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RESEARCH ARTICLE

Tree diversity and carbon important species vary with traditional agroforestry managers in the Indian Eastern Himalayan region

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Abstract

Traditional agroforestry systems, one of the time tested and dominant land use from tropical to sub-tropical regions, were recognized for their contributions to food production, biodiversity conservation, and atmospheric carbon sequestration. Their management often varies from region to region. However, these systems frequently mimic economically managed land uses due to increased pressure on the monetary requirement of their managers. The present study aims to evaluate (i) tree density, (ii) tree diversity indices, and (iii) identify the biomass carbon important tree species managed by different communities of the Indian Eastern Himalayan region. We found that the Mizo community harbored the highest number of tree species (35) in the traditional agroforestry system with the highest tree diversity index (3.47). Total biomass carbon of tropical agroforestry systems managed by different communities ranged between 4.72 Mg ha^{-1} (Meitei) and 29.26 Mg ha^{-1} (Bengali). Similarly, in the sub-tropical traditional agroforestry system, the highest and the lowest biomass carbon was observed in Mizo- (10.93 Mg ha^{-1}) and Angami- (6.05 Mg ha^{-1}) managed systems. Of the 31 biomass carbon, important species found across the traditional agroforestry systems, *Artocarpus heterophyllus*, had the highest occurrence (50%), followed by *Parkia timoriana* (37.5) and *Amoora rohituka*, *Delonix regia*, *Mangifera indica*, and *Toona ciliata* (25% for each species). Farmers' preference to cash return of a species, trees density, and basal area were the determinant factors in the carbon stock potential of these systems. The present study suggests that the farmers' preferred and dominant species in their agroecosystems have a limited scope of enhanced biomass carbon storage. Therefore, improvement of traditional agroforestry systems through selective incorporation of biomass carbon important tree species is recommended to enhance the carbon sink capacity of these systems.

Keywords Rural community · Biomass carbon · Farmers' preference · Tropical agroforestry · Economic importance

Introduction

The global human population is currently estimated at nearly 7.7 billion and projected to increase to 8.6 billion in 2030, 9.7 billion in 2050, and 10.9 billion in 2100 (2019).

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The population increase coupled with current environmental degradation implies the need for more productive and sustainable use of our land resources (Nath et al. 2021a; Reang et al. 2022). For ages, various communities in the rural landscape to improve livelihood, household food security, and income diversification have practiced integrating trees with agriculture (Jeeceelee and Sahoo 2022; Thangjam et al. 2022). The traditional agroforestry systems (TAFS), an age-old intentional intensified cultivation system with varying structures consisting of socio-economic and ecological services, are considered sustainable agroforestry (Kumar and Nair 2006) and have received increasing attention in recent years due to increasing global temperature and their role in reducing carbon footprints. TAFS have great potential for livelihood improvement due to the integration of trees, crops, and animal components in the same unit of land and thereby offer opportunities and multiple alternatives to increase income through improved production to the farmers. Ecosystem-based measures to address climate change, including indigenous people and local communities, are gaining momentum in the scientific communities (Epple et al. 2016; Reang et al. 2021a, b). The trees, especially native ones, are of immense importance to mitigate climate change by reducing greenhouse gas (GHG) emissions and providing diverse household requirements (Reang et al. 2021a; Thangjam et al. 2022). In general, TAFS have a higher capacity to store biomass among different land uses and offer better protection to the ecological systems in the changing climate, economy, and society (Watson et al. 2000; Nath et al. 2021b).

The Indian Eastern Himalayan region (IEHR) is home to numerous tribes, sub-tribes, and socially distinct non-tribal communities. The IEHR is one of the wealthiest multiple linguistic regions of the world, with a whopping 200 dialects spoken while it merely represents 8.5% of India's land surface area. The tribes broadly belong to Indo-European, Sino-Tibetan, Tai-Kadai, and Austro-Asiatic language families that share common structural features (https://thekootneeti.in/2017/11/03/indigenous-culture-and-tribes-of-north-east/). Ethnic diversity is further characterized by distinct variations in traditions, culture, and their ways of life not only between the ethnic communities but also among the closely related ethnic groups in the region. Planting trees and nurturing them in their landscape is part of the ethnic culture (Reang et al. 2021b; Thangjam et al. 2022). The harmonious living embedded in spiritual relationships with land and water is the primary reason for self-sustaining (Das and Das 2005). The diversity of trees and associated crops under TAFS has evolved across the region among the ethnic communities. The species composition is influenced by cultural and customary practices and food habits.

Moreover, geographical terrain and pedo-climatic conditions profoundly influence plant diversity and cropping composition in these TAFS. For example, in the IEHR, alder-based agroforestry system in Nagaland (Gokhale et al. 1985; Giri et al. 2018), alnus-cardamom agroforestry system in Sikkim (Sharma et al. 2009), piper-based agroforestry systems in southern Assam (Das et al. 2020), and oil-palm-based agroforestry in Lushai Hills, Mizoram (Ahirwal et al. 2022) vary widely in their species composition and function, yet deliver a great variety of ecosystem services and constitute cultural heritage. At the same time, the role of trees in such systems is crucial in sustaining production and improving the environment in rural areas. These systems have withstood the test of time and changing demands and maintained traditional practices that otherwise would negatively affect the culture that defines farmers and their knowledge of the land. The farmers, for many different reasons, grow the trees. Personal preferences, socio-economic status, and culture seem to be the primary determinant of the appearance, structure, and function of many of the TAFS (Reang et al. 2021b). These factors have probably contributed to the TAFS ecological, economic, and social sustainability (Singh and Sahoo 2018). Thus, the anthropogenic selection of trees is one of the determinant factors for maintaining tree diversity. In contrast, the limitation to higher diversity in a specific region might be linked to the unavailability of suitable germplasm and sufficient genetic variability (Watson and Eyzaguirre 2002). It is evident from the literature that there exists an inherent linkage between TAFS and the cultural uniqueness of surrounding communities. However, it is paramount to evaluate the constituent trees and their ability to sequester carbon, store in biomass, and quantify to what extent the farmer-preferred tree species provide carbon service and play an essential role in mitigating climate change.

Notwithstanding the dominant culturally significant and economically important species, they hold significant value from the climate change mitigation. The NITI Aayog (National Institute for Transforming India) in 2018 has recommended recognizing these TAFS as distinct agricultural land use category and emphasized dedicated schemes for their promotion to achieve sustainable development goals in the region. The present study aimed to (i) estimate tree diversity indices of different TAFS located at varying altitudes, (ii) estimate the agroecological importance value of the primary tree species, and (iii) identify the carbon important tree species being managed by the different communities. The present study hypothesized that community-based TAFS varies in relation to (a) species diversity, (b) preferred species, and (c) carbon important species. The study's findings are expected to provide management implications for the rapidly deteriorating environment and eroding culture in the region accentuated further by climate change.

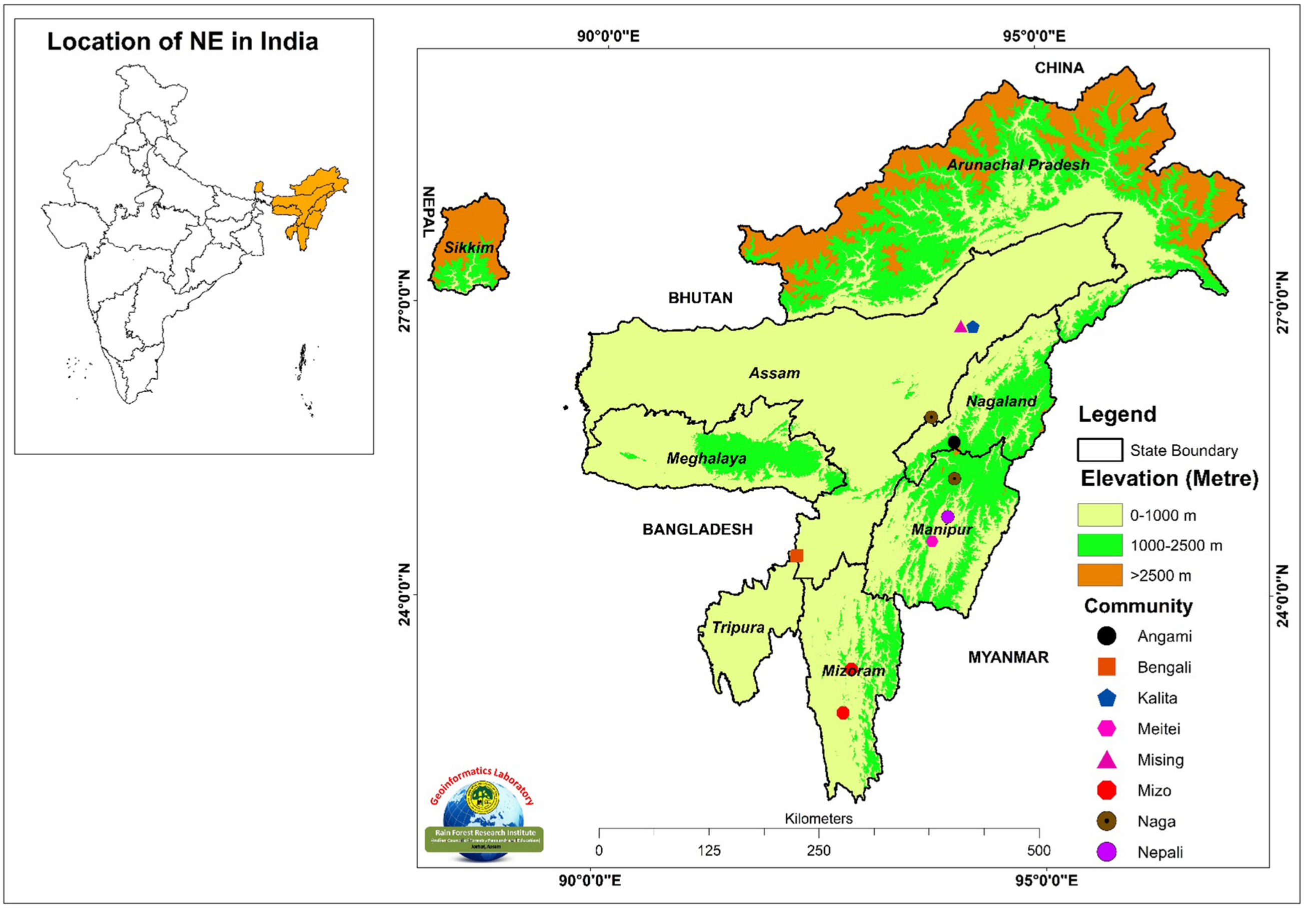

Fig. 1 Elevation map of the study area showing different communities studied

Materials and methods

The study area

The present study was conducted in the IEHR states that lie in the foothills of the Eastern Himalayas and are part of the Indo-Burma biodiversity hotspot (Fig. 1). The Brahmaputra and Barak are the two major rivers with their tributaries and distributaries covering the whole region of the IEHR. The region shares international trade boundaries in the east with Myanmar, west with Bangladesh, and in the north with China, Bhutan, and Nepal. Based on floristic composition, the whole region is divided into two bio-geographic zones: Eastern Himalayas and Northeast India (Chakravarty et al. 2012). Due to abruptly rising hills and high precipitation of monsoon wind blowing from the Bay of Bengal in Arunachal Pradesh and Sikkim constitutes the Easter Himalayas bio-geographic zone. The Northeast India bio-geographic zone with the remaining states is considered the most critical transition zone between the Indian, Indo-Chinese, and Indo-Malayan zones (Chakravarty et al. 2012). The IEHR region is considered the gateway of India's major flora and fauna. The distribution of vegetation from tropical rain forests in the foothills to alpine meadows and cold deserts constitutes one-third of the entire country's biodiversity (Chatterjee et al. 2006; Chakravarty et al. 2012). The region is a confluence of temperate east Himalayan flora, paleo-arctic flora of Tibetan highland, and wet-evergreen flora of Southeast Asia and Yunnan, forming a bowl of biodiversity. Thus, the flora of the region is unique and diverse. Diverse ecological niches in the region result from wide altitudinal variation and significant influence of southwest and north-west monsoon.

Selection of rural and ethnic communities

The IEHR has captured the interest of anthropologists from all over the world due to the great diversity of indigenous communities preferred to live in mountainous ranges ranging from as low as 18 m asl (in Tripura) to as high as 8586 m asl (in Sikkim). These communities differ significantly in tradition and most of them are agrarian. The altitudinal distribution of TAFS up to 1000 and > 1000 m asl was regarded as tropical and sub-tropical agroforestry systems, respectively.

Based on indigenous knowledge of resource management, we purposively selected eight communities for inclusion and elaborated a detailed inventory of their TAFS for the present study.

The Kalita community in Assam is considered next to the Brahmins in the caste hierarchy of the state. According to history, Kalitas are the non-Vedic Aryans who had brought the Aryan culture to Assam (Sharma and Sharma 2005). The ethnic and non-ethnic communities of Assam have rich culture with diverse farming systems. These communities depend on an agrarian economy comprising rice, tea, and sugarcane as the major crops. Agarwood also contributes significantly to the economy of the region (Saikia et al. 2012). Besides, traditional homegarden is also a part of their subsistence.

The Mising (Mishing), an Indo-Mongoloid group called Miri, is the second-largest ethnic group in Assam. Paddy cultivation is the primary agricultural practice of the community. Besides, fishing and home garden management have long been part of their livelihood to cultivate pulses, maize, vegetables, tobacco, bamboo, areca, fruits, etc. (Bhandari 1984). Making household tools and utilities is also part of their livelihood.

Meitei an ethnic community that dominates Imphal valley originated from the Mongoloid group. While most of them are East Asian, some are Indo-European admixture, speak Meiteilon, a Tibeto-Burman language, practice variants of Hinduism, and are mainly agriculturalists. The women members tend to dominate the local market as sellers of agricultural food items and traditional clothing.

Nepali are a group of a community composed of different sub-cultural stock, composed of two distinct races (Mongoloid that constitute 80%, while Aryan 20% of the total population). In Manipur, Nepalese are settled mainly in the Senapati district and practicing agriculture, with cow rearing as the primary source of living.

Mizo an indigenous community covering several ethnic groups who speak the Kuki-Chin-Mizo dialect and prefers to live in the highlands. Mizo is a close-knit society that practices shifting cultivation (locally known as *Jhum*) as a primary livelihood source. Homegardening is another integral part of most rural households.

Naga is a major ethnic group living on the Indo-Burma border occupying the Ukhrul and Kamjang districts of Manipur and Somra tract hills of Burma. Each *Tangkhual Naga* village has its dialect, and its culture revolves around traditional beliefs and customs. The majority of them follow Christianity have traditional home gardens and shift cultivation as a subsistence source. The group culturally share a close affinity with *the Meitei* community of Imphal valley. Naga (Reang), also known as Bru, is one of the Tripuri clan of the Indian states of Mizoram and Tripura. However, some of its community has settled in Nagaland, who speak Reang dialect of Kokborok language, Tibeto-Burmese in origin, and practice shifting cultivation as the primary source of livelihood.

Angami is a Naga tribe inhabitant of Khonoma village of Kohima, Nagaland. Khonoma, the first Green Village of India and also an Asia region declared in the year 2005, is located about 20 km from the state capital of Nagaland and referred to as Khwunoria (named after the Angami term for a local plant, *Gaultheria fragrantissima*). The origin of this village is estimated to be around 700 years old and spread over an area of 123 km^2. The village is well known for *Alnus nepalensis* (Himalayan alder)–based shifting cultivation system in the Eastern Himalayan region of India. The Angami community has maintained about 100 years old alder trees in their farmlands for crop cultivation in a sustainable manner without destroying the surrounding forest areas (Giri et al. 2018). Their ancestors, who have maintained the system for millennia, have handed down this traditional *Jhum* cultivation practice to Angami people.

Bengali community can be traced back to the British colonial period when East India Company (EAC) relied upon their policy framing and legal and revenue administration of acquired Assam on Bengali Amlahs (administrative officials). The modern-day Bengali of Northeast India became culturally diverse due to the composition of Hindu and non-Hindu groups. It can also trace back to the Pundras, Suhmas, and Vengas—tribes that flourished in the Bengal even before the first century AD who were textile workers and cultivars of paddy. With the advancement in knowledge, to fulfill the economic needs, the Bengali community enhanced their cultivation and management systems. Homegarden forms an essential constituent of their landscape.

Plot selection and vegetation sampling

We analyzed the TAFS for their physiognomic composition (species composition, structure, architecture, etc.), variability, and biomass carbon storage. Usually, due to steep terrain and small, marginal, and fragmented land holdings which had compacted sampling quadrat sizes, and it ranged between 0.01 and 0.1 ha. Two-stage sampling was followed to execute the objectives. At the first stage, 10 quadrats were laid randomly over the selected agroforestry systems in each selected community (Nath et al. 2020). Trees within each laid quadrats were enumerated and circumference at breast height (CBH) at 1.37 m above the ground was measured. At the second stage, a simultaneous questionnaire survey was conducted with the land owners of the agroforestry systems to ascertain their preference for tree species in their managed systems. The farmers' ranking was calculated based on the cumulative weightage of agroecological, economic, and cultural importance values. Agroecological importance value refers to the dominant species (calculated based on importance value index, IVI); the economic importance of a species was determined by that species' percent economic contribution to the home garden profit. The use value of the species determined the relative cultural importance (RCI). Farmers raised a species in a home garden for various uses such as construction, food, fodder, medicine, and others and derived other non-tangible benefits such as soil protection, water conservation, soil fertility enhancement, easy management option, etc. Use value illustrated the relative local importance of trees and calculated as $\Sigma Ui/N$, where Ui is the number of uses mentioned by each respondent for a given species and N is the number of the respondent. Farmers gave weightage to each of these determinant factors while making the choice for tree species to be planted. Tree biomass was estimated using the biomass equation proposed by Nath et al. (2019) for North East India [$AGB_{est} = 0.18D^{2.16} \times 1.32$; where D is the diameter at breast height (1.37 m)]. Additionally, due to differences in the tree architecture of *Alnus nepalensis*, *Areca catechu*, and *Cocos nucifera*, their respective biomass equation proposed by Sharma (2011), Das et al. (2021), and Kumar et al. (2016) were used. Following the IPCC Guideline (2006), a conversion factor of 0.47 was used to compute the biomass carbon data. The qualitative description of the study sites is presented in Table 1.

Statistical analyses

Ahead of formal analysis, normality of data was tested using the Shapiro–Wilk test, and homogeneity of variances was tested using Levene's test. Mean difference was analyzed through one-way ANOVA (least significant difference LSD) and one-sample t-test at $p < 0.05$ and correlated by Spearman's rho. All the statistical analyses were performed in IBM SPSS Statistics 21.

The vegetation data was analyzed with diversity indices like the Shannon–Wiener diversity index (Shannon and Weaver 1963), species richness (Margalef 1958), and species evenness (Pielou 1966). The importance value index (IVI) of each species was calculated as the sum of *Relative density + Relative frequency + Relative dominance* (Nguyen et al. 2014). Tree density per hectare was calculated by the expanded values of each 0.01, 0.04, and 0.1 ha quadrat by multiplying with hectare conversion factors 100, 25, and 10, respectively (Das et al. 2020). The top five tree species based on the relative dominance (importance value index), carbon storage, and farmers' preference in all TAFS were evaluated. Similarity indices were estimated by the Sorensen similarity index (Kent and Coker 1992). The basal area (m^2 ha^{-1}) of each quadrat was estimated from the extrapolated values of each stem into hectares by multiplying the stem density and averaging (Brahma et al. 2018).

Results

Community-managed tropical and sub-tropical agroforestry systems were found to be rich with 100 different plant species. Kalita, Mising, Bengali, Meitei, Nepali, Mizo, Naga, and Angami communities were found to manage 23, 29, 19, 13, 14, 35, 20, and 8 different plant species respectively in their tree-based farming systems.

Tree diversity

The Shannon diversity index ranged between 1.78 and 3.47, where Mizo TAFS harbor the maximum diversity and Angami the lowest with the total dominance of alder trees across the entire study area. The maximum and minimum tree diversity in the tropical agroforestry was found in Mising (3.01), and Meitei (2.54) ethnic communities. Similarly, species richness was the highest in Mizo (4.82) and the lowest in Angami (1.09) among all the studied agroforestry systems. The species richness in Meitei and Mising communities was found to be 2.04 and 4.23, respectively (Table 2). In tropical agroforestry systems, the highest species evenness index (0.99) was found in Meitei and the lowest (0.89) in Kalita, Mising, and Bengali communities. The highest and lowest evenness index in the sub-tropical agroforestry system was 0.99 in Naga and 0.86 in Angami TAFS. The highest (5200 stems ha^{-1}) and the lowest (363 stems ha^{-1}) tree density was recorded in the agroforestry system managed by the Bengali and Meitei communities respectively, which significantly differed between the groups ($p < 0.01$, $F = 1453.64$) (Table 2). A non-significant negative correlation was observed between species evenness and tree density among all the communities ($p = 0.244$, $r = -0.466$).

Biomass carbon

Total biomass carbon of tropical agroforestry systems managed by different communities ranged between 4.72 Mg ha^{-1} (Meitei) and 29.26 Mg ha^{-1} (Bengali). In the sub-tropical systems, the highest and the lowest biomass carbon was observed in Mizo (10.93 Mg ha^{-1}) and Angami (6.05 Mg ha^{-1}) (Fig. 2; Supplementary Table 1a–h). Total biomass carbon significantly differed ($p < 0.05$, $t = 3.530$) between the TAFS and was significantly correlated with tree density ($p < 0.01$, $r = 0.976$) and basal area ($p < 0.05$, $r = 0.833$).

Among the tropical systems, the contribution of the top five species to biomass carbon ranged from 54.11 to 71.96% (Mising–Meitei), and in sub-tropical systems ranged from 34.15 to 91.20% (Mizo–Angami) (Fig. 3). The values significantly differed ($p < 0.01$, $t = 9.917$, $F = 119.51$) when

Table 1 Site-specific description of the selected TAFS

System	Rural communities	Elevation (m)	Annual rainfall (mm)	Mean temperature (°C)	Management attributes	Soil textural class	Land use history
Tropical agroforestry	Kalita	63–94	2700	23.70	They mainly use their homegarden for cultivation of seasonal vegetables. Pond is common in most of the households. Cows are very common and used for milk production and cow dung is used as manure	Clay loam	Since centuries
	Mising	67–79	2700	23.70	Mising tribe use their homegarden for cultivation of seasonal vegetables. They inhabit near the Brahmaputra river and plant mainly *Bambax ceiba* trees along the farm to reduce soil loss through erosion. Weaving is the common practice among the women for economic support	Clay loam	Since centuries
	Bengali	25–40	3300	25.80	Periodical planting, harvesting of trees, crop rotation, use of organic residues including cow dung	Sandy clay loam	Since five decades the land is in constant use under homegarden agroforestry system
	Meitei	798–829	1225	21.28	Multiple cropping and crop rotation practiced; seasonal crops are grown in sunken beds and perennial crops in flat beds; fields are surrounded by agroforestry trees such as *Parkia timoriana, Mangifera indica*, *Punica granatum*, etc.; soils are periodically nourished with cow dung and dried chicken feces; irrigation is mostly rainfed; however, ponds are also common in most of the localities	Sandy clay loam	Since centuries
	Nepali	570–710	2085	22.92	Mixed cropping practiced; agroforestry trees are mostly fruit-bearing or fodder giving; cows are mostly reared and used for milk production and dried ruminant as fertilizer; well is common in most of the household	Sandy clay loam	Since five decades
Sub-tropical agroforestry	Mizo	1460–1676	2805	21.22	Cultivating diverse crops suiting to households' need; cutting, lopping, and pruning of trees to meet fuelwood and small timber requirements; ruminant animals often integrated into the system and their by-products incorporated into soil to enhance crop yield; womenfolk contributing mostly to agroforestry management	Sandy clay loam	Since centuries
	Naga	1442–1600	2200	20.48	Mixed cropping of need-based crops such as wild indigenous edible plants with common vegetable crops; leguminous trees are retained and pruned periodically to improve soil fertility; women are the main cultivators and are responsible for selection of species for planting in home gardens; irrigation is mostly rainfed	Sandy clay loam	Since centuries
	Angami	1400–1900	2200	17.30	*Alnus nepalensis* (alder) trees of more than 100 years of age are maintained in the crop fields for soil fertility enrichment. Pollarding operation is carried out during crop cultivation period followed by abandoning the land after 2 years of cultivation for natural build-up of soil fertility and regeneration of vegetation for 3–5 years	Sandy clay loam	Since centuries

Table 2 Diversity indices of tropical and sub-tropical agroforestry systems managed by different rural and ethnic communities

Systems	Rural communities	Species diversity	Species richness	Species evenness	Tree density (stems ha^{-1})
Tropical agroforestry	Kalita	2.80	3.40	0.89	649 (38)ae
	Mising	3.01	4.23	0.89	751 (49)a
	Bengali	2.61	2.10	0.89	5200 (362)b
	Meitei	2.54	2.04	0.99	363 (21)ce
	Nepali	2.55	2.09	0.97	498 (54)e
Sub-tropical agroforestry	Mizo	3.47	4.82	0.98	1155 (105)d
	Naga	2.96	2.99	0.99	575 (61)ace
	Angami	1.78	1.09	0.86	626 (73)ae

Value within parentheses are standard error of mean; the same letters under each column represent non-significant difference ($p<0.05$) as per LSD test

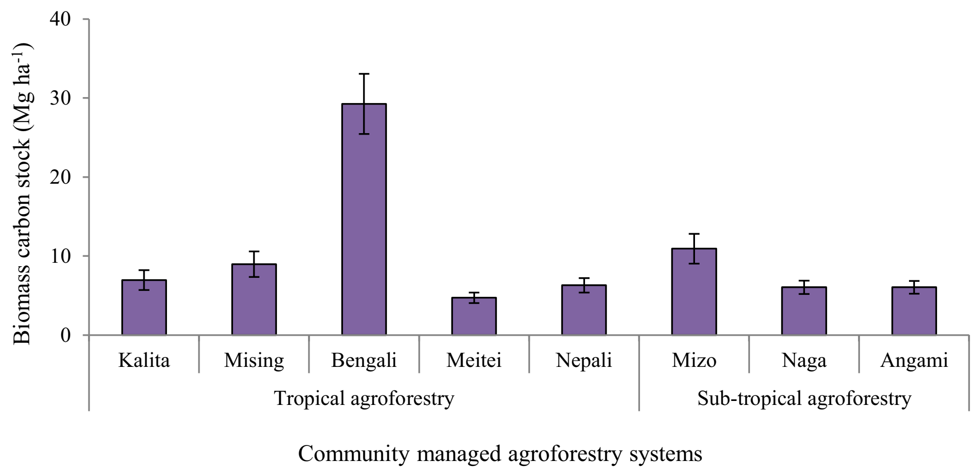

Fig. 2 Total biomass carbon stocks of TAFS under different community management. The error bar represents the standard error of the mean

compared between the ethnic groups managing different TAFS systems.

Biomass carbon contribution of top five species within a community

In the tropical system managed by the Kalita community, *Mangifera indica* contributed the highest biomass carbon (1.1 Mg ha^{-1}), while the lowest by *Areca catechu* (0.183 Mg ha^{-1}). In the Mising community AFS, the highest and the lowest biomass carbon contributing species were *Amoora rohituka* (0.614 Mg ha^{-1}) and *Cocos nucifera* (0.296 Mg ha^{-1}). In the Bengali community, the highest and the lowest biomass carbon storage species were *Aquilaria malaccensis* (3.511 Mg ha^{-1}) and *Eleocarpus* sp. (1.013 Mg ha^{-1}). In Meitei and Nepali communities, the highest biomass carbon storage was *Parkia timoriana* (0.561 and 0.482 Mg ha^{-1} respectively), while the lowest was *Toona ciliata* (0.158 Mg ha^{-1}) and *Delonix regia* (0.317 Mg ha^{-1}) (Fig. 4A–E).

Biomass carbon (kg ha^{-1}) observed to be significantly positively correlated with tree density of the top five carbon important species (stems ha^{-1}) for Bengali ($p<0.05$, $r=0.894$), Meitei ($p<0.01$, $r=0.980$) and Angami ($p<0.05$, $r=0.910$) community.

Species similarity and occurrence

Among the top five biomass carbon important species, the Sorensen's similarity index represented the highest similarity of tree species managed by Nepali and Mizo (0.6) and the lowest species similarity (0.2) between Kalita and Mising, Kalita and Nepali, Bengali and Meitei, Meitei and Naga, Nepali and Naga. However, Angami community did not show any similarity with any other TAFS (Table 3).

A total of 31 biomass carbon important species were found across all the TAFS. Among these, *Artocarpus heterophyllus* had the highest occurrence (50%) followed by *Parkia timoriana* (37.5) and *Amoora rohituka*, *Delonix regia*, *Mangifera indica*, and *Toona ciliata* (25% for each species). The high valued cash crops like *Aquilaria malaccensis* and *Areca catechu* had low occurrence (12.5%) in the TAF systems managed by different communities (Table 4).

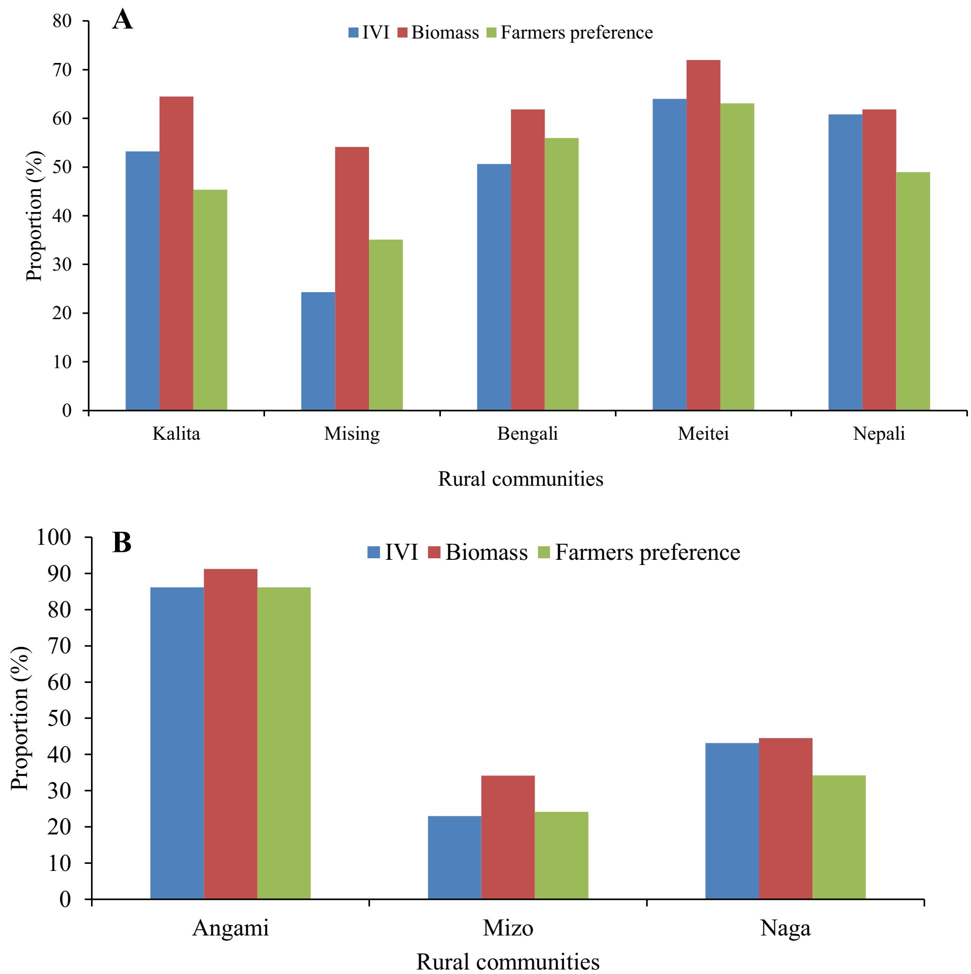

Fig. 3 Biomass carbon contribution by top five species based on IVI, biomass storage, and farmers' preferred tree species in **A** tropical and **B** sub-tropical traditional agroforestry systems in the Indian Eastern Himalayan region

Discussion

The community-managed agroforestry systems have been found to act as a buffer to the sustenance of IEHR's natural forests that are subjected to varying constant threats due to the growing demand for resource extraction and over-exploitation of the ever-burgeoning population (Nath et al. 2021a). The studied TAFS were species-rich with higher tree densities that help farmers to meet their multiple household requirements. However, variations in preferred tree species are influenced by the altitude (Chirimwami et al. 2019; Malizia et al. 2020) and the community practicing the system. The choice of species and tree density also varied among the communities. The Bengali and Mizo communities preferred more high-value crops than others did, which may be due to the high intensification of such systems for attaining increased monetary gain. Therefore, TAFS managed by these communities were consistently associated with compact planting of economically valuable tree species (Abebe et al. 2013; Majid et al. 2019; Nath et al. 2020).

Similarly, at high altitude, the farmers' preferred alder (*Alnus nepalensis*) help them to maintain soil fertility through symbiotic nitrogen fixation, faster leaf litter decomposition, and rapid nutrient cycling in the soil–plant system and ensure sustained crop productivity (Gairola et al. 2012; Barrios et al. 2018; Giri et al. 2018). This system promotes mainly alder trees and thus had lower stand density as compared to the other reported TAFS in the region and other parts of India (Ranabhatet al. 2008; Kalita et al. 2016; Brahma et al. 2018; Das et al. 2020; Nath et al. 2020; Kumar et al. 2021). The observed range of species diversity and richness in the present study was in congruence with the range reported by other researchers in the region (Naidu and Kumar 2016; Saikia and Khan 2016; Kanwal et al. 2018; Das et al. 2020; Sinku et al. 2021) and other parts of India (Uthappa et al. 2016; Doddabasawa et al. 2018; George and Christopher 2020; Nath et al. 2021a).

TAFS provide the opportunity for the onsite management of large-sized trees. Due to increased household monetary needs, some farmers have also intentionally introduced economically viable and allied non-timber forest products (NTFPs) trees in their tree-based farming systems (see Nath et al. 2020). Retention of large trees and the introduction of economically important trees have resulted in a significant

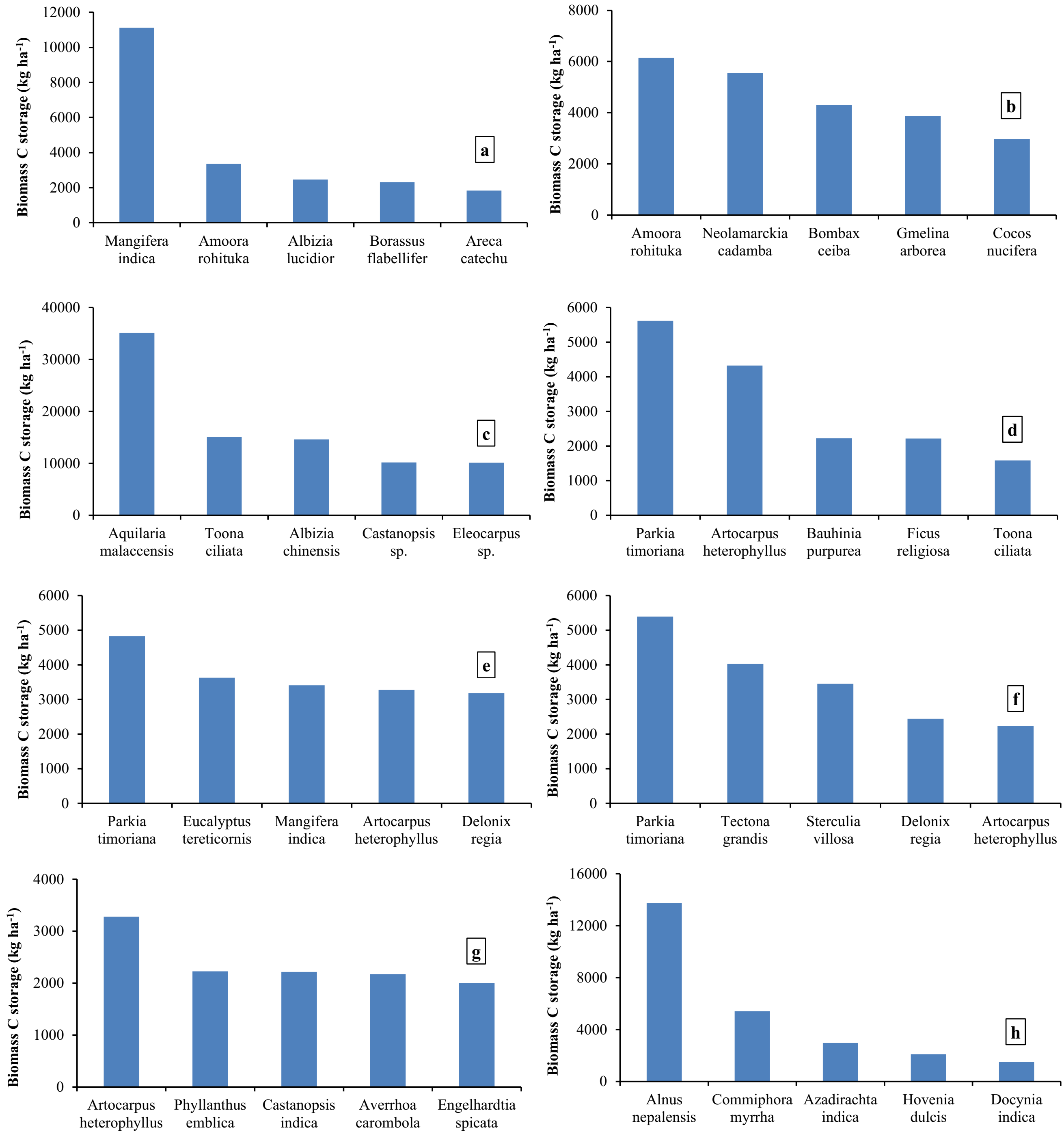

Fig. 4 Biomass carbon storage of top five species managed under tropical (**A** Kalita, **B** Mising, **C** Bengali, **D** Meitei, **E** Nepali) and sub-tropical (**F** Mizo, **G** Naga, **H** Angami) agroforestry by ethnic communities

increase in total biomass carbon in these systems (Khadanga and Jayakumar 2020) and enhanced the net financial gain of the farming communities. The agroecological importance, monetary contribution, ecosystem services, and use value of tree species have caused variation in the top five carbon accumulation among the studied TAFS.

Observations of our study revealed that the farmers' preference for the relative monetary contribution of a species was the determinant factor in the carbon stock potential of these systems. The economically viable tree species were the major contributors to biomass carbon in the studied tropical and sub-tropical agroforestry systems. Among the major biomass carbon

Table 3 Sorensen's similarity index between tropical and subtropical agroforestry systems managed by different rural and ethnic communities

Ethnic communities		Tropical agroforestry					Sub-tropical agroforestry		
		Kalita	Mising	Bengali	Meitei	Nepali	Mizo	Naga	Angami
Tropical agroforestry	Kalita	1	0.2	0	0	0.2	0	0	0
	Mising		1	0	0	0	0	0	0
	Bengali			1	0.2	0	0	0	0
	Meitei				1	0.4	0.4	0.2	0
	Nepali					1	0.6	0.2	0
Sub-tropical agroforestry	Mizo						1	0	0
	Naga							1	0
	Angami								1

Table 4 Occurrence of carbon important species in tropical and sub-tropical agroforestry systems

Species name	Tropical agroforestry					Sub-tropical agroforestry			Occurrence (%)
	Kalita	Mising	Bengali	Meitei	Nepali	Mizo	Naga	Angami	
Albizia chinensis (Osbeck) Merr	-	-	+	-	-	-	-	-	12.5
Albizia lucidior (Steud.) I.C. Nielsen	+	-	-	-	-	-	-	-	12.5
Alnus nepalensis D. Don	-	-	-	-	-	-	-	+	12.5
Amoora rohituka (Roxb.) Wigt & Arn	+	+	-	-	-	-	-	-	25.0
Aquilaria malaccensis Lam	-	-	+	-	-	-	-	-	12.5
Areca catechu L	+	-	-	-	-	-	-	-	12.5
Artocarpus heterophyllus Lam	-	-	-	+	+	+	+	-	50.0
Averrhoa carombola L	-	-	-	-	-	-	+	-	12.5
Azadirachta indica A. Juss	-	-	-	-	-	-	-	+	12.5
Bauhinia purpurea L	-	-	-	+	-	-	-	-	12.5
Bombax ceiba L	-	+	-	-	-	-	-	-	12.5
Borassus flabellifer L	+		-	-	-	-	-	-	12.5
Castanopsis indica (Roxb. ex Lindl.) A. DC	-	-	-	-	-	-	+	-	12.5
Castanopsis sp.	-	-	+	-	-	-	-	-	12.5
Cocos nucifera L	-	+	-	-	-	-	-	-	12.5
Commiphora myrrha (Nees) Engl	-	-	-	-	-	-	-	+	12.5
Delonix regia (Hook.) Raf	-	-	-	-	+	+	-	-	25.0
Docynia indica (Wall.) Decne	-	-	-	-	-	-	-	+	12.5
Eleocarpus sp.	-	-	+	-	-	-	-	-	12.5
Engelhardtia spicata Lechen ex Blume	-	-	-	-	-	-	+	-	12.5
Eucalyptus tereticornis Sm	-	-	-	-	+	-	-	-	12.5
Ficus religiosa L	-	-	-	+	-	-	-	-	12.5
Gmelina arborea Roxb	-	+	-	-	-	-	-	-	12.5
Hovenia dulcis Thunb	-	-	-	-		-	-	+	12.5
Mangifera indica L	+		-	-	+	-	-	-	25.0
Neolamarckia cadamba (Roxb.) Bosser	-	+	-	-	-	-	-	-	12.5
Parkia timoriana (DC.) Merr	-	-	-	+	+	+	-	-	37.5
Phyllanthus emblica L	-	-	-	-	-	-	+	-	12.5
Sterculia villosa Roxb	-	-	-	-	-	+	-	-	12.5
Tectona grandis L.f	-	-	-	-	-	+	-	-	12.5
Toona ciliata M.Roem	-		+	+	-	-	-	-	25.0

contributor species, *Artocarpus heterophyllus*, *Mangifera indica*, and *Parkia timoriana* were selected by the farmers for their fruit and timber yields. *Areca catechu*, *Cocos nucifera*, and high perfumery valued *Aquilaria malaccensis* were solely managed for immediate and long-term household monetary needs. However, other biomass carbon important tree species were selected for their non-tangible farm services and partial contribution to the household economy. Farming communities introduced a variety of multipurpose tree species (MPTs) in their agroforestry systems, and the role of such trees has been reported by several authors across the country (Das and Das 2013; Sahoo and Rocky 2015; Saikia and Khan 2016; Bora et al. 2019; Das et al. 2020; Hauchhum and Singson 2019; Vibhuti and Bargali 2019; Nath et al. 2020; Kumar et al. 2021). Though different MPTs contribute differentially to carbon stock mediated by the growth and age of the species, we found that the coupling effect of tree density and basal area played a significant role in these managed ecosystems' biomass carbon stock potential.

A higher similarity in species between TAF systems within an altitude range revealed that the communities living in such altitudes adopt to cultivate similar tree species unless there is some specific household need from some other tree species. The higher similarity between Nepali and Mizo community TAF systems, a moderate similarity value between Meitei and Nepali and between Meitei and Mizo, and closer similarity values between Kalita and Mising; Bengali and Meitei; Meitei and Naga; and Nepali and Naga confirm to their affinity and culture in tree domestication. However, the restricted ecological amplitude of certain species may not support their growth at high altitude (Acharya et al. 2011; Joseph et al. 2012; Gebrehiwot et al. 2019). Some common MPTs found in tropical and sub-tropical TAF systems include *Artocarpus heterophyllus*, *Parkia timoriana*, *Mangifera indica* valued for their fruits, and *Toona ciliata*, *Amoora rohituka*, and *Delonix regia* for timber extraction. However, high perfumery valued *Aquilaria malaccensis* and economically important *Areca catechu* and *Cocos nucifera* were restricted to tropical TAF. Farmers' preference and regional edaphic and climatic factors affect the abundance and distributions of farm species in different localities across the world (Mulugeta and Admassu 2014; Dimobe et al. 2018). Cultural variations among communities and their remoteness to market often discourage commercially and economically valued tree species, especially at higher altitudes. Similar restricted distribution of dominant tree species at varying altitudes has been reported in different parts of the globe (Gairola et al. 2008; Gairola et al. 2011; Sahoo and Rocky 2015; Gebrewahid et al. 2018; Vibhuti and Bargali 2018; Gebrewahid and Abrehe 2019). Yasin et al. (2019) reported 18 to 51 trees ha^{-1}. The estimated total tree carbon stock ranged from 0.0003 to 8.79 Mg ha^{-1} with the smallest mean value of 0.39 Mg ha^{-1} for tehsil Faisalabad, and the largest mean value of 1.41 Mg ha^{-1} for tehsil Chiniot Pakistan. It was suggested that the increased tree stocking to the farmers' average maximum desired stocking can double the carbon stock in the system. The complete distinctness in species diversity, farmer's preference, and carbon contributing species in alder-based TAF system of Angami community indicate that the practice is unique to a particular geographical location and community-specific.

Conclusions and recommendations

Traditional agroforestry systems maintain tree diversity and have the potential of storing increased biomass carbon. Regarding carbon storage by farmers' preferred and dominant top five species in the IEHR, community-managed TAFS endowed with the limited scope of enhanced biomass storage. However, the TAFS is enhanced with inherited potential to meet the demand–supply of resources for the cultivation managers and biodiversity conservation. Nevertheless, improving community-based TAFS through a selective preference for biomass essential tree species is recommended to enhance these systems' capacity to store the dominant portion of the biomass carbon of exclusive land use.

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Author contribution PCN, UT, and SSK generated the data. PCN and AJN analyzed the data. KG, UKS, and AJN prepared the draft manuscript. All authors (PCN, UT, SSK, UKS, KG, AJN) reviewed and approved the manuscript.

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