stokland and Alfredsen 2024). In Nepal, studies focusing on non-living biomass C sequestration are very limited, yet they are critical for understanding the true C potential of these ecosystems. Given Nepal's commitment to sustainable forest management and climate mitigation under the Paris Agreement of United Nations Framework Convention on Climate Change, it is essential to assess all C pools in order to inform national and regional climate policies. This study aimed to explore the potential of deadwood and forest soil in C storage, contributing to climate change mitigation.

MATERIALS AND METHODS

Study area

This study was conducted in Chitwan National Park (CNP), located in south-central Nepal, spanning an area of 952.63 km² in the tropical lowlands of the Inner Terai (Figure 1). Elevations range from approximately 100 m in the river valleys to 815 m in the Siwalik Hills. Established in 1973 as Nepal's first national park, CNP holds unique ecosystems of global significance. In 1996, a 750 km² buffer zone surrounding the park, consisting of forests, private lands, and cultivated areas, was designated to enhance conservation efforts. The park contains tropical and subtropical forests, with *Shorea robusta* (Sal) forests covering around 70% of its area. Grasslands make up 20%, riverine forests 7%, and *Shorea robusta* mixed with Chirpine 3%. The riverine forests, largely in the floodplains, consist mainly of *Acacia catechu*, *Dalbergia sissoo*, and *Bombax ceiba*, while *Pinus roxburghii* is found at higher elevations. The park experiences average winter temperatures of 25°C, reaching up to 43°C during the summer (CNP 2022).

Sampling and data collection

Deadwood sampling was conducted using a line transect method, with a total of 158 transect lines randomly laid for inventory, following methods by De Meo et al. (2019) and Neumann et al. (2023). Each transect line measured 100 m in length. Every piece of wood intersecting the line had its diameter measured, and decomposition class recorded. Only fallen deadwoods with a minimum diameter of 10 cm were measured. Wood samples were classified into three decomposition classes—sound (very hard), intermediate (hard), and rotten (soft)—determined by striking the wood with a sharp blade. If the blade rebounded, the wood was categorized as sound; if it slightly penetrated, intermediate; and if it split apart, rotten (Pearson et al. 2007).

Standing dead trees and stumps were sampled within 158 circular plots of 100 m² each, following carbon measurement guidelines by ANSAB (2010). For each plot, diameter at breast height (DBH) and height were measured. Standing dead trees were identified based on criteria from ANSAB (2010): (a) trees with branches and twigs but no leaves, (b) trees with no twigs but with small and large branches, (c) trees with only large branches, and (d) trunks without branches. These samples were classified by decomposition state using methods by Pearson et al. (2007).

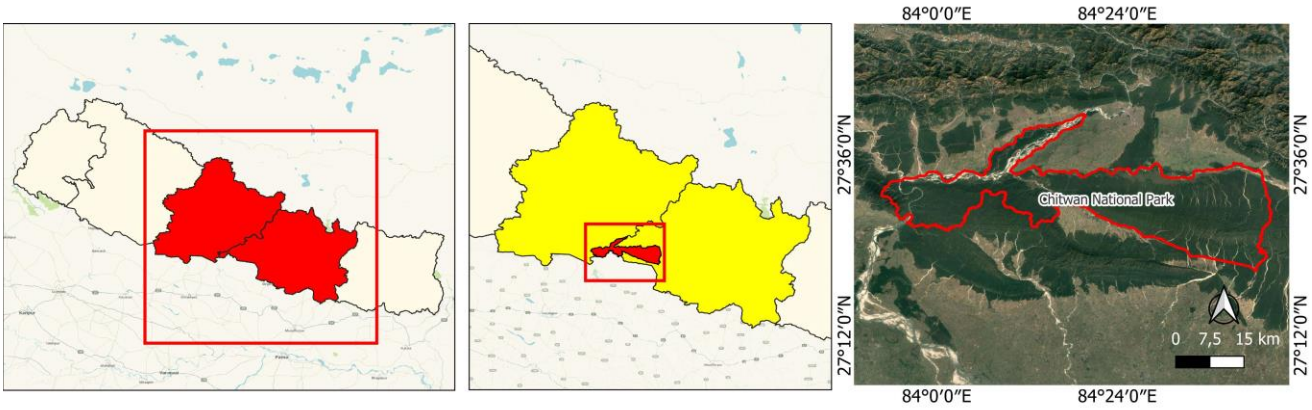

Figure 1. Location map of Chitwan National Park, Nepal and its buffer zone area

Soil samples were collected from 40 soil pits, with two samples taken per pit (depths of 0-15 and 16-30 cm). Each soil core sample, approximately 200 cm^3, was collected using a cylindrical metal core (5 cm diameter and 5 cm length). Additional soil samples (100 g each) were taken from each depth for bulk density and organic carbon analysis. Samples were labeled and sent to a soil laboratory for further analysis (ANSAB 2010).

Estimation of biomass and carbon stock in fallen deadwoods

The volume of fallen deadwoods per unit area was estimated for each decomposition class using the following formula (Kafle et al. 2019):

Volume (m^3 ha^{-1}) = $\pi^2 * [(d1^2 + d2^2 + d3^2 \ldots\ldots..+dn^2)/8L]$

Where:

d1, d2, d3,…, dn: The diameter (cm) of each of the n pieces intersecting the transect line

L: The transect line length (100 m)

Average dry density of deadwoods was calculated for each class, adjusting by a proportion factor: 90% for sound, 70% for intermediate, and 40% for rotten wood (ANSAB 2010; Kafle et al. 2019). Biomass and carbon stocks were then estimated using the formula suggested by Pearson et al. (2007):

Biomass stock (t ha^{-1}) = ∑ (average dry wood density × volume of deadwoods for each decomposition class)

Carbon stock of fallen deadwoods (t ha^{-1}) = Biomass stock/2

Estimation of biomass and carbon stock in standing dead trees and stumps

The biomass of each dead tree or stump was estimated using the allometric equation by Chave et al. (2005):

$$B = 0.112 \times (\rho D^2 h)^{0.916}$$

Where:

B: The biomass (kg)

ρ: The wood specific gravity (g cm^{-3})

D: DBH (cm)

h: Tree height (m)

Biomass density for each plot was calculated, then converted to tons per hectare (t ha^{-1}) by multiplying by 10. Carbon stock densities were derived by applying the IPCC (2006) default carbon fraction of 0.47 (ANSAB 2010).

Soil organic carbon analysis

Soil bulk density was calculated using core sampling method (ANSAB 2010). Samples were oven-dried at 105°C to adjust for moisture, then calculated as follows:

Bulk density (g cm^{-3}) = Oven dry weight of soil (g)/ Volume of the soil (cm^3)

Soil organic carbon (SOC) per unit area (t ha^{-1}) was measured using the Walkley-Black wet oxidation method (Walkley and Black 1934), involving oxidation by potassium dichromate and sulfuric acid, with titration of excess dichromate by ferrous ammonium sulfate. SOC stock was calculated with Chhabra et al. (2003) equation:

SOC = ρ×*d× %C

Where:

ρ: The bulk density

d: Soil horizon depth (cm),

%C: The organic carbon percentage.

To assess variations in deadwood C stocks among decomposition classes, a one-way ANOVA was performed at a 5% significance level. Differences in SOC between soil depths were evaluated with an independent t-test at the same significance level.

RESULTS AND DISCUSSION

Volume of standing and fallen deadwoods

In Chitwan National Park (CNP), the volume of standing deadwoods across three decomposition classes—rotten, intermediate, and sound—was calculated. The total volume of standing deadwoods was found to be 13.40 m^3 ha^{-1}. The intermediate class had the highest volume of standing deadwood at 5.44 m^3 ha^{-1}, followed by the sound class at 4.92 m^3 ha^{-1}, and the rotten class at 3.05 m^3 ha^{-1}. Similarly, the total volume of fallen deadwoods was measured at 11.26 m^3 ha^{-1}. Among the decomposition classes for fallen deadwoods, the intermediate class again had the highest volume at 4.76 m^3 ha^{-1}, followed by the sound class at 3.62 m^3 ha^{-1}, and the rotten class at 2.88 m^3 ha^{-1}. Table 1 presents the descriptive statistics for the volume of standing and fallen deadwoods in each decomposition class within the CNP forest.

Table 1. Statistics of standing and fallen deadwoods volume in Chitwan National Park, Nepal

Deadwoods category	Decomposition classes	Volume (m^3 ha^{-1})			
		Mean±SE	Maximum	Minimum	Total
Standing	Rotten	0.163±0.044	0.82	0.02	3.05
	Intermediate	0.130±0.020	0.88	0.01	5.44
	Sound	0.082±0.018	0.65	0.00	4.92
	Total	0.125±0.028			13.40
Fallen	Rotten	0.082±0.015	0.50	0.02	2.88
	Intermediate	0.089±0.017	0.58	0.04	4.76
	Sound	0.117±0.022	0.52	0.01	3.62
	Total	0.960±0.018			11.26

Table 2. Biomass of standing and fallen deadwood in Chitwan National Park, Nepal

Deadwoods category	Decomposition classes	Biomass stock (t ha^{-1})			
		Mean±SE	Maximum	Minimum	Total
Standing	Rotten	0.085±0.016	0.28	0.01	1.61
	Intermediate	0.0.68±0.005	0.21	0.01	2.83
	Sound	0.0493±0.004	0.30	0.00	2.54
	Total	0.125±0.028			6.98
Fallen	Rotten	0.043±0.016	0.27	0.01	1.46
	Intermediate	0.046±0.008	0.30	0.03	2.52
	Sound	0.058±0.012	0.28	0.01	1.88
	Total	0.960±0.018			5.86

Table 3. Bulk density and organic carbon content on different soil depths in Chitwan National Park, Nepal

Attributes	Soil depths (cm)			
	0-15		16-30	
	Mean	SE	Mean	SE
Bulk density (gm cm^{-3})	1.19	0.01	1.27	0.01
Organic carbon content (%)	2.14	0.02	1.64	0.01

Table 4. Total soil organic carbon stock at different soil depths in Chitwan National Park, Nepal

Soil depths (cm)	Mean SOC (t ha^{-1})	SE	*p*-value (t-test)
0-15	38.20	1.72	0.001*
16-30	31.24	1.30	
Total	69.64		

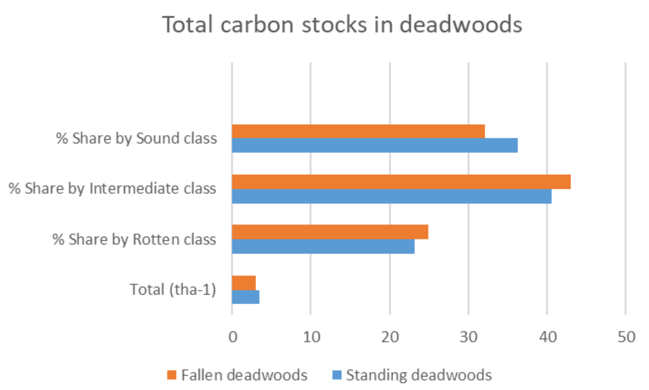

Figure 2. Total carbon stock in deadwoods in Chitwan National Park, Nepal

Biomass of standing and fallen deadwoods

A total of 6.98 t ha^{-1} of biomass was recorded in standing deadwoods and 5.86 t ha^{-1} in fallen deadwoods. The intermediate decomposition class had the highest biomass in both standing (2.83 t ha^{-1}) and fallen deadwood (2.52 t ha^{-1}) categories. Conversely, the lowest biomass was observed in the rotten class for both standing and fallen deadwood categories (Table 2).

ANOVA results indicated no significant difference in the mean biomass stock across decomposition classes for both standing deadwood ($p>0.05$) and fallen deadwood ($p>0.05$). This suggests that the mean carbon stocks for each decomposition class contributed approximately equally within the CNP forest (Table 2).

Total carbon stocks of deadwoods in CNP

In the CNP forest, the total carbon stock in deadwood was 6.43 t ha^{-1}, with 3.5 t ha^{-1} contributed by standing deadwood and 2.93 t ha^{-1} by fallen deadwood. Within the standing deadwood category, 40.57% of the carbon stock was attributed to the intermediate decomposition class, followed by 36.29% in the sound class and 23.14% in the rotten class (Figure 2). Similarly, in the fallen deadwood category, the intermediate class accounted for 43.01% of the carbon stock, followed by 32.08% in the sound class and 22.91% in the rotten class. The total carbon stock in standing deadwood was thus 1.20 times higher than in fallen deadwood. Additionally, the study found a significant difference between the total carbon stocks in standing and fallen deadwood ($p<0.003$) in the CNP forest.

Bulk density and organic carbon content

The average bulk density in the CNP forest was 1.23 g cm^{-3}, with an average bulk density of 1.19 g cm^{-3} in the 0-15 cm soil profile depth and 1.27 g cm^{-3} in the 16-30 cm profile depth (Table 3). The highest bulk density was recorded in the 16-30 cm profile depth at 1.63 g cm^{-3}, while the lowest value was recorded in the 0-15 cm profile depth at 0.80 g cm^{-3}.

Similarly, the average organic carbon content in the CNP forest was 1.89%, with 2.14% in the 0-15 cm soil profile depth and 1.64% in the 16-30 cm profile depth (Table 3). The highest organic carbon content was found in the 0-15 cm profile depth at 2.39%, while the lowest was recorded in the 16-30 cm profile depth at 0.35%.

Soil organic carbon stock

The distribution of mean soil organic carbon (SOC, t ha^{-1}) in both soil profile depths is shown in Table 4. The total SOC in CNP was found to be 69.64 t ha^{-1}. The average SOC was higher in the 0-15 cm soil depth, with 38.20 t ha^{-1}, while the 16-30 cm depth had a lower average of 31.24 t ha^{-1}. The quantity of SOC decreased with increasing soil depth (Table 4). The independent t-test indicated a significant difference in the mean SOC between the two soil profile depths ($p<0.001$).

Deadwoods are an important carbon (C) pool and a significant source of carbon that must be accounted for (Wijas et al. 2024). They are a vital component of forest ecosystems, contributing significantly to carbon storage and cycling, thus aiding in climate change mitigation (Moreno-Fernández et al. 2020; Liu and Fan 2023). In this study, the total biomass and C stock of standing deadwoods were higher than those of fallen deadwoods (Figure 2). The total C stock in standing deadwoods was found to be 1.20 times higher than that of fallen deadwoods. In both standing and fallen deadwoods, the proportion of biomass and C stock was predominantly dominated by the intermediate decomposition class. The intermediate class shared 40.57% of the total C in standing deadwoods, while in fallen deadwoods, it contributed 43.01%. These results are consistent with those of Kafle et al. (2019), who reported higher biomass and C stock in standing deadwoods than fallen deadwoods in Parsa National Park, Nepal. Kafle et al. (2019) also found that the intermediate class contributed the highest biomass and C stock for both standing and fallen deadwoods. Furthermore, a study by Kirby et al. (1998) in the USA reported that the volume of fallen deadwoods in British broadleaved forests was less than 20 m^3 ha^{-1}. Alberdi et al. (2020) also reported deadwood biomass of 2.92 Mg ha^{-1} in the mixed forests of southwestern Europe, which is double the stock found in conifer and broadleaved forests. Understanding and preserving the role of deadwoods in carbon dynamics is crucial for sustainable forest management and global climate regulation.

Soil organic carbon (SOC) is a critical component of soil health and plays a pivotal role in forest productivity, ecosystem resilience, and the global carbon cycle (Lal et al. 2015). This study quantified SOC stocks up to a depth of 30 cm. SOC content ranged from 0.35 to 2.39% in the study area. The higher SOC content in the upper soil layers may be attributed to increased organic matter content and reduced influence of parent materials (Lal et al. 2015; Ghimire et al. 2018). The average SOC stock up to 30 cm depth was found to be 34.82 t ha^{-1}. The SOC stock was higher in the upper soil layers than in the lower layers. Pandey and Bhusal (2016) reported that SOC decreases with increasing soil depth in *Shorea robusta* forests of Nepal's hills and Terai regions. Ghimire et al. (2018) found SOC stocks of 24.65 t ha^{-1} up to 40 cm in the *Shorea robusta*-dominated lowland forests of Makawanpur District, Nepal. In addition, SOC in the Terai and Chure regions of Nepal was estimated to be 33.66 t ha^{-1} and 31.44 t ha^{-1}, respectively, within 30 cm depth (DFRS 2016), which aligns with the current findings of 34.82 t ha^{-1}. This similarity may be due to comparable physiographical locations and forest types. Bono et al. (2024) reported that temperate old-growth forests in the Dinaric Alps contain some of the largest carbon stocks in Europe, with 67 Mg C ha^{-1} in dead biomass and 96 Mg C ha^{-1} in soil to a depth of 60 cm. Similarly, Seedre et al. (2015) estimated 15 Mg C ha^{-1} and 171 Mg C ha^{-1} of C stock in dead biomass and soil, respectively, in a montane Norway spruce (*Picea abies* Karst.) old-growth forest in the Bohemian Forest, Czech Republic. Chhabra et al. (2003) found 70 Mg ha^{-1} of SOC in tropical deciduous forests in India at a 1-meter soil profile depth. Compared to IPCC estimates for European mountain temperate primary forests (IPCC 2019; Yona et al. 2020), the total C stock of 328 Mg C ha^{-1} is much higher than our estimate of 75.87 Mg C ha^{-1}, which excludes living biomass. Healthy SOC levels support diverse soil life, reduce erosion and pollution, and contribute to sustainable land management and global food security (Ghimire et al. 2023; Mo et al. 2023).

Moreover, the findings from this study consistent with global research emphasizing the significance of non-living carbon pools in forest carbon accounting. For instance, in a comprehensive study of carbon stocks across global forests, Pan et al. (2011) reported that deadwood and soil together contribute approximately 40% of the total forest carbon pool in boreal and tropical forests. Similarly, Poudel et al. (2019) reported that community managed forest of tropical area of Nepal exhibited higher carbon stock (176. 8 t ha^{-1}) than agricultural land (73.42 t ha^{-1}). The carbon stored in the forest biomass was found to be 1.5 times higher than in the forest soils. This substantial proportion under importance of including deadwood and soil carbon pools in forest carbon inventories and management strategies. By expanding the focus of carbon sequestration studies beyond live biomass, we can gain a more accurate picture of carbon storage potential, as seen in this study on Chitwan National Park.

In conclusion, this study highlights the critical roles of deadwood and forest soil in carbon sequestration within Chitwan National Park, Nepal. Deadwood, a critical component of forest biomass, serves as both a carbon sink and a reservoir, storing carbon over long periods as it decomposes slowly. Forest soils also hold large amounts of carbon through organic matter accumulation, making them essential for long-term carbon storage. Together, deadwood and forest soil are vital contributors to mitigating climate change by reducing atmospheric carbon levels. This study found that standing deadwoods contributed more carbon stock than fallen deadwoods, with the former being 1.20 times greater. Furthermore, the average carbon stock in both standing and fallen deadwoods was higher in the sound class compared to the intermediate and rotten classes. As significant carbon pools, deadwood and soil contribute meaningfully to the total carbon stock, providing long-term storage that is crucial in mitigating climate change. Findings of this study are consistent with existing research in Nepal, reinforcing the importance of incorporating deadwood and soil organic carbon into national carbon accounting. For policymakers, this study offers valuable insights for developing holistic approaches to carbon management, which are essential as Nepal targets its climate goals under the Paris Agreement. By recognizing the roles of deadwood and soil, conservation efforts can prioritize these components to maximize carbon sequestration, support forest resilience, and contribute to mitigating the effect of global warming.

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REFERENCES

Alberdi I, Moreno-Fernández D, Canellas I, Adame P, Hernández L. 2020. Deadwood stocks in south-western European forests: Ecological patterns and large scale assessments. Sci Total Environ 747: 141237. DOI: 10.1016/j.scitotenv.2020.141237.

ANSAB. 2010. Forest Carbon Stock Measurement: Guideline for measuring carbon stocks in community managed forests. Asia Network for Sustainable Agriculture and Bioresources (ANSAB), Kathmandu, Nepal. https://ansab.org.np/wp-content/uploads/2010/08/forest-carbon-measurement-guideline.pdf.

Blonska E, Kacprzyk M, Spolnik A. 2017. Effect of deadwood of different tree species in various stages of decomposition on biochemical soil properties and carbon storage. Ecol Res 32: 193-203. DOI: 10.1007/s11284-016-1430-3.

Blonska E, Lasota J, Tullus A, Lutter R, Ostonen I. 2019. Impact of deadwood decomposition on soil organic carbon sequestration in Estonian and Polish forests. Ann For Sci 76: 102. DOI: 10.1007/s13595-019-0889-9.

Bono A, Alberti G, Berretti R, Curovic M, Dukic V, Motta R. 2024. The largest European forest carbon stocks are in the Dinaric Alps old-growth forests: comparison of direct measurements and standardized approaches. Carbon Balance Manag 19: 15. DOI: 10.1186/s13021-024-00262-4.

Boubehziz S, Piccini C, Jiménez-González MA, Almendros G. 2024. Spatial distribution of soil organic carbon quality descriptors determining factors that affect its sequestration in Northeast Algeria. J Environ Manag 358: 120772. DOI: 10.1016/j.jenvman.2024.120772.

Chhabra A, Palria S, Dadhwal VK. 2003. Soil organic carbon pool in Indian forests. For Ecol Manag 173: 187-199. DOI: 10.1016/S0378-1127(02)00016-6.

Chave J, Andalo C, Brown S, Cairns MA, Chambers JQ, Eamus D, Fölster H, Fromard F, Higuchi N, Kira T, Lescure JP, Nelson BW, Ogawa H, Puig H, Riéra B, Yamakura T. 2005. Tree allometry and improved estimation of carbon stocks. Oecologia 145: 87-99. DOI: 10.1007/s00442-005-0100-x.

CNP. 2022. Annual Progress Report. Chitwan National Park (CNP), Kasara, Chitwan, Nepal. https://chitwannationalpark.gov.np/index.php/reports/annual-reports.

Department of Forest Research and Survey (DFRS). 2016. State of Nepal's forests. Forest Resource Assessment (FRA). Department of Forest Research and Survey (DFRS), Babaemahal, Kathmandu, Nepal. https://frtc.gov.np/en/sources/22/5599363.

De Meo I, Lagomarsino A, Agnelli AE, Paletto A. 2019. Direct and indirect assessment of carbon stock in deadwood: Comparison in Calabrian Pine (*Pinus brutia* Ten. subsp. *brutia*) forests in Italy. For Sci 65 (4): 460-468. DOI: 10.1080/17583004.2023.2197762.

Ghimire P. 2022. Vegetation and soil carbon pool in Chirpine (*Pinus roxburghii* Sarg.) forest of Mahabharat Hill, Nepal. Indian J Ecol 49 (2): 424-429. DOI: 10.55362/IJE/2022/3540.

Ghimire P, Bhatta B, Pokhrel B, Kafle G, Paudel P. 2018. Soil organic carbon stocks under different land uses in Chure region of Makawanpur District, Nepal. SAARC J Agric 16: 13-23. DOI: 10.3329/sja.v16i2.40255.

Ghimire P, Lamichhane U, Bolakhe S, Jeb Lee CH. 2023. Impact of land use types on soil organic carbon and nitrogen stocks: A study from the Lal Bakaiya Watershed in Central Nepal. Intl J For Res 2023: 9356474. DOI: 10.1155/2023/9356474.

Gren M, Aklilu AZ. 2016. Policy design for forest carbon sequestration: A review of the literature. For Policy Econ 70: 128-136. DOI: 10.1016/j.forpol.2016.06.008.

Intergovernmental Panel on Climate Change (IPCC). 2006. Intergovernmental Panel on Climate Change (IPCC), Guidelines for National Greenhouse Gas Inventories, Volume 4. Agriculture Forestry and other land use. Institute for Global Environmental Strategies (IGES), Hayanma, Japan. https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html.

Intergovernmental Panel on Climate Change (IPCC). 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IPCC, Switzerland. https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories.

Intergovernmental Panel on Climate Change (IPCC). 2023. Summary for Policymakers. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland. DOI: 10.59327/IPCC/AR6-9789291691647.001.

Kafle G, Timilsina YP, Sharma RP, Rijal ML, Bartaula B, Pokhrel B, Thakur V. 2019. Contribution of dead wood and forest soil to carbon sequestration in Parsa National Park, Nepal. J Agric For Univ 3: 113-123.

Kirby KJ, Reid CM, Thomas RC, Goldsmith FB. 1998. Preliminary estimates of fallen dead wood and standing dead trees in managed and unmanaged forests in Britain. J Appl Ecol 35: 148-155. DOI: 10.1046/j.1365-2664.1998.00276.x.

Lal R, Negassa W, Lorenz K. 2015. Carbon sequestration in soil. Curr Opin Environ Sustain 15: 79-86. DOI: 10.1016/j.cosust.2015.09.002.

Liu X, Fan W. 2023. Exploring the Ecological Benefits of Dead Wood and the Opportunities of Interpreting Dead Wood to the Public. Urban Stud Public Adm 6 (3): 63-74. DOI: 10.22158/uspa.v6n3p63.

Mo L, Zohner CM, Reich PB et al. 2023. Integrated global assessment of the natural forest carbon potential. Nature 624: 92-101. DOI: 10.1038/s41586-023-06723-z.

Moreno-Fernández D, Hernández L, Cañellas I, Adame P, Alberdi I. 2020. Analyzing the dynamics of the deadwood carbon pool in Spain through the European Level I Monitoring Programme. For Ecol Manag 463: 118020. DOI: 10.1016/j.foreco.2020.118020.

Neumann M, Echeverria S, Hasenauer H. 2023. A simple concept for estimating deadwood carbon in forests. Carbon Manag 14 (1): 2197762. DOI: 10.1080/17583004.2023.2197762.

Pan Y, Birdsey RA, Fang J, Houghton R, Kauppi PE, Kurz WA, Phillips OL, Shvidenko A, Lewis SL, Canadell JG, Ciais P. 2011. A large and persistent carbon sink in the world's forests. Science 333 (6045): 988-993. DOI: 10.1126/science.1201609.

Paletto A, Agnelli AE, De Meo I. 2021. Carbon stock in deadwood: the mountain birch (*Betula pubescens* subsp. *czerepanovii*) forests in the Khibiny Mountains (Russia). J Sustain For 40 (4): 385-400. DOI: 10.1080/10549811.2020.1767144.

Pandey HP, Bhusal M. 2016. A comparative study on carbon stock in Sal (*Shorea robusta*) forest in two different ecological regions of Nepal. Banko Janakari 26 (1): 24-31. DOI: 10.3126/banko.v26i1.15498.

Pearson TRH, Brown SL, Birdsey RA. 2007. Measurement guidelines for the sequestration of forest carbon. USDA Forest Service, Newtown Square, PA, USA. https://winrock.org/wp-content/uploads/2016/03/Measurement-Guidelines.pdf.

Poudel A, Shrestha HL, Bajracharya RM. 2019. Quantification of carbon stock under different land use regimes of Chitwan district, Nepal. Banko Janakari 29 (2): 13-19. DOI: 10.3126/banko.v29i2.28095.

Raihan A, Begum RA, Mohd Said MN, Abdullah SMS. 2019. A review of emission reduction potential and cost savings through forest carbon sequestration. Asian J Water Environ Pollut 16 (3): 1-7. DOI: 10.3233/AJW190027.

Seedre M, Kopáček J, Janda P, Bače R, Svoboda M. 2015. Carbon pools in a montane old-growth Norway spruce ecosystem in Bohemian Forest: Effects of stand age and elevation. For Ecol Manag 346: 106-113. DOI: 10.1016/j.foreco.2015.02.034.

Seibold S, Bässler C, Brandl R, Gossner MM, Thorn S, Ulyshen MD, Müller J. 2015. Experimental studies of dead-wood biodiversity—a review identifying global gaps in knowledge. Biol Conserv 191: 139-149. DOI: 10.1016/j.biocon.2015.06.006.

Seibold S, Rammer W, Hothorn T, Seidl R, Ulyshen MD, Lorz J, Cadotte MW, Lindenmayer DB, Adhikari YP, Aragón R, Bae S. 2021. The contribution of insects to global forest deadwood decomposition. Nature 597: 77-81. DOI: 10.1038/s41586-021-03740-8.

Senhofa S, Jaunslaviete I, Šņepsts G, Jansons J, Liepa L, Jansons A. 2020. Deadwood characteristics in mature and old-growth birch stands and their implications for carbon storage. Forests 11 (5): 536. DOI: 10.3390/f11050536.

Stokland J, Alfredsen G. 2024. From deadwood to forest soils: quantifying a key carbon flux in boreal ecosystems. Biogeochemistry 167: 1225-1242. DOI: 10.1007/s10533-024-01170-y.

Subedi BP, Gauli K, Joshi NR, Pandey A, Charmakar S, Poudel A, Murthy MRS, Glani H, Khanal SC. 2015. Forest Carbon Assessment in Chitwan-Annapurna Landscape. Study Report, WWF Nepal Hariyo Ban Program, Baluwatar, Kathmandu, Nepal. https://wwfasia.awsassets.panda.org/downloads/forest_carbon_assessment_in_chitwan_annapurna_landscape_1_1.pdf.

USGCRP. 2017. Climate Science Special Report: Fourth National Climate Assessment, Volume I. U.S. Global Change Research Program, Washington, DC, USA. DOI: 10.7930/J0J964J6.

Walkley A, Black IA. 1934. An examination of Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci 37: 29-37. DOI: 10.1097/00010694-193401000-00003.

Wijas BJ, Allison SD, Austin AT, Cornwell WK, Cornelissen JHC, Eggleton P, Fraver S, Ooi MKJ, Powell JR, Woodall CW, Zanne AE. 2024. The role of deadwood in the carbon cycle: Implications for models, forest management, and future climates. Ann Rev Ecol Evol Syst 55: 133-155. DOI: 10.1146/annurev-ecolsys-110421-102327.

Woodall CW, Heath LS, Smith JE. 2008. National inventories of down and dead woody material forest carbon stocks in the United States: Challenges and opportunities. For Ecol Manag 256: 221-228. DOI: 10.1016/j.foreco.2008.04.003.

Yona L, Cashore B, Jackson RB, Ometto J, Bradford MA. 2020. Refining national greenhouse gas inventories. Ambio 49: 1581-1586. DOI: 10.1007/s13280-019-01312-9.

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Inclusivity in decentralized forest management and its effects on economic resilience and nature sustainability in East Central Tanzania

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Abstract. *Ngowi NJ. 2024. Inclusivity in decentralized forest management and its effects on economic resilience and nature sustainability in East Central Tanzania. Asian J For 8: 165-173.* Inclusivity plays a crucial role in engaging all members of society in efforts to reduce risks to their welfare while maximizing the environmental sustainability of natural resources. However, decentralized forest management systems often fail to demonstrate well the connection between inclusivity and balanced decision-making, especially when it comes to evaluating the state of environmental sustainability and the well-being of local communities. This study sought to bridge this gap by examining the effects of inclusivity on economic resilience and nature sustainability in decentralized Ihombwe forest in east-central Tanzania (ECT) over the period from 2021 to 2022. A combination of qualitative and quantitative approaches was employed, including a household survey of 56 carefully chosen families, focus group discussions, and document analysis, to gain a deeper understanding of inclusivity, economic welfare, and sustainability within the Ihombwe forest in ECT, as well as the key driving factors. The results showed a steady decline in the benefits of increased access to forest resources; this did not translate into improved outcomes for the community's welfare or the forest's environmental sustainability. These findings reveal a complex relationship where inclusivity and access alone might not be enough to encourage sustainable development. However, they offer theoretical insights and policy recommendations aimed at fostering greater inclusivity in decentralized forest management frameworks to improve both forest conservation and the welfare of local populations in the ECT.

Keywords: Community forests, gender, inclusivity, sustainability, UNSDGs

INTRODUCTION

Inclusivity enhances engagement and participation among all community members, including marginalized groups, in decision-making processes (Agrawal and Gibson 1999; Katani and Babili 2012; Datta 2021; Gonzalez and Botero 2021), providing benefits for management practices. Linking inclusivity to local institutions, including village governments and traditional leaders, is critical in addressing gender disparity by ensuring women's equitable participation in accessing resources and decision-making (Agarwal 2001) for effective forest resource management (Ostrom 1990; Gibson et al. 2000). On the other hand, a decentralized framework is instrumental in facilitating the integration of community knowledge and priorities into forest management plans, enhancing the legitimacy and effectiveness of conservation efforts through various stakeholder mobilization (Kauffman et al. 2016), community inclusivity (Mogoi et al. 2022), and translating global goals into local actions (Stoker 2011; Sujarwoto 2017; Ansell et al. 2022).

Sustainable Development Goals (SDGs) emphasize community participation, particularly in Tanzania, where decentralized forest management sustains well-being and ecological health (UN 2015). Inclusivity advances SDGs (Hajjar and Holley 2017) in terms of poverty reduction (SDG 1), improved ecosystems and biodiversity through agroforestry (SDG 2), and gender equality in decision-making (SDG 5) (Blomley et al. 2008; Agarwal 2009). Additionally, inclusive forest management fosters sustainable livelihoods and employment, enhancing economic resilience (SDG 8) (Sunderlin et al. 2005). Tanzania's community-managed forests have significantly contributed to SDG 15 (life on land) by conserving and restoring ecosystems (Meshack et al. 2006). Forest management also intersects with other SDGs, such as water and sanitation (SDG 6), climate action (SDG 13) (Mamuya and Kalpers 2023), and life below water (SDG 14) (Poudel et al. 2014). Transparency and participation are essential for achieving SDG 16 (peace, justice, and strong institutions) and SDG 17 (partnerships) (Ribot et al. 2010). Furthermore, inclusivity promotes social justice and reduces gender disparities, aligning forest management with local community needs (FAO 2020).

Forests play a crucial role in the three pillars of sustainability—ecological, economic, and social—and require diverse management strategies tailored to different landscapes, cultures, and institutions. In this respect, Community-Based Natural Resources Management (CBNRM) initiatives were introduced in selected regions—Africa, Asia, and South America—between the 1980s and 1990s following the failure of central approaches in managing natural resources (Murphree 2009; Zulu 2012). These initiatives emphasize community participation in managing local environments, aiming to enhance human well-being while maintaining nature sustainability

(Schmidt and Vellend 2020; Ngowi 2022).

To combat rising deforestation costs and boost revenues in the forest sector, Tanzanian government has embarked on reforms aimed at developing a coordinated strategy for natural resources management under the Forest and Beekeeping Division and the Tanzania Forest Services Agency (TFS). Building on CBNRM's success, Tanzania adopted Community-Based Forest Management (CBFM) in 2001 (Lund 2015; Bredin et al. 2020;). This decentralized forest management approach has reduced deforestation rates by approximately 0.1% annually, covering over 3.6 million hectares of forests under Village Land Forest Reserves (VLFRs) (Von Hippel et al. 2011; MNRT 2015; Nzali and Kaswamila 2019). CBFM has improved local well-being, given communities control over forest resources, aligned conservation efforts with local needs, promoted sustainable use, and ensured equitable benefit distribution (Mbeyale et al. 2021; Mogoi et al. 2022). Despite challenges posed by centralized management (Mung'ong'o et al. 2003; Dressler et al. 2010; Capitani et al. 2016), decentralization remains key to inclusivity, community well-being, and sustainability (Kaufmann et al. 2010; Busse and Gröning 2013).

One such decentralized forest management area is Ihombwe Village Land Forest Reserve (VLFR) in East Central Tanzania. Although CBFM has increased village revenue from forest resources, the role of grassroots governance in promoting local economic development remains underexplored. Therefore, this study aims to identify the drivers and determinants of inclusivity within decentralized forest governance in East-Central Tanzania using Ihombwe VLFR as a case study. This study aligns with global SDGs, Tanzania's Development Vision 2025, and the National Environmental Policy (URT 2021), emphasizing inclusivity for sustainability and economic well-being.

The adaptive governance and social capital approach, which holds that power sharing and decentralization in management improve participation, provides the framework for the study. Additionally, the method demonstrates that adaptive management is not always the result of decentralizing rights and authority to management (Folke et al. 2005). It highlights how community-based projects are adaptive resource management tailored to specific situations and supported by various levels and institutions. As a result, this method is particularly relevant for examining how inclusivity operates in decentralization and forest management contexts.

MATERIALS AND METHODS

Description of the study area

The study was conducted in Ihombwe Village, Kilosa District, Morogoro Region, East Central Tanzation (Figure 1). The village consists of a population of about 2,210 residents (Ngowi and Ngalawa 2023). In 2013, Ihombwe Village placed its forest under decentralized conservation management. The forest reserve, covering 9,597 hectares, is divided into six patches, demonstrating a structured approach to forest management (Ruvuga et al. 2020). This initiative highlights the importance of community-led conservation efforts in achieving sustainability targets. The village's forest reserve, managed by the Village Natural Resources Committee (VNRC), exemplifies local stewardship over natural resources. The VNRC's role involves daily forest management activities, aligning with SDG 15 (life on land), which promotes sustainable use of terrestrial ecosystems. These efforts contribute to biodiversity conservation and climate resilience, addressing both local and global environmental goals.

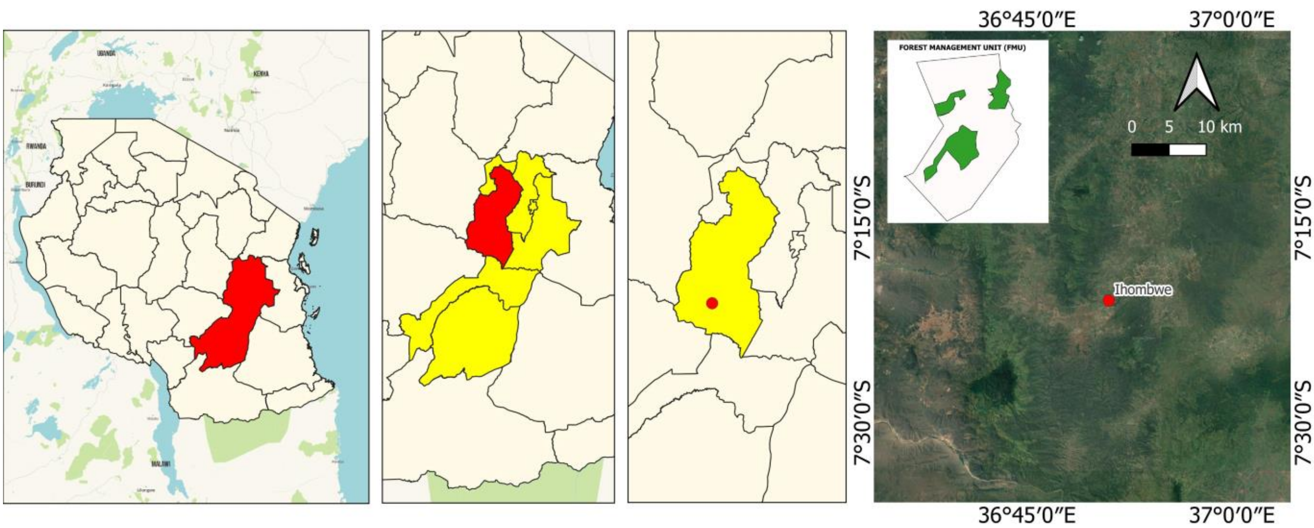


Figure 1. Map of the study area in Ihombwe Village, Kilosa District, Morogoro Region, East Central Tanzania

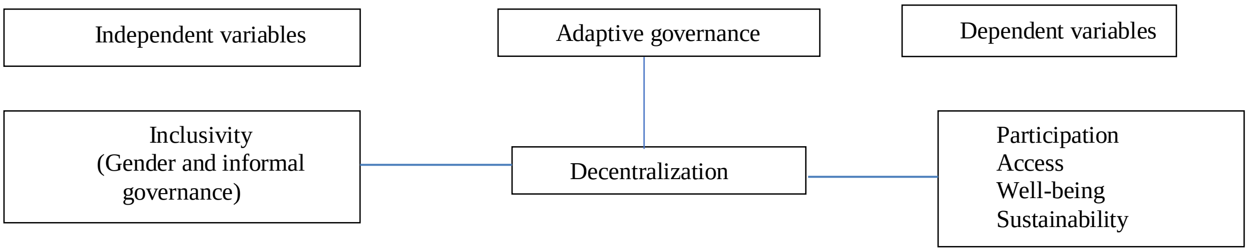


Figure 2. A research framework to explore the role of inclusivity in decentralized forest management

Despite the significant contributions of local governance, challenges remain. Implementing SDGs at the grassroots level requires overcoming obstacles such as limited financial resources, insufficient technical expertise, and the need for stronger institutional support (IISD 2024). However, the potential for local action to drive sustainable development is immense. The VNRC's success in managing the Ihombwe forest demonstrates the potential for scaling similar models across other regions in Tanzania. The integration of local governance with global SDG frameworks ensures that local actions align with broader sustainability objectives. This alignment enhances the effectiveness of both local and global efforts, creating a synergistic impact on sustainable development (Kauffman 2024). Local governance structures, through initiatives like community policing and innovative urban planning, can mobilize resources and foster holistic problem-solving, contributing to the attainment of multiple SDG targets at the same time.

Research framework

The study explored the role of inclusivity in term of gender and informal governance in decentralized forest management for economic and environmental resilience in Ihombwe Village using the research framework as shown in Figure 2.

The gender is used in the context of inclusivity as a component of social capital within the framework of adaptive governance for decentralized forest management. This aspect is critical in examining whether individuals of different genders are equitably represented, included, and empowered within a network or system. Analyzing gender or sex is particularly significant when assessing inclusivity in decision-making processes, access to resources, and participation in social, economic, or political activities. It is expected to influence key dependent variables, including community participation, improved well-being, and the sustainability of forest resources.

Another key element in the inclusivity is informal governance, which significantly influences decision-making and policy outcomes. These factors, often operating outside official decentralized institutions or legal frameworks, can shape how decisions are made, how stakeholders interact, and how forest resources are allocated. Informal governance plays a vital role in ensuring that diverse groups, particularly those without formal authority or recognition, still have a voice in the decision-making process. However, it's important to acknowledge that these unofficial structures can sometimes limit participation, favor certain groups, or create barriers for others.

Data collection

Research design and sample size

The study used documentary reviews for secondary data and surveys for primary data, along with supplemental tools to capture data not obtained through surveys. A purposive sampling method was applied to choose one study village based on its highest forest royalty revenue and the participation of village councils in management. This approach ensures the village is representative of successful forest management practices and substantial community involvement. The total number of households (N) was 430, determined using Israel's (1992) equation. In this equation, *n* represents the sample size, *N* is the total number of households from which the sample was drawn, and *e* denotes the sampling error, set at 5%.

$$\mathbf{n} = \frac{\mathbf{N}}{\mathbf{1 + N \cdot (e)^2}}$$

A simple random sampling method was used to select 56 respondents from the 430 households in the village. Every eighth household was chosen to create a random and representative sample. This approach minimizes selection bias and enhances data reliability. The sampling interval of 8 was calculated using the formula N/n = 430/56 ≈ 8N/n = 430/56 \approx 8N/n = 430/56≈8. Therefore, every eighth household is selected to achieve a sample size of 56. This systematic approach ensures that the sample is both manageable and representative of the population in the area.

Community survey

In examining the practice of the local community regarding inclusivity and the changes in well-being, accountability, and sustainability of forest resources that have occurred since the establishment of the decentralized forest management framework, a questionnaire with a five-point Likert scale, based on Ajzen (2002), was developed and administered to heads of households. The five-point include: 5: 'strongly agree', 4: 'agree', 3: 'neutral', 2: 'disagree', and 1: 'strongly disagree'. The eight statements were designed to collect data on: (i) changes in forest guidelines; (ii) gender equality; (iii) culture; (iv) inclusivity; (v) forest management institutions; (vi) access to forest resources; (vii) the role of village government; and (viii) sustainability of nature. Each household respondent's response was used to indicate their level of agreement with the statements.

Supplementary data collection

The following tools were used to supplement data not collected through the survey method. Focus Group Discussions (FGDs) were conducted with members of village natural resources committees in Kilombero, Kisiwani, and Minazini hamlets. FGDs involved adults aged 18 years and older who were involved in forestry management. Information on forest management processes and inclusivity was collected, as well as its effect on forest resource use, household incomes, and sustainability of nature (Kumar 1989).

Key informant interviews were conducted with village leaders, district government officials, and representatives from non-governmental organizations (NGOs) working in the area. These interviews provided insights into broader community perspectives, policy implementation, and potential challenges (Bernard 2018).

A gender analysis was conducted to understand access to forest resources between men and women. This analysis focused on the inclusion of women in forest management decision-making processes and their access to benefits from forest resources. This aligns with SDG 5 (Gender Equality), which promotes inclusivity (Agarwal 2001).

Transect walks were conducted to observe changes in the forest environment and land use practices in and around it over time. This method allowed researchers to gather data on forest cover, agricultural activities, and other environmental drivers (Chambers 1994a).

Participatory Rural Appraisal (PRA) techniques were used to collect qualitative data from community members regarding community access to forest resources. PRA resource mapping promoted community engagement and provided insights into the management practices of community forest, as explained by Chambers (1994b).

Data analysis

The data was analyzed using descriptive statistics in IBM SPSS. Descriptive statistics have been presented in percentages, tables, and graphs. Data on the strength of inclusivity on [income and economy] of selected groups was analyzed by summing scores on questions against three levels (weak, average, or strong). The latter indicated the strongest strengths. The information gathered through focus group discussions was compiled and analyzed to identify details and supplement the data from the other methods.

RESULTS AND DISCUSSION

The demographics of the respondents

Table 1 presents the demographic characteristics of the participants in the study. The male-led households comprised a significant proportion with 35 (62.5%) respondents across all age groups (18-35; 35-50; and over 50), while female-led households comprised 21 (37.5%) respondents. The findings indicate that 28 (50%) the majority were ordinary villagers with no official roles. They were followed by 12 respondents (21.4%) in various positions and 9 respondents (16.1%) who were members of the committee for natural resources and/or forests. Only one village chief (1.8%) and respected elder made up the remaining six respondents (10.7%). The results suggest that half of the respondents were ordinary villagers who could easily provide relevant information without fear of retaliation from the village leaders.

The impact of inclusivity on forest governance

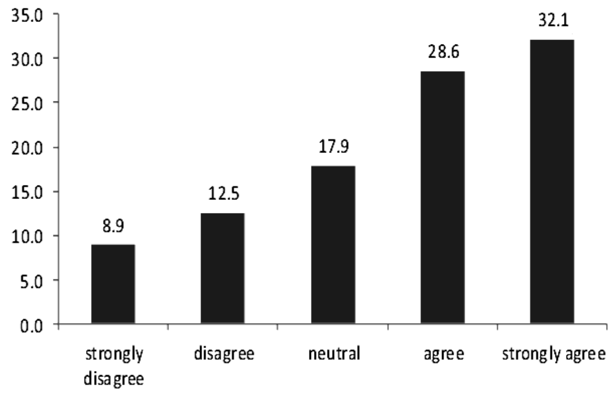
The results presented in Figure 3.A show that over 60% of the respondents agree or strongly agree that inclusivity has increased the number of female members in the village forest and natural resources committee (VNRC). On the other hand, the results presented in Figure 3.B show that nearly half (48%) of the respondents agreed or strongly agreed that committees with more women members are more transparent in decision-making than male-dominated ones.

The findings suggest that the inclusive approach has increased the number of female members in the village forest committee. These findings were also supported by Henriksen et al. (2023) and the villagers interviewed during the FGD, who reported that:

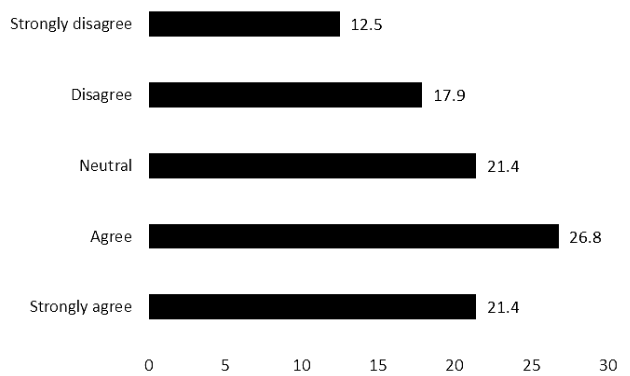
> *There was a fourfold increase in the number of female members on the forest committee. They noted that there were only three active members.*

Table 1. The demographics of the respondent

			Role of respondents					Total
			Village leader	**Respected elder**	**Member of VNRC**	**Ordinary villager**	**Other**	
Sex	Female	Count	2	0	2	13	4	21
		% of Total	3.6%	0.0%	3.6%	23.2%	7.1%	37.5%
	Male	Count	4	1	7	15	8	35
		% of Total	7.1%	1.8%	12.5%	26.8%	14.3%	62.5%
Total		Count	6	1	9	28	12	56
		% of Total	10.7%	1.8%	16.1%	50.0%	21.4%	100.0%



A



B

Figure 3. Villagers' perception on: A. Inclusivity in village forest governance; B. Effect of gender on accountability in decision making

However, the number of female members does not meet the national guideline, which requires at least a 50% female-to-male ratio. This study found that the current gender inclusive committee had fewer female members (4) and 12 male members in a committee of at least 16 members. When asked why there were fewer female members in the committee, despite the call for greater female representation under decentralized management, they explained that women are often engaged with other household responsibilities and are less interested in such committees.

Despite the few female members in the forest committee, their participation in the decentralized framework of forest management plays a crucial role in improving committee transparency, decision-making, and accountability. These findings were also supported by Nyaki and Ngorora (2023) and the villagers interviewed during the focus group discussion (FGD), who reported similar views:

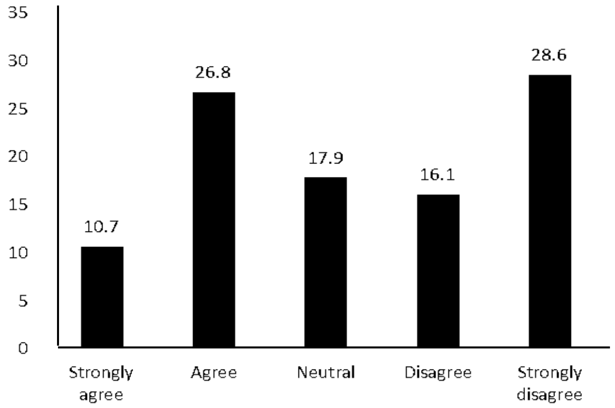
Women's inclusion in the village forest management committee increases transparency, and committees with more female members tend to be more transparent in decision-making. The new committee, consisting of young people, is not functioning as expected in the area. The changes in forest management, including the addition of new committee members overseeing forest resource utilization, are viewed as a disadvantageous because the current committee does not report on income and expenditures. However, encouraging greater women's participation is crucial, as only 4 out of the 16 members are women.

UNDP (2020), FAO (2018), and Duguma et al. (2022) report that notable advancements in female inclusivity within the local institutions responsible for managing forest resources have promoted leadership, environmental resilience, nature conservation, information sharing, and decision-making (Duguma et al. 2022). This study shows that women's inclusivity plays a crucial role in achieving Sustainable Development Goal 5 (gender equality), as well as Sustainable Development Goal 15 (life on land) and Sustainable Development Goal 16 (inclusive governance). As reported in East Africa by Kramer et al. (2017), Meshack et al. (2006) found that implementing decentralized community-managed forests in Tanzania has improved inclusivity and helped achieve other Sustainable Development Goals (SDGs).

The impact of inclusivity on the economic resilience of the local community

Only over 38% (agree to strongly agree) of the interviewees stated that inclusion had an impact on the local community's economic prosperity (SDG 1 - poverty reduction) regarding how it affected its economic operations, according to the results shown in Figure 4.A. Regarding the inclusion of women and their economic well-being, the results of Figure 4.B demonstrate that 78.6% of respondents (who agreed or strongly agreed) indicated that women experienced significant economic gains from joining the village's forest management committee.

Regarding the economic well-being of the various groups of the local communities of the area, findings suggest that of all the people interviewed, 78.6% indicate that women' have significantly improved their economic gains after being integrated to the village's forest management committee. Women's inclusion in forest management provides opportunities to enhance household livelihoods. These results are supported by a study by Grove et al. (2019) who show economic resilience and Silvano (2024), which shows that women's involvement in forest management activities through VNRC had increased income from the sale of non-timber forest products and participation in eco-tourism initiatives.



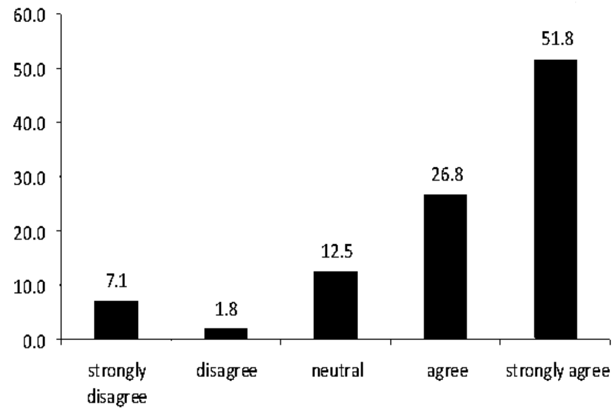


Figure 4. Villagers' perception on the impact of inclusivity on: A. Local economic prosperity; and B. Women's economic well-being

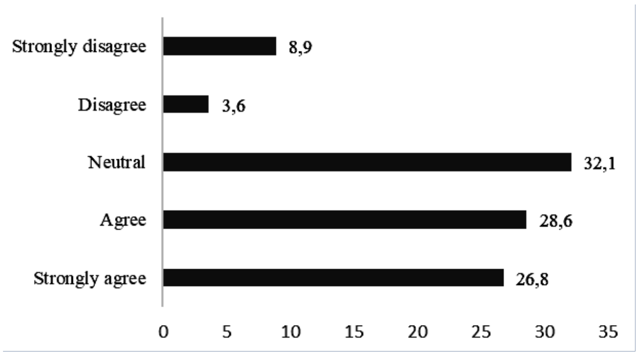


Figure 5. Villagers' perception on the impact of inclusivity on forest sustainability

Impact of inclusivity on the sustainability of natural forests

The results presented in Figure 5 show that 37.5% of respondents agreed or strongly agreed that the sustainability of forests was slightly enhanced after implementing inclusivity, compared to 30.4% of respondents who disagreed or strongly disagreed. The findings indicate that inclusivity in the decentralized forest management institutions did not have a significant effect on increasing natural forest sustainability in the area which has been affected with deforestation (Grogan et al. 2013). The results from those who reported an impact and those who reported no impact differ by only seven percent. These findings contradict the desires of the majority of the committee members.

In this context, the paper examined focus group participants' reactions regarding the condition of the forest and the extent to which sustainability was not achieved. All three discussion groups provided the following answers:

Several factors are contributing to the decline of forest resources, including decreasing rainfall, an increasing human population driving agricultural growth, and activities related to raising free-range animals. Additionally, people are encroaching on and harvesting resources for charcoal production without notice. As a result, new farms and settlements are being established in certain areas of the forests leading to empty spaces.

In addition, the local community in the area shows that several factors, including inadequate feedback on income and expenses, sometimes discouraged people from attending meetings.

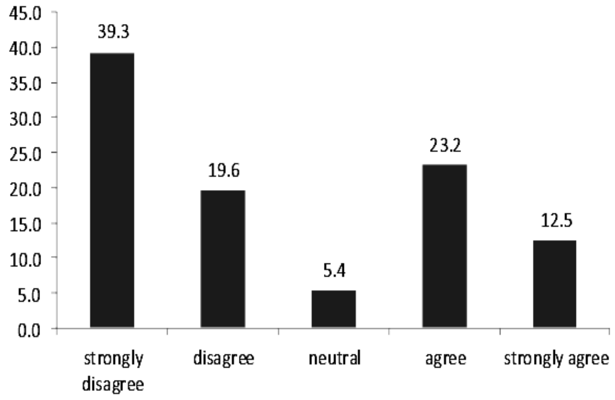
The impact of inclusivity on forest access and monitoring

According to the results shown in Figure 6.A, the inclusion reforms have not increased the number of people gaining access to forest resources, as indicated by 59% of respondents who disagreed or strongly disagreed. The results presented in Figure 6.B show that over 85% of respondents (agree to strongly agree) felt that the decentralized framework reforms, which involve community monitoring of forest conditions, have not had a noticeable effect on the ground. This lack of effect impacts the sustainability of forests.

When asked about the ease of harvesting forest resources without informing the village or the committee, they observed a lack of initiative among the village council and a deficiency of civic duty. The changes were complex, and the community was resistant to the guiding principles. Furthermore, the activities of charcoal and wood production have increased, with most operations requiring approval from higher authorities, which makes it difficult for the village committee to manage them effectively.

In light of the decentralized framework in place, this article examined focus group participants' attitudes toward the trend of committee members monitoring the forest resources for sustainability. Participants expressed the following opinions:

Much less forest monitoring has been conducted. They also raised the possibility that the deterioration of the Ihombwe forest may accelerate and worsen at an alarming rate in the not-too-distant future. This is partly due to the fact that the committee's regular functions have been impeded by district-level issues, as the committee's oversight of forests has no sanctioning authority within the existing framework. The district level has not taken action, and immigrants are encroaching upon the forests without proper oversight. For instance, the district authority requested 2,000 pieces of timber for the construction of a community secondary school. The village reports to the central government but no action is taken.



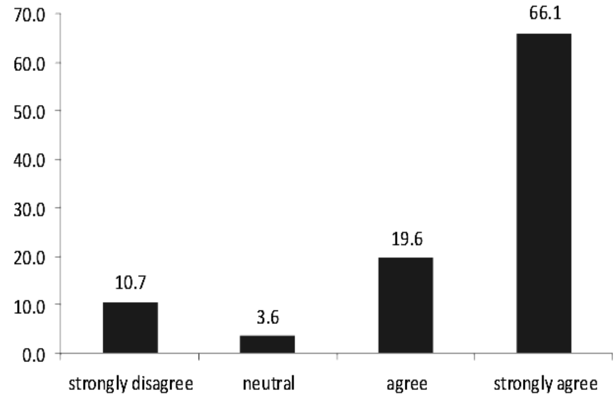


Figure 6. Villagers' perception on the impact of inclusivity on A. People access to forest resources; B. Community forest monitoring

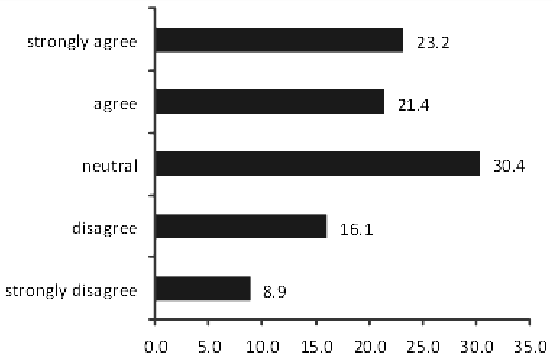


Figure 7. Villagers' perception on non-formal forces hampering inclusivity

Non-formal factors hampering inclusivity

The findings presented in Figure 7 show that over 44% of respondents (agree to strongly agree) believe that non-formal factors, including directives from higher authorities outside the village domain, have hampered inclusivity. This issue arose due to lack of coordination among local area-based committees, district councils, and national authorities. As a result, each party acted according to their own judgment, leading to poor governance.

The focus group discussions revealed a significant reduction in technical measurements and the confiscation of forest resources due to weaknesses in proper forest management and links between committees and other administrators. For example, a district requested permission to harvest timber but harvested 2,000 pieces without any further request or justification. The area chairperson and executive officer are problematic, advocating for their actions instead of taking responsibility for them. For instance, in multi-level governance systems, the impact of these non-formal governance variables, such as social norms and trust networks, is important in determining sustainability and inclusivity as they support policies and decision-making across the levels of governments. These variables often fill in the gaps left by formal organizations, encouraging cooperation and flexibility. For example, Ostrom (1990) in the Institutional Analysis and Development Theory shows how non-formal institutions facilitate formal regulations to improve governance results. These non-formal channels can also promote fair resource distribution and improve actor engagement. Achieving inclusivity and sustainable governance practices requires addressing these interactions with formal systems. However, options of combining these variables for positive results need further investigation (Meadowcroft 2007).

In conclusion, the study found that inclusivity has improved women's economic well-being and transparency in decision-making but did not enhance community access to forest resources or ecological sustainability. Factors beyond the decentralized institutions in place also impacted forest governance. Repackaging public education messages to emphasize the importance of good governance and community participation is necessary to achieve ecological sustainability. Village governments and marginalized groups influence local government decision-making. The decline in forest resources was attributed to encroachment, weak rule enforcement, and external forces, not just the reform framework. The study expressed concern for the gender imbalance in the committee and recommended actions to raise awareness and increase female membership, thereby improving their participation in committee meetings and allowing them to voice their opinions in the village.

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REFERENCES

Agarwal B. 2001. Participatory exclusions, community forestry, and gender: An analysis for South Asia and a conceptual framework. World Dev 29 (10): 1623-1648. DOI: 10.1016/S0305-750X(01)00066-3.

Agarwal B. 2009. Gender and forest conservation: The impact of women's participation in community forest governance. Ecol Econ 68 (11): 2785-2799. DOI: 10.1016/j.ecolecon.2009.04.025.

Agrawal A, Gibson CC. 1999. Enchantment and disenchantment: The role of community in natural resource conservation. World Dev 27 (4): 629-649. DOI: 10.1016/S0305-750X(98)00161-2.

Ajzen I. 2002. Perceived behavioral control, self-efficacy, locus of control, and the Theory of Planned Behavior. J Appl Soc Psychol 32 (4): 665-683. DOI: 10.1111/j.1559-1816.2002.tb00236.x.

Ansell C, Sørensen E, Torfing J. 2022. The Key Role of Local Governance in Achieving the SDGs. In: Ansell C, Sørensen E, Torfing J (eds.). Co-Creation for Sustainability. Emerald Insight, Leeds.

Bernard HR. 2018. Research Methods in Anthropology: Qualitative and Quantitative Approaches. Rowman & Littlefield, Lanham, Maryland.

Blomley T, Pfliegner K, Isango J, Zahabu E, Ahrends A, Burgess N. 2008. Seeing the wood for the trees: Towards an objective assessment of the impact of Participatory Forest Management on forest condition in Tanzania. Oryx 42 (3): 380-391. DOI: 10.1017/S0030605308001886.

Bredin YK, Peres CA, Haugaasen T. 2020. Assessing the effectiveness of decentralized forest management: Lessons from Tanzania. For Ecol Manag 473: 118297. DOI: 10.1016/j.foreco.2020.118297.

Busse M, Gröning S. 2013. The resource curse revisited: governance and natural resources. Public Choice 154 (1): 1-20. DOI: 10.1007/s11127-011-9812-0.

Capitani C, Mukama K, Mbilinyi B, Malugu IO, Munishi PKT, Burgess ND, Platts PJ, Sallu SM, Marchant R. 2016. From local scenarios to national maps: a participatory framework for envisioning the future of Tanzania. Ecol Soc 21 (3): 4. DOI: 10.5751/ES-08565-210304.

Chambers R. 1994a. Participatory Rural Appraisal (PRA): Analysis of Experience. World Dev 22 (9): 1253-1268. DOI: 10.1016/0305-750X(94)90003-5.

Chambers R. 1994b. The origins and practice of participatory rural appraisal. World Dev 22 (7): 953-969. DOI: 10.1016/0305-750X(94)90141-4.

Datta S. 2021. Making Decentralisation Work: A Comparative Ethnographic Analysis of Forest Conservation and Village Governance in West Bengal, India. Conserv Soc 19 (4): 205-217. DOI: 10.4103/cs.cs_20_81.

Dressler W, Büscher B, Schoon M, Brockington, Hayes T, Kull A, Shrestha K. 2010. From hope to crisis and back again? A critical history of the global CBNRM narrative. World Dev 37: 5-15. DOI: 10.1017/S0376892910000044.

Duguma LA, Nzyoka J, Obwocha E, Minang P, Wainaina P, Muthee K. 2022. The forgotten half? Women in the forest management and development discourse in Africa: A review. Front For Glob Change 5: 948618. DOI: 10.3389/ffgc.2022.948618.

FAO. 2018. Food and agriculture organization of the United Nations. Rome. http://faostat.fao.org.

FAO. 2020. Forests and sustainable production and consumption. Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/sustainable-development-goals/goals/goal-15/en/.

Folke C, Hahn T, Olsson P, Norberg J. 2005. Adaptive governance of social-ecological systems. Ann Rev Environ Resour 30 (1): 441-473. DOI: 10.1146/annurev.energy.30.050504.144202.

Gibson CC, Ostrom E, Ahn TK. 2000. The concept of scale and the human dimensions of global change. Ecol Econ 32 (2): 217-239. DOI: 10.1016/S0921-8009(99)00092-0.

Gonzalez JE, Botero C. 2021. Community participation in forest management: A review of inclusivity and equity in Tanzania. Sustainability 13 (1): 84. DOI: 10.3390/su13010084.

Grogan K, Birch-Thomsen T, Lyimo J. 2013. Transition of Shifting Cultivation and its Impact on People's Livelihoods in the Miombo Woodlands of Northern Zambia and South-Western Tanzania. Hum Ecol 41 (1): 77-92. DOI: 10.1007/s10745-012-9537-9.

Grove S, Saarman NP, Gilbert GS, Faircloth B, Haubensak KA, Parker IM. 2019. Ectomycorrhizas and tree seedling establishment are strongly influenced by forest edge proximity but not soil inoculumEctomycorrhizas and tree seedling establishment are strongly influenced by forest edge proximity but not soil inoculum. Ecol Appl 29 (2): e01867. DOI: 10.1002/eap.1867.

Hajjar R, Holley C. 2017. The role of forest governance in achieving sustainable development goals: Evidence from Tanzania. Glob Environ Chang 46: 76-85. DOI: 10.1016/j.gloenvcha.2017.06.004.

Henriksen LF, Kamnde K, Silvano P, Olwig MF, Mwamfupe A, Gallemore C. 2023. Strong collaborative governance networks support effective Forest Stewardship Council-certified community-based forest management: Evidence from Southeast Tanzania. Glob Environ Change 82: 102734. DOI: 10.1016/j.gloenvcha.2023.102734.

IISD. 2024. Sustainable Development Goals. International Institute for Sustainable Development, Geneva.

Israel GD. 1992. Sampling the evidence of extension program impact. University of Florida Cooperative Extension Service, Institute of Food and Agriculture Sciences, EDIS, Gainesville, FL.

Katani JZ, Babili IH. 2012. Exploring forest governance in Tanzania. In: Arts B, van Bommel S, Ros-Tonen M, Verschoor G (eds.). Forest-people interfaces. Wageningen Academic Publishers, Wageningen. DOI: 10.3920/978-90-8686-749-3_16.

Kauffman CM. 2016. Grassroots Global Governance: Local Watershed Management and Sustainable Development. Oxford Academic, New York.

Kauffman JM, Anastasiou D, Badar J, Travers JC, Wiley AL 2016. Inclusive education moving forward. In: Bakken JP, Obiakor FE (eds.). General and Special Education Inclusion in an Age of Change: Roles of Professionals Involved. Emerald Group Publishing Limited, Leeds. DOI: 10.1108/S0270-401320160000032010.

Kaufmann D, Kraay A, Mastruzzi M. 2010. The worldwide governance indicators: Methodology and analytical issues. Hague J Rule Law 3 (2): 220-246. DOI: 10.1596/1813-9450-5430.

Kramer DB, Hartter J, Boag AE, Jain M, Stevens K, Nicholas K A, McConnell WJ, Liu J. 2017. Top 40 questions in coupled human and natural systems (CHANS) research. Ecol Soc 22 (2): 44. DOI: 10.5751/ES-09429-220244.

Kumar K. 1989. Conducting Focus Group Interviews in Developing Countries. AID Program Design and Evaluation Methodology Report No. 8. U.S. Agency for International Development, Pennsylvania.

Lund JF. 2015. Paradoxes of participation: The logic of professionalization in participatory forestry. For Policy Econ 60: 1-6. DOI: 10.1016/j.forpol.2015.07.009.

Mbeyale GE, Dugilo NM, Lusambo LP. 2021. Impacts of community-based forest management on governance in Selela village forest reserve, Monduli District, Tanzania. Tanzania J For Nat Conserv 90 (3): 117-129.

Meadowcroft J. 2007. Who is in charge here? Governance for sustainable development in a complex world. J Environ Policy Plan 9 (3-4): 299-314. DOI: 10.1080/15239080701631544.

Meshack CK, Ahdikari B, Doggart N, Lovett JC. 2006. Transaction costs of community-based forest management: Empirical evidence from Tanzania. Afr J Ecol 44 (4): 468-477. DOI: 10.1111/j.1461-0248.2006.00756.x.

Ministry of Natural Resources and Tourism (MNRT). 2015. National Forest Resources Monitoring and Assessment of Tanzania Mainland. Tanzania Forest Services Agency (TFS), Dar es Salaam, Tanzania.

Mogoi JM, Wanyonyi KW, Abdillahi UA. 2022. Moderating influence of organization ambidexterity on the link between strategic planning and organization in the county of Turkana Kenya. J Intl Business Innov Strategic Manag 6 (1): 73-96.

Mung'ong'o CG, Mwakaje A, Kijazi A. 2003. Baseline survey of the eastern pilot Wildlife Management Areas. Volume III Twatwatwa. Final Report to Wildlife Division, Ministry of Natural Resources and Tourism, Dar es Salaam.

Murphree M. 2009. The strategic pillars of communal natural resource management: benefit, empowerment and conservation. Biodivers Conserv 18 (2): 2551-2562. DOI: 10.1007/s10531-009-9644-0.

Nelson V, Stathers T. 2009. Resilience, power, culture, and climate: a case study from semi-arid Tanzania, and new research directions. Gender Dev 17 (1): 81-94. DOI: 10.1080/13552070802696946.

Ngowi NJ, Ngalawa AA. 2023. Recycling for deforestation reduction in Tanzania: Why are households not using waste charcoal? Asian J For 7 (1): 1-8. DOI: 10.13057/asianjfor/r070101.

Ngowi NJ. 2022. Application of geoinformation technology to the management of community-based natural resources for tourism development in northern Tanzania. In: Mensah I, Afenyo-Agbe E (eds.). Prospects and Challenges of Community-Based Tourism and Changing Demographics. IGI Global Publisher, New York. DOI: 10.4018/978-1-7998-7335-8.ch008.

Nzali AC, Kaswamila A. 2019. Prospects and Challenges of Village Land

Forest Reserves Management in Mbarali District, Tanzania. Open J For 9 (2): 159-167. DOI: 10.4236/ojf.2019.92007.
Ostrom E. 1990. Governing the Commons: The Evolution of Institutions for Collective Action. Cambridge University Press. Cambridge. DOI: 10.1017/CBO9780511807763.
Poudel M, Thwaites R, Race D, Dahal GR. 2014. REDD+ and community forestry: Implications for local communities and forest management—A case study from Nepal. Intl For Rev 16 (1): 39-54. DOI: 10.1016/j.forpol.2015.07.005.
Ribot JC, Lund JF, Treue T. 2010. Democratic decentralization in sub-Saharan Africa: Its contribution to forest management, livelihoods, and enfranchisement. Environ Conserv 37 (1): 35-44.
Ruvuga PR, Wredle E, Mwakaje A, Selemani IS, Sangeda AZ, Nyberg G, Kronqvist C. 2020. Indigenous rangeland and livestock management among pastoralists and agro-pastoralists in Miombo Woodlands, Eastern Tanzania. Rangel Ecol Manag 73 (2): 313-320. DOI: 10.1016/j.rama.2020.05.001.
Schmidt M, Vellend M. 2020. Community-driven forest management: Evidence from Tanzania's forest policies. Land Use Policy 99: 104892. DOI: 10.1016/j.landusepol.2020.104892.
Silvano P. 2024. Socio-economic Outcomes of Gendered Participation in Forest Management in Tanzania. J Geogr Assoc Tanzania 44 (1): 26-46. DOI: 10.56279/jgat.v44i1.265.
Stoker G. 2011. Was local governance such a good idea? A global comparative perspective. Public Administration 89 (1): 15-31. DOI: 10.1111/j.1467-9299.2011.01900.x.
Sujarwoto S. 2017. Geography and communal conflict in Indonesia. Indones J Geogr 49 (1): 89-96. DOI: 10.22146/ijg.26889.
Sunderlin WD, Angelsen A, Belcher B, Burgers P, Nasi R, Santoso L, Wunder S. 2005. Livelihoods, forests, and conservation in developing countries: An overview. World Dev 33 (9): 1383-1402. DOI: 10.1016/j.worlddev.2005.04.002.
Tanzania's Development Vision. 2025. www.mof.go.tz/mofdocs/overarch/vision2025.htm.
UN. 2015. Transforming Our World: The 2030 Agenda for Sustainable Development. United Nations, New York.
UNDP. 2020. Gender Equality and Women's Empowerment in Public Administration. United Nations Development Programme, New York.
URT. 2021. National Environment Policy. Vice President Office, Environment. United Republic of Tanzania, Dodoma.
Von Hippel E, Ogawa S, De Jong JP. 2011. The age of the consumer-innovator. MIT Sloan Manag Rev 53 (1): 27-35.
Zulu LC. 2012. Neoliberalization, decentralization and community-based natural resources management in Malawi. Prog Dev Stud 12 (2-3): 193-212. DOI: 10.1177/146499341101200307.

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Natural regeneration of woody species in *Acacia mangium* and *A. auriculiformis* stands in Anguédédou, Abidjan, Côte d'Ivoire

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Abstract. *Kouadio KR, Kougbo MD, Touré SG, Coulibaly B, N'guessan AK, Bakayoko A. 2024. Natural regeneration of woody species in* Acacia mangium *and* A. auriculiformis *stands in Anguédédou, Abidjan, Côte d'Ivoire. Asian J For 8: 174-183.* In the current context of climate change, forest landscape restoration is promoted to reverse forest ecosystem degradation. In Côte d'Ivoire, leguminous plants, notably Australian Acacias, have been introduced since 1980 at Anguédédou to restore the fertility of degraded farmland. The introduction of Acacias was seen as a potential disturbance to the local flora, as these non-native species are sometimes invasive. However, observation of these *Acacia*-based landscapes revealed good regeneration of woody species. The aim of this study was to assess the natural regeneration of woody plants under Acacias stands and its relation with stand ages. We assessed the floristic composition and studied the dynamics of natural regeneration of local woody species in four *Acacia* stands as a function of age. The results showed that the most widespread family of naturally regenerating plants in *Acacia* stands is Fabaceae. We noted an increase in the number of species as a function of stand age. The number of species rose from 20 (3-year-old stand) to 51 (27-year-old stand), with 28 species and 24 species in the 8-year-old and 11-year-old stands respectively. In all stands, mesophanerophytes represent the dominant plant life form. The Shannon-Wiener diversity index of natural regeneration increased from 1.66±0.44 (3-year-old *Acacia* stand) to 2.45±0.36 (27-year-old *Acacia* stand). In contrast, as the *Acacia* stands aged, the regeneration index decreased, with values of 1 (for the 3-year-old and 8-year-old *Acacia* stands), 0.94 (for the 11-year-old *Acacia* stand) and 0.81 (for the 27-year-old *Acacia* stand). This study shows that Acacias improve the local flora by promoting natural regeneration and the development of woody species.

Keywords: Acacias, forest restoration, natural regeneration

INTRODUCTION

The health of the world's forests is a major global concern as maintaining their ecological functions has a positive impact on living beings. Forests play an important role in mitigating climate change effects. Forests are the major ecosystems that maintain the microclimate and act as carbon sinks by sequestering and storing carbon (Verkerk et al. 2022). Every year, almost a third of global carbon emissions -2.6 billion tonnes of carbon dioxide- from fossil fuel combustion are absorbed by forests (UICN 2022). In addition, forests deliver a wide range of ecosystem goods and services (Gosain et al. 2015; Awasthi et al. 2022a). These include the provision of timber and non-timber products, the protection of biological diversity, the supply of food and medicines and the maintenance of cultural and recreation services (Nakajima et al. 2017; Akujärvi et al. 2021; Mason et al. 2022; Hu et al. 2022).

Despite their importance role, many forest ecosystems in the world are threatened by anthropogenic activities (Trumbore et al. 2015) including agricultural expansion and intensification, invasion of invasive species and infrastructure development (Htun et al. 2011; Bargali et al. 2019; Fartyal et al. 2022; Negi et al. 2024; Pandey et al. 2024). Over the past three decades, global forest cover has declined by 420 million hectares, although the rate of deforestation fell from 16,106 ha per year in the 1990s to 10,106 ha per year between 2015 and 2020 (FAO 2020). Various disturbances on forest ecosystems cause biodiversity loss, disturb microbial activities and nutrient cycling and reduce forest productivity (Manral et al. 2020; Vibhuti et al. 2020; Padalia et al. 2022).

The loss of plant diversity is a major challenge faced by forest ecosystems in maintaining ecological sustainability (Hua et al. 2022; Bisht et al. 2023). To address such problem, reforestation efforts are promoted in tropical regions where deforestation and land degradation remains the major threats (Chazdon 2014; García et al. 2014). As a result, numerous international reforestation initiatives are being carried out in tropical countries. The aim of these commitments is the resilience of forest functions by halting deforestation and forest degradation and increasing forest cover (Curtis et al. 2018; Song et al. 2018; Chazdon et al. 2020). The downward trend in deforestation is therefore partly the result of global forest recovery through the regeneration of forest species in deforested areas (Garcia et al. 2020).

There are many approaches in forest restoration, from large-scale reforestation, agroforestry, natural regeneration, artificial regeneration and so on. All these practices have the same objective, namely to re-establish the ecological mechanisms that accelerate the recovery of forest formation, ecological functioning and biodiversity toward a climax forest (Elliot et al. 2013). However, across forest restoration efforts globally, they differ in planning, implementation and financial resources. Clearly, large-scale reforestation projects are very costly and therefore difficult to implement in many countries around the world. On the other hand, natural forest regeneration does not involve high economic costs (Fagan et al. 2020; Garcia et al. 2020; Holl and Brancalion 2020). Thus, forest restoration using natural regeneration approach seems indispensable, because it minimizes the implementation budgets (Garcia et al. 2020). Several methods are used to stimulate the natural regeneration of forest species. The process of natural regeneration is vital for forest ecosystems, as it enables these biotopes to renew themselves and conserve biodiversity. Natural regeneration impacts the stability and evolutionary succession of forests (Jin et al. 2018; Johnson et al. 2021; Zhang et al. 2022).

In Côte d'Ivoire, Australian Acacias were introduced in 1982 at Anguédédou to restore wasteland abandoned due to the loss of fertility caused by agricultural overexploitation (Kouadio et al. 2016). These wastelands originate from clandestinely established cultivation stands in the classified forest of Anguédédou. Thus, these Acacias were intended to contribute to forest reconstitution, but their presence has raised concerns for the local flora. Indeed, these leguminous plants can be invasive for native species and prevent their development. However, good plant diversity has been observed under *Acacia* stands in Anguédédou, Côte d'Ivoire (Kouadio et al. 2018). This raises questions as to whether *Acacia* stands promote the regeneration of woody species and whether the floristic diversity of natural woody regeneration improves with stand age.

The aim of this work is to analyze the floristic composition of the natural regeneration of woody flora and to characterize the regeneration potential of woody species under two Acacias species (*Acacia mangium* Wild and *Acacia auriculiformis* A.Cunn. ex Benth.). Specifically, the objectives of the present study were to assess (i) the diversity of woody flora and their regeneration pattern and (ii) characterize the effect of the age of *Acacia* stands on the natural regeneration process of woody species. Ultimately, this article will demonstrate that leguminous trees can contribute to forest restoration by promoting spontaneous regeneration of forest woody species.

MATERIALS AND METHODS

Study area

This study was conducted in the classified forest of Anguédédou, located in the District of Abidjan (southern Côte d'Ivoire) at the coordinates of 5°22'-5°26' N and 4°04'-4°13' W (Figure 1). The dominant vegetation in the study area is dense evergreen rainforest (Guillaumet and Adjanohoun, 1971). The climate is tropical equatorial, characterized by abundant annual rainfall (around 2,000 mm) and four seasons: a long rainy season (April-July), a short dry season (August-September), a short rainy season (October-November) and a long dry season (December-March). Average monthly temperatures range from 24.2°C to 27.4°C, with average monthly relative humidity ranging from 78 to 87% (Bi et al. 2010). The area's relief is marked by high plateaus (40 to 50 m and 100 to 120 m), mid-altitude plateaus (8 to 12 m), plains and deep valleys ranging from 12 to 40 m (Kablan 2016).

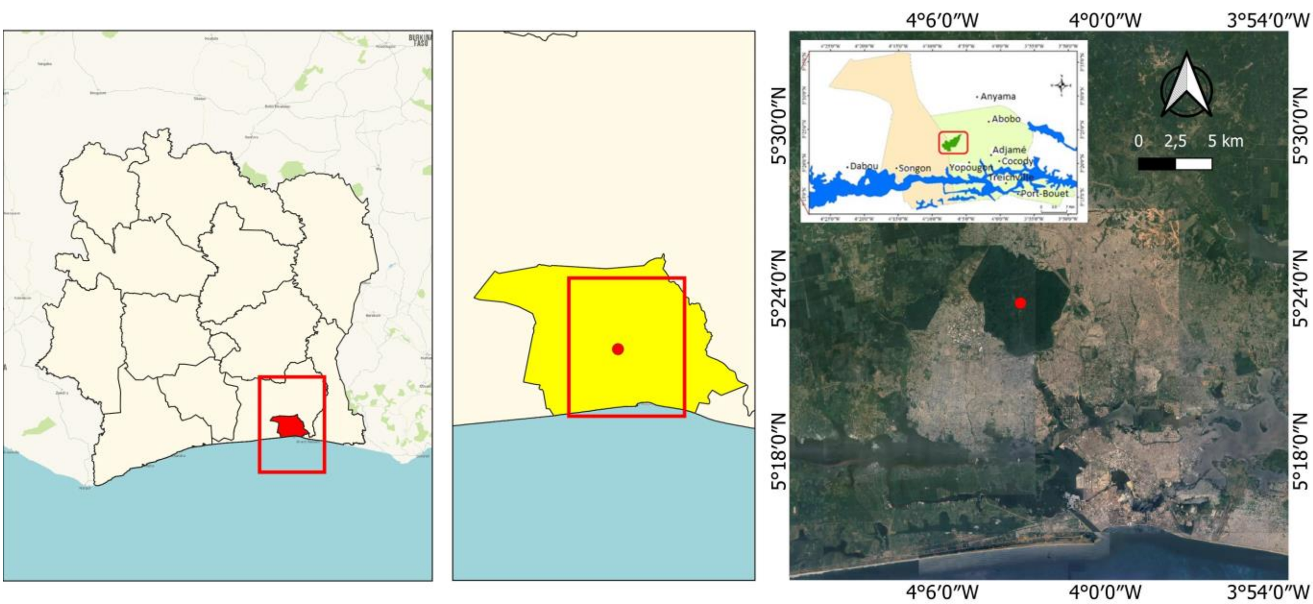

Figure 1. Map of study area in the classified forest of Anguédédou, District of Abidjan, Côte d'Ivoire

Data collection

A system of rectangular stands (50 × 35 m) was set up in the *Acacia* stands to collect data by means of floristic inventories. Four stand classes were defined based on the age of the *Acacia* species, i.e. 3 years (parc3), 8 years (parc8), 11 years (parc11) and 27 years (parc27). On each rectangular stand, five square plots (6x6 m) were installed, one at each corner and in the center of the stand. We combined the area survey (in the square stands) and the roving inventory (in the rectangular stands). All species present were first inventoried, then diameter measurements were taken on individuals at breast height, i.e., 1.30 m above ground level. To study natural regeneration, all individuals with a diameter of less than 5 cm were taken into account. This dendrometric threshold, already used by Assédé et al. (2015), makes it possible to minimize the inclusion in regeneration of mature individuals of shrub species predominantly present in the stands studied. Species were determined in the field or by laboratory identification (herbarium) of plant species samples collected. The nomenclature adopted was APG IV (2016).

Floristic analysis

Floristic analysis of natural regeneration focused on floristic composition and three regeneration parameters, namely specific regeneration rate, stand regeneration index and stand regeneration importance value. The life cycle of a tree is characterized by three stages following Baboo et al. (2017) as adults (dbh ≥ 10 cm), perches (3.2 ≤ dbh < 10 cm) and seedlings (dbh < 3.2 cm; height ≥ 30 cm). In this study, regeneration individuals have a diameter of less than 5 cm and a height greater than or equal to 30 cm.

Floristic composition

Floristic composition expresses the total number of taxa (families, genera, species) recorded, their taxonomic distribution and their biological and ecological characteristics. The parameters of floristic composition be considered in this study are floristic richness and biological types.

Floristic richness

In the sample of a plant community studied or in an ecosystem, the number of species, genera and families encountered represents floristic richness (Marcon 2015).

Plant life-form

This study considers only phanerophytes according to Raunkiaer (1934). The interest of addressing these plant life-form for natural regeneration is the prediction of the vertical structure of the future regenerated forest stand under acacias. Depending on the height of the species, a distinction must be made between: (i) megaphanerophytes (MP), trees with a height of over 30 meters ; (ii) mesophanerophytes (mP), trees between 8 and 30 meters tall ; (iii) microphanerophytes (mp), shrubs between 2 and 8 meters tall ; (iv) nanophanerophytes (np), shrubs less than 2 meters high.

Species diversity index

The species diversity of natural regeneration was addressed using the Shannon-Wiener index (Shannon-Wiener 1963). This is a diversity index used to compare distinct plant communities. It associates the number of species and the relative abundance of each species in a given community. Its value commonly varies between 1.5 and 3.5 (Magurran 1988). The Shannon Index (H') is calculated by the following formula:

$$H' = -\sum_{i=1}^{S} pi.\log_2(pi)$$

Where:
S: Total number of species present,
pi: Abundance percentage of species present (pi = ni/N),
ni: number of each present species individuals
N: total number of all species individuals ;
log2: base-2 logarithm

Species regeneration rate (SRR)

The specific regeneration rate is used to assess the relative abundance of a species within the natural regeneration of a group of stands. It is expressed as a percentage and is obtained by dividing the number of regenerating individuals of a species by the total number of regenerating individuals in the stand or stand concerned. Regeneration individuals are young individuals, i.e. those with a diameter of 5 cm or less. The Specific Regeneration Rate (SRR) is determined using the formula below:

$$SRR = \left(\frac{n}{N}\right) \times 100$$

Where :
n: Number of seedlings of each species,
N: Total number of surveyed seedlings

Regeneration index (RI)

The value of each stand's regeneration index (RI) is determined by the ratio of the number of regenerating individuals (diameter ≤ 5 cm) to the number of individuals of all diameters. This index is used to assess the age of the stand and has range between 0 and 1. The older the stand, the more the RI tends towards 0, while the younger the stand, the more the RI tends towards 1. The formula for calculating the Regeneration Index is as follows:

$$RI = \frac{r}{T}$$

Where:
r: number of regeneration individuals (diameter ≤ 5 cm)
T: number of all diameters individuals

Regeneration Importance Value (RIV)

The Regeneration Importance Value (RIV) was developed in this study to assess the weight of natural regeneration within each stand type. It is an index that integrates the number of species resulting from natural regeneration and the regeneration rate of each species. For every stand, the higher the RIV, the more remarkable the level of natural regeneration. The RIV formula is as follows:

$$RIV = \left(\frac{r}{T}\right) . \sqrt{sp}$$

Where:
r: number of regeneration individuals (diameter ≤ 5 cm)
T: number of all diameters individuals
sp: number of natural regeneration species in the stand

Statistical analysis

All data were entered into an Excel spreadsheet and processed using R software. The mean Shannon-Wiener diversity indices of the different stands were compared using a one-factor analysis of variance (ANOVA 1), and a Fisher test was performed to distinguish statistically different means. The significance level chosen for this test was 5%. A factorial analysis of correspondences (FAC) was carried out to observe the distribution of woody regeneration species according to the age of the *Acacia* stands. This distribution is based on the relative abundance of species expressed by the specific regeneration rate.

RESULTS AND DISCUSSION

Floristic richness

In total, the natural regeneration of woody flora included 67 species belonged to 55 genera and 30 families. The Fabaceae family was the best represented with 14.93% of species, followed by Annonaceae (10.45%), Sapindaceae (10.45%), Meliaceae (5.97%) and Moraceae, Olacaceae and Rubiaceae with 4.48% of species each (Figure 2). The remaining 31 families accounted for 44.76% of species in natural regeneration.

At Parc3, the natural regeneration contained 20 species belonged to 18 genera and 12 families. This stand was dominated by Fabaceae and Sapindaceae, each accounting for 15% of species (Figure 3.A). These two families were ahead of four others, which individually accounted for 10% of species, namely the Apocynaceae, Malvaceae, Meliceae and Olacaceae (Figure 3.A). Parc8 consisted of 28 natural regeneration species belonged to 27 genera and 17 families. In this stand, the Fabaceae was the most dominant with 20.69% of species, followed by Sapindaceae with 10.34% (Figure 3.B). In third place, there were five families with 6.9% of species, namely Annonaceae, Apocynaceae, Lecythidaceae, Malvaceae, Meliaceae and Rubiaceae (Figure 3.B). At Parc11, the natural regeneration comprises 24 species belonged to 22 genera and 14 families. This stand was heavily populated by the Fabaceae and Sapindaceae families, which accounted for 20.83% and 16.67% of species respectively (Figure 3.C). These families were followed by Annonaceae, Apocynaceae and Euphorbiaceae, which each accounted for 8.33% of species (Figure 3.C). At Parc27, there were 51 naturally regenerating species belonged to 43 genera and 26 families. The dominant families were Annonaceae and Fabaceae, each with 11.76% of species (Figure 3.D). These two families were followed by the Sapindaceae with 9.8% of species, the Meliaceae with 7.84% and the Apocynaceae with 5.88% (Figure 3.D).

Plant life-form

The most widespread plant life-form in all four stand age groups were mesophanerophytes (Figure 4). They accounted for almost half of the species found on the other stands. At Parc3, 50% of species were mesophanerophytes, while at Parc8, Parc11 and Parc27, respectively 41.38, 41.67, and 47.06% of the species recorded were mesophanerophytes (Figure 4). Next in order of preponderance were microphanerophytes with 35% at Parc3, 37.93% at Parc8 and at Parc11 with 37.5% of species (Figure 4). This order is overturned at Parc27, where microphanerophytes ranked third with 21.57% of species (Figure 4). Finally, the extremes (nanophanerophytes and megaphanerophytes) were the least represented in the stands. These two plant life-forms accounted for 15% of species at Parc3, with 10% nanophanerophytes and 5% megaphanerophytes (Figure 4). At Parc8, we counted 6.9% nanophanerophytes and 13.79% megaphanerophytes, while Parc11 contained 12.5% nanophanerophytes and 8.33% megaphanerophytes. At Parc27, we recorded 7.84% nanophanerophytes, with the exception of megaphanerophytes, which ranked second with 23.53% of species (Figure 4).

Species diversity index

The Shannon-Wiener diversity index of the stands was less than 2.5. It was estimated at 1.66±0.44 for Parc3; 2.09±0.14 for Parc8; 1.98±0.37 for Parc11 and 2.45±0.36 for Parc27 (Table 1). Statistical analysis of these values showed significant differences between them ($F = 7.308$; $P = 0.001$) and three groups emerged (Table 1). The lowest index was for Parc3, and the highest was for Parc27. Between these two values, we had the second group, made up of roughly equal Shannon indexes, corresponding to Parc8 and Parc11 (Table 1).

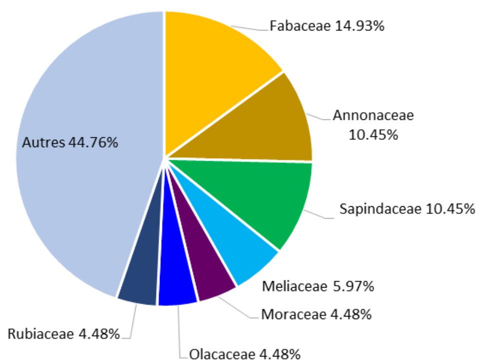

Figure 2. The proportion of naturally regenerating species of each family across all stands

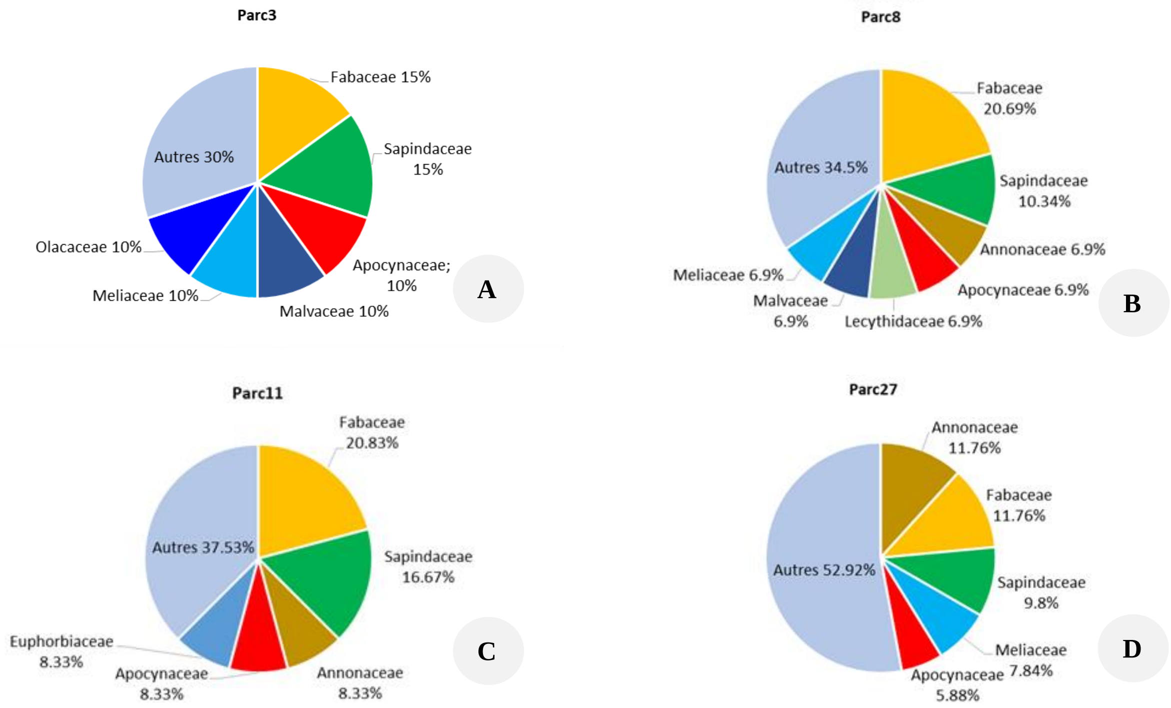

Figure 3. The proportion of naturally regenerating species of each family at each stand age. A. Parc3; B. Parc8; C. Parc11 ; D. Parc27

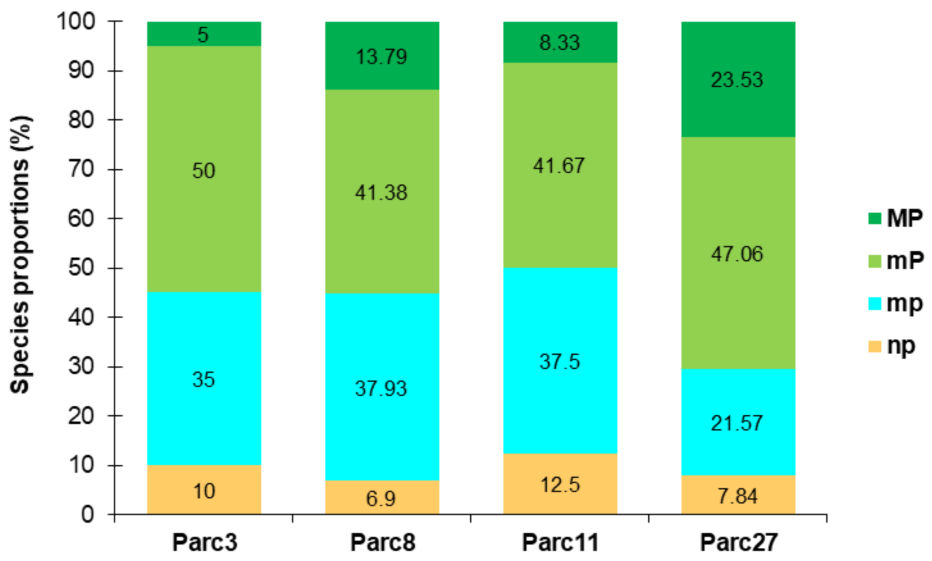

Figure 4. Plant life-form of natural regeneration vegetation at each stand. Note: MP: Megaphanerophytes, mP: Mesophanerophytes, mp: Microphanerophytes, np: Nanophanerophytes

Table 1. Shannon-Wiener species diversity index of naturally regenerating plant at each stands

	Shannon index
Parc3	1.66±0.44b
Parc8	2.09±0.14ab
Parc11	1.98±0.37ab
Parc27	2.45±0.36a
Statistical parameters	F=7.308 ; P=0.001

Table 2. Eigenvalues and percentage inertia of factorial analysis of correspondences (FAC) main axes

Axes	dim1	dim2	dim3
Eigenvalue	0.362	0.285	0.174
Percentage of variance (%)	44.08	34.70	21.22
Cumulative percentage of variance	44.08	78.78	100

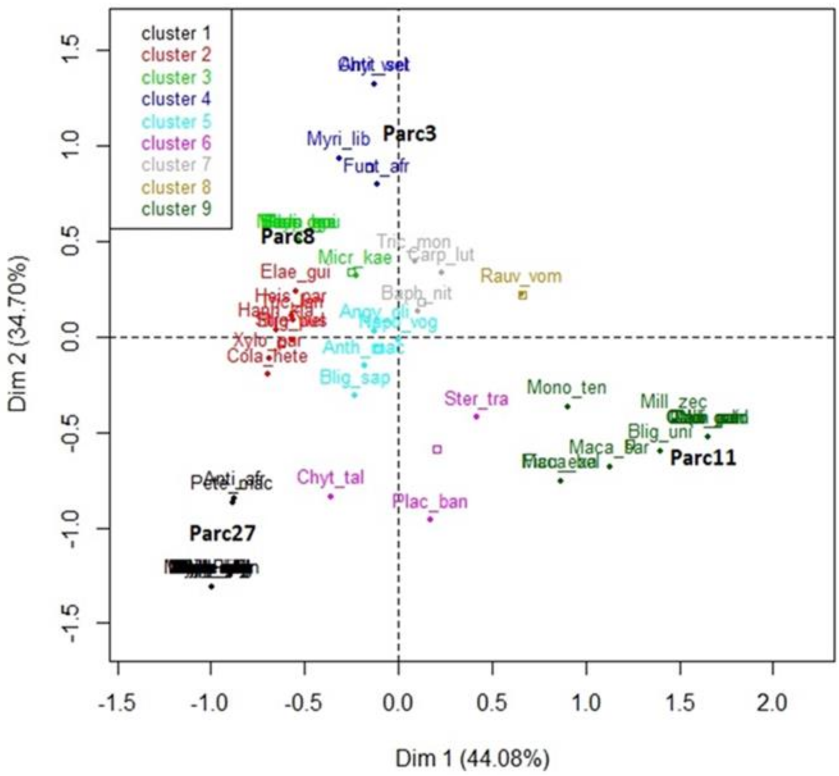

Figure 5. Diagram of species distribution on the factorial plane (F1 and F2)

Specific regeneration rate (SRR)

At Parc3, the dominant naturally regenerating species was *Funtumia africana* with SRR of 21.62%, followed by *Baphia nitida* (16.22%), *Microdesmis keayana* (12.16%) and *Rauvolfia vomitoria* (10.81%). These species were the most important in the natural regeneration of Parc3, with a cumulative SRR of 60.81%. At Parc8, *M. keayana* dominated with a SRR of 22.22%, followed by *B. nitida* (15.15%), *Cola heterophylla* (11.45%) and *Angylocalyx oligophyllus* (7.74%). These four species largely dominated the other twenty-five species at this stand, which had a cumulative SSR of 43.43%. At Parc11, *B. nitida* was the most widespread naturally regenerating plant with an SRR of 15.83%, followed by *R. vomitoria* (14.17%), *Macaranga barteri* (10%) and *Millettia zechiana* (7.5%). At Parc27, *B. nitida* was the most abundant with a SSR of 10.18%, followed by *C. heterophylla* (9.12%), *Chrysophyllum subnudum* (7.02%) and *M. keayana* (7.02%), while the remaining 47 species had an accumulative SSR of 66.66%.

Species distribution by stand age

Three factorial axes (Dim1, Dim2 and Dim3) explained the distribution of species within stands, which varied from 0.174 to 0.362, i.e. from 21.22 to 44.08% (Table 2). The FAC revealed that the distribution of species within the stands is mainly represented by the factorial plane formed by the Dim1 and Dim2 axes (Figure 5). The observation is therefore made on these two axes, which accounted for 78.78% of total inertia. The Dim2 axis (34.7%) discriminated the oldest stands (Parc11 and Parc27) from the youngest (Parc3 and Parc8) and the Dim1 axis (44.08%) separated the oldest stands from each other (Figure 5). The FAC revealed nine groups of species distributed according to the age of the *Acacia* stands. Species such as *Myrianthus libericus*, *Antiaris welwitschii*, *Chytranthus setosus* and *F. africana* are mainly found at Parc3. Species such as *Vismia guineensis*, *Massularia acuminata*, *M. keayana*, *Heisteria parvifolia*, *Hannoa klaineana*, *Xylopia parvifolia* and *A. oligophyllus* were found at Parc8. *Ceiba pentandra*, *Monodora tenuifolia*, *M. zechiana*, *M. barteri*, *Blighia unijugata*, *Ficus exasperata*, *Macaranga beillei*, *Albizia adianthifolia* were more widely distributed at Parc11. Finally, species such as *Piptadeniastrum africanum*, *Sphenocentrum jollyanum*, *Entandrophragma angolense*, *Antiaris africana* and *Petersianthus macrocarpus* were more common at Parc27.

Regeneration index (RI) of the stand

At Parc3, we recorded 74 young individuals out of a total of 74 individuals in this stand, giving a value of 1 as the stands regeneration index (Table 3). The same trend was observed at Parc8, where the RI was equal to 1, suggesting that all the individuals inventoried were young individuals (Table 3). At Parc11, we recorded 129 individuals of all diameters, including 121 young individuals, giving us a RI of 0.94 for Parc11 (Table 3). Finally, the RI for Parc27 is estimated at 0.81, i.e. 285 of the 350 individuals in this block are young (Table 3). The regeneration index in the stands regressed with age (Figure 6).

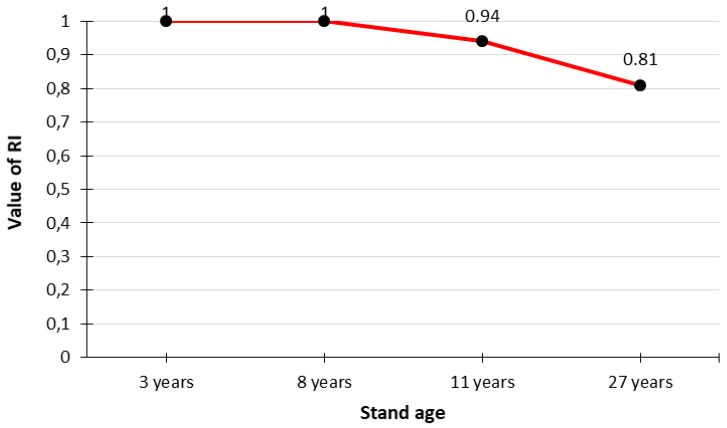

Figure 6. Trend of regeneration index according to stand age

Table 3. Assessment of regeneration indices for the different blocks of stands with varying ages

	Stand3	Stand8	Stand11	Stand27
Young individuals (diameter ≤5 cm)	74	300	121	285
Total individuals (individuals of all diameters)	74	300	129	350
Regeneration index (RI)	1	1	0.94	0.81

Table 4. Summary of regeneration importance values for the different stand blocks

	Stand3	Stand8	Stand11	Stand27
R	74	300	121	285
T	74	300	129	350
Sp	20	29	24	51
RIV	4.47	5.39	4.6	5.8

Stand regeneration importance value (RIV)

The natural regeneration of the flora was most important at the oldest stand (Parc27) where the RIV was 5.8 (Table 4), while the lowest RIV (4.47) was recorded at the youngest stand (Parc3). The other two stands, Parc8 and Parc11, had RIV of 5.39 and 4.6 respectively (Table 4).

Discussion

In the *Acacia* stands, we have recorded the typical species inventoried by Tiébré et al. (2015). All the stands differ in species composition and regeneration pattern because in the dissected landscapes, bioclimatic conditions change rapidly and may vary within short distances resulting in a pronounced heterogeneity of soil types (Bäumler 2015; Awasthi et al. 2022b) hence influence the distribution of vegetation and their regeneration pattern (Bargali et al. 2019; Manral et al. 2022). Vegetation cover in any ecosystems varies in space and time because of variation in topography, climate, weathering processes, physico-chemical properties of soil and microbial activities (Paudel and Sah 2003; Manral et al. 2023) and several other biotic and abiotic factors (Pandey et al. 2023). Vegetation and its regeneration therefore vary within short distances according to parent rocks, soil types and land use pattern. This proves the restoration capacity of the local flora under the Acacias, which seem to offer the soil seed stock optimal germination conditions. At all stands, the flora of the natural regeneration is dominated by the Fabaceae family. These results are in line with those of Ameja et al. (2022), who conclude that regenerating environments are dominated by Fabaceae. The abundance of species in this family would depend on their effective and successful dispersal strategies on the one hand, and their high potential for adaptation in more varied ecosystems on the other (Yemata and Haregewoien 2022). After this family, we have, to a lesser extent, the Sapindaceae and Apocynaceae as preponderant families. Commonly, these families appear as the most important in forests of the same study area with Apocynaceae concerning the Anguédédou forest (Tiébré et al. 2015) and Fabaceae and Apocynaceae in the Mabi forest (Amba et al. 2021). Our results show that natural regeneration under Acacias retains the characteristics of dense evergreen forests in Côte d'Ivoire.

Analysis of the Shannon-Wiener index recorded in the various stands suggests that woody regeneration under Acacias is moderately diverse. Indeed, in all stands, around 20% of the species inventoried account for more than half of the individuals found. As pointed out by Barmo et al. (2019), the Shannon-Wiener index is minimal when the stand is dominated by one species and other species are poorly represented. However, natural regeneration becomes increasingly diverse as the age of *Acacia* stands increases. This observation can be explained by the proliferation of woody species over time, encouraged by the reduction in herbaceous cover due to the presence of arborescent legumes. Thanks to their role in fixing atmospheric nitrogen, leguminous trees exert control over grasses and weeds (Kouadio et al. 2018). Indeed, a two-thirds reduction in herbaceous cover was observed after thirteen years of leguminous presence in native grasslands in Uruguay (Jaurena et al. 2016). *Acacia* stands are unfavorable environments for the propagation of herbaceous flora, creating ideal conditions for the regeneration of woody species. Furthermore, some authors (Carnus et al. 2006; Paquette and Messier 2013) claim that the aging of forest tree plantations is a factor reinforcing the availability of ecological niches as well as the high and diverse presence of species. All *Acacia* stands, whatever their age, are home to all the biological types of arborescent phanerophytes, which are varied forms of woody plants. This observation follows the logic of the floristic composition of tropical forests, since phanerophytes make up the majority of the flora at the expense of other biological types, which are in reduced proportions. Acacias are arborescent leguminous plants that control herbaceous flora. Moreover, thanks to their tree cover, these species create a microclimate that prevents the colonization of the environment by herbaceous species. The variability of vascular plant species is proof that *Acacia* stands provide a suitable environment for the regeneration and growth of woody species. Also, some authors (Keil and Chase 2019; Liang et al. 2022) have established a link between environmental conditions and the diversity of woody species and forest tree species. In other words, when the undergrowth is rich and diverse, the environment becomes favorable to interactions and the presence of several plant species (Yang et al. 2023). Moreover, the diversity of tree species in forest communities is fundamental to the conservation of ecosystem services such as carbon storage, groundwater protection, wood supply and soil stabilization (Esquivel et al. 2020; Hua et al. 2022; Duan et al. 2023).

Over time, the diversity of naturally regenerating plants has improved. This result could be explained by an average accumulation of nitrogen in the soil from the nitrogen fixed by the roots of these tree legumes. This activity of the *Acacia* rhizosphere leads to an improvement in soil productivity in these *Acacia* stands. Indeed, total nitrogen is an edaphic factor influencing vegetation growth, regeneration and the development of a plant stand (Qian et al. 2014). When the nitrogen stock in the soil is moderate, it stimulates the uptake and activity of soil nutrients (Luo et al. 2022), resulting in improved vegetation productivity (O'Sullivan et al. 2019). The ultimate goal of vegetation recovery is to increase biodiversity and ecosystem stability (Midolo et al. 2019; Li et al. 2021). Natural regeneration is an effective method of restoring vegetation, helping to store soil carbon, fix soil nitrogen, restore degraded ecosystems and improve soil quality (Hu et al. 2021). It helps to increase the diversity of plants in the understory and ensures the sustainable restoration of the forest canopy (Wang et al. 2019). In addition to this, vegetation restoration helps to increase the soil carbon sink, and especially the reservoir of biodegradable carbon contained in the soil (Liu et al. 2020; Hu et al. 2021). Soil carbon is very important, as it is involved in the nitrogen fixation process by *Acacia* roots. There is a symbiosis between the *Rhizobiums* (soil nitrogen-fixing bacteria) and the roots of leguminous plants, which provide these bacteria with carbon as a source of energy. In return, the *Rhizobiums* use their energy source and become active, fixing nitrogen for the leguminous roots that host them. Previous studies (Ferguson et al. 2019; Roy et al. 2020; Yang et al. 2022) have explained that legume root nodules host *Rhizobium*. Supplied with nutrients by legumes, these bacteria convert atmospheric nitrogen into reduced forms that can be used by host plants. It is worth pointing out that a forest's resilience process relies on seed germination, seedling establishment and survival (Taeroe et al. 2019), which in reality depend on environmental conditions. Through their role in capturing nitrogen, Acacias improve soil fertility, creating edaphic conditions favorable to natural regeneration. In the process of forest resilience, seedlings resulting from seed germination survive and grow thanks to numerous biotic and abiotic factors, including water, nutrients and soil properties (Rozendaal et al. 2019; Zhang et al. 2022). The other striking fact is the decline in the regeneration index as the stands age. This finding would mean that there is a progressive maturity of regenerated woody flora under the Acacias marked by the increasing proportion of mature individuals. This proves that the individuals that regrow in the natural regeneration process initiated under the Acacias are developing well.

In conclusion, we noticed that the presence of Acacias on a degraded potion of the Anguédédou Forest has restored soil fertility and tree cover in these areas. The new environmental conditions created by the Acacias have encouraged the regeneration and development of woody species. Therefore, there is a good natural regeneration of woody species under Acacias planted in a degraded forest landscape. We noted an increase in the species richness and an improvement in the specific diversity of the regenerated woody flora as the *Acacia* stands aged. These results show that Acacias, in addition to their agronomic benefits, can be used to naturally regenerate a forest at lower cost. Our study leads us to conclude that tree legumes in general, and Acacias (notably *A. mangium* and *A. auriculiformis*) in particular, are useful species both in agricultural systems and in forestry. These Acacias species therefore appear to be strategically important species in the management of agroforestry systems and forest restoration.

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REFERENCES

Akujärvi A, Repo A, Akujärvi AM, Liski J. 2021. Bridging mapping and simulation modelling in the ecosystem service assessments of boreal

forests: Effects of bioection on carbon dynamics. For Ecosyst 8: 4. DOI: 10.1186/s40663-021-00283-2.
Amba AJG, Gnahoré E, Diomandé S, Bakayoko A. 2021. Diversité floristique et structurale de la forêt classée de la Mabi au Sud-Est de la Côte d'Ivoire. Afr Sci 18 (1): 159-171.
Ameja LG, Ribeiro N, Sitoe AA, Guillot B. 2022. Regeneration and restoration status of miombo woodland following land use land cover changes at the buffer zone of Gile National Park, Central Mozambique. Trees For People 9: 100290. DOI: 10.1016/j.tfp.2022.100290.
Assédé ÉS, Azihou FA, Adomou AC, Oumorou M, Sinsin B. 2015. Effet du relief sur la régénération des espèces ligneuses en zone soudanienne du Bénin. Bois For Trop 326 (4): 15-24. DOI: 10.19182/bft2015.326.a31280.
Awasthi P, Bargali K, Bargali SS, Jhariya MK. 2022a. Structure and fFunctioning of *Coriaria nepalensis* Wall dominated Shrublands in degraded hills of Kumaun Himalaya. I. dry matter dynamics. Land Degrad Dev 33 (9): 1474-1494. DOI: 10.1002/ldr.4235.
Awasthi P, Bargali K, Bargali SS, Khatri K. 2022b. Nutrient return through decomposing *Coriaria nepalensis* litter in degraded hills of Kumaun Himalaya, India. Front For Glob Change 5: 1008939. DOI: 10.3389/ffgc.2022.1008939.
Baboo B, Sagar R, Bargali SS, Verma H. 2017. Tree species composition, regeneration and diversity within the protected area of Indian dry tropical forest. Trop Ecol 58 (3): 409-423.
Bargali SS, Padalia K, Bargali K. 2019. Effects of tree fostering on soil health and microbial biomass under different land use systems in central Himalaya. Land Degrad Dev 30 (16): 1984-1998. DOI: 10.1002/ldr.3394.
Barmo S, Amani A, Soumana I, Ichaou A, Karim S, Mahamane A. 2019. Structure et diversité des parcs agroforestiers adjacents à la forêt protégée de Baban Rafi, Niger. Afr l'Ouest Afr Sci 15 (2): 166-185.
Bäumler R. 2015. Soils. In: Miehe G, Pendry CA (eds.). Nepal: An Introduction to the Natural History, Ecology and Human Environment in the Himalayas - A Companion to the Flora of Nepal, Edition: 1st. The Royal Botanical Garden, Edinburgh.
Bi TG, Soro GE, Dao A, Kouassi FW, Srohourou B. 2010. Frequency analysis and new cartography of extremes daily rainfall events in Côte d'Ivoire. J Appl Sci 10: 1684-1694. DOI: 10.3923/jas.2010.1684.1694.
Bisht S, Bargali SS, Bargali K, Rawat YS, Rawat GS. 2023. Dry matter dynamics and carbon flux along riverine forests of Gori valley, Western Himalaya. Front For Glob Change 6: 1206677. DOI: 10.3389/ffgc.2023.1206677.
Carnus JM, Parotta J, Brockerhoff E, Arbez M, Jactel H, Kremer A, Lamb D, O'Hara K, Walters B. 2006. Planted forests and biodiversity. J For 104 (2): 65-77. DOI: 10.1093/jof/104.2.65.
Chazdon RL, Gutierrez V, Brancalion PHS, Laestadius L, Guariguata MR. 2020. Co-creating conceptual and working frameworks for implementing forest and landscape restoration based on core principles. Forest 11 (6): 706. DOI: 10.3390/f11060706.
Chazdon RL. 2014. Second growth: The promise of tropical forest regeneration in an age of deforestation. University of Chicago Press, Chicago. DOI: 10.7208/chicago/9780226118109.001.0001.
Curtis PG, Slay CM, Harris NL, Tyukavina A, Hansen MC. 2018. Classifying drivers of global forest loss. Science 361: 1108. DOI: 10.1126/science.aau3445.
Duan PP, Fu RT, Nottingham AT, Domeignoz-Horta LA, Yang X, Du H, Wang K, Li D. 2023. Tree species diversity increases soil microbial carbon use efficiency in a subtropical forest. Glob Change Biol 29 (24): 7131-7144. DOI: 10.1111/gcb.16971.
Elliott SD, Blakesley D, Hardwick K. 2013. Restauration des forêts tropicales: un guide pratique. Royal Botanic Gardens, Kew.
Esquivel J, Echeverría C, Saldaña A, Fuentes R. 2020. High functional diversity of forest ecosystems is linked to high provision of water flow regulation ecosystem service. Ecol Indic 115: 106433. DOI: 10.1016/j.ecolind.2020.106433.
Fagan ME, Reid JL, Holland MB, Drew JG, Zahawi RA. 2020. How feasible are global forest restoration commitments? Conserv Lett 13 (3): e12700. DOI: 10.1111/conl.12700.
FAO. 2020. The State of the World's Forests 2020. FAO, Rome, Italy. DOI: 10.4060/ca8642en.
Fartyal A, Khatri K, Bargali K, Bargali SS. 2022. Altitudinal variation in plant community, population structure and carbon stock of *Quercus semecarpifolia* Sm. forest in Kumaun Himalaya. J Environ Biol 43 (1): 133-146. DOI: 10.22438/jeb/43/1/MRN-2003.
Ferguson BJ, Mens C, Hastwell AH, Zhang M, Su H, Jones CH, Chu X, Gresshoff PM. 2019. Legume nodulation: The host controls the party. Plant Cell Environ 42: 41-51. DOI: 10.1111/pce.13348.
García C, Espelta JM, Hampe A. 2020. Managing forest regeneration and expansion at a time of unprecedented global change. J Appl Ecol 57: 2310-2315. DOI: 10.1111/1365-2664.13797.
García C, Moracho E, Díaz-Delgado R, Jordano P. 2014. Long-term expansion of juniper populations in managed landscapes: Patterns in space and time. J Ecol 102: 1562-1571. DOI: 10.1111/1365-2745.12297.
Gosain BG, Negi GCS, Dhyani PP, Bargali SS, Saxena R. 2015. Ecosystem services of forests: Carbon Stock in vegetation and soil components in a watershed of Kumaun Himalaya, India. Intl J Ecol Environ Sci 41 (3-4): 177-188.
Holl KD, Brancalion PHS. 2020. Tree planting is not a simple solution. Science 368: 580. DOI: 10.1126/science.aba8232.
Htun NZ, Mizoue N, Yoshida S. 2011. Tree species composition and diversity at different levels of disturbance in Popa Mountain Park, Myanmar. Biotropica 43: 597-603. DOI: 10.1111/j.1744-7429.2011.00753.x.
Hu P, Zhang W, Chen H, Li D, Zhao Y, Zhao J, Xiao J, Wu F, He X, Luo Y, Wang K. 2021. Soil carbon accumulation with increasing temperature under both managed and natural vegetation restoration in calcareous soils. Sci Total Environ 767: 145298. DOI: 10.1016/j.scitotenv.2021.145298.
Hua FY, Bruijnzeel LA, Meli P, Martin PA, Zhang J, Nakagawa S, Miao X, Wang W, McEvoy C, Peña-Arancibia JL, Brancalion PHS, Smith P, Edwards DP, Balmford A. 2022. The biodiversity and ecosystem service contributions and trade-offs of forest restoration approaches. Science 376 (6595): 839-844. DOI: 10.1126/science.abl4649.
Jaurena M, Lezama F, Salvo L, Cardozo G, Ayala W, Terra J, Nabinger C. 2016. The dilemma of improving native grasslands by overseeding legumes: Production intensification or diversity conservation. Rangel Ecol Manag 69 (1): 35-42. DOI: 10.1016/j.rama.2015.10.006.
Jin Y, Russo SE, Yu M. 2018. Effects of light and topography on regeneration and coexistence of evergreen and deciduous tree species in a Chinese subtropical forest. J Ecol 106: 1634-1645. DOI: 10.1111/1365-2745.12911.
Johnson DJ, Magee L, Pandit K, Bourdon J, Broadbent EN, Glenn K, Kaddoura Y, Machado S, Nieves J, Wilkinson BE, Zambrano AMA, Bohlman SA. 2021. Canopy tree density and species influence tree regeneration patterns and woody species diversity in a longleaf pine forest. For Ecol Manag 490: 119082. DOI: 10.1016/j.foreco.2021.119082.
Kablan M. 2016. Vulnérabilité et adaptation des populations urbaines aux effets des variations climatiques (température et pluviométrie): analyse de la situation dans la commune de Cocody, Abidjan, Côte d'Ivoire. [Thèse de doctorat]. Université Félix Houphouët-Boigny de Cocody-Abidjan, Côte d'Ivoire, Abidjan.
Keil P, Chase JM. 2019. Global patterns and drivers of tree diversity integrated across a continuum of spatial grains. Nat Ecol Evol 3 (3): 390-399. DOI: 10.1038/s41559-019-0799-0.
Kouadio KR, Bakayoko A, N'Guessan KA, Konan D. 2016. Diversité et structure floristiques sous des peuplements d'acacias australiens en zone forestière de la Côte d'Ivoire. Eur Sci J 12 (34): 227-244. DOI: 10.19044/esj.2016.v12n35p227.
Kouadio KR, N'Guessan KA, Soro D. 2018. Effect of legumineous trees on the floral diversity and ligneous regeneration in zone of evergreen wet dense forest of Ivory Coast. J Biodivers Environ Sci 13 (5): 230-235.
Larson JE, Funk JL. 2016. Regeneration: An overlooked aspect of trait-based plant community assembly models. J Ecol 104 (5): 1284-1298. DOI: 10.1111/1365-2745.12613.
Li J, Sang C, Yang J, Qu L, Xia Z, Sun H, Jiang P, Wang X, He H, Wang C. 2021. Stoichiometric imbalance and microbial community regulate microbial elements use efficiencies under nitrogen addition. Soil Biol Biochem 156: 108207. DOI: 10.1016/j.soilbio.2021.108207.
Liang J, Gamarra JG, Picard N, Zhou M, Pijanowski B, Jacobs DF, Reich PB, Crowther TW, Nabuurs GJ, De-Miguel S, Fang J. 2022. Co-limitation towards lower latitudes shapes global forest diversity gradients. Nat Ecol Evol 6 (10): 1423-1437. DOI: 10.1038/s41559-022-01831.
Liu X, Chen D, Yang T, Huang F, Fu S, Li L. 2020. Changes in soil labile and recalcitrant carbon pools after land-use change in a semi-arid agro-pastoral ecotone in Central Asia. Ecol Indic 110: 105925. DOI: 10.1016/j.ecolind.2019.105925.

Luo L, Yu J, Zhu L, Gikas P, He Y, Xiao Y, Deng S, Zhang Y, Zhang S, Zhou W, Deng O. 2022. Nitrogen addition may promote soil organic carbon storage and CO_2 emission but reduce dissolved organic carbon in Zoige peatland. J Environ Manag 324: 116376. DOI: 10.1016/j.jenvman.2022.116376.

Magurran AE. 1988. Ecological Diversity and Its Measurements. Princeton University Press, Princeton, NJ. DOI: 10.1007/978-94-015-7358-0.

Manral V, Bargali K, Bargali SS, Jhariya MK, Padalia K. 2022. Relationships between soil and microbial biomass properties and annual flux of nutrients in Central Himalayan forests, India. Land Degrad Dev 33 (12): 2014-2025. DOI: 10.1002/ldr.4283.

Manral V, Bargali K, Bargali SS, Karki H, Chaturvedi RK. 2023. Seasonal dynamics of soil microbial biomass C, N and P along an altitudinal gradient in Central Himalaya, India. Sustainability 15: 1651. DOI: 10.3390/su15021651.

Manral V, Bargali K, Bargali SS, Shahi C. 2020. Changes in soil biochemical properties following replacement of Banj oak forest with Chir pine in Central Himalaya, India. Ecol Process 9: 30. DOI: 10.1186/s13717-020-00235-8.

Marcon E. 2015. Mesures de la Biodiversité. Master. Kourou, France.

Mason WL, Diaci J, Carvalho J, Valkonen S. 2022. Continuous cover forestry in Europe: Usage and the knowledge gaps and challenges to wider adoption. Forestry 95: 1-12. DOI: 10.1093/forestry/cpab038.

Midolo G, Alkemade R, Schipper AM, Benítez-López A, Perring MP, De Vries W. 2019. Impacts of nitrogen addition on plant species richness and abundance: A global meta-analysis. Global Ecol Biogeogr 28: 398-413. DOI: 10.1111/geb.12856.

Nakajima T, Shiraishi N, Kanomata H, Matsumoto M. 2017. A method to maximise forest profitability through optimal rotation period selection under various economic, site and silvicultural conditions. N Z J For Sci 47: 1-13. DOI: 10.1186/s40490-016-0079-6.

Negi B, Khatri K, SS Bargali SS, Bargali K. 2024. Factors determining the invasion pattern of *Ageratina adenophora* Spreng. in Kumaun Himalaya India. Environ Exp Bot 228 (B): 106027. DOI: 10.1016/j.envexpbot.2024.106027.

O'Sullivan M, Spracklen DV, Batterman SA, Arnold SR, Gloor M, Buermann W. 2019. Have synergies between nitrogen deposition and atmospheric CO_2 driven the recent enhancement of the terrestrial carbon sink? Glob Biogeochem Cycles 33: 163-180. DOI: 10.1029/2018GB005922.

Padalia K, Bargali SS, Bargali K, Manral V. 2022. Soil microbial biomass phosphorus under different land use systems. Trop Ecol 63: 30-48. DOI: 10.1007/s42965-021-00184-z.

Pandey R, Bargali SS, Bargali K, Karki H, Chaturvedi RK. 2024. Dynamics of nitrogen mineralization and fine root decomposition in sub-tropical *Shorea robusta* Gaertner f. forests of Central Himalaya, India. Sci Total Environ 921: 170896. DOI: 10.1016/j.scitotenv.2024.170896.

Pandey R, Bargali SS, Bargali K, Pandey VC. 2023. Temporal variability in fine root dynamics in relation to tree girth size in sub-tropical *Shorea robusta* forests. Land Degrad Dev 34 (5): 1522-1537. DOI: 10.1002/ldr.4550.

Paquette A, Messier C. 2013. Managing tree plantations as complex adaptive systems. In: Messier C, Puettmann KJ, Coates KD (eds.). Managing Forests as Complex Adaptive Systems: Building Resilience to the Challenge of Global Change. EarthScan, New York, NY, USA.

Paudel S, Sah JP. 2003. Physico chemical characters of soil in tropical soil (*Shorea robusta* Gaertn.) forests in eastern Nepal. Himalayan J Sci 1 (2): 107-110. DOI: 10.3126/hjs.v1i2.207.

Pukkala T. 2022. Assessing the externalities of timber production. For Policy Econ 135: 102646. DOI: 10.1016/j.forpol.2021.102646.

Qian Z, Yun YC, Yu XP, Gao HD, Lv R, Zhang WY. 2014. Changes of vegetation characteristics and soil properties in Mu Us Sandy Land by aerial seeding afforestation. J Cent South Univ Technol 34: 102-107. DOI: 10.14067/j.cnki.1673-923x.2014.04.021.

Raunkiaer C. 1934. The life forms of plants and statistical plant geography. Oxford Clarendon Press, Oxford.

Roy S, Liu W, Nandety RS, Crook A, Mysore KS, Pislariu CI, Frugoli J, Dickstein R, Udvardi MK. 2020. Celebrating 20 years of genetic discoveries in legume nodulation and symbiotic nitrogen fixation. Plant Cell 32 (1): 15-41. DOI: 10.1105/tpc.19.00279.

Oliveira Neto SN, Villa P, Rozendaal D, Bongers F, Aide TM, Alvarez-Dávila E, Ascarrunz N, Balvanera P, Becknell JM, Bentos TV, Brancalion PH. 2019. Biodiversity recovery of Neotropical secondary forests. Sci Adv 5 (3): eaau3114. DOI: 10.1126/sciadv.aau3114.

Shannon CE, Wiener W. 1963. The mathematical theory of communication. University of Illinois Press, Urbana, IL.

Song XP, Hansen MC, Stehman SV, Potapov PV, Tyukavina A, Vermote EF, Townshend JR. 2018. Global land change from 1982 to 2016. Nature 560: 639-643. DOI: 10.1038/s41586-018-0411-9.

Taeroe A, de Koning JHC, Löf M, Tolvanen A, Heiðarsson L, Raulund-Rasmussen K. 2019. Recovery of temperate and boreal forests after windthrow and the impacts of salvage logging. A quantitative review. Ecol Manag 446: 304-316. DOI: 10.1016/j.foreco.2019.03.048.

The Angiosperm Phylogeny Group (APG). 2016. An update of the Angiosperm Phylogeny Group classification for the orders and families of flowering plants: APG IV. Bot J Linn Soc 181: 1-20. DOI: 10.1111/boj.12385.

Tiébré MS, Vroh BTA, Kouamé D, N'da KD, Adou Yao CY. 2015. Effets d'un arbre exotique envahissant Hopea odorata Roxb. (Dipterocarpaceae) sur la diversité floristique et le stockage de carbone du Parc National du Banco en Côte d'Ivoire. Intl J Innov Appl Stud 10 (1): 207-216

Trumbore S, Brando P, Hartmann H. 2015. Forest health and global change. Science 349: 814. DOI: 10.1126/science.aac6759.

UICN. 2022. Rapport annuel de l'UICN 2021. Gland, Suisse : UICN.

Verkerk H, Delacote P, Hurmekoski E, Kunttu J, Matthews R, Mäkipää R, Mosley F, Perugini L, Reyer C, Roe S, Trømborg E. 2022. Forest-Based Climate Change Mitigation and Adaptation in Europe. From Science to Policy 14. European Forest Institute. DOI: 10.36333/fs14.

Vibhuti, Bargali VK, Bargali SS. 2020. Effect of size and altitude on soil organic carbon stock in homegarden agroforestry system in Central Himalaya, India. Acta Ecol Sin 40 (6): 483-491. DOI: 10.1016/j.chnaes.2020.10.002.

Wang ZB, Yang HJ, Wang DH, Zhao Z. 2019. Spatial distribution and growth association of regeneration in gaps of Chinese pine (*Pinus tabuliformis* Carr.) plantation in northern China. For Ecol Manag 432: 387-399. DOI: 10.1016/j.foreco.2018.09.032.

Yang H, Pan C, Wu Y, Qing S, Wang Z, Wang D. 2023. Response of understory plant species richness and tree regeneration to thinning in *Pinus tabuliformis* plantations in northern China. For Ecosyst 10: 100105. DOI: 10.1016/j.fecs.2023.100105.

Yang J, Lan L, Jin Y, Yu N, Wang D, Wang E. 2022. Mechanisms underlying legume-rhizobium symbioses. J Integr Plant Biol 64 (2): 244-267. DOI: 10.1111/jipb.13207.

Yemata G, Haregewoien G. 2022. Floristic composition, structure and regeneration status of woody plant species in Northwest Ethiopia. Trees For People 9: 100291. DOI: 10.1016/j.tfp.2022.100291.

Zhang HN, Chen S, Zheng X, Ge X, Li Y, Fang Y, Cui P, Ding H. 2022. Neighborhood diversity structure and neighborhood species richness effects differ across life stages in a subtropical natural secondary forest. For Ecosyst 9: 100075. DOI: 10.1016/j.fecs.2022.100075.

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Species distribution modelling to identify invasion hotspots of *Ageratina riparia* in Mizoram, India

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Abstract. *Sengupta R, Dash SS. 2024. Species distribution modelling to identify invasion hotspots of* Ageratina riparia *in Mizoram, India. Asian J For 8: 184-193.* The accelerated pace of globalization, increased human mobility, and the intensification of global trade have significantly amplified the spread of non-native species worldwide. The introduction of these alien species has triggered invasive consequences, further intensified by climate change. Accurately predicting the spread of invasive species under changing climatic conditions is essential for identifying vulnerable regions and formulating effective management strategies to limit their spread. This study projected and identified invasion hotspots for the neo-invasive species *Ageratina riparia* in Mizoram, using its current distribution patterns and projected climate changes. Habitat suitability modelling, performed with the Maximum Entropy (MaxEnt) machine learning algorithm using default settings, showed that the current distribution of *A. riparia* encompasses 4.78% of Mizoram's area, deemed suitable for varying levels of invasion. Projections for 2050 and 2070 indicated that suitable habitats for *A. riparia* could expand to 6.19% of Mizoram's area by 2050 under the RCP 4.5 scenario, relative to its present distribution. This anticipated expansion, combined with an upward shift in elevation, highlights the urgent need for effective management strategies to mitigate the invasion by *A. riparia*. The findings provide critical insights for identifying and projecting invasion hotspots, which are essential for early-stage management of *A. riparia* invasions.

Keywords: *Ageratina riparia*, alien plants, Asteraceae, habitat suitability, MaxEnt, plant invasion

Abbreviations: AUC: Area Under the Curve, IAPs: Invasive alien plants, TSS: True Skill Statistic

INTRODUCTION

In recent years, invasive alien plants (hereafter IAPs) have emerged as significant drivers of global environmental change, posing immediate threats to biodiversity, ecosystem services, and ecosystem functions (Vilà et al. 2010; Adhikari et al. 2023). Richardson and Rejmánek (2011) projected that the ongoing progression of global climate change would gradually intensify the incidence of invasions within natural forests. The combined effects of human activities and global climate change are critical factors contributing to the widespread establishment and expansion of IAPs.

Understanding the complex interactions between climate change and IAPs, however, remains challenging (Merow et al. 2017). Key challenges in the study of biological invasions include identifying invasive traits of alien species, assessing habitat vulnerabilities, evaluating the impacts of invasions, predicting invasive tendencies, and developing effective management strategies for invasions within natural forest ecosystems (Essl et al. 2020). The first three of these challenges represent core research areas within biological invasion studies, and a thorough understanding of these aspects provides a solid foundation for effective control and management of biological invasions (Mačić et al. 2018). Consequently, the primary objective of biological invasion research is to control and manage alien plant invasions in specific natural forested regions (Ahmed et al. 2022).

Ageratina riparia (Regel) R.M. King & H. Rob., introduced to India as an ornamental plant in the early 1900s, likely spread to Mizoram during the Second World War through contaminated meadow and forest seeds (Sengupta and Dash 2020). In invasion scenarios, this IAP poses serious risks to natural forests, protected areas, and agricultural lands in Mizoram (Sengupta and Dash 2023b).

A. riparia is a perennial herb or sub-shrub with an erect growth form, characterized by a slender, striated stem reaching heights of 30 cm to 1 m. The plant has simple, oppositely arranged leaves with tapered petioles, featuring narrowly lanceolate to elliptical blades that taper at both ends and display irregular serrations. The leaf surfaces are smooth on top, with short hairs beneath. Small, bell-shaped clusters of capitula form loose inflorescences, with each capitulum containing approximately 20-25 tubular white florets (Figure 1). The fruit is a black achene with five ribs and a pappus tuft. The rounded, striated stem can reach up to 1-1.5 m in height (Sengupta and Dash 2020).

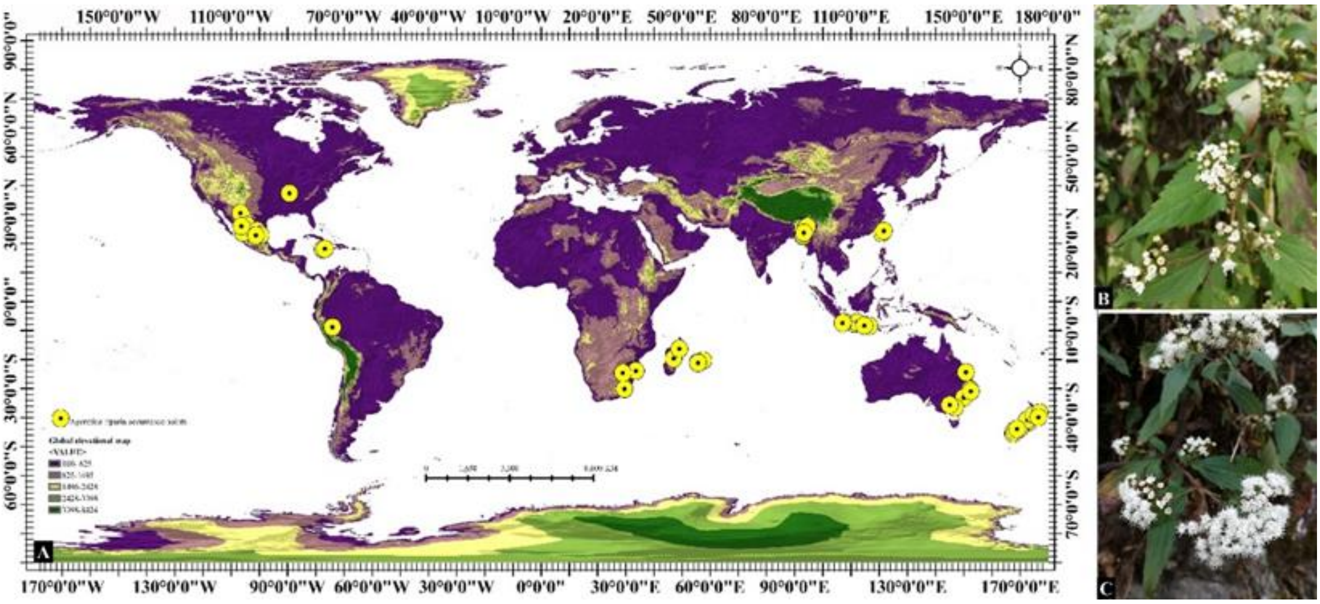

Figure 1. A. Global distribution of *Ageratina riparia* (yellow points) occurrence, B. Habit, C.Flower close up

The distribution of many invasive species is increasingly shaped by human-facilitated movement, which threatens biodiversity, agriculture, disrupts ecosystems, and hampers conservation efforts (Adhikari et al. 2015). Anthropogenic environmental changes, such as nitrification, elevated CO_2 levels, and shifting climate patterns, can promote invasive plant species by increasing the availability of limiting resources (Hautier et al. 2015). In light of these human-driven environmental shifts, species distribution modelling can be employed at early stages to predict climate change impacts and identify potential invasion hotspots.

A critical initial management step to mitigate the impact of alien plants on native vegetation is to assess their invasiveness potential, especially in the context of climate change (Fournier et al. 2019). Ecological Niche Modelling (ENM), or Species Distribution Modelling (SDM), uses mathematical algorithms, species occurrence data, and environmental variables to predict species distribution (Valavi et al. 2022). SDM has proven to be a valuable tool for examining the impact of Invasive Alien Plants (IAPs) and predicting future spread. For instance, the Maximum Entropy (MaxEnt) algorithm has been applied to predict the distribution of *Ageratina adenophora* (Spreng.) R.M.King & H.Rob. in South Africa (Tererai and Wood 2014) and Nepal (Poudel et al. 2020), *Mikania micrantha* Kunth in India (Rameshprabu and Swamy 2015), *Chromolaena odorata* (L.) R.M.King & H.Rob. in the Eastern Ghats (Saranya et al. 2021) and Mizoram (Sengupta and Dash 2023b). Recent studies have assessed potential shifts in IAP distributions under various climate change scenarios at regional (Adhikari et al. 2015) and global scales (Vaz et al. 2018). Using SDMs and bioclimatic data, these studies have identified invasion hotspots for alien plants across North-East India, such as *Ageratum conyzoides* L. and *Imperata cylindrica* (L.) Raeusch. (Ray et al. 2019), Assam for *M. micrantha* (Choudhury et al. 2021), Jammu & Kashmir for *Parthenium hysterophorus* L. (Mushtaq et al. 2021), Eastern India for *Lantana camara* L. (Tiwari et al. 2022), South East Asia for *Tithonia diversifolia* (Hemsl.) A. Gray (Boral and Moktan 2022), and Mizoram for *C. odorata* (Sengupta and Dash 2023b). However, studies on the potential invasion of neo-invasive species such as *A. riparia* in the Indian Himalayan Region (IHR), including Mizoram, remain limited. MaxEnt modelling relies on species occurrence data and environmental variables to estimate potential habitats for invasive species, demonstrating high predictive accuracy (Phillips and Dudík 2008; Phillips et al. 2017).

Managing and preventing the invasion of *A. riparia* is both costly and time-consuming. However, predictive modelling can help identify future invasion hotspots, which is crucial for anticipating the spread of *A. riparia* in Mizoram. Currently, no studies have addressed the prediction of future invasion scenarios for this species in Mizoram. To fill this gap, our study evaluates the potential invasion and establishment of *A. riparia* in Mizoram's natural forests using the MaxEnt model for habitat suitability. We utilized current occurrence data for *A. riparia*, along with environmental and anthropogenic factors affecting its spread. This research aims to provide decision-makers with essential insights to develop effective strategies for the prevention and management of *A. riparia* invasion in Mizoram.

MATERIALS AND METHODS

Study sites

The study was conducted in Mizoram, located within the Indo-Burma biodiversity hotspot (Figure 1). Field research was carried out between July 2021 and September 2023, focusing on floristic and ecological surveys across various regions of Mizoram, including protected areas, as part of the lead author's doctoral research. Mizoram is bordered by the Indian states of Tripura, Assam, and Manipur to the west, north, and east, respectively. Forests cover 84.53% of Mizoram's total geographical area, with only 6.75% designated as protected areas. The region experiences summer temperatures ranging from 18°C to 29°C (March to May) and winter temperatures ranging from 11°C to 24°C (August to December), with an annual rainfall between 2,160 mm and 3,500 mm (FSI 2021).

Species occurrence data

Occurrence data for *A. riparia* was collected through field surveys during the floristic and ecological assessments. Geographic coordinates were recorded with a Garmin Montana 680 GPS device, resulting in 228 unique occurrence points for this neo-invasive species in Mizoram. These coordinates were incorporated into a digital elevation map of the study area (Figure 2). The data underwent screening to remove any erroneous or duplicate records outside the study area, maintaining a 1 km (30 arc-seconds) minimum distance between points using ArcGIS (ArcMap 10.8.2) to ensure data quality. To enhance model accuracy and reduce sampling bias, a presence-background approach with site-occupancy data was employed (Botella et al. 2020).

Bioclimatic and environmental variables

Elevation and environmental data (Table 1) for both current and future climate scenarios were sourced from the WorldClim global database (Hijmans et al. 2005) at a resolution of ~1 km² (30 arc-seconds). Future climate projections were based on 19 bioclimatic variables under RCP 2.6, 4.5, and 8.5 scenarios for the years 2050 and 2070, utilizing the GFDL-CM3 climate model (CMIP5; Griffies et al. 2011). The Mizoram study area was extracted, and data was converted to ASCII format in ArcGIS 10.8.2. To ensure model robustness, only uncorrelated variables were selected for MaxEnt modelling, with multicollinearity (r > 0.9) eliminated using SDM Toolbox 2.0 (Brown et al. 2017). Models were developed with a 30% random test set, and ten replicated runs were executed to produce average, maximum, minimum, median, and standard deviation outputs for each run (Thapa et al. 2018).

Table 1. Uncorrelated bioclimatic variables used in the study (source: https://www.worldclim.org/)

Abbreviation	Bioclimatic variables
BIO2	Mean Diurnal Range (Mean of monthly (max temp - min temp))
BIO3	Isothermality (BIO2/BIO7) (×100)
BIO5	Max Temperature of Warmest Month
BIO7	Temperature Annual Range (BIO5-BIO6)
BIO12	Annual Precipitation
BIO14	Precipitation of Driest Month
BIO15	Precipitation Seasonality (Coefficient of Variation)
BIO18	Precipitation of Warmest Quarter
BIO19	Precipitation of Coldest Quarter
Elev	Elevation

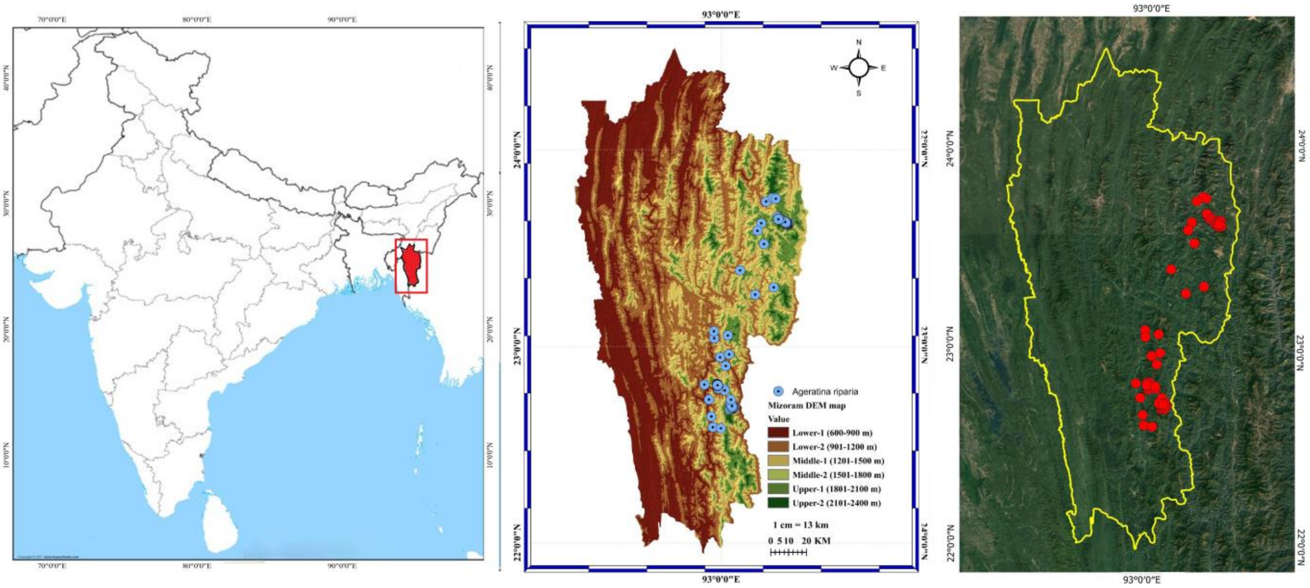

Figure 2. The digital elevation map of Mizoram, India showing the present occurrence points of *Ageratina riparia*

Model building and evaluation

The MaxEnt algorithm (version 3.4.4), a 'presence-only' machine learning approach (Phillips et al. 2023), was employed to identify suitable habitats for *A. riparia* under current and future climate scenarios. This approach allows modelling of the species' fundamental niche based on environmental variables. Only uncorrelated bioclimatic variables (Tables 1 and 2) were incorporated, following a 10-percentile training presence threshold rule with ten replications and auto feature settings enabled. MaxEnt delineates ecological niche boundaries by constraining the probability distribution to the environmental parameters associated with species presence at grid-cell locations (Phillips et al. 2017). Models were run using default settings with uncorrelated variables. To evaluate model accuracy, Area Under the Curve (AUC) values were interpreted as follows: poor (AUC < 0.8), fair (0.8 < AUC < 0.9), good (0.9 < AUC < 0.95), and very good (0.95 < AUC ≤ 1.0) (Adhikari et al. 2023). To evaluate the model's performance, in addition to AUC, the use of TSS is recommended. The TSS score ranges from -1 to 1 and is categorized as follows: poor (-1 to 0.4), fair (0.4 to 0.5), good (0.5 to 0.7), very good (0.7 to 0.85), excellent (0.85 to 0.9), and perfect (0.9 to 1) (Lobo et al. 2008; Wang et al. 2024). Validation relied on the average AUC and the True Skill Statistic (TSS), calculated as TSS=(sensitivity+specificity) −1 (Allouche et al. 2006). These metrics provided a robust assessment of the model's predictive accuracy and suitability.

Mapping and suitable area calculation

The MaxEnt output was evaluated and analyzed using ArcGIS (version 10.8.2) to visualize and interpret the potential invasion areas for *A. riparia*. Potentially suitable areas were identified by delineating regions at risk of future invasion based on MaxEnt predictions, highlighting locations where the species may expand under projected climate conditions.

RESULTS AND DISCUSSION

Model performance and variable contribution in the present scenario

The habitat suitability model for *A. riparia* indicated that suitable habitats in Mizoram to be primarily distributed in the middle (1500-1700 m) to higher altitudes (up to 2055 m), particularly in Eastern to South-Eastern regions of Mizoram (Figure 3.A). The analysis highlighted that areas within the elevational range of 680-2000 m are highly susceptible to invasion by *A. riparia*, with a maximum occurrence probability of 0.98. Validation through present climatic scenarios, including the ROC curve and jackknife of regularized training gain, confirmed these findings (Figures 3.B-C).

The model demonstrated strong performance, achieving a True Skill Statistic (TSS) value of 0.768 and an Area Under the Curve (AUC) score of 0.977, indicating high predictive accuracy (Table 3). The temperature annual range (BIO7) emerged as the most influential variable, contributing 61.5% to the model, followed by the highest temperature of the warmest month (BIO5, 11.2%) and precipitation seasonality (BIO15, 6.1%). The warmest quarter precipitation (BIO18) contributed the least at 0.3%. Consistent with these findings, the jackknife test highlighted that the highest training gain and AUC value were driven by the annual temperature range (BIO7), highlighting its importance in the current spatial distribution of *A. riparia* in Mizoram.

Table 2. Potential suitable habitats in Mizoram, India vulnerable to invasion by *Ageratina riparia*

Districts	Areas vulnerable to *A. riparia* invasion
Champhai	Selam, Ngopa, Vapar, Murlen National Park
Hnahthial	Thiltlang, Hnahthial, Darzo
Khawzawl	Zuchhip
Lawngltai	Sangau, S. Vanlaiphai, Vathuampui, Phawngpui National Park, Cheural
Lunglei	Serkawn, Lunglei,
Saiha	Chakhang, Zawngling
Serchiip	N. Vanlaiphai

Table 3. Prediction outcomes of *Ageratina riparia* habitat suitability modelling

	Prediction parameters	Current	2050			2070		
			RCP26	RCP45	RCP85	RCP26	RCP45	RCP85
Ageratina riparia	AUC	0.977	0.981	0.977	0.988	0.975	0.987	0.991
	TSS	0.768	0.618	0.766	0.746	0.839	0.851	0.709
	Code	**BIO7**	**BIO2**	**BIO2**	**BIO2**	**ELEV**	**BIO14**	**BIO2**
	Percentage of contribution	61.5%	28.8%	52.7%	32.2%	58.6%	38%	28.1%
	Code	**BIO7**	**BIO2**	**BIO2**	**ELEV**	**BIO5**	**ELEV**	**ELEV**
	Permutation of importance	55.3	44.2	26.6	30.5	22	34.4	31.9
	Percentage of suitable habitat	4.78	4.92	6.09	2.31	6.23	3.65	1.78

Note: ***Percentage of contribution & Permutation of importance at 10th percentile training presence threshold

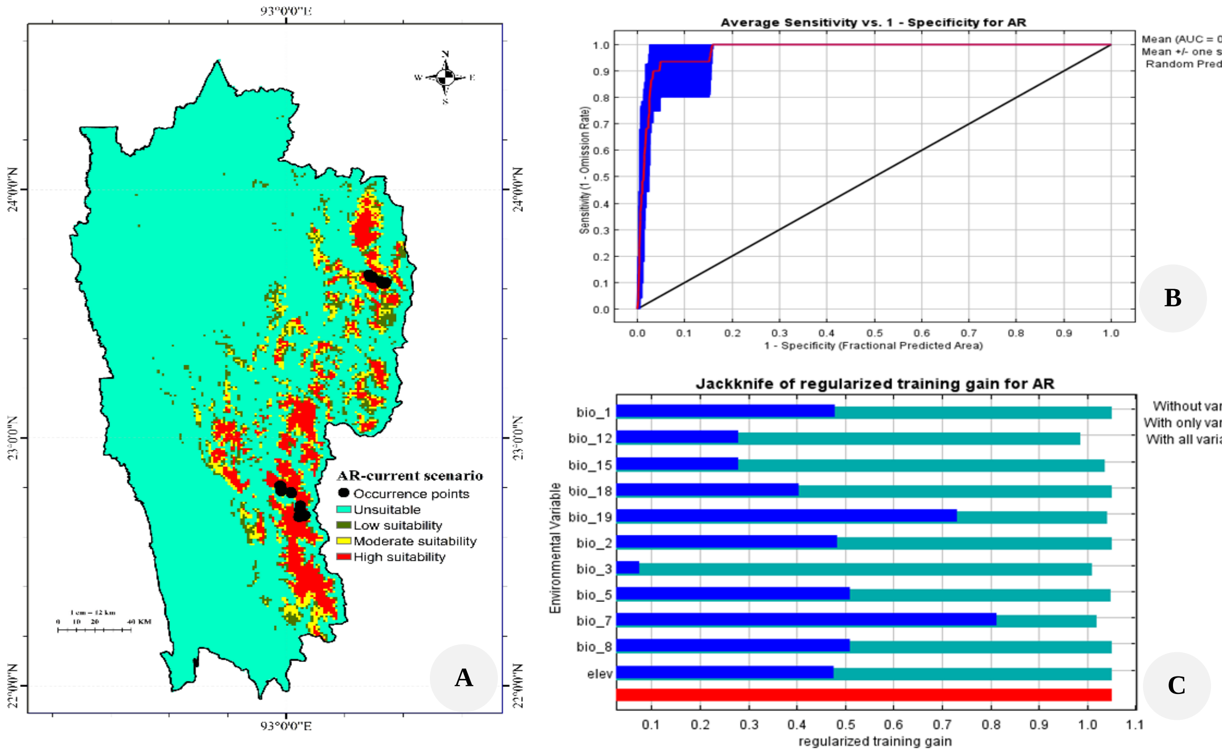

Figure 3. A. The present potential suitability invasion distribution of *A. riparia* in Mizoram, India under current climatic conditions; B. The present ROC curve under current climatic conditions of *A. riparia* in Mizoram; C. The Jackknife of regularized training gain under current climatic conditions of *A. riparia* in Mizoram

Present potential distribution

The potential invasion distribution of *A. riparia* showed relatively low suitability in Mizoram under current climatic conditions. Only 4.78% (1007.95 km²) of the area in Mizoram is suitable to varying degrees (from low to high suitability) for invasion by *A. riparia* (Figure 3.A and Table 3). Nearly seven districts in Mizoram, with limited areas at elevations ranging from 1500 to 1835 m.a.s.l., exhibited high suitability for *A. riparia* invasion based on climatic factors. Forested regions in Sangau, Hnahthial, Darzo, South Vanlaiphai, Thaltlang, and Sentetfiang, situated in the eastern to southern parts of the state, showed vulnerability to *A. riparia* invasion, particularly in the middle to upper elevational zones. In southern Mizoram, the most suitable habitats included the natural forests of Hnahthial, Sangau, and Hmunlai. High-altitude areas of Mizoram (above 1750 m), such as South Vanlaiphai and Darzo, also demonstrated higher suitability for invasion, a trend that aligned with field observations. The natural forest areas within the boundaries of protected areas like Murlen National Park, Phawngpui National Park, and parts of Lengteng Wildlife Sanctuary exhibited the highest percentage of suitable area for *A. riparia* invasion (Figure 3 and Table 2).

Future invasion risk and change in habitat suitability

The habitat modelling outcomes projected the most climatically favorable areas for *A. riparia* invasion in Mizoram. These results indicated that the risk of invasion would increase under the RCP 2.6 climate scenario for 2050 and 2070. Significant risks of invasion were anticipated for 2070, with a growth of 1.45% under RCP 2.6, and for 2050, with a growth of 1.31% under RCP 4.5. Increased invasion risk was projected in the southeastern regions of the state, including areas such as Serchhip, Lunglei, Lawngtlai, South Vanlaiphai, Darzo, Sangau, and Hnahthial, where suitable habitats are expected to expand.

Shifting from RCP 4.5 to RCP 8.5 is projected to decrease climatically suitable areas for *A. riparia* invasion in 2050 and 2070 (Figures 4 and 5; Table 3). While the projections under the extreme climate scenario (RCP 8.5) show a reduction in suitable areas, an expansion in the upper elevational range is expected for both 2050 and 2070 (Figures 4 and 5). Conversely, under the moderate emission scenario of RCP 4.5, the model predicts a contraction in the upper elevational range for these years (Figures 4 and 5).

With changing climatic conditions, all geographical regions in Mizoram, except the highest mountainous areas, are expected to experience an increase in climatically suitable zones for *A. riparia*. Although a slight decrease in suitable areas is projected for the mid-mountain region, it is anticipated to remain the most favorable for *A. riparia* invasion, followed by shifting cultivation fields and fallow lands at mid-altitudes across all future climate scenarios (Table 3). Under the four future climate scenarios—RCP 2.6 for 2050 and 2070, and RCP 4.5 for 2050 and 2070—the central and eastern regions of Mizoram are projected to experience the greatest increase in climatically suitable areas, followed by southern Mizoram. However, under the RCP 8.5 scenario for 2050 and 2070, the central and northwestern parts of Mizoram are expected to lose all suitable areas for *A. riparia* invasion.

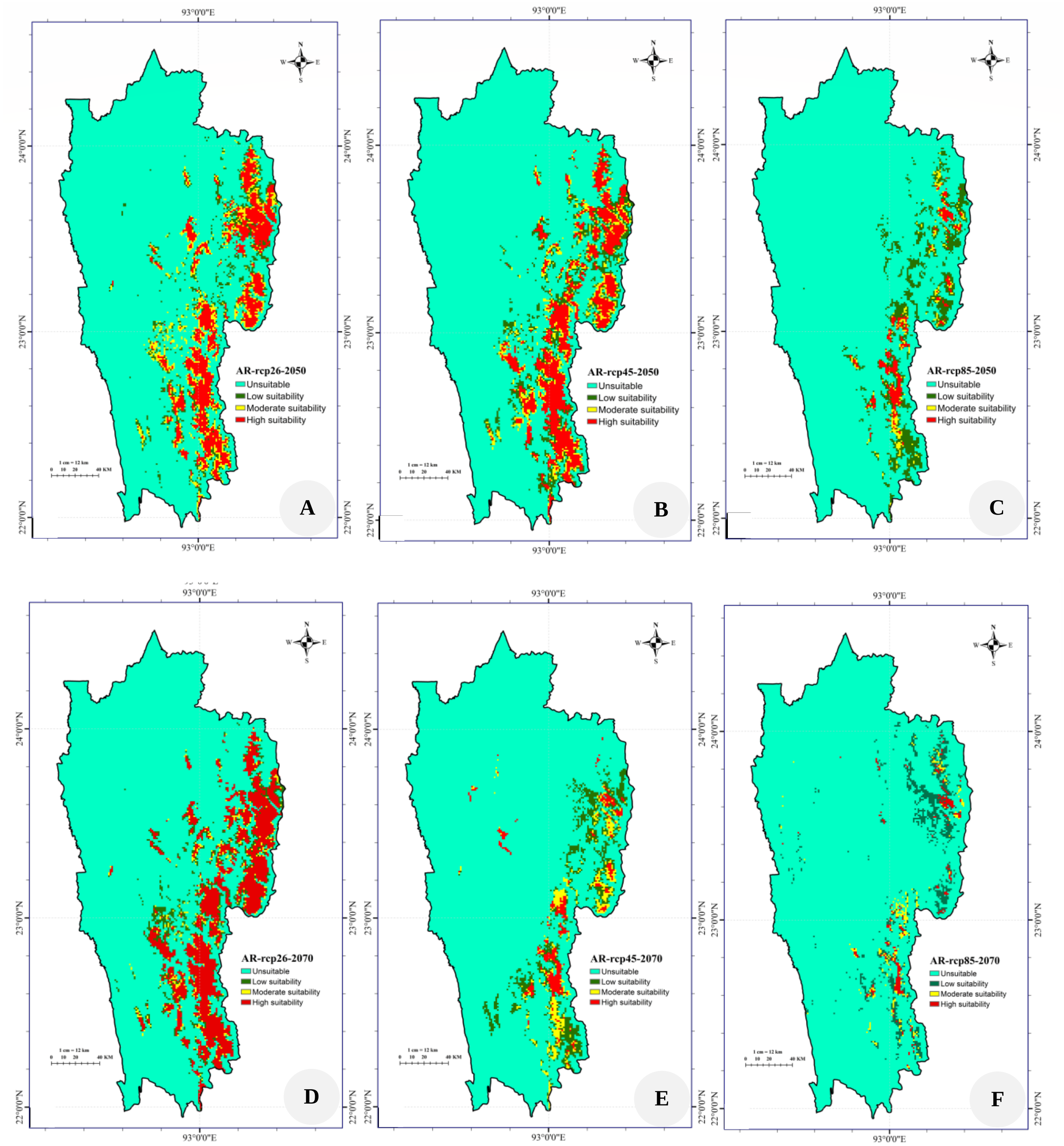

Figure 4. Potential distribution of *Ageratina riparia* under future climate in the Year 2050 in A. RCP 2.6; B. RCP 4.5; C. RCP 8.5 and under future climate: Year 2070 in D. RCP 2.6; E. RCP 4.5; F. RCP 8.5

Additionally, under RCP 4.5 and RCP 8.5 scenarios for 2050 and 2070, climatically suitable areas in southern Mizoram, particularly around Siaha and the western parts of Lawngtlai district, are projected to decline. According to future climate projections under RCP 2.6, RCP 4.5, and RCP 8.5 for 2050 and 2070, protected areas such as Phawngpui National Park and Murlen National Park are also at risk of *A. riparia* invasion (Figures 4 and 5). If the current invasion trend continues, these projections suggest high suitability for invasion in Murlen National Park, Phawngpui National Park, Lengteng Wildlife Sanctuary, and surrounding areas.

Under current climate conditions, the highest controlling factors for *A. riparia* invasion are BIO7 (annual temperature range) and BIO19 (rainfall of the coldest quarter) (Figure 3). Altitude, BIO2 (mean diurnal range), and BIO14 (rainfall of the driest month) significantly influence the future projections of *A. riparia* invasion. Additionally, BIO7 was found to have the highest independent training gain (Figure 5).

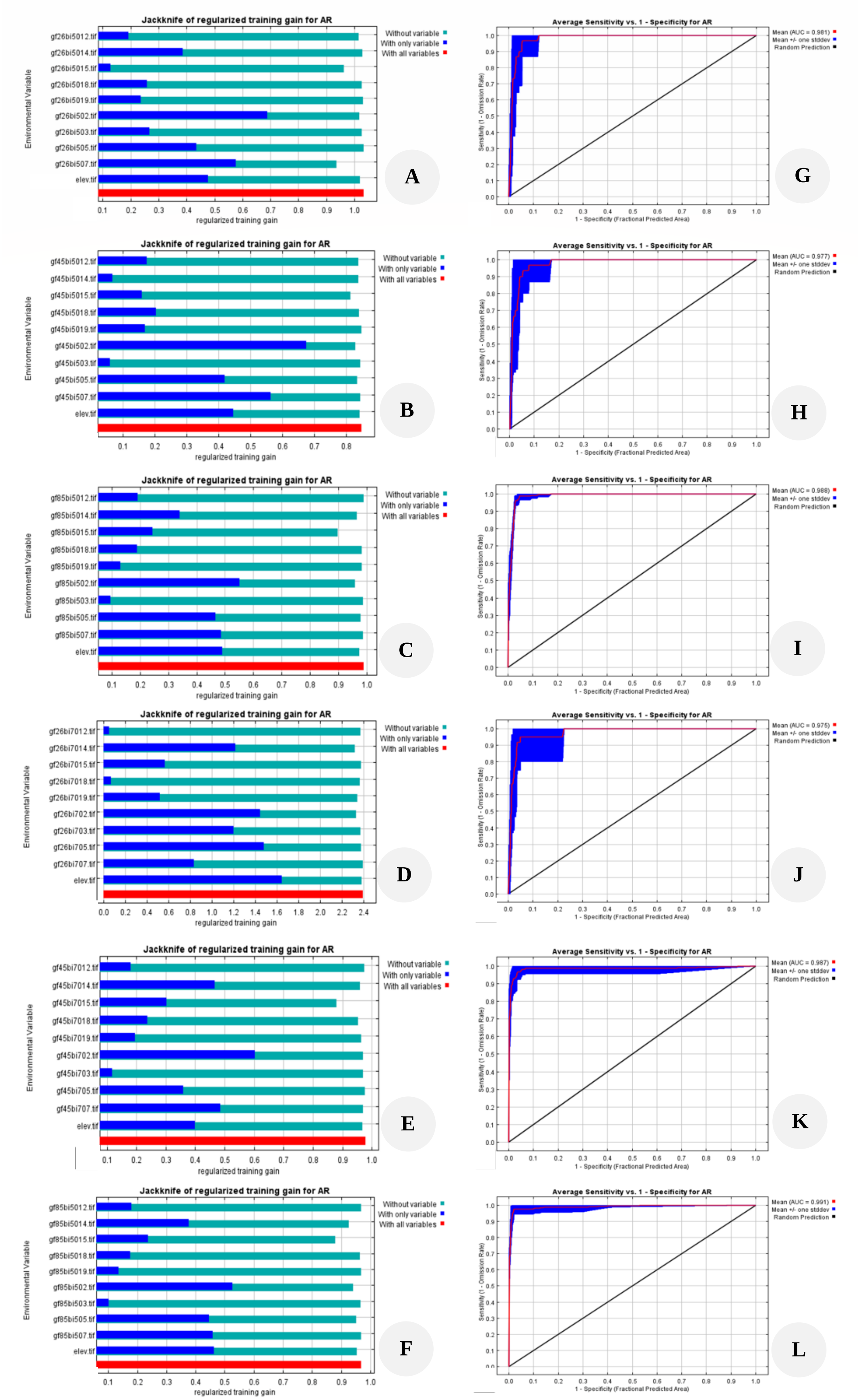

Figure 5. Jackknife & ROC curve of *Ageratina riparia* under future climate in the year 2050: RCP 2.6, A. Jackknife and G. ROC curve; RCP 4.5, B. Jackknife and H. ROC curve; RCP 8.5, C. Jackknife and I. ROC curve and under future climate in the year 2070: RCP 2.6, D. Jackknife and J. ROC curve; RCP 4.5, E. Jackknife and K. ROC curve; RCP 8.5, F. Jackknife and L. ROC curve

Discussion

Neo-invasive Invasive Alien Plant species (IAPs) such as *A. riparia* have caused significant economic damage and pose a global threat to biodiversity (Changjun et al. 2021). Seebens et al. (2017) projected that the cumulative presence of IAPs on continents will increase by 36% from the present scenario to 2050. Identifying invasion hotspots through habitat suitability modelling is the most effective damage control strategy to mitigate invasion by IAPs (Fournier et al. 2019). While *A. riparia* has limited occurrence in Mizoram, its impact remains concerning (Sengupta and Dash 2020), necessitating management under both current and future climate change scenarios to mitigate its detrimental effects on natural forests in the region. Historical herbarium records indicate that *A. riparia*, native to Mexico, was introduced to India as an ornamental plant at the Calcutta Botanical Gardens in 1901, now known as Acharya Jagadish Chandra Bose Indian Botanic Garden (Calcutta, 05.03.1901, G.J. Lane Esgre, CAL0000204374).

The current potential habitat distribution of *A. riparia* aligns closely with existing occurrence records used in the model analysis (Figure 2), supporting the findings of Fang et al. (2021) and Li et al. (2022). These studies reported that invasive species distributions in China are highly concentrated in regions like Yunnan and coastal provinces, while western areas, such as the Tibetan Plateau, exhibit the least. Our models yielded AUC values above 0.91, indicating excellent results and confirming the robustness of the habitat suitability models in this study (Adhikari et al. 2023).

Climatic variables, such as the mean diurnal range (BIO2), annual temperature range (BIO7), and precipitation during the driest month (BIO14), alongside topographical variables like elevation, were found to be the most influential factors in projecting the future distribution of *A. riparia* in Mizoram. In China, similar climatic factors, including precipitation, temperature, and elevation, have been reported to influence the invasion of an allied species, *A. adenophora* (Xian et al. 2022). Anthropogenic disturbances and population density also correlate strongly with invasive species richness in neighboring countries like China (Yang et al. 2017) and Nepal (Shrestha et al. 2015). In India, the same patterns have been observed in the Central Himalayas (Bhattarai et al. 2014) and the Western Himalayas (Lamsal et al. 2018), highlighting anthropogenic disturbances as key factors in the spread of IAPs. The optimum growth of *A. riparia* occurs in temperatures ranging from 15-30°C, with seasonality in rainfall, as shown by the response curves. This finding is consistent with research conducted in other subtropical regions such as southwest China (Li et al. 2022) and Nepal (Poudel et al. 2020) for other Asteraceae invasive species.

This study provides the first-ever habitat distribution modelling for *A. riparia*. During field surveys in Mizoram, *A. riparia* was found to have a restricted distribution, mostly in disturbed landscapes in Eastern and Southern Mizoram. The habitat suitability modelling, which utilized uncorrelated climatic variables, showed similar trends, predicting that only higher altitudes will be vulnerable to *A. riparia* invasion, influenced by high precipitation, temperature variation, moderate annual temperature, and various anthropogenic disturbances. Pure patches of *A. riparia* were observed in areas such as Hnahthial, Vapar, Murlen, Sangau, and Thaltlang, primarily at middle to upper altitudes. Light exposure and temperature variation were found to be important factors influencing the occurrence of *A. riparia*, similar to observations in Meghalaya at mid-altitudes (around 1500 m; Tripathi et al. 2012). The changes in the suitable habitat areas were less than 15%, with most areas remaining stable for *A. riparia* invasion (Table 3). In particular, the habitat of *A. riparia* is expected to shift gradually toward the extreme Southern and Eastern parts, including Phawngpui National Park and Murlen National Park. This habitat shift mirrors the findings of Goncalves et al. (2014), who described the proliferation of *L. camara* in India, reflecting the multidirectional risk of future invasions. Such habitat shifts may also be attributed to phenotypic plasticity, which enables species to dominate native species in the same region (Li et al. 2022), allowing *A. riparia* to migrate into favorable climatic regions for rapid invasion.

While bioclimatic variables are crucial, land-use changes, forest clearing for increased sunlight exposure, soil conditions, and escalating anthropogenic disturbances also influence the distribution of invasive species in Mizoram. These species have spread to abandoned fallow lands, urban environments, and roadside habitats (Adhikari et al. 2023; Sengupta and Dash 2023b).

There is growing evidence that climate change will likely increase the risk of plant invasions, creating more suitable areas in the future (Adhikari et al. 2023). This study's results project that climate change will lead to an increase in suitable areas for *A. riparia* invasion. The species is expected to expand its habitat under six future climate scenarios: RCP 2.6 (2050 and 2070), RCP 4.5 (2050 and 2070), and RCP 8.5 (2050 and 2070). Similar projections have been made in various regions in India, showing the expansion of climatically suitable areas for Asteraceae invasives under future climate scenarios (Adhikari et al. 2015; Datta et al. 2019), and in neighboring countries (Poudel et al. 2020; Xian et al. 2022). Some projections suggest a gradual decline in climate suitability after reaching peak levels (Fandohan et al. 2015), a trend also observed in the suitability models under the RCP 8.5 scenario for 2050 and 2070. These findings suggest that while climate-driven increases in suitability are apparent, they may be influenced by other complex factors.

The use of noxious IAPs for bioprospecting could be an effective management strategy for *A. riparia* invasion in Mizoram (Sengupta and Dash 2023a). This study provides essential insights into potential invasion hotspots for A. riparia, offering a crucial database for developing long-term, scientifically informed management strategies. Sustainable practices such as regulated traditional slash-and-burn cultivation, strict quarantine protocols for food crop imports, and controlled introductions of exotic plants should be prioritized to strengthen these efforts. Sengupta and Dash (2023a) have highlighted the ethnobotanical uses of *A. riparia* in Mizoram, noting that an infusion made from dried leaves and capitula (8-10 dried capitula per 100 ml) is traditionally used as an herbal remedy for hypertension and diabetes. Additionally, the plant collected from Mizoram has high proximate values and mineral content, indicating its potential as a bioprospecting resource for the local community. Inhabitants of Vapar and Sangau also use the plant to create partitions between lands and gardens or reinforce embankments.

Establishing a control and management framework for IAPs in Mizoram's natural forests is critical. Effective control strategies for *A. riparia* should include (i) Ecological restoration of invaded ecosystems by promoting dominant native plant species capable of outcompeting invasives, (ii) Mechanical control methods combined with crop competition techniques in disturbed areas near national parks, and (iii) Using the cut-root-stock method alongside the introduction of native fast-growing grasses and legumes. Awareness programs and workshops should be organized in affected areas to educate villagers, local forest departments, and students about the impact of IAPs and sustainable control and management practices.

In conclusion, this study presents the first state-level modelling of habitat suitability for *A. riparia* in Mizoram, marking an initial effort in North-East India to assess the potential invasion of this neo-invasive species. The predicted habitat distribution aligns with the global spread of various Asteraceae invaders and highlights key invasion hotspots for *A. riparia* within Mizoram. The modelling results indicate that large areas of Mizoram, including its natural forests, exhibit favorable climatic conditions conducive to the acclimatization and potential spread of *A. riparia*. However, despite the identified suitability, the expansion of this Invasive Alien Plants (IAPs) remains within a controllable stage in many regions, particularly in certain parts of the state. Effective management of this invasion requires continuous monitoring, as changing climatic and anthropogenic conditions could facilitate the spread of *A. riparia* into newly suitable areas. Notably, the current model does not account for potential changes in anthropogenic disturbances, which may further exacerbate the risk of invasion. The study successfully identifies the primary invasion hotspots based on the current distribution of *A. riparia*, providing valuable insights into regions at risk of future invasion. This information, when combined with additional ecological data, such as the presence of vulnerable ecosystems and biodiversity hotspots, can help prioritize areas for targeted management. Preventing the spread of *A. riparia* through early intervention is more cost-effective and sustainable than undertaking eradication efforts after the species has already proliferated. Therefore, proactive management strategies, including strengthening oversight of anthropogenic disturbances and promoting ecological restoration, are critical for mitigating the future impact of *A. riparia* on Mizoram's natural forests.

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REFERENCES

Adhikari D, Tiwary R, Barik SK. 2015. Modeling hotspots for invasive alien plants in India. PloS one 10 (7): e0134665. DOI: 10.1371/journal.pone.0134665.

Adhikari P, Lee YH, Poudel A, Hong SH, Park YS. 2023. Global spatial distribution of *Chromolaena odorata* habitat under climate change: random forest modeling of one of the 100 worst invasive alien species. Sci Rep 13: 9745. DOI: 10.1038/s41598-023-36358-z.

Ahmed DA, Hudgins EJ, Cuthbert RN, Haubrock PJ, Renault D, Bonnaud E, Courchamp F. 2022. Modeling the damage costs of invasive alien species. Biological Invasions 24: 1949-1972. DOI: 10.1007/s10530-021-02586-5.

Allouche O, Tsoar A, Kadmon R. 2006. Assessing the accuracy of species distribution models: Prevalence kappa and the True Skill Statistic (TSS). J Appl Ecol 43 (6): 1223-1232. DOI: 10.1111/j.1365-2664.2006.01214.x.

Bhattarai KR, Måren IE, Subedi SC. 2014. Biodiversity and invasibility: Distribution patterns of invasive plant species in the Himalayas, Nepal. J Mount Sci 11: 688-696. DOI: 10.1007/s11629-013-2821-3.

Boral D, Moktan S. 2022. Mapping the spatial distribution of the invasive Mexican Sunflower *Tithonia diversifolia* (Asteraceae) in South East Asia. J Asia-Pac Biodivers 15 (3): 425-434. DOI: 10.1016/j.japb.2022.03.006.

Botella C, Joly A, Monestiez P, Bonnet P, Munoz F. 2020. Bias in presence-only niche models related to sampling effort and species niches: Lessons for background point selection. PLoS One 15 (5): e0232078. DOI: 10.1371/journal.pone.0232078.

Brown JL, Bennett JR, French CM. 2017. SDMtoolbox 2.0: The next generation Python-based GIS toolkit for landscape genetic, biogeographic and species distribution model analyses. PeerJ 5: e4095. DOI: 10.7717/peerj.4095.

Changjun G, Yanli T, Linshan L, Bo W, Yili Z, Haibin Y, Bohao C. 2021. Predicting the potential global distribution of *Ageratina adenophora* under current and future climate change scenarios. Ecol Evol 11 (17): 12092-12113. DOI: 10.1002/ece3.7974.

Choudhury MR, Deb P, Singha H, Chakdar B, Medhi M. 2016. Predicting the probable distribution and threat of invasive *Mimosa diplotricha* Suavalle and *Mikania micrantha* Kunth in a protected tropical grassland. Ecol Eng 97: 23-31. DOI: 10.1016/j.ecoleng.2016.07.018.

Datta A, Schweiger O, Kühn I. 2019. Niche expansion of the invasive plant species *Ageratina adenophora* despite evolutionary constraints. J Biogeogr 46 (7): 1306-1315. DOI: 10.1111/jbi.13579.

Essl F, Lenzner B, Bacher S et al. 2020. Drivers of future alien species impacts: An expert-based assessment. Glob Chang Biol 26 (9): 4880-4893. DOI: 10.1111/gcb.15199.

Fandohan AB, Oduor AM, Sodé AI, Wu L, Cuni-Sanchez A, Assédé E, Gouwakinnou GN. 2015. Modeling vulnerability of protected areas to invasion by *Chromolaena odorata* under current and future climates. Ecosyst Health Sustain 1 (6): 11878996. DOI: 10.1890/EHS15-0003.1.

Fang Y, Zhang X, Wei H, Wang D, Chen R, Wang L, Gu W. 2021. Predicting the invasive trend of exotic plants in China based on the ensemble model under climate change: A case for three invasive plants of Asteraceae. Sci Total Environ 756: 143841. DOI: 10.1016/j.scitotenv.2020.143841.

Forest Survey of India (FSI). 2021. State of Forest Report Ministry of Environment Forest and Climate Change, Dehradun. https://fsi.nic.in/forest-report-2021-details.

Fournier A, Penone C, Pennino MG, Courchamp F. 2019. Predicting future invaders and future invasions. Proc Natl Acad Sci 116 (16): 7905-7910. DOI: 10.1073/pnas.1803456116.

Goncalves E, Herrera I, Duarte M, Bustamante RO, Lampo M, Velasquez G, Sharma GP, García-Rangel S. 2014. Global invasion of *Lantana camara*: Has the climatic niche been conserved across continents? PLoS One 9 (10): e111468. DOI: 10.1371/journal.pone.0111468.

Griffies SM, Winton M, Donner LJ et al. 2011. The GFDL CM3 coupled climate model: Characteristics of the ocean and sea ice simulations. J Clim 24 (13): 3520-3544. DOI: 10.1175/2011JCLI3964.1.

Hautier Y, Tilman D, Isbell F, Seabloom EW, Borer ET, Reich PB. 2015. Anthropogenic environmental changes affect ecosystem stability via biodiversity. Science 348 (6232): 336-340. DOI: 10.1126/science.aaa1788.

Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A. 2005. Very high-resolution interpolated climate surfaces for global land areas. Intl J Climatol 25 (15): 1965-1978. DOI: 10.1002/joc.1276.

Lamsal P, Kumar L, Aryal A, Atreya K. 2018. Invasive alien plant species dynamics in the Himalayan region under climate change. Ambio 47 (6): 697-710. DOI: 10.1007/s13280-018-1017-z.

Li Y, Song T, Lai Y, Huang Y, Fang L, Chang J. 2022. Status, mechanism, suitable distribution areas and protection countermeasure of invasive species in the karst areas of Southwest China. Front Environ Sci 10: 957216. DOI: 10.3389/fenvs.2022.957216.

Mačić V, Albano PG, Almpanidou V et al. 2018. Biological invasions in conservation planning: A global systematic review. Front Mar Sci 5: 178. DOI: 10.3389/fmars.2018.00178.

Merow C, Bois ST, Allen JM, Xie Y, Silander Jr JA. 2017. Climate change both facilitates and inhibits invasive plant ranges in New England. Proc Natl Acad Sci 114 (16): e3276-e3284. DOI: 10.1073/pnas.1609633114.

Mushtaq S, Reshi ZA, Shah MA, Charles B. 2021. Modelled distribution of an invasive alien plant species differs at different spatiotemporal scales under changing climate: A case study of *Parthenium hysterophorus* L. Trop Ecol 62 (3): 398-417. DOI: 10.1007/s42965-020-00135-0.

Phillips SJ, Anderson RP, Dudík M, Schapire RE, Blair ME. 2017. Opening the black box: An open-source release of MaxEnt. Ecography 40 (7): 887-893. DOI: 10.1111/ecog.03049.

Phillips SJ, Dudík M. 2008. Modeling of species distributions with MaxEnt: New extensions and a comprehensive evaluation. Ecography 31 (2): 161-175. DOI: 10.1111/j.0906-7590.2008.5203.x.

Poudel AS, Shrestha BB, Joshi MD, Muniappan R, Adiga A, Venkatramanan S, Jha PK. 2020. Predicting the current and future distribution of the invasive weed *Ageratina adenophora* in the Chitwan–Annapurna Landscape Nepal. Mount Res Dev 40 (2): R61. DOI: 10.1659/MRD-JOURNAL-D-19-00069.1.

Rameshprabu N, Swamy PS. 2015. Prediction of environmental suitability for invasion of *Mikania micrantha* in India by species distribution modeling. J Environ Biol 36 (3) : 565-570.

Ray D, Behera MD, Jacob J. 2019. Comparing invasiveness of native and non-native species under changing climate in North-East India: Ecological niche modeling with plant types differing in biogeographic origin. Environ Monit Assess 191: 793. DOI: 10.1007/s10661-019-7685-8.

Richardson DM, Rejmánek M. 2011. Trees and shrubs as invasive alien species–a global review. Divers Distrib 17 (5): 788-809. DOI: 10.1111/j.1472-4642.2011.00782.x.

Saranya KRL, Lakshmi TV, Reddy CS. 2021. Predicting the potential sites of *Chromolaena odorata* and *Lantana camara* in forest landscape of Eastern Ghats using habitat suitability models. Ecol Inf 66: 101455. DOI: 10.1016/j.ecoinf.2021.101455.

Seebens H, Blackburn TM, Dyer EE et al. 2017. No saturation in the accumulation of alien species worldwide. Nat Commun 8: 14435. DOI: 10.1038/ncomms14435.

Sengupta R, Dash SS. 2020. Invasion status of three non-native species from family Asteraceae in Mizoram. Nelumbo 62 (1): 27-39. DOI: 10.20324/nelumbo/v62/2020/153742.

Sengupta R, Dash SS. 2023a. Ecological impact of alien plant invasion in national parks of an Indo-Burma biodiversity hotspot in India. J Agric Ecol 15: 109-124. DOI: DOI: 10.58628/JAE-2315-119.

Sengupta R, Dash SS. 2023b. Predicting the potential invasion hotspots of *Chromolaena odorata* under current and future climate change scenarios in heterogeneous ecological landscapes of Mizoram India. Res Ecol 5(4): 1-12. DOI: 10.30564/re.v5i4.5920.

Shrestha BB, Shabbir A, Adkins S W. 2015. *Parthenium hysterophorus* in Nepal: a review of its weed status and possibilities for management. Weed Res 55 (2): 132-144. DOI: 10.1111/wre.12133.

Tererai F, Wood AR. 2014. On the present and potential distribution of *Ageratina adenophora* (Asteraceae) in South Africa. S Afr J Bot 95: 152-158. DOI: 10.1016/j.sajb.2014.09.001.

Thapa S, Chitale V, Rijal SJ, Bisht N, Shrestha BB. 2018. Understanding the dynamics in distribution of invasive alien plant species under predicted climate change in Western Himalaya. PloS one 13 (4): e0195752. DOI: 10.1371/journal.pone.0195752.

Tiwari S, Mishra SN, Kumar D, Kumar B, Vaidya SN, Ghosh BG, Rahaman SM, Khatun M, Garai S, Kumar A. 2022. Modelling the potential risk zone of *Lantana camara* invasion and response to climate change in eastern India. Ecol Process 11: 10. DOI: 10.1186/s13717-021-00354-w.

Tripathi RS, Yadav AS, Kushwaha SPS. 2012. Biology of *Chromolaena odorata*, *Ageratina adenophora* and *Ageratina riparia*: A review Invasive alien plants. An ecological appraisal of Indian Subcontinent 32: 43-56, Springer. DOI: 10.1079/9781845939076.0043.

Valavi R, Guillera-Arroita G, Lahoz-Monfort JJ, Elith J. 2022. Predictive performance of presence-only species distribution models: A benchmark study with reproducible code. Ecol Monogr 92 (1): e01486. DOI: 10.1002/ecm.1486.

Vaz AS, Alcaraz-Segura D, Campos JC, Vicente JR, Honrado JP. 2018. Managing plant invasions through the lens of remote sensing: A review of progress and the way forward. Sci Total Environ 642: 1328-1339. DOI: 10.1016/j.scitotenv.2018.06.134.

Vilà M, Basnou C, Pyšek P et al. 2010. How well do we understand the impacts of alien species on ecosystem services? A pan-European cross-taxa assessment. Front Ecol Environ 8 (3): 135-144. DOI: 10.1890/080083.

Xian X, Zhao H, Wang R, Zhang H, Chen B, Huang H, Liu W, Wan F. 2022. Predicting the potential geographical distribution of *Ageratina adenophora* in China using equilibrium occurrence data and ensemble model. Front Ecol Evol 10: 973371. DOI: 10.3389/fevo.2022.973371.

Yang G, Gui F, Liu W, Wan F. 2017. Crofton weed *Ageratina adenophora* Sprengel. In: Wan F, Jiang M, Zhan A (eds). Biological Invasions and Its Management in China. Springer, Singapore. DOI: 10.1007/978-981-10-3427-5_8.

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Undergrowth vegetation in the riparian zone of the Upper Bengawan Solo River, Central Java, Indonesia and its potential uses

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[1]Department of Environmental Science, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret. Jl. Ir. Sutami 36A Surakarta 57126, Central Java, Indonesia. Tel./fax.: +62-271-663375, [♥]email: volatileoils@gmail.com

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Manuscript received: 31 March 2024. Revision accepted: 15 December 2024.

Abstract. *Saputra AF, Utomo AN, Pramesthi AZ, Madjid AA, Sulton MN, Dewangga A, Setyawan AD. 2024. Undergrowth vegetation in the riparian zone of the Upper Bengawan Solo River, Central Java, Indonesia and its potential uses. Asian J For 8: 194-206.* Riparian zone is the transitional zone between terrestrial water and land ecosystems, and an important part of river ecosystem. In riparian zone, the presence of vegetation, ranging from trees to undergrowth, is important to maintain ecosystem functions. Undergrowth vegetation in riparian zone is also widely utilized by local people for various purposes. This study aimed to determine the understory vegetation in riparian zone of the Upper Bengawan Solo River, Central Java, Indonesia and its potential use in the community. This research was conducted in three stations, i.e., Giriwono Village, Wonogiri District for the upstream, Sidowarno Village, Klaten District for the middle stream, and Gadingan Village, Sukoharjo District for the downstream. Data collection used transect method with size of 2×2 for seedlings and herbaceous plants and 5×5 plots for saplings and shrubs, each with five replications at each station. The study documented 78 species from 38 families of undergrowth vegetation across the three riparian locations. The vegetation diversity index (H') studied across the three stations is included in the medium category. The plant with the highest Index of Important Value (IVI) for seedlings and herbaceous plants was *Chromolaena odorata* with 15.56%, while that for saplings and shrubs was *Bambusa blumeana* with 47.74%. The higher elevation in the upstream (Wonogiri District) led to higher soil temperatures, while the midstream (Klaten District) had a more acidic soil pH and the highest air humidity. In the downstream (Sukoharjo District), high humidity due to proximity to the river, led to lower soil temperatures. Riparian vegetation along the Upper Bengawan Solo River also has diverse potentials with the dominance of medicinal uses, while other plants are used as animal feed, ornamental plants, food ingredients, and others.

Keywords: Potential use, riparian zone, undergrowth plant, vegetation

INTRODUCTION

Riparian zone is an ecotone in terrestrial realm in the form of transitional zone between land and river or stream. The riparian zone is one of the most important ecosystems on earth. As the boundary between terrestrial water bodies and land, it plays various ecosystem functions (Singh et al. 2021) and delivering numerous ecosystem services (Fu et al. 2016). Bank stabilization, buffering of pollutants and sediments, temperature regulation, provision of energy for riverine food webs and communities, groundwater recharge and provision of ecological corridors and habitat for wildlife, are some of the key ecosystem functions of the riparian zone that play a major role in river health (Singh et al. 2021). Riparian zone also functions as a place to reduce mercury heavy metal contamination that appears in subsurface streams with Hg-rich wet organic soils (Vidon et al. 2019). More recently, riparian zone also contribute to climate change mitigation as the vegetation can sequester and store carbon in great capacity (Paradika et al. 2021).

Riparian zone is covered with diverse vegetation ranging from shrubs to trees. According to Park and Kim (2020), elevation and distance from the water surface are the main factors that influence vegetation structure in riparian. Riparian vegetation is an important component of fluvial systems and has various socio-ecological functions (Dufour et al. 2019). More importantly, riparian vegetation helps to maintain water quality. According to Lyu et al. (2021), riparian vegetation determines soil's ability to absorb and maintain water quality in the watershed ecosystem.

Despite their importance, many riparian ecosystems are nowadays being threatened due to several pressures, such as urbanization, intensive agriculture, and river engineering works (Borisade et al. 2021; Urbanič et al. 2022). There is also accumulation of pollution which can reduce river water quality (Pangastuti et al. 2022). For example, riparian zones in Surabaya, Indonesia which were previously green open space, have been heavily degraded due to the high rate of population growth and development, turning the previously vegetated area into settlements and industrial areas, thereby reducing the carrying capacity of the environment, and reduce river water quality (Yudianingrum and Mangkoedihardjo 2016).

Bengawan Solo is recognized as one of most important river systems in Indonesia, encompassing two provinces in Java Island with the largest human population. There are several species of vegetation present in the riparian zone of the upper zone Bengawan Solo River with the prominence of understory vegetation. Understory plants are types of vegetation that live at the base of a tree community (Andriyani et al. 2023). Understory plants that make up an area have a certain distribution pattern and are usually found living near the parent plant (Iryadi and Wardhani 2023). Altitude has strong influence on the types of understory plants (Suprapta 2021) and this also applies to the riparian zone of the Bengawan Solo River. The existence of undergrowth that can grow easily in the riparian zone in Bengawan Solo provides benefits to local people, including from being used as medicine, animal feed, processed into food ingredients, etc. (Hanum et al. 2022). According to Liana et al. (2023), undergrowth is commonly utilized by local people as traditional medicines. However, if the river is polluted, it might impact on the condition of riparian zone, which is the habitat for understory plants. Therefore, this study was aimed to determine the understory vegetation in the Bengawan Solo River area and its potential uses by the community. We expected, the results of this study might be used as a reference for sustainable management and utilization of undergrowth by communities in the Upper Bengawan Solo River.

MATERIALS AND METHODS

Study area

The research was conducted in March 2024 and located in the Upper Bengawan Solo River, Central Java, Indonesia. Data collection was conducted at three stations, namely Giriwono Village, Wonogiri District for the upstream (7°47'45.10 "S and 110°56'12.70 "E), Sidowarno Village, Klaten District for the midstream (7°38'35.80 "S and 110°47'29.80 "E), and Gadingan Village, Sukoharjo District for the downstream (7°34'38.00 "S-110°50'45.10 "E) (Figure 1). In Giriwono Village, there is a special purpose forest area (KHDTK) called Alas Kethu where the KHDTK is located on the river bank or close to the river so there is a lot of undergrowth vegetation (Rindarto et al. 2021). Alas Kethu is a conservation forest dedicated for research and environmental education and conservation. Sidowarno Village was chosen because there is a bosket near the Bengawan Solo riverbank that makes it easier to find the undergrowth vegetation like bamboo and other plants. This village is located next to the river and has the characteristics of agroforestry land, where agriculture and forestry are integrated to maximize environmental and economic benefits. Gadingan Village was chosen because there was a lot of undergrowth vegetation on the riverbanks, beside that this zone is reachable to go inside the bosket. The Gadingan area is a forest area located in the riparian zone, which is known for its rich and diverse ecosystem because it is close to the river. The combination of these three locations provides a comprehensive picture of the variation in vegetation and environmental conditions along the river.

Data collection

Data collection used transect and purposive sampling methods. The transect method aims to understand the relationship between changes in vegetation and the environment, as well as to quickly determine the relationship between vegetation on a land (Sari et al. 2019). Meanwhile, purposive sampling is a sampling technique where researchers select samples based on certain assessments and criteria that are relevant to the research objectives (Etikan et al. 2016). The plots were determined by systematic sampling with initial randomization. First, a sampling point was determined randomly then a plot was made. Within the plot, the undergrowth vegetation in the form of herbaceous plants (seedlings) was counted in the 2×2 meter area and shrubs and small woody plants (poles) in the 5×5 meter area (Destaranti et al. 2017). Each station, there were five plots created with a distance of about 20 m, from upstream to downstream, totaling 15 plots in this study.

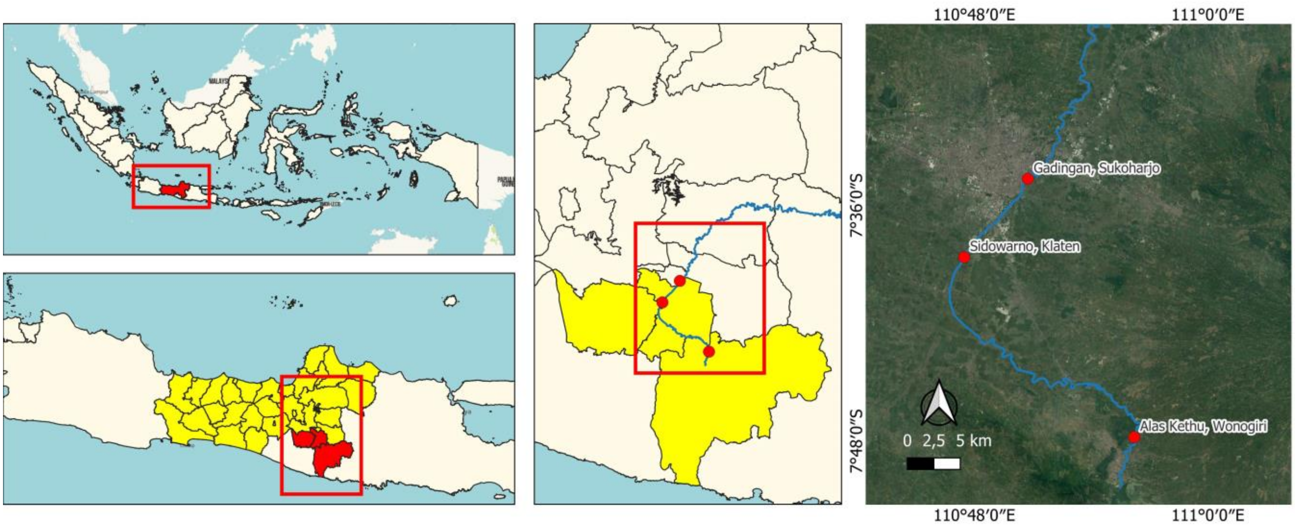

Figure 1. Map of research location at three stations along the Upper Bengawan Solo River in Central Java Province, Indonesia

The environmental variables measured include altitude above sea level, water pH, soil pH, air humidity, and air and soil temperature. Tools used for this measurement include an altimeter to measure altitude, a pH meter to measure the pH of water and soil, a hygrometer to measure air humidity, and a thermometer to measure air and soil temperature. The materials required include water and soil samples taken from the measurement location as well as buffer solution used to calibrate the pH meter before measurement.

Data analysis

The collected data was then analyzed descriptively and quantitatively. To analyze plant species, we first made direct observations at the research sites. These observations were recorded on a tally sheet. After that, we analyzed the data samples using the reference from Pertiwi et al. (2021) and the Global Biodiversity Information Facility (GBIF) website (www.gbif.org) for identification. Analysis was also carried out to understand the potential utilization of each plant from secondary data (journals, books, or articles). The data that has been identified is then analyzed to determine the dominant species in the three areas on the riparian of Bengawan Solo River, by calculating the Important value index and diversity index, which can be calculated by the following formula (Hutasuhut 2018).

Important value index (IVI)

IVI is a metric in ecology to evaluate the importance of a species in a plant community (Krebs 1989).

Density of a species

$$D = \frac{Number\ of\ Individuals\ of\ All\ Types}{\text{Area of All Sample Plots}}$$

Relative Density Species (RDi)

$$RDi = \frac{Density\ of\ a\ species}{Density\ of\ all\ species} x100\%$$

Frequency of a species

$$F = \frac{Number\ of\ sampled\ areas\ where\ species\ occurred}{number\ of\ total\ sampled\ areas}$$

Relative Frequency (RF)

$$RF = \frac{Frekuensi\ of\ a\ species}{Frekuensi\ of\ all\ species} x100\%$$

Important Value Index (IVI)

IVI = RDi+ RF

Shannon-Wiener Diversity Index (H')

Diversity Index is a metric indicating the level of species diversity in a community (Mokodompit et al. 2022)

$$H' = -\sum_{i=1}^{s} Pi(lnPi)$$

Where:

H': Species Diversity Index

pi: The ratio of the number of species I (ni) to the total number of individual species in the community (N)

In: Logarithms

S: Number of species that make up the community

From the magnitude of the diversity index value obtained, it can be categorized as follows:

A value of H'>3 indicates that the species diversity of a place is high. A value of 1≤H'≤3 indicates that the diversity of species in a place is moderate. A value of H'<1 indicates that the species diversity in a place is low

RESULTS AND DISCUSSION

Undergrowth species in the riparian zone of Bengawan Solo River

A total of 78 plant species from 38 families were recorded in the riparian zone of the study site (Table 1). Families with the largest number of species recorded were Poaceae and Fabaceae with nine species for each family. According to Usman et al. (2022), Fabaceae is the second most diverse family in the plant kingdom, and species from the family are widely distributed throughout the world. Families with the lowest number of species was Loganiaceae, Onagraceae, Vitaceae, Araliaceae, Anacardiaceae, Rhamnaceae, Apocynaceae, Rutaceae, Basellaceae, Sapindaceae, Pteridaceae, Lamiaceae, Amaranthaceae with only one species. The diversity of a vegetation community often cannot be estimated comprehensively using random sampling method (Roswell et al. 2021). In another study in Siwaluh River, there were 15 species at the stages of trees and poles, while for sapling there were 25 species and seedling were 179 species (Pramadaningtyas et al. 2023).

The most dominant species of seedling and herbaceous plants (i.e. in the 2×2 m plot) in the river upstream was *Microstegium vimineum* with 127 individuals, while the most dominant species of sapling and shrubs (i.e. in 5×5 m plot) was *Pleurolobus gangeticus* with 11 individuals (Table 1). Meanwhile, the most dominating species of seedling and herbaceous plants in the midstream was *Richardia scabra* with 137 individuals, and *Bambusa blumeana* dominated the shrubs and saplings with 79 individuals. The most dominant species of seedling and herbaceous plants in the downstream was *Mercurialis perennis* with 53 individuals, and the most dominant species shrubs and saplings was *B. blumeana* with 75 individuals. Bamboo is the plant most commonly found in this research, because the environmental conditions in the river are suitable for the bamboos to grow (Sutiyono et al. 2022).

Shannon-Wiener Diversity Index (H')

The Shannon-Wiener Diversity Index, denoted as H', is a commonly used metric to examine species diversity of plant community (Sun and Ren 2021). The H' at the three stations is included in the medium category where in the upstream the H' was 2.707, the midstream was 2.742, and the downstream was 2.488 (Table 2). Vegetation analysis is useful for assessing the current condition of the vegetation and monitoring future changes (Rambey et al. 2021). Other study in Siwaluh River, Indonesia showed a high diversity category (Pramadaningtyas et al. 2023).

Table 1. Undergrowth species found in the riparian zone of upper Bengawan Solo River, Central Java, Indonesia

Scientific name	Family	Local name	UP	MD	DN	Number of individuals
Seedling and herbaceous plants						
Alpinia galanga (L.) Willd.	Zingiberaceae	*Lengkuas*	3		3	6
Amaranthus spinosus L.	Amaranthaceae	*Bayam duri*		1		1
Amorphophallus oncophyllus Prain ex Hook.f.	Araceae	*Porang*	5			5
Anredera cordifolia (Ten.) Steenis	Basellaceae	*Binahong*	3			3
Bidens pilosa L.	Asteraceae	*Ketul*			17	17
Carica papaya L.	Caricaceae	*Pepaya*			1	1
Chromolaena odorata (L.) R.M.King & H.Rob.	Asteraceae	*Balakasida*	70	76		146
Colocasia esculenta (L.) Schott	Araceae	*Talas*			18	18
Curcuma longa L.	Zingiberaceae	*Kunyit*	9			9
Cyperus rotundus L.	Cyperaceae	*Rumput teki*	43	78		121
Dactyloctenium aegyptium (L.) *Willd.*	Poraceae	*Rumput mesir*		10		10
Dimocarpus longan Lour.	Sapindaceae	*Kelengkeng*			1	1
Dioscorea hispida Dennst.	Dioscoreaceae	*Gadung tikus*			8	8
Elephantopus scaber L.	Asteraceae	*Tapak liman*		21		21
Euphorbia heterophylla Desf.	Euphorbiaceae	*Patik emas*	6			6
Euphorbia hirta L.	Euphorbiaceae	*Patikan kebo*	11			11
Ficus septica Burm.fil.	Moraceae	*Awar-awar*			11	11
Hedera helix L.	Araliaceae	*Ivy*			6	6
Leea indica (Burm.fil.) *Merr.*	Vitaceae	*Girang merah*			3	3
Leucaena leucocephala (Lam.) *de Wit*	Fabaceae	*Lamtoro*		21		21
Ludwigia palustris (L.) Elliott	Onagraceae	*Buang-buang*		84		84
Macroptilium atropurpureum (DC.) Urb.	Fabaceae	*Siratro*	8			8
Manihot esculenta Crantz	Euphorbiaceae	*Singkong*		1	2	3
Manihot glaziovii Muell	Euphorbiaceae	*Singkong karet*		33		33
Microstegium vimineum (Trin.) A.Camus	Poaceae	*Rumput pengepakan*	127			127
Mikania micrantha Kunth	Asteraceae	*Sambung rambat*			56	56
Mimosa pudica L.	Fabaceae	*Putri malu*	52	38		90
Momordica charantia L.	Cucurbitaceae	*Pare*			15	15
Moringa oleifera Lam.	Moringaceae	*Kelor*	9			9
Musa paradisiaca L.	Musaceae	*Pisang*		7		7
Oplismenus hirtellus (L.) P.Beauv.	Poaceae	*Rumput keranjang*	53			53
Ottochloa nodosa (Kunth) Dandy	Poaceae	*Rumput sarang buaya*		81		81
Oxalis barrelieri L.	Oxalidaceae	*Belimbing tanah*	16	3		19
Pennisetum purpureum Schumach.	Poaceae	*Rumput gajah*		8	8	16
Peperomia pellucida (L.) *Kunth*	Piperaceae	*Daun suruhan*			2	2
Phyllanthus niruri L.	Phyllantaceae	*Meniran hijau*	61			61
Physalis angulata L.	Solanaceae	*Ciplukan*		2		2
Pilea pumila (L.) A.Gray	Urticaceae	*Clearweed*		21		21
Pteris vittata L.	Adiantaceae	*Pakis rem cina*	12			12
Richardia scabra L.	Rubiaceae	*Semanggi meksiko*		137		137
Rosa multiflora L.	Rosaceae	*Mawar rambler*		1		1
Ruellia angustifolia Sw.	Acanthaceae	*Kencana ungu*		7	8	15
Ruellia tuberosa L.	Acanthaceae	*Pletekan*		6		6
Sauropus androgynus (L.) Merr.	Phyllanthaceae	*Katuk*			4	4
Senna siamea (Lam.) H.S.Irwin & Barneby	Fabaceae	*Johar*		3		3
Spigelia anthelmia L.	Loganiaceae	*Kemangi cina*	13			13
Swietenia macrophylla G.King	Meliaceae	*Mahoni*			2	2
Synedrella nodiflora (L.) Gaertn.	Asteraceae	*Jotang kuda*		70	77	147
Syzygium polyanthum (Wight) Walp.	Myrthaceae	*Salam*			4	4
Tectona grandis L.f.	Lamiaceae	*Jati*	2			2
Tradescantia fluminensis Vell.	Commelinaceae	*Telinga kera*	10			10
Urena lobata L.	Malvaceae	*Pulutan*	11			11
Zea mays L.	Poaceae	*Jagung*		7		7
Zingiber zerumbet (L.) Roscoe ex Sm.	Zingiberaceae	*Lempuyang*	8			8
Total			**532**	**716**	**246**	**1494**
Sapling and small woody plants						
Bambusa blumeana Schult.f.	Poaceae	*Bambu duri*		79	75	154
Baptisia australis (L.) R.Br.	Fabaceae	*Nila biru*	10			10
Capsium frutescens L.	Solanaceae	*Cabai*		1		1
Citrus hystrix DC.	Rutaceae	*Jeruk purut*			1	1
Curcuma longa L	Zingiberaceae	*Kunyit*		14		14

Cyperus rotundus L.	Cyperaceae	*Rumput rotundus*		40		40
Dimocarpus longan Lour.	Sapindaceae	*Kelengkeng*			1	1
Ficus hispida L.fil.	Moraceae	*Luwingan*	1			1
Ficus septica Burm.fil.	Moraceae	*Awar-awar*	2			2
Gynura divaricata (L.) DC.	Asteraceae	*Daun dewa*	1			1
Hibiscus similis Bl.	Malvaceae	*Waru tisuk*		4		4
Laportea decumana (Roxb.) Wedd.	Urticaceae	*Pohon gatal*		6		6
Leucaena leucocephala (Lam.) de Wit	Fabaceae	*Petai cina*		36	4	40
Mangifera indica L.	Anacardiaceae	*Mangga*			3	3
Manihot glaziovii Muell	Euphorbiaceae	*Singkong karet*		3		3
Mitragyna speciosa Korth.	Rubiaceae	*Kratom*	2			2
Moringa oleifera Lam.	Moringaceae	*Kelor*	10		6	16
Muntingia calabura L.	Muntingiaceae	*Kersen*	1			1
Parkia speciosa Hassk.	Fabaceae	*Mlanding*			1	1
Pisum sativum L.	Fabaceae	*Kacang kapri*			2	2
Pleurolobus gangeticus (L.) J.St.-Hil. ex H.Ohashi & K.Ohashi	Fabaceae	*Daun bulu ayam*	11			11
Rosa multiflora L.	Rosaceae	*Mawar*			1	1
Saccharum spontaneum L.	Poaceae	*Rumput gelagah*		17		17
Sauropus androgynus (L.) Merr.	Phyllanthaceae	*Katuk*			4	4
Schizolobium parahyba (Vell.) S.F.Blake	Fabaceae	*Pakis brazil*		5		5
Sida rhombifolia L.	Malvaceae	*Seleguri*	2			2
Swietenia mahagoni (L.) Jacq.	Meliaceae	*Mahoni*		2		2
Syzygium polyanthum (Wight) Walp.	Myrtaceae	*Salam*			1	1
Tectona grandis L.f.	Lamiaceae	*Jati*		11	2	13
Vernonia amygdalina Delile	Asteraceae	*Daun afrika*	5			5
Wrightia pubescens R.Br.	Apocynaceae	*Bentawas*			1	1
Ziziphus mauritiana Lam.	Rhamnaceae	*Bidara*	5			5
Total			**50**	**218**	**102**	**370**

Note: UP: Upstream (Giriwono Village, Wonogiri District), MD: Middlestream (Sidowarno Village, Klaten District), DN: Downstream (Gadingan Village, Sukoharjo District)

Table 2. Shannon Wiener Diversity index of undergrowth in the riparian zone of Upper Bengawan Solo River, Central Java, Indonesia

Station	H'	Category
Upstream (Wonogiri)	2.707	Medium
Midstream (Klaten)	2.742	Medium
Downstream (Sukoharjo)	2.488	Medium

Important Value Index (IVI)

Seedlings and herbaceous plants

Plants exhibiting the highest IVI values at the seedling level play significant roles in the ecosystem dynamics. *Chromolaena odorata*, belonging to the Asteraceae family and locally known as *balakasida*, stands out with an IVI value of 15.56% (Table 3). This species demonstrates its ecological importance with a total of 146 individuals dispersed across five out of the fifteen existing plots. Following are *Synedrella nodiflora* and *Cyperus rotundus*, with IVI values of 13.74% and 13.70%, respectively. *S. nodiflora*, also a member of the Asteraceae family known as *jotang kuda* locally, and *C. rotundus*, part of the Cyperaceae family with the local name *rumput teki*, contribute significantly to the vegetation composition and structure. In another study in the Siwaluh River, species with the highest IVI was *Kerivoula africana* in which this species is known to thrive in habitats characterized by fertile soil with a high clay content. *K. africana* shows extraordinary resistance to dry conditions and can thrive in various heights ranging from 50 meters above sea level to 800 meters above sea level (Pramadaningtyas et al. 2023).

It's noteworthy that both the first and second highest IVI values originate from the Asteraceae family, renowned for its high diversity and extensive distribution within the Plant Kingdom. This underscores the ecological prominence of this family in shaping terrestrial ecosystems (Azzaroiha et al. 2022). Despite their significance, certain plant species exhibit notably smaller IVI values, indicating their limited presence and impact within the studied area. *Carica papaya* and *Amaranthus spinosus*, for instance, possess IVI values as low as 1.02% (Table 3). These plants are represented by only one individual each across the entire plot, reflecting their minimal contribution to the overall vegetation dynamics.

Saplings and shrubs

The highest IVI value recorded was *B. blumeana*, a member of the Poaceae family locally known as *pring ori*, reaching 47.74% (Table 4). *B. blumeana* can be used to eradicate certain species of pathogenic bacteria and fungi using minimum inhibitory concentrations via the agar well diffusion method (Saducos 2022). This species dominated the plots with 157 individuals spread across the three stations, indicating its considerable ecological importance.

Table 3. Frequency (F), Relative Frequency (RF), Density (D), Relative Density Species (RDi) and Important Value Index (IVI) of seedlings and herbaceous plants

Scientific name	Family	Local name	D	RDi (%)	F	RF (%)	IVI (%)
Alpinia galanga (L.) Willd.	Zingiberaceae	*Lengkuas*	0.100	0.45	0.133	1.89	2.33
Amaranthus spinosus L.	Amaranthaceae	*Bayam duri*	0.017	0.07	0.067	0.94	1.02
Amorphophallus oncophyllus Prain ex Hook.f.	Araceae	*Porang*	0.083	0.37	0.133	1.89	2.26
Anredera cordifolia (Ten.) Steenis	Basellaceae	*Binahong*	0.050	0.22	0.067	0.94	1.17
Bidens pilosa L.	Asteraceae	*Ketul*	0.283	1.26	0.067	0.94	2.21
Carica papaya L.	Caricaceae	*Pepaya*	0.017	0.07	0.067	0.94	1.02
Chromolaena odorata (L.) R.M.King & H.Rob.	Asteraceae	*Balakasida*	2.433	10.84	0.333	4.72	15.56
Colocasia esculenta (L.) Schott	Araceae	*Tales*	0.300	1.34	0.133	1.89	3.22
Curcuma longa L.	Zingiberaceae	*Kunyit*	0.150	0.67	0.200	2.83	3.50
Cyperus rotundus L.	Cyperaceae	*Rumput teki*	2.017	8.98	0.333	4.72	13.70
Dactyloctenium aegyptium (L.) Willd.	Poaceae	-	0.167	0.74	0.067	0.94	1.69
Dimocarpus longan Lour.	Sapindaceae	*Kelengkeng*	0.017	0.07	0.133	1.89	1.96
Dioscorea hispida Dennst.	Dioscoreaceae	*Gadung tikus*	0.133	0.59	0.133	1.89	2.48
Elephantopus scaber L.	Asteraceae	*Tapak liman*	0.350	1.56	0.067	0.94	2.50
Euphorbia heterophylla Desf.	Euphorbiaceae	*Patik emas*	0.100	0.45	0.067	0.94	1.39
Euphorbia hirta L.	Euphorbiaceae	*Patik emas*	0.183	0.82	0.067	0.94	1.76
*Ficus septica Burm.*fil.	Moraceae	*Awar-awar*	0.183	0.82	0.267	3.77	4.59
Hedera helix L.	Asteraceae	*Patik emas*	0.100	0.45	0.133	1.89	2.33
Leea indica (Burm.fil.) Merr.	Vitaceae	*Girang merah*	0.050	0.22	0.067	0.94	1.17
Leucaena leucocephala (Lam.) de Wit	Fabaceae	*Lamtoro*	0.350	1.56	0.333	4.72	6.28
Ludwigia palustris (L) Elliott	Onagraceae	*Krokot air*	1.400	6.24	0.133	1.89	8.12
Macroptilium atropurpureum (DC.) Urb.	Fabaceae	*Siratro*	0.133	0.59	0.067	0.94	1.54
Manihot esculenta Crantz	Euphorbiaceae	*Singkong*	0.050	0.22	0.133	1.89	2.11
Manihot glaziovii Muell	Euphorbiaceae	*Singkong karet*	0.550	2.45	0.267	3.77	6.22
Microstegium vimineum (Trin.) A.Camus	Poaceae	*Rumput pengepakan*	2.117	9.43	0.133	1.89	11.32
Mikania micrantha Kunth	Asteraceae	*Sambung rambat*	0.933	4.16	0.133	1.89	6.04
Mimosa pudica L.	Fabaceae	*Putri malu*	1.333	5.94	0.200	2.83	8.77
Momordica charantia L.	Cucurbitaceae	*Pare*	0.250	1.11	0.133	1.89	3.00
Moringa oleifera Lam.	Moringaceae	*Kelor*	0.150	0.67	0.200	2.83	3.50
Musa paradisiaca L.	Musaceae	*Pisang*	0.117	0.52	0.133	1.89	2.41
Oplismenus hirtellus (L.) P.Beauv.	Poaceae	*Rumput keranjang*	0.883	3.93	0.067	0.94	4.88
Ottochloa nodosa (Kunth) Dandy	Poaceae	*Rumput sarang buaya*	1.350	6.01	0.067	0.94	6.96
Oxalis barrelieri L.	Oxalidaceae	*Belimbing tanah*	0.317	1.41	0.200	2.83	4.24
Pennisetum purpureum Schumach.	Poaceae	*Rumput gajah*	0.267	1.19	0.067	0.94	2.13
Peperomia pellucida (L.) Kunth	Piperaceae	*Suruh*	0.033	0.15	0.067	0.94	1.09
Phyllanthus niruri L.	Phyllanthaceae	*Meniran hijau*	1.017	4.53	0.267	3.77	8.30
Physalis angulata L.	Solanaceae	*Ciplukan*	0.033	0.15	0.067	0.94	1.09
Pilea pumila (L.) A.Gray	Urticaceae	*Pilea pumila*	0.350	1.56	0.067	0.94	2.50
Pteris vittata L.	Pteridaceae	*Paku*	0.200	0.89	0.133	1.89	2.78
Rosa multiflora L.	Rosaceae	*Mawar*	0.017	0.07	0.133	1.89	1.96
Ruellia angustifolia Sw.	Acanthaceae	*Kencana ungu*	0.250	1.11	0.133	1.89	3.00
Ruellia tuberosa L.	Acanthaceae	*Pletekan*	0.100	0.45	0.067	0.94	1.39
Sauropus androgynus (L.) Merr.	Phyllanthaceae	*Katuk*	0.067	0.30	0.133	1.89	2.18
Senna siamea (Lam.) H.S.Irwin & Barneby	Fabaceae	*Johar*	0.050	0.22	0.067	0.94	1.17
Spigelia anthelmia L.	Loganiaceae	*Kemangi cina*	0.217	0.97	0.067	0.94	1.91
Swietenia macrophylla G.King	Meliaceae	*Mahoni*	0.033	0.15	0.067	0.94	1.09
Synedrella nodiflora (L.) Gaertn.	Asteraceae	*Jotang kuda*	2.450	10.91	0.200	2.83	13.74
Syzygium polyanthum (Wight) Walp.	Myrtaceae	*Salam*	0.067	0.30	0.133	1.89	2.18
Tectona grandis L.f.	Lamiaceae	*Jati*	0.033	0.15	0.333	4.72	4.87
Tradescantia fluminensis Vell.	Comellinaceae	*Telinga kera*	0.167	0.74	0.067	0.94	1.69
Urena lobata L.	Malvaceae	*Pulutan*	0.183	0.82	0.067	0.94	1.76
Zea mays L.	Poaceae	*Jagung*	0.117	0.52	0.067	0.94	1.46
Zingiber zerumbet (L.) Roscoe ex Sm.	Zingiberaceae	*Lempuyang*	0.133	0.59	0.133	1.89	2.48

Table 4. Frequency (F), Relative Frequency (RF), Density (D), Relative Density Species (RDi) and Important Value Index (IVI) of saplings and shrubs

Scientific name	Family	Local name	D	RDi (%)	F	RF (%)	IVI (%)
Bambusa blumeana Schult.f.	Poaceae	*Pring ori*	0.411	41.62	0.200	6.12	47.74
Baptisia australis (L.) R.Br.	Fabaceae	*Nila biru*	0.027	2.70	0.067	2.04	4.74
Capsium frutescens L.	Solanaceae	*Cabai*	0.003	0.27	0.067	2.04	2.31
Citrus hystrix DC.	Rutaceae	*Jeruk purut*	0.003	0.27	0.067	2.04	2.31
Curcuma longa L	Zingiberaceae	*Kunyit*	0.037	3.78	0.200	6.12	9.91
Cyperus rotundus L.	Cyperaceae	*Rumput teki*	0.107	10.81	0.067	2.04	12.85
Dimocarpus longan Lour.	Sapindaceae	*Kelengkeng*	0.003	0.27	0.067	2.04	2.31
Ficus hispida L.fil.	Moraceae	*Luwingan*	0.003	0.27	0.067	2.04	2.31
Ficus septica Burm.fil.	Moraceae	*Awar-awar*	0.005	0.54	0.067	2.04	2.58
Gynura divaricata (L.) DC.	Asteraceae	*Daun dewa*	0.003	0.27	0.067	2.04	2.31
Hibiscus similis Bl.	Malvaceae	*Waru tisuk*	0.011	1.08	0.067	2.04	3.12
Laportea decumana (Roxb.) Wedd.	Urticaceae	*Daun gatal*	0.016	1.62	0.067	2.04	3.66
Leucaena leucocephala (Lam.) de Wit	Fabaceae	*Mandingan*	0.107	10.81	0.267	8.16	18.97
Mangifera indica L.	Anacardiaceae	*Mangga*	0.008	0.81	0.200	6.12	6.93
Manihot glaziovii Muell	Euphorbiaceae	*Singkong karet*	0.008	0.81	0.133	4.08	4.89
Mitragyna speciosa Korth.	Rubiaceae	*Kratom*	0.005	0.54	0.067	2.04	2.58
Moringa oleifera Lam.	Moringaceae	*Kelor*	0.043	4.32	0.133	4.08	8.41
Muntingia calabura L.	Muntingiaceae	*Kersen*	0.003	0.27	0.067	2.04	2.31
Parkia speciosa Hassk.	Fabaceae	*Mlanding*	0.003	0.27	0.067	2.04	2.31
Pisum sativum L.	Fabaceae	*Kacang kapri*	0.005	0.54	0.067	2.04	2.58
Pleurolobus gangeticus (L.) J.St.-Hil. ex H.Ohashi & K.Ohashi	Fabaceae	*Daun picah*	0.029	2.97	0.200	6.12	9.10
Rosa multiflora L.	Rosaceae	*Mawar*	0.003	0.27	0.133	4.08	4.35
Saccharum spontaneum L.	Poaceae	*Rumput gelagah*	0.045	4.59	0.067	2.04	6.64
Sauropus androgynus (L.) Merr.	Phyllanthaceae	*Katuk*	0.011	1.08	0.067	2.04	3.12
Schizolobium parahyba (Vell.) S.F.Blake	Fabaceae	*Pakis brazil*	0.013	1.35	0.067	2.04	3.39
Sida rhombifolia L.	Malvaceae	*Seleguri*	0.005	0.54	0.067	2.04	2.58
Swietenia mahagoni (L.) Jacq.	Mileaceae	*Mahoni*	0.005	0.54	0.067	2.04	2.58
Syzygium polyanthum (Wight) Walp.	Myrtaceae	*Salam*	0.003	0.27	0.067	2.04	2.31
Tectona grandis L.f.	Lamiaceae	*Jati*	0.035	3.51	0.267	8.16	11.68
Vernonia amygdalina Delile	Asteraceae	*Daun afrika*	0.013	1.35	0.067	2.04	3.39
Wrightia pubescens R.Br.	Apocynaceae	*Bentawas*	0.003	0.27	0.067	2.04	2.31
Ziziphus mauritiana Lam.	Rhamnaceae	*Bidara*	0.013	1.35	0.067	2.04	3.39

Following was *Leucaena leucocephala*, a Fabaceae species known as *mandingan* locally, exhibited an IVI value of 18.97%, highlighting its role in the ecosystem. *L. leucocephala* has a common biological property that occurs when allelopathic plants produce allelochemicals that have a positive or negative impact on the growth, survival, development, and reproduction of other nearby plant species in the same ecosystem (Men 2021). Similarly, *C. rotundus*, belonging to the Cyperaceae family and commonly referred to as *rumput teki*, displayed an IVI value of 12.85%, signifying its contribution to the vegetation dynamics. *C. rotundus* is a species that is widely used in traditional medicine in various parts of the world, especially in Asian countries such as India and Pakistan. The anticancer potential of this species has been reported in the literature, suggesting that its chemical compounds may be effective against various types of tumor cells (Bezerra and Pinheiro 2022).

The IVI parameter serves as a crucial indicator of a species' ecological significance, with a threshold of IVI>15% suggesting a substantial role within the ecosystem (Irwansyah et al. 2019). However, some species showed notably lower IVI values, indicating their lesser influence on the surrounding vegetation. For instance, a collective IVI value of 2.31% was recorded for nine plant species, including *Capsicum frutescens*, *Citrus hystrix*, *Dimocarpus longan*, *Ficus hispida*, *Gynura divaricata*, *Muntingia calabura*, *Parkia speciosa*, *Syzygium polyanthum*, and *Wrightia pubescens*. Despite their presence, these species only accounted for one individual each across the entire plot, indicating their limited ecological impact within the studied area. *Capsicum* is a very important plant crop and is widely consumed throughout the world because it is an important source of several nutritional and dietary compounds including capsaicinoids, vitamins A and C, pigments, minerals and essential oils. Among the five *Capsicum* spp. cultivated, *C. annuum* has received maximum attention from researchers (Jaiswal et al. 2021). *C. hystrix* contains phytochemical compounds, including β-pinene, sabinene, citronellal, and citronellol; and the extract shows potential antidiabetic, antihyperlipidemic and anti-obesity activity, as well as preventing the development of hypertension (Siti et al. 2022).

Abiotic factors

Abiotic factors are non-biological components that make up an ecosystem and significantly affect the lives of organisms (Rahmawanto et al. 2015). Abiotic factor data from the three stations showed variations that can affect the distribution and adaptation of organisms in each location (Table 5). Such variations related to environmental and geographic factors such as altitude, soil type, land use and vegetation (Xie et al. 2019). The higher elevation in the upstream (Wonogiri District) caused higher ground temperatures, while soil pH in the midstream (Klaten District) was more acidic due to local factors. The highest air humidity was recorded in the midstream, possibly due to denser vegetation, while the downstream (Sukoharjo District) had high humidity due to its proximity to the river. Downstream soil temperature was lower due to higher soil moisture and thicker vegetation which provide shade. These factors collectively influence the physical and chemical conditions at each research station.

Abiotic factors also affect plants, i.e. light intensity affects photosynthesis in plants, pH determines the organisms that can live in the environment, air humidity affects water evaporation and transpiration in plants, temperature affects metabolism, reproduction, and distribution of organisms, and altitude or slope of the land affects temperature, air pressure, and oxygen availability. The differences in abiotic factors across the three stations create unique and diverse habitats, which in turn support different communities of organisms. Understanding the variation and influence of abiotic factors is essential for studying the ecology and distribution of organisms in different ecosystems.

Potential utilization of undergrowth plants

Lower plants show numerous potentials of utilization (Zaki et al. 2022) as shown in Table 6. It can be seen that the dominance of the potential utilization of lower plants in the research location is for medicinal purposes. For example, *Musa paradisiaca* has the potential to control blood pressure and improve digestion (Sirappa 2021) as well as *P. gangeticus* (Mohan et al. 2023). The utilization of lower plants as medicines has been carried out for generations (Rambey et al. 2024). There are also species that can be used as animal feed, including *Macroptilium atropurpureum* (Andini 2022) and *Pilea pumila* (Yang et al. 2021). Other potential uses are for ornamental plants, food ingredients, and others. This potential provides benefits to the community both from use value or economic value (Wahidah et al. 2022).

Table 5. Abiotic factors in three stations in the riparian zone of Upper Bengawan Solo River, Central Java, Indonesia

Station	Altitude (masl)	pH		Humidity (%)	Temperature (°C)	
		Water	Soil		Air	Soil
Upstream (Wonogiri)	122	7.2	7	60.6	30.6	32
Midstream (Klaten)	88	7.2	5.5	72.3	29.6	29
Downstream (Sukoharjo)	82	7.7	7	70	30.6	27.2

Table 6. Potential utilization of undergrowth plants in the riparian zone of Upper Bengawan Solo River, Central Java, Indonesia

Species	Local name	Utilization
Alpinia galanga (L.) Willd.	*Lengkuas*	As a natural fungicide (Cahyaningrum et al. 2023)
Amaranthus spinosus L.	*Bayam duri*	Wound healing in incision (Nasution 2018)
Amorphophallus oncophyllus Prain ex Hook.f.	*Porang*	Food, antioxidant and antibacterial (Utaminingsih and Muhtadi 2021)
Anredera cordifolia (Ten.) Steenis	*Binahong*	Growth inhibition of *E. coli* ATCC 35216 bacteria (Mamangkey et al. 2022)
Baptisia australis (L.) R.Br.	*Nila biru*	Effective for multiple shoot induction (Padmanabhan et al. 2017)
Bambusa blumeana Schult.f.	*Pring ori*	Making charcoal (Adawi et al. 2021)
Bidens pilosa L.	*Ketul*	Medication for malaria, diabetes mellitus, and inflammation (Silalahi et al. 2021)
Capsium frutescens L.	*Cabai*	Food, anti-inflammatory (Ismail et al. 2022)
Carica papaya L.	*Pepaya*	Food, increase milk production (Sebayang 2020)
Chromolaena odorata (L.) R.M.King & H.Rob.	*Balakasida*	Healing cut wounds (Zahira 2023)
Citrus hystrix DC.	*Jeruk purut*	Overcoming body fatigue and weakness after a serious illness (Karlina and Nasution 2022)
*Colocasia esculenta (*L.) Schott	*Tales*	Accelerates healing of contaminated wounds (Ristanti et al. 2021)
Curcuma longa L.	*Kunyit*	Antioxidants (Cahnia et al. 2022)
Cyperus rotundus L.	*Rumput teki*	Diarrhea, diabetes, pyrosis, inflammation, and malaria medication (Kamala et al. 2018)
Dactyloctenium aegyptium (L.) Willd.	*Tapak jalak*	Animal feed (Janbaz and Saqib 2015)
Dimocarpus longan Lour.	*Kelengkeng*	Food, lower uric acid levels (Asrimi 2023)
Dioscorea hispida Dennst.	*Gadung tikus*	Improves digestive tract health (Setiarto 2017)
Elephantopus scaber L.	*Tapak liman*	Antimicrobial (Nonci et al. 2014)
Euphorbia heterophylla Desf.	*Patik emas*	Laxatives (Somadayo 2015)
Euphorbia hirta L.	*Patik kebo*	Medicinal plants, anti-inflammatory (Komarudin et al. 2023)

Ficus hispida L.fil.	*Luwingan*	Medicinal plants (Fitria et al. 2021)
Ficus septica Burm.fil.	*Awar-awar*	Anti-inflammatory (Arief et al. 2018)
Gynura divaricata (L.) DC.	*Daun dewa*	Anti-inflammatory (Aprilliani et al. 2021)
Hedera helix L.	*Daun ivi*	Natural antioxidants (Candraningtyas et al. 2023)
Hibiscus similis Bl.	*Waru tisuk*	Antioxidants (Syahputra 2022)
Laportea decumana (Roxb.) Wedd.	*Pohon gatal*	Pain relief (Wailegi et al. 2024)
Leea indica (Burm.fil.) Merr.	*Girang merah*	Natural dyes (Astuti and Widihastuti 2022)
Leucaena leucocephala (Lam.) de Wit	*Lamtoro*	Medicinal plants, anti-inflammatory, antioxidant (Sudirman et al. 2023)
Ludwigia palustris (L.) Elliott	*Daun buang-buang*	Acne medication (Indayani 2023)
Macroptilium atropurpureum (DC.) Urb.	*Siratro*	Superior feed for livestock (Andini 2022)
Mangifera indica L.	*Mangga*	Food, anthelmintic (Afrian 2021)
Manihot esculenta Crantz	*Singkong*	Food, antioxidant, may increase appetite (Apriyani et al. 2022)
Manihot glaziovii Muell	*Singkong karet*	Raw materials for making ethanol (Aznury and Rezky 2020)
Microstegium vimineum (Trin.) A.Camus	*Rumput pengepakan*	As a weed (Logan 2021)
Mikania micrantha Kunth	*Sambung rambat*	Antitumor, cytotoxic, and analgesic (Amelia et al. 2020)
Mimosa pudica L.	*Putri malu*	Anti-inflammatory (Arfiandi et al. 2022)
Mitragyna speciosa Korth.	*Kratom*	Diarrhea, pain relief, cough, and hypertension medications (Raini 2017)
Momordica charantia L.	*Pare*	Acne medication and skin infection medication (Yusuf et al. 2022)
Moringa oleifera Lam.	*Kelor*	Hypoglycemic drugs, inflammation, bacterial/viral infections and cancer (Nurmalasari et al. 2021)
Muntingia calabura L.	*Kersen*	Boosts the immune system (Bamasri 2021)
Musa paradisiaca L.	*Pisang*	Food, controls blood pressure, improves digestion (Sirappa 2021)
Oplismenus hirtellus (L.) P.Beauv.	*Rumput keranjang*	Animal feed (Rachmalia et al. 2023)
Ottochloa nodosa (Kunth) Dandy	*Rumput sarang buaya*	Animal feed (Grinnell et al. 2022)
Oxalis barrelieri L.	*Belimbing tanah*	Antibacterial (Pazra et al. 2022)
Parkia speciosa Hassk.	*Mlandingan*	Medicine for liver disease, edema, and kidney inflammation (Verawaty and Novel 2018)
Pennisetum purpureum Schumach.	*Rumput gajah*	Animal feed (Sugandi et al. 2016)
Peperomia pellucida (L.) Kunth	*Daun suruhan*	Remedy for abscesses, boils, acne, and skin inflammation (Pratiwi et al. 2021)
Phyllanthus niruri L.	*Meniran hijau*	Traditional medicine (Ayuningsih 2021)
Physalis angulata L.	*Ciplukan*	Antifungal, diabetes, and influenza medication (Lau and Herman 2020)
Pilea pumila (L.) A.Gray	*Pilea*	Animal feed (Yang et al. 2021)
Pisum sativum L.	*Kacang kapri*	Food ingredients (Prasetyowati et al. 2023)
Pleurolobus gangeticus (L.) J.St.-Hil. ex H.Ohashi & K.Ohashi	*Daun picah*	Medicinal plants (Mohan et al. 2023)
Pteris vittata L.	*Pakis rem cina*	Houseplants (Efendi and Iswahyudi 2020)
Rosa multiflora L.	*Mawar*	Houseplants (Muzaki et al. 2021)
Ruellia angustifolia Sw.	*Kencana ungu*	Houseplants and antibacterial plants (Wati and Wakhidah 2023)
Ruellia tuberosa L.	*Pletekan*	Prevent diabetes, antioxidant (Pham et al. 2022)
Saccharum spontaneum L.	*Rumput gelagah*	Natural source of sugar (Zhang et al. 2022)
Sauropus androgynus (L.) Merr.	*Katuk*	Treat acid reflux (Zhang et al. 2020)
Schizolobium parahyba (Vell.) S.F.Blake	*Pakis brazil*	An effective adsorbent for treating drug containing wastewater (de O Salomón et al. 2022)
Senna siamea (Lam.) H.S.Irwin & Barneby	*Johar*	Antimicrobial (Kambale et al. 2020)
Sida rhombifolia L.	*Seleguri*	Natural antioxidants (Xu et al. 2022)
Spigelia anthelmia L.	*Kemangi cina*	Plenty of calcium to strengthen bones and teeth (Awotedu et al. 2020)
Swietenia macrophylla G.King	*Mahoni*	Midges (Telrandhe et al. 2022)
Swietenia mahagoni (L.) Jacq.	*Mahoni*	Antidiabetic (Sukardiman and Ervina 2020)
Synedrella nodiflora (L.) Gaertn.	*Jotang kuda*	Antimalarials (Chaniad et al. 2021)
Syzygium polyanthum (Wight) Walp.	*Daun salam*	Antibacterial (Nordin et al. 2019)
Tectona grandis L.f.	*Jati*	Building materials (Vyas et al. 2019)
Tradescantia fluminensis Vell.	*Telinga kera*	Phenol component (Míguez et al. 2022)
Urena lobata L.	*Pulutan*	Anti-inflammatory (Wahyuningsih et al. 2022)
Vernonia amygdalina Delile	*Daun afrika*	Antibacterial (Olusola-Makinde et al. 2021)
Wrightia pubescens R.Br.	*Bentawas*	Boosts metabolism (Karim et al. 2023)
Zea mays L.	*Jagung*	Food ingredients (Rizwan et al. 2019)
Zingiber zerumbet (L.) Roscoe ex Sm.	*Lempuyang*	Spices (Chavan and Dey 2023)
Ziziphus mauritiana Lam.	*Daun bidara*	Antibacterial (Jain et al. 2019)

In conclusion, the study documented 78 species from 38 family of undergrowth in the riparian zones of Upper Bengawan Solo River from three sites. The vegetation Diversity Index (H') is included in the medium category. Plant with the highest Index of Important Value (IVI) for seedlings and herbaceous plants was *C. odorata* with 15.56%, while that of saplings and shrubs was the *B. blumeana* with 47.74%. The higher elevation in the upstream (Wonogiri District) led to higher soil temperature, while the midstream (Klaten District) had a more acidic soil pH and the highest air humidity. In the downstream (Sukoharjo District), high humidity due to proximity to the river, led to lower soil temperatures. Undergrowth vegetation along the Bengawan Solo River also has diverse potential with the dominance of medicinal uses, and some plants are used as animal feed, ornamental plants, food ingredients, and others.

REFERENCES

Adawi TF, Aji IML, Rini DS. 2021. Pengaruh suhu dan konsentrasi asam fosfat (H_3PO_4) terhadap kualitas arang aktif cabang bambu duri (*Bambusa blumeana* Bi.Ex. Schult.F.). Jurnal Penelitian Kehutanan FALOAK 5 (1): 62-73. DOI: 10.20886/jpkf.2021.5.1.62-73. [Indonesian]

Afrian R. 2021. Potensi ANTIHELMINTIK MANGGA ARUMANIS (*Mangifera indica* L.). Jurnal Medika Hutama 2: 497-501. [Indonesian]

Amelia A, Andriani Y, Andriani L. 2020. Gambaran histopatologi otak mencit (*Mus musculus* L) setelah pemberian fraksi daun sembung rambat (*Mikania micrantha* Kunth) sebagai aktivitas neuroprotektan. Jurnal Farmamedika 5 (1): 30-37. DOI: 10.47219/ath.v5i1.91. [Indonesian]

Andini YT. 2022. Manajemen Pemberian Pakan Sapi Potong Pada Koperasi Produksi Ternak Maju Sejahtera Kabupaten Lampung Selatan. [Diploma Thesis]. Politeknik Negeri Lampung, Bandar Lampung. [Indonesian]

Andriyani RT, Hastaniah, Matius P, Diana R, Sutedjo. 2023. Identification and analysis of understory species diversity in Sangkima Jungle Park secondary forest in Kutai National Park pre-fire affected areas, East Kalimantan. Pros Sem Nas Masy Biodiv Indones 9: 59-66. DOI: 10.13057/psnmbi/m090109.

Aprilliani A, Fhatonah N, Ashari NA. 2021. Uji efektivitas antiinflamasi ekstrak etanol 70% daun dewa (*Gynur pseudochina* (L.) DC.) pada luka bakar tikus putih jantan galur Wistar. Jurnal Farmagazine 8 (2): 52-58. DOI: 10.47653/farm.v8i2.564. [Indonesian]

Apriyani D, Loviriani S, Amanda PF, Putri AU, Lazuarni S. 2022. Pemanfaatan olahan singkong menjadi kue dalam meningkatkan kreativitas masyarakat di Desa Alai Selatan. Selaparang: Jurnal Pengabdian Masyarakat Berkemajuan 6 (3): 1582-1586. DOI: 10.31764/jpmb.v6i3.10505. [Indonesian]

Arfiandi A, Nofita D, Fadjria N. 2022. Efek antiinflamasi ekstrak etanol daun putri malu (*Mimosa pudica* Linn). J Pharm Sci 5 (2): 274-278. DOI: 10.36490/journal-jps.com.v5i2.145. [Indonesian]

Arief R, Thahir, Z, Kristiana K. 2018. Uji aktivitas antiinflamasi sediaan salep ekstrak daun awar-awar (*Ficus septica* Burm. F) terhadap udema kulit punggung mencit (*Mus musculus*). Jurnal Kesehatan Yamasi Makassar 2 (2): 1-5. [Indonesian]

Asrimi R. 2023. Uji Aktivitas Ekstrak Etanol Daun Kelengkeng (*Dimocarpus longan* Lour) terhadap Penurunan Kadar Asam Urat Mencit (*Mus musculus*) Hiperurisemia. [Diploma Thesis]. Universitas Katolik Widya Mandala Surabaya, Surabaya. [Indonesian]

Astuti KT, Widihastuti W. 2022. Pengaruh jenis zat fiksasi terhadap ketahanan luntur warna dan arah warna pada kain mori primissima menggunakan zat warna alam buah girang (*Leea indica*). Jurnal Fesyen: Pendidikan dan Teknologi 11 (1). DOI: 10.21831/teknik%20busana.v11i1.19545. [Indonesian]

Awotedu OL, Ogunbamowo PO, Ariwoola OS, Chukwudebe EP. 2020. Phytochemical and phytomineral status of *Spigelia anthelmia* Linn leaves. Intl J Biochem Res Rev 29 (2): 33-40. DOI: 10.9734/ijbcrr/2020/v29i230170.

Ayuningsih F. 2021. Pengaruh Ekstrak Meniran (*Phyllanthus niruri* L.) terhadap Kadar Kolesterol dalam Darah pada Dewasa Tua di Desa Banjarharjo Kecamatan Salaman Tahun 2020. [Skripsi]. Universitas Muhammadiyah Magelang, Magelang. [Indonesian]

Aznury M, Resky R. 2020. Pengaruh agitasi dan waktu fermentasi pada pembuatan bioetanol dari pati singkong karet (*Manihot glaziovii*). Kinetika 11 (1): 51-54. [Indonesian]

Azzaroiha C, Husna FN, Rahayu M, Salsabila SN, Hanifah UN. 2022. Keanekaragaman Famili Asteraceae di Pematang Sawah Desa Ubung Kaja, Denpasar Utara, Denpasar. Biota: Jurnal Ilmiah Ilmu-Ilmu Hayati 7 (3): 199-206. DOI: 10.24002/biota.v7i3.5237. [Indonesian]

Bamasri TH. 2021. Daun kersen *Muntingia calabura* sebagai antibakteri. Jurnal Penelitian Perawat Profesional 3 (2): 231-236. DOI: 10.37287/jppp.v3i2.396. [Indonesian]

Bezerra JJL, Pinheiro AAV. 2022. Traditional uses, phytochemistry, and anticancer potential of *Cyperus rotundus* L. (Cyperaceae): A systematic review. S Afr J Bot 144: 175-186. DOI: 10.1016/j.sajb.2021.08.010.

Borisade TV, Odiwe AI, Akinwumiju AS, Uwalaka NO, Orimoogunje OI. 2021. Assessing the impacts of land use on riparian vegetation dynamics in Osun State, Nigeria. Trees For People 5: 100099. DOI: 10.1016/j.tfp.2021.100099.

Cahnia MS, Muhaimin M, Yuliawati Y, Sani KF. 2022. Formulasi, uji efektivitas dan uji hedonik masker gel peel off kombinasi ekstrak rimpang kunyit (*Curcuma longa* L.) dan madu (*Mel depuratum*) sebagai peningkat elastisitas kulit. Jurnal Ilmiah Kefarmasian Medical Sains 7 (2): 23-36. DOI: 10.37874/ms.v7i2.328. [Indonesian]

Cahyaningrum GS, Slamet S, Wirasti W, Pambudi DB. 2023. Uji aktivitas antifungi ekstrak lengkuas (*Alpinia galanga* (L) Willd) terhadap jamur *Candida albicans* dengan metode sumuran. Prosiding University Research Colloquium 16: 677-683. [Indonesian]

Candraningtyas CF, Karina R, Mardianto MB, Ramadhani G. 2023. Identifikasi jenis-jenis tumbuhan asing invasif di Desa Wisata Nganggring dan rekomendasi pengelolaannya. Innovative: J Soc Sci Res 3 (6): 9599-9612. DOI: 10.31004/innovative.v3i6.6682. [Indonesian]

Chaniad P, Techarang T, Phuwajaroanpong A, Na-Ek P, Viriyavejakul P, Punsawad C. 2021. In vivo antimalarial activity and toxicity study of extracts of *Tagetes erecta* L. and *Synedrella nodiflora* (L.) Gaertn. from the Asteraceae family. Evid-based Complement Altern Med 2021: 1270902. DOI: 10.1155/2021/1270902.

Chavan JJ, Dey A. 2023. *Zingiber zerumbet* (L.) Roscoe ex Sm.: biotechnological advancements and perspectives. Appl Microbiol Biotechnol 107 (18): 5613-5625. DOI: 10.1007/s00253-023-12682-2.

de O Salomón YL, Georgin J, Franco DS, Netto MS, Piccilli DG, Foletto EL, Manera C, Godinho M, Perondi D, Dotto GL. 2022. Development of activated carbon from *Schizolobium parahyba* (guapuruvu) residues employed for the removal of ketoprofen. Environ Sci Pollut Res 29: 21860-21875. DOI: 10.1007/s11356-021-17422-5.

Destaranti N, Sulistyani, Yani E. 2017. Structure and undergrowth vegetation under pine stands in RPH Kalirsatria and RPH Baturraden Banyumas. Script Biol 4 (3): 155-160. DOI: 10.20884/1.sb.2017.4.3.407.

Dufour S, Rodríguez-González PM, Laslier M. 2019. Tracing the scientific trajectory of riparian vegetation studies: Main topics, approaches and needs in a globally changing world. Sci Total Environ 653: 1168-1185. DOI: 10.1016/j.scitotenv.2018.10.383.

Efendi WW, Iswahyudi S. 2020. Keanekaragaman Tumbuhan Paku di Jawa Timur. Graha Ilmu, Surabaya. [Indonesian]

Etikan I, Musa SA, Alkassim RS. 2016. Comparison of convenience sampling and purposive sampling. Am J Theor Appl Stat 5 (1): 1-4. DOI: 10.11648/j.ajtas.20160501.11.

Fitria L, Na'ilah LN, Handayani L. 2021. Toksisitas oral subakut filtrat buah luwingan (*Ficus hispida* Lf) pada Tikus Riul [*Rattus norvegicus* (Berkenhout, 1769)] Wistar jantan. Jurnal Biologi Indonesia 17 (1): 81-91. DOI: 10.47349/jbi/17012021/81. [Indonesian]

Fu B, Li Y, Wang Y, Zhang B, Yin S, Zhu H, Xing Z. 2016. Evaluation of ecosystem service value of riparian zone using land use data from 1986 to 2012. Ecol Indic 69: 873-881. DOI: 10.1016/j.ecolind.2016.05.048.

Grinnell NA, van der Linden A, Azhar B, Nobilly F, Slingerland M. 2022. Cattle-oil palm integration–a viable strategy to increase Malaysian beef self-sufficiency and palm oil sustainability. Livest Sci 259: 104902. DOI: 10.1016/j.livsci.2022.104902.

Hanum U, Ramadhan MF, Armando MF, Sholiqin M, Rachmawati S. 2022. Analisis kualitas air dan strategi pengendalian pencemaran air di Sungai Pepe Bagian Hilir, Surakarta. Prosiding Sains dan Teknologi 1 (1): 376-386. [Indonesian]

Hutasuhut MA. 2018. Keanekaragaman tumbuhan herba di cagar alam Sibolangit. Klorofil: Jurnal Ilmu Biologi dan Terapan 1 (2): 69-77. DOI: 10.30821/kfl:jibt.v1i2.1598. [Indonesian]

Indayani S. 2023. Analisis Fitokimia, Bioaktivitas Antioksidan dan Antibakteri Ekstrak Etanol Daun Cacabean (*Ludwigia octovalvis*). [Diploma Thesis]. Politeknik Pertanian Negeri Samarinda, Samarinda. [Indonesian]

Irwansyah I, Sugiyarto S, Mahajoeno E. 2019. Struktur komunitas ekosistem mangrove di Teluk Serewe Pulau Lombok Nusa Tenggara Barat. Bioeksperimen: Jurnal Penelitian Biologi 5 (2): 126-130. DOI: 10.23917/bioeksperimen.v5i2.9242. [Indonesian]

Iryadi R, Wardhani PK. 2023. The influence of environmental conditions on the distribution and abundance of Sauromatum horsfieldii Miq. at Mount Tapak, Bali. Buletin Kebun Raya 26 (2): 73-83. DOI: 10.55981/bkr.2023.1369.

Ismail R, Abdullah A, Sangkal A, Toboleu RR. 2022. Aktivitas anti inflamasi gel cabai rawit (*Capsicum frutescens* L.) pada tikus putih (*Rattus norvegicus*). J Pharm Sci 6 (1): 59-64. DOI: 10.36341/jops.v6i1.3012. [Indonesian]

Jain P, Haque A, Islam T, Alam MA, Reza HM. 2019. Comparative evaluation of *Ziziphus mauritiana* leaf extracts for phenolic content, antioxidant and antibacterial activities. J Herbs Spices Med Plants 25 (3): 236-258. DOI: 10.1080/10496475.2019.1600627.

Jaiswal V, Gahlaut V, Kumar N, Ramchiary N. 2021. Genetics, genomics and breeding of chili pepper *Capsicum frutescens* L. and other *Capsicum* species. In: Al-Khayri JM, Jain SM, Johnson DV (eds). Advances in Plant Breeding Strategies: Vegetable Crops. Volume 9: Fruits and Young Shoots. Springer, Cham. DOI: 10.1007/978-3-030-66961-4_2.

Janbaz KH, Saqib F. 2015. Pharmacological evaluation of *Dactyloctenium aegyptium*: An indigenous plant used to manage gastrointestinal ailments. Bangladesh J Pharmacol 10 (2): 295-302. DOI: 10.3329/bjp.v10i2.21811.

Kamala A, Middha SK, Karigar CS. 2018. Plants in traditional medicine with special reference to *Cyperus rotundus* L.: A review. 3 Biotech 8 (7): 309. DOI: 10.1007/s13205-018-1328-6.

Kambale EK, Nkanga CI, Mutonkole BPI, Bapolisi AM, Tassa DO, Liesse JMI., Krause RWM, Memvanga PB. 2020. Green synthesis of antimicrobial silver nanoparticles using aqueous leaf extracts from three Congolese plant species (*Brillantaisia patula*, *Crossopteryx febrifuga* and *Senna siamea*). Heliyon 6 (8): e04493. DOI: 10.1016/j.heliyon.2020.e04493.

Karim HAA, Ismail NH, Rasol NE, Osman CP. 2023. Dereplication of *Wrightia dubia* and *Wrightia pubescens* by UPLC-ESI-Orbitrap-MS/MS. Plant Med 89 (14): 1409. DOI: 10.1055/s-0043-1774221.

Karlina VR, Nasution HM. 2022. Skrining fitokimia dan uji aktivitas antibakteri ekstrak etanol daun jeruk purut (*Citrus hystrix* DC) terhadap bakteri *Staphylococcus aureus* dan *Escherichia coli*. J Health Med Sci 1 (2): 131-139. DOI: 10.35760/jff.2023.v1i2.8511. [Indonesian]

Komarudin D, Hardiyati I, Hidayat F, Dipta E, Widiyanti N, Fauziah S, Hartono A. 2023. Uji toksisitas akut ekstrak etanol 70% daun patikan kebo (*Euphorbia hirta* L.) terhadap tikus putih jantan (*Rattus norvegicus*). Jurnal Farmasi Kryonaut 2 (1): 21-28. DOI: 10.59969/jfk.v2i1.19. [Indonesian]

Krebs CJ. 1989. Ecological Methodology. Harper Collins Publisher, New York.

Lau SHA, Herman H. 2020. Formulasi dan uji stabilitas fisik sediaan bedak tabur ekstrak etanol daun ciplukan (*Physalis angulata* L.) sebagai anti fungi di Desa Tammatto Kabupaten Bulukumba. Jurnal Ilmiah Kesehatan Sandi Husada 9 (2): 1117-1126. DOI: 10.35816/jiskh.v10i2.472. [Indonesian]

Liana L, Pasambo OM, Maria M, Sada NH. 2023. Diversity and potential of undergrowth as traditional medicine in Sangtandung Village, North Walenrang Sub District, Luwu. Jurnal Penelitian Kehutanan Bonita 5 (2): 38-47. DOI: 10.55285/bonita.v5i2.2391.

Logan CM. 2021. Evaluating the Effects of Japanese Stiltgrass on Ground-Layer Arthropod Diversity. Virginia Tech, Blacksburg.

Lyu C, Li X, Yuan P, Song Y, Gao H, Liu X, Liu R, Yu H. 2021. Nitrogen retention effect of riparian zones in agricultural areas: A meta-analysis. J Clean Prod 315: 128143. DOI: 10.1016/j.jclepro.2021.128143.

Mamangkey J, Pardosi L, Wahyuningtyas, RS. 2022. Aktivitas mikrobiologi endofit dari ekstrak daun binahong (*Anredera cordifolia* (Ten.) Steenis). Jurnal Pro-Life 9 (1): 377-386. DOI: 10.33541/jpvol6Iss2pp102. [Indonesian]

Men TT. 2021. Research on allelopathy: Potential wild plant species in Vietnam. Recent Prog Plant Soil Res 3: 108-118. DOI: 10.9734/bpi/rppsr/v3/14536D.

Míguez C, Cancela Á, Álvarez X, Sánchez Á. 2022. The reuse of bio-waste from the invasive species *Tradescantia fluminensis* as a source of phenolic compounds. J Clean Prod 336: 130293. DOI: 10.1016/j.jclepro.2021.130293.

Mohan PK, Krishna TA, Stephy PP, Thirumurugan A, Kumar TS, Kumari BR. 2023. Nano-engineered silver rods from *Pleurolobus gangeticus* root extract and their antilithiatic and cytoprotective role on oxalate injured renal epithelial cells. Biocatal Agric Biotechnol 52: 102837. DOI: 10.1007/s12010-022-04017-0.

Mokodompit R, Kandowangko NY, Hamidun MS. 2022. Keanekaragaman tumbuhan di Kampus Universitas Negeri Gorontalo Kecamatan Tilong Kabila Kabupaten Bone Bolango. Biosfer 7 (1): 75-80. DOI: 10.23969/biosfer.v7i1.5651. [Indonesian]

Muzaki A, Wahyuni S, Hanik NR. 2021. Identifikasi jenis hama dan penyakit yang sering menyerang tumbuhan bunga mawar (*Rosa hybrida* L.) di Daerah Manyaran. Florea: Jurnal Biologi dan Pembelajarannya 8 (1): 52-61. DOI: 10.25273/florea.v8i1.8587. [Indonesian]

Nasution SB. 2018. Pengaruh perebusan sayur bayam merah (*Amaranthacea gangeticus*) terhadap kandungan Nitrit (No_2^-) dengan berbagai variasi waktu. Jurnal Ilmiah PANNMED 13 (1): 61-64. DOI: 10.36911/pannmed.v13i1.181. [Indonesian]

Nonci FY, Rusli R, Atqiyah A. 2014. Antimikroba ekstrak etanol daun tapak liman (*Elephantopus scaber* L.) dengan menggunakan metode klt bioautografi. Jurnal Farmasi UIN Alauddin Makassar 2 (4): 144-148. DOI: 10.24252/jurfar.v2i4.2160. [Indonesian]

Nordin ML, Othman AA, Kadir AA, Shaari R, Osman AY, Mohamed M. 2019. Antibacterial and cytotoxic activities of the *Syzygium polyanthum* leaf extract from Malaysia. Vet World 12 (2): 236-242. DOI: 10.14202/vetworld.2019.236-242.

Nurmalasari Y, Alim W, Aryayunengsih S. 2021. Penerapan program Abikama (Ayo Budidaya Kelor Bersama) melalui metode Asik (Aktif, Sosialisasi, Inovatif, dan Kreatif). Cerdika: Jurnal Ilmiah Indonesia, 1(5), 588-596. DOI: 10.59141/cerdika.v1i5.83. [Indonesian]

Olusola-Makinde O, Olabanji OB, Ibisanmi TA. 2021. Evaluation of the bioactive compounds of *Vernonia amygdalina* Delile extracts and their antibacterial potentials on water-related bacteria. Bull Natl Res Centre 45: 191. DOI: 10.1186/s42269-021-00651-6.

Padmanabhan P, Shukla MR, Sullivan JA, Saxena PK 2017. Iron supplementation promotes in vitro shoot induction and multiplication of *Baptisia australis*. Plant Cell Tissue Organ Cult 129: 145-152. DOI: 10.1007/s11240-016-1165-4.

Pangastuti EI, Nurdin EA, Mujib MA, Alfani AF, Nalurita VA, Fatmawati D. 2022. Analisis dan pemetaan tingkat pencemaran air sungai Pada Sub DAS Bedadung Tengah Kabupaten Jember. Jurnal Pendidikan dan Ilmu Geografi 7 (2): 137-149. DOI: 10.21067/jpig.v7i2.7191. [Indonesian]

Paradika GY, Kissinger K, Rezekiah AA. 2021. Pendugaan cadangan karbon vegetasi di sempadan sungai pada Kawasan Hutan Dengan Tujuan Khusus (KHDTK) Universitas Lambung Mangkurat. Jurnal Sylva Scienteae 4 (1): 98-106. DOI: 10.20527/jss.v4i1.3098. [Indonesian]

Park H, Kim JG. 2020. Temporal and spatial variations of vegetation in a riparian zone of South Korea. J Ecol Environ 44 (1): 9. DOI: 10.1186/s41610-020-00152-z.

Pazra DF, Multida I, Sari M, Nurlita S. 2022. Pemanfaatan tanaman cacalincingan (*Oxalis barrelieri* L.) sebagai bahan dasar hand sanitizer tanpa alkohol. Jurnal Triton 13 (1): 11-21. DOI: 10.47687/jt.v13i1.222. [Indonesian]

Pertiwi YAB, Zaki MG, Nufus M, Sakya AT. 2021. Keragamanan Jenis Tumbuhan Bawah di KHDTK Gunung Bromo. CV. INDOTAMA SOLO, Surakarta. [Indonesian]

Pham TNT, Nguyen TT, Le Thi Nguyen T, Nguyen Tran AM, Nguyen TN, Tong DT, Tien Le D. 2022. Antioxidant and anti-inflammatory activities of phytochemicals from *Ruellia tuberosa*. J Chem 2022: 4644641. DOI: 10.1155/2022/4644641.

Pramadaningtyas PS, Chandrasari N, Izdihar RS, Iqbal WM, Cahyaningsih AP, Setyawan AD. 2023. Analysis of riparian vegetation in the Siwaluh River, Karanganyar District, Central Java, Indonesia. Intl J Bonorowo Wetlands 13: 45-56. DOI: 10.13057/bonorowo/w130201.

Prasetyowati AT, Pranata FS, Swasti YR. 2023. Kualitas cookies substitusi tepung sorgum (*Sorghum bicolor*) dan tepung kacang polong (*Pisum sativum*). Jurnal Teknologi Pangan dan Gizi 22 (1): 33-43. DOI: 10.33508/jtpg.v22i1.4261. [Indonesian]

Pratiwi PY, Atikah N, Nurhaeni F, Salamah UN. 2021. Aktivitas antioksidan ekstrak etanol herba suruhan (*Peperomia pellucida* (L.) HBK) dengan Metode DPPH (2, 2-Difenil-1-Pikrilhidrazil). Prosiding University Research Colloquium 13: 447-454. [Indonesian]

Rachmalia F, Fauziyyah MD, Faturrahman AD, Ramadhan MF, Indriyani S, Aurnina DM, Septiasari A, Setyawan AD. 2023. Study of the potential use of non-timber vascular plants in Donorejo Village, Kaligesing District, Purworejo, Central Java, Indonesia. Pros Sem Nas Masy Biodiv Indon 9: 16-28. DOI: 10.13057/psnmbi/m090203.

Rahmawanto DG, Muhibuddin A, Aini LQ. 2015. Pengaruh faktor abiotik kimia tanah terhadap supressifitas tanah dalam mengendalikan penyakit layu bakteri (Ralstonia solanacearum) pada tanaman tomat (*Lycopersicon esculentum* Mill). Jurnal HPT (Hama Penyakit Tumbuhan) 3 (2): 1-8. [Indonesian]

Raini M. 2017. Kratom (*Mitragyna speciosa* Korth): Manfaat, efek samping dan legalitas. Media Litbangkes 27 (3): 175-184. DOI: 10.22435/mpk.v27i3.6806.175-184. [Indonesian]

Rambey R, Susilowati A, Rangkuti AB, Onrizal O, Desrita, Ardhi R, Hartanto A. 2021. Plant diversity, structure and composition of vegetation around Barumun Watershed, North Sumatra, Indonesia. Biodiversitas 22: 3250-3256. DOI: 10.13057/biodiv/d220819.

Rambey R., Nusantary M, Sihite F, Saputra MH, Kembaren Y, Sahala S, Marpaung M. 2024. Diversity of undergrowth types in frankincense stands in Humbang Hasundutan Regency. IOP Conf Ser: Earth Environ Sci 1302 (1): 012046. DOI: 10.1088/1755-1315/1302/1/012046.

Rindarto BN, Hidayati F, Sunarti S, Nirsatmanto A. 2021. Physical and mechanical properties of the three breeding generations of *Acacia mangium* planted in Central Java, Indonesia. J Indian Acad Wood Sci 18 (2): 83-88. DOI: 10.1007/s13196-021-00283-3.

Ristanti AA, Safita N, Khairunnisa R, Ermawati S. 2021. Efektivitas gel ekstrak tangkai dan daun talas (*Colocasia esculenta*) terhadap penyembuhan luka diabetes. Prosiding University Research Colloquium 13: 378-388. [Indonesian]

Rizwan M, Ali S, ur Rehman MZ, Adrees M, Arshad M, Qayyum MF, Ali L, Hussain A, Chatha SAS, Imran M. 2019. Alleviation of cadmium accumulation in maize (*Zea mays* L.) by foliar spray of zinc oxide nanoparticles and biochar to contaminated soil. Environ Pollut 248: 358-367. DOI: 10.1016/j.envpol.2019.02.031.

Roswell M, Dushoff J, Winfree R. 2021. A conceptual guide to measuring species diversity. Oikos 130 (3): 321-338. DOI: 10.1111/oik.07202.

Saducos AG. 2022. Potentials of kawayang tinik (*Bambusa blumeana*) as new source antimicrobial agents.Plant Sci Today 9 (3): 518-523. DOI: 10.14719/pst.1451. [Indonesian]

Sari DN, Wijaya F, Mardana MA, Hidayat M. 2019. Analisis vegetasi tumbuhan dengan metode transek (line transect) dikawasan Hutan Deudap Pulo Aceh Kabupaten Aceh Besar. Prosiding Seminar Nasional Biologi, Teknologi dan Kependidikan 6 (1): 165-173. DOI: 10.22373/pbio.v6i1.4253. [Indonesian]

Sebayang WB. 2020. Pengaruh konsumsi buah pepaya (*Carica papaya* L.) terhadap peningkatan produksi asi. Jurnal Ilmiah Kebidanan Imelda 6 (1): 13-16. DOI: 10.52943/jikebi.v6i1.352. [Indonesian]

Setiarto HB. 2017. Produksi tepung gadung (*Dioscorea hispida* Dennst) kaya pati resisten melalui fermentasi bakteri asam laktat dan pemanasan bertekanan-pendinginan. Jurnal Pangan 26 (2): 137-152. DOI: 10.33964/jp.v26i2.352. [Indonesian]

Silalahi M, Silalahi M, Nababan RK. 2021. *Bidens pilosa* L.: Botani, manfaat dan bioaktivitasnya. Jurnal Pro-Life 8 (2): 99-111. DOI: 10.33541/jpvol6Iss2pp102. [Indonesian]

Singh R, Tiwari AK, Singh GS. 2021. Managing riparian zones for river health improvement: an integrated approach. Landsc Ecol Eng 17 (2): 195-223. DOI: 10.1007/s11355-020-00436-5.

Sirappa MP. 2021. Potensi pengembangan tanaman pisang: Tinjauan syarat tumbuh dan teknik budidaya pisang dengan metode bit. Agrosaint 12 (2): 54-65. [Indonesian]

Siti HN, Mohamed S, Kamisah Y. 2022. Potential therapeutic effects of *Citrus hystrix* DC and its bioactive compounds on metabolic disorders. Pharmaceuticals 15 (2): 167. DOI: 10.3390/ph15020167.

Somadayo NAS. 2015. Uji khasiat infusa daun kate mas (*Euphorbia heterophylla* Desf) sebagai laksansia pada tikus putih jantan galur wistar (*Rattus novergicus*). Farmacon 4 (4): 224-232. DOI: 10.35799/pha.4.2015.10211. [Indonesian]

Sudirman S, Firmansyah F, Syachriyani S. 2023. Uji aktivitas antibakteri fraksi etil asetat daun lamtoro (*Leucaena leucocephala* Lamk.) terhadap pertumbuhan *Staphylococcus aureus* dan *Escherichia coli*. Fito Med: J Pharm Sci 15 (1): 1-7. DOI: 10.47650/fito.v15i1.938. [Indonesian]

Sugandi WK, Yusuf A, Saukat M. 2016. Rancang bangun dan uji kinerja mesin pencacah rumput gajah untuk pakan ternak dengan menggunakan pisau tipe. Jurnal Ilmiah Rekayasa Pertanian dan Biosistem 4 (1): 200-206. [Indonesian]

Sukardiman, Ervina M. 2020. The recent use of *Swietenia mahagoni* (L.) Jacq. as antidiabetes type 2 phytomedicine: A systematic review. Heliyon 6 (3): e03536. DOI: 10.1016/j.heliyon.2020.e03536.

Sun W, Ren C. 2021. The impact of energy consumption structure on China's carbon emissions: Taking the Shannon–Wiener index as a new indicator. Energy Rep 7: 2605-2614. DOI: 10.1016/j.egyr.2021.04.061.

Suprapta B. 2021. Flora and fauna based on Old Javanese literary reading in the Malang Highlands Region. Wacana, J Hum Indonesia 22 (3): 3. DOI: 10.17510/wacana.v22i3.962.

Sutiyono, Dharmawan, IWS, Darmawan, UW. 2022. Kesuburan tanah di bawah tegakan berbagai jenis bambu pada tanah Andosol-Regosol. Jurnal Ilmu Lingkungan 20 (3): 517-523. DOI: 10.14710/jil.20.3.517-523. [Indonesian]

Syahputra N. 2022. Uji Aktivitas Antioksidan Ekstrak Daun Waru (*Hibiscus tiliaceus*) Dengan Pelarut N-Heksan, Eti Asetat, Dan Etanol Menggunakan Metode DPPH (2, 2-difenil-1-pikrilhidrazil). [Masters Thesis]. UIN Ar-Raniry, Banda Aceh. [Indonesian]

Telrandhe UB, Kosalge SB, Parihar S, Sharma D, Hemalatha S. 2022. Collection and cultivation of *Swietenia macrophylla* King. Sch Acad J Pharm 11 (1): 13-19. DOI: 10.36347/sajp.2022.v11i01.003.

Urbanič G, Politti E, Rodríguez-González PM et al. 2022. Riparian zones—From policy neglected to policy integrated. Front Environ Sci 10: 868527. DOI: 10.3389/fenvs.2022.868527.

Usman M, Khan WR, Yousaf N, Akram S, Murtaza G, Kudus KA, Ditta A, Rosli Z, Rajpar MN, Nazre M. 2022. Exploring the phytochemicals and anti-cancer potential of the members of Fabaceae family: A comprehensive review. Molecules 27 (12): 3863. DOI: 10.3390/molecules27123863.

Utaminingsih DS Muhtadi M. 2021. Analisis kadar glukomanan dan asam oksalat beserta uji aktivitas antioksidan dan antibakteri dari ekstrak etanol umbi iles-iles (*Amorphophallus oncophyllus*). Prosiding University Research Colloquium 13: 593-603. [Indonesian]

Verawaty V, Novel DC. 2018. Efek ekstrak etanol kulit petai (*Parkia speciosa* Hassk) terhadap penurunan kadar glukosa darah mencit jantan. Jurnal Katalisator 3 (1): 1-6. DOI: 10.22216/jk.v3i1.2178. [Indonesian]

Vidon PG, Welsh MK, Hassanzadeh YT. 2019. Twenty years of riparian zone research (1997–2017): where to next? J Environ Qual 48 (2): 248-260. DOI: 10.2134/jeq2018.01.0009.

Vyas P, Yadav DK, Khandelwal P. 2019. *Tectona grandis* (teak)–A review on its phytochemical and therapeutic potential. Nat Prod Res 33 (16): 2338-2354. DOI: 10.1080/14786419.2018.1440217.

Wahidah BF, Afiati N, Jumari. 2022. Ecological role and potential extinction of *Amorphophallus variabilis* in Central Java, Indonesia. Biodiversitas 23: 1765-1773. DOI: 10.13057/biodiv/d230407.

Wahyuningsih D, Purnomo Y, Tilaqza A. 2022. In silico study of pulutan (*Urena lobata*) leaf extract as anti inflammation and their ADME prediction. J Trop Pharm Chem 6 (1): 30-37. DOI: 10.25026/jtpc.v6i1.323.

Wailegi M, Assem VS, Astuti RA. 2024. Formulasi sediaan krim ekstrak etanol daun gatal (*Laportea decumana*) sebagai antinyeri pada mencit (*Mus musculus*) jantan. Biolearn J 11 (1): 10-16. [Indonesian]

Wati SS, Wakhidah AZ. 2023. Kencana ungu (*Ruellia tuberosa* L.): Botani, fitokimia dan pemanfaatannya di Indonesia. Indobiosains 5 (1): 33-42. DOI: 10.31851/indobiosains.v5i1.9742. [Indonesian]

Xie X, He Z, Chen N, Tang Z, Wang Q, Cai Y. 2019. The roles of environmental factors in regulation of oxidative stress in plant. BioMed Res Intl 2019: 9732325. DOI: 10.1155/2019/9732325.

Xu Z, Gao P, Liu D, Song W, Zhu L, Liu X. 2022. Chemical composition and in vitro antioxidant activity of *Sida rhombifolia* L. volatile organic compounds. Molecules 27 (20): 7067. DOI: 10.3390/molecules27207067.

Yang J, Luo J, Gan Q, Ke L, Zhang F Guo H, Zhao F, Wang Y. 2021. An ethnobotanical study of forage plants in Zhuxi County in the Qinba mountainous area of central China. Plant Divers 43 (3): 239-247. DOI: 10.1016/j.pld.2020.12.008.

Yudianingrum D, Mangkoedihardjo S. 2016. Evaluasi dan Perencanaan Ruang Terbuka Hijau Zona Riparian sungai Surabaya. [Thesis]. Institut Teknologi Sepuluh Nopember, Surabaya. [Indonesian]

Yusuf AL, Nugraha D, Wahlanto P, Indriastuti M, Ismail R, Himah FA. 2022. Formulasi dan evaluasi sediaan gel ekstrak buah pare (*Momordica charantia* L.) dengan variasi konsentrasi Carbopol 940. Pharm Genius 1 (1): 50-61. DOI: 10.56359/pharmgen.v1i01.149. [Indonesian]

Zahira N. 2023. Uji aktivitas Fraksi Ekstrak Etanol Daun Kirinyuh (*Chromolaena odorata* (L.) RM King & H. Rob) dalam Penyembuhan Luka Sayat pada Tikus Putih (*Rattus norvegicus*). [Thesis]. Universitas Jambi, Jambi. [Indonesian]

Zaki AGA, Pertiwi YAB, Nufus M, Sakya AT. 2022. The composition of undergrowth vegetation in forest area with the special purpose of Gunung Bromo, Karangayar, Central Java, Indonesia. Jurnal Sylva Lestari 10 (1): 127-140. DOI: 10.23960/jsl.v10i1.553.

Zhang BD, Cheng JX, Zhang CF, Bai YD, Liu WY, Li W, Koike K, Akihisa T, Feng F, Zhang J. 2020. *Sauropus androgynus* L. Merr.-A phytochemical, pharmacological and toxicological review. J Ethnopharmacol 257: 112778. DOI: 10.1016/j.jep.2020.112778.

Zhang Q, Qi Y, Pan H et al. 2022. Genomic insights into the recent chromosome reduction of autopolyploid sugarcane *Saccharum spontaneum*. Nat Genet 54 (6): 885-896. DOI: 10.1038/s41588-022-01084-1.