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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.

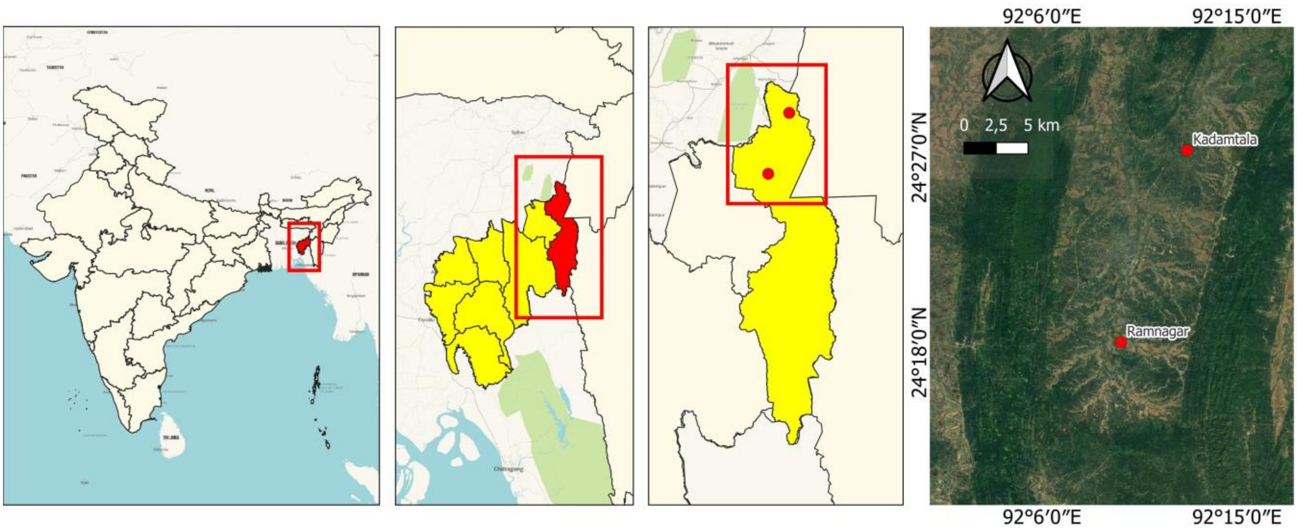

Figure 1. Map of Ramnagar and Kadamtala Blocks of North Tripura, Tripura, Northeast India, showing the locations of the study sites

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)	$D = \frac{\text{Total number of individuals of a species in all quadrates}}{\text{Total number of quadrates studied}}$	Muller-Dombois and Ellenberg (1974)
Relative Density (RD)	$RD = \frac{\text{Density of species}}{\text{Sum of the density of all species}} \times 100$	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)	$RF = \frac{\text{Frequency of species}}{\text{Sum of frequency of all species}} \times 100$	Kelbessa and Demissew (2014)
Basal Area (BA)	$BA = \frac{\pi d^2}{4}$	EWNHS (1996)
Dominance (DO)	$DO = \frac{\text{Basal area of species}}{\text{area of quadrates in hectare}}$	Kelbessa and Demissew (2014)
Relative Dominance (RDO)	$RDO = \frac{\text{Dominance of species}}{\text{Sum of dominance of all species}} \times 100$	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)	$D = \sum_{i=1}^{n} Pi^2$	Magurran (1988)
Simpson (D′)	$D' = 1 - D$	Magurran (1988)
Shannon (H)	$H = \sum_{i=1}^{n} Pi^2 \ln(Pi)$	Michael (1990)
Evenness (E) / Equitability (J)	$E = \frac{H}{\ln(S)}$	Pielou (1966)
Brillouin (H_B)	$HB = \frac{\ln(N) - \sum_{i=1}^{n} \ln(ni)}{N}$	Brillouin (1962)
Menhinick (M)	$M = \frac{S}{\sqrt{N}}$	Menhinick (1964)
Margalef (R)	$R = \frac{(S-1)}{\ln(N)}$	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).

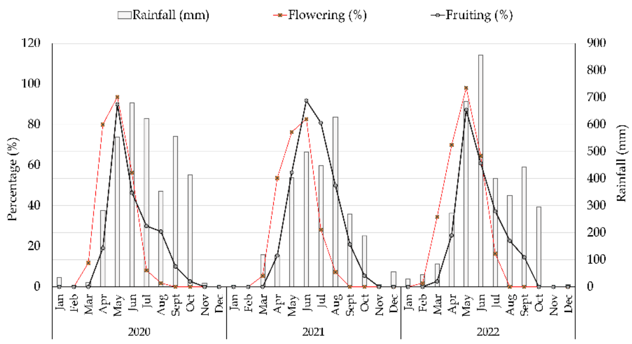

Figure 2. Relationship between monthly rainfall with *A. malaccensis* plant flowering and fruiting in monthly intervals from 2020 to 2022 [POWER | Data Access Viewer (nasa.gov)]

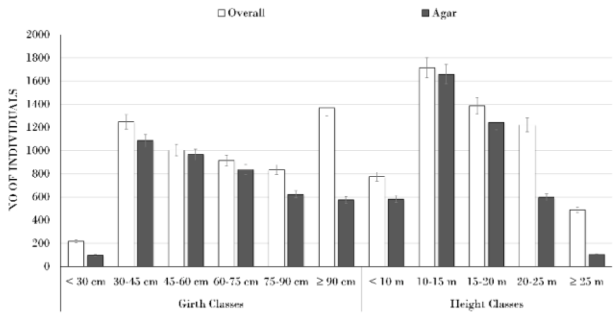

Figure 3. Comparison of individuals based on their girth and height classes between agarwood plants and other associated tree species

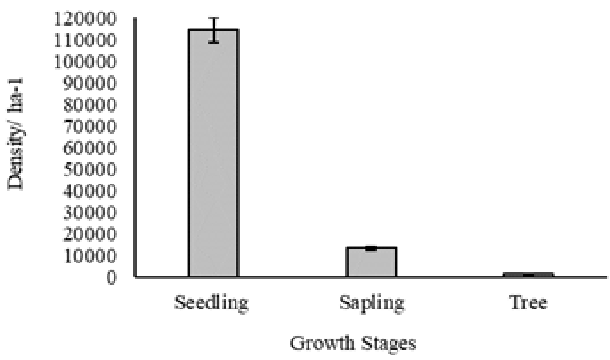

Figure 4. Seedling, sapling, and tree density ha^{-1} of agarwood in the studied home gardens of North Tripura, India

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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