Agricultural Systems 215 (2024) 103842

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Does human intervention modulate the above-ground carbon biomass of agroforestry systems? A study of homegardens in Jaffna peninsula, Sri Lanka

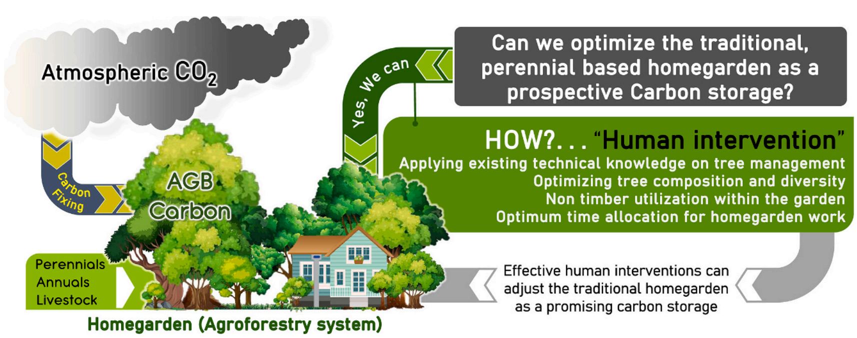
Ayesh Lowe [a,b,*], Niluka Kuruppuarachchi [a], Pradeepa Silva [b], Gamini Pushpakumara [b], Lalith Suriyagoda [b], Jeevika Weerahewa [b]

[a] Postgraduate Institute of Agriculture, University of Peradeniya, Peradeniya, Sri Lanka
[b] Faculty of Agriculture, University of Peradeniya, Peradeniya, Sri Lanka

HIGHLIGHTS

- Humans play a vital role in mediating each element of homegardens, including the above-ground biomass (AGB).
- The study aimed to assess the relations of AGB *vs* human interventions, in modulating homegardens as AGB carbon storages.
- Tree diversity, time spent on homegarden, technical awareness and non-timber usage, significantly affected the AGB.
- The model suggests that effective mediation of humans could optimize traditional homegardens at storing AGB carbon.
- The impact of human intervention on homegardens by means of a promising carbon storage is hardly discussed in literature.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Jagadish Timsina
Guest editor: Jagadish Timsina

Keywords:
Above-ground biomass
Homegarden
Household
Trees
Diversity
Human intervention

ABSTRACT

CONTEXT: Accumulating above-ground biomass (AGB) and conservation of biodiversity are two major services provided by any ecosystem and homegardens are no exceptions. The permanent structure of a homegarden is owing to its perennial tree-community which steadily builds up and maintains the tree diversity and AGB accumulation. Being a manmade agroforestry system, humans play a vital role in mediating each component of homegarden ecosystem including its carbon stock and biodiversity through management of the tree community.
OBJECTIVE: The objectives of this study were to compute the tree diversity and AGB and human interventions in homegarden ecosystem in Jaffna peninsula and to identify the most prominent factors affecting the AGB.
METHODS: A primary survey was conducted capturing 135 homegardens from two agro-ecological regions (DL_3 and DL_4) in Jaffna peninsula (Northern province, Sri Lanka), where homegardens are observed as the primary tree-based vegetation. Data on floral composition, livestock and, household-interventions in homegardens were gathered through a structured questionnaire. Tree diversity and AGB were computed using Shannon-Wiener

* Corresponding author.
E-mail address: ayeshlowe@agri.pdn.ac.lk (A. Lowe).

https://doi.org/10.1016/j.agsy.2023.103842
Received 24 April 2023; Received in revised form 11 December 2023; Accepted 12 December 2023

index (SWI) and carbon stock respectively. A multiple linear regression model was estimated to determine the effects of pre-defined interventions on AGB of homegardens.
RESULTS AND CONCLUSIONS: The study sample consisted of 122 small-scale (<0.2 ha), 11 medium-scale (0.2–0.8 ha) and 02 large-scale (>0.8 ha) homegardens. The mean tree diversity as estimated by SWI was 1.1 ± 0.6 with 38 perennial species and 1286 trees; 32 genera and 17 families. An average homegarden is estimated to store 23.8 ± 20.9 Mg C/ha as AGB. Homegardens which reared livestock animals, had a significantly lower SWI value, yet, a higher AGB stock, compared to the opposed group ($p < 0.05$). The SWI, time allocation (hours) for homegarden/week/ha, technical knowledge on farming and non-timber usage within homegarden have significantly ($p < 0.05$) contributed to the AGB of homegardens, with regression-coefficients of 6.12, 0.02, 1.38 and 7.91, respectively. The results indicate that up-keeping the commitment of households in managing their homegardens contribute to environmental sustainability.
SIGNIFICANCE: The results revealed a significant contribution of human interactions on the size of the AGB of homegardens in Jaffna peninsula. This contribution was not adequately discussed in previously literature and the findings suggest the need to manage human interactions in homegarden agroforestry systems to optimize carbon stock in traditional homegardens.

1. Introduction

Agriculture sector is estimated to be responsible for 25% of the overall greenhouse gas emissions leading to global warming worldwide where CO_2 is the major contributor (Gifawesen et al., 2020). The process of accumulating atmospheric carbon into biomass, carbon sequestration, has now been identified as a promising pathway to reduce greenhouse gases and mitigate matters linked with climate change (Gedefaw et al., 2014; Henry et al., 2009). Carbon sequestration is known as one of the major environmental services of any ecosystem, including homegardens (Kumar, 2006). Accordingly, Roshetko et al. (2002) showed that homegardens can be modified to accumulate carbon as biomass while contributing towards household requirements and other services as well. It is obvious that the natural forest cover plays the primary role in storing atmospheric carbon in Above-Ground Biomass (AGB) (Gedefaw et al., 2014; Yohannes, 2015; Abere et al., 2017). However, Siyum and Tassew (2019) argued that homegardens with an adjoining forest cover also possess a similar capacity in terms of AGB accumulation while Roshetko et al. (2002) and Bargali and Bargali (2020) reported that homegardens could store carbon stocks similar to secondary forests. Susanto et al. (2021) also suggested that the homegarden tree community could be reflected as a selectively logged forest. In that ecosystem, the carbon stock of trees with a diameter at breast height (DBH) of >30 cm has contributed 30% to the total AGB primarily by the dominating fruit tree community aged 0–10 years. Thus, in the long run, atmospheric carbon is fixed significantly in the vegetation of the homegarden, predominantly in its tree community as AGB carbon (Gifawesen et al., 2020).

Species richness and abundance of a homegarden is fundamentally controlled by the landscape structure and the interest of the household members, who make decisions on planting and managing trees. Rooduijn et al. (2018) discussed how the interventions made and supervision of the household members, govern the abundance of each established species within the garden. Karki et al. (2021) and Shahi et al. (2023) presented how the carbon stock in the AGB of an agroforestry system is modulated by precise human interventions. Tropical homegardens tend to have fruit-baring perennial species, the majority of which have been confirmed as species with high CO_2 fixing capacities (Susanto et al., 2021) and, depending on the build and growth rates, and management of the tree communities, they result in higher or lower stocks of AGB carbon in these agroforestry systems. Therefore, it is obvious that there is a promising potential to utilize simple human interventions in optimizing the homegarden towards an enhanced ecosystem for carbon absorption.

Several studies found that tree diversity is the most vital factor to be considered when addressing homegardens as carbon storage. High tree diversity essentially nurtures the AGB of a homegarden ecosystem (Lowe et al., 2022; Baul et al., 2021; Brakas and Aune, 2011; Jaman et al., 2016; Mattsson et al., 2015; Rahman et al., 2021; Siyum and Tassew, 2019). Furthermore, the combination of trees at different ages and different structural statures may also result in significantly higher AGB carbon stocks, when it comes to these man-managed agroforestry systems, *i.e.*, homegardens. As pointed out by Santhoshkumar and Ichikawa (2010), Soemarwoto (1987), Ninez (1985) and Ruthenberg (1971), the tree diversity and convenience of access to the garden are governed by the household members who deliberately manage, modify and change the arrangement of the garden. In this regard, any modifications, which are applicable technically as well as legally to the homegarden in terms of tree composition, could be applied considering expansion, replacement, substitution, and management of the perennial tree community (Pushpakumara et al., 2012).

Homegardens feature a systematic management system among crop-tree-animal units by household members, which essentially linked with the household requirement and level of knowledge (Kumar and Nair, 2004; Lope-Alzina & Howard, 2012). Thus, due to this effective association of crops and trees with animals and fish, homegardens can be viewed as a timely intervention to minimize food insecurity at the household level by providing staple food items at supplement levels, ready to consume food items, and ready to trade products. (Mulugeta, 2014). Both plant based and animal based food items can be incorporated as an element of the homegarden, so that the household can enrich its dietary diversity. According to Talukder et al. (2000), animal-based food items in the diet offer a greater source of micronutrients than plant-based foods, emphasizing the advantage of keeping livestock as a protein food source among the homegarden components.

The compositional arrangement of the tree community of the homegarden can essentially provide for the household with plant based food sources to enhance the dietary diversity and assist domestic food security as well. For an instance, homegarden and its different resources usually provide a variety of food items as a supplement, including staple food, vegetables, fruits, medicines, fodder, livestock, and sometimes fish (Pandey et al., 2017; Pushpakumara et al., 2012). Thus, properly maintained homegardens carry a comparatively undisturbed food production due to the proper combination and management of crops with different life cycles throughout the year (Lope-Alzina & Howard, 2012). However, the tree composition in this regard is primarily influenced by the preferences, requirement and expectations of the household (Mattsson et al., 2015). Therefore, it is an obvious fact that the homegardens could be a timely strategy to address these situations in a more integrated approach.

Some authors consider that humans do not essentially require scientific knowledge and skills to manage a homegarden (Kumar and Nair, 2004) while counter-arguments does exist regarding the opinion. Gajaseni and Gajaseni (1999) discuss that lack of familiarity and knowledge in agronomic practices might suppress the true potential of the resource utilization of a homegarden to its maximum. Accordingly, proper management of the tree community is proved to be the key to the establishment of a sustainable agroforestry system (Gajaseni and

Gajaseni, 1999; Galhena et al., 2013; Kumar and Nair, 2004), where the owner of the homegarden is responsible to ensure the proper founding and survival of the key perennial species of the garden for a sustainable progression. This is an enduring activity that requires critical agronomic decisions at certain points. For an instance, even from the establishment of the homegarden a proper management is required. Thus, the ultimate expectation is that the trees reach proper standing qualities at maturity, ending up as improved carbon-storing units as well as providers for household as well.

The current study was conducted to assess the tree diversity, composition, and role of livestock and poultry in homegardens and AGB. The primary objective was to compute the tree diversity and AGB and human interventions in homegarden ecosystem in Jaffna peninsula and to identify the most prominent factors affecting the AGB. Further, to suggest a generalized model, for the given context, with the most prominent factors affecting AGB of an agroforestry system of Jaffna peninsula in the northern province of the island.

2. Materials and methods

2.1. Location of study

The study was conducted in the Jaffna peninsula of Sri Lanka, which is located in the northern province of the island; 9.6930° N, 80.1652° E in Low Country Dry zone. Jaffna is well known for smallholder agriculture and widespread homegardening. Approximately 50% of the homegardens are engaged in livestock farming activities. The forest cover is relatively lesser in Jaffna and homegardens are observed as the primary tree based vegetation (Jeyavanan et al., 2017; Lowe et al., 2021). Jaffna peninsula is divided into two agro-ecological regions (AERs), namely DL_3 and DL_4 (where DL denotes low country dry zone), which are unique to the northern region and north-western coastal areas of the island (Table 1). The study site represents an exclusive ecosystem along with agricultural activities and ecological conditions owing to its soil types and climate. The DL_3 and DL_4 are considered two of the three AERs which receive the least amount of annual rainfall compared to all other AERs of Sri Lanka (Punyawardena, 2009). DL_3 region consists of Red -Yellow Latosols and Regosols soil types whereas DL_4 consists of Solodized Solonetz, Solonchaks and Grumusols soil types.

2.2. Methods of sampling of homegardens

Homegardens for the survey were sampled along a transect which was identified based on climatic data, elevation gradient, and soil type with the representation of the DL_3 and DL_4 regions. In addition, the transect was identified to capture homegardens which were ranging from urban and suburban to rural areas running up to natural ecosystems of the district. Thus, the transect constructed stretched through four local administrative units (villages); *Jaffna, Kodikamum, Delft Island* and *Kankesanthurai.* Each village consisted of 8–10 surveying points which is a random cluster of homegardens within a 5 km radius. Around 2–4 households were sampled at each surveying point. These surveying points were selected purposively to capture a variation from urban, suburban to rural areas of the village based on observations. The Latin hypercube sampling (LHS) method was adopted to select homegardens for the survey while keeping the sample as random as possible (Minasny and McBratney, 2006). LHS method enables capturing of a nearly random sample, while collectively considering multiple parameters. In addition, it allows to search the desired sample from a multidimensional distribution.

Table 1
Description of two Agro-ecological regions in the study site.

AER	General description of land use systems	Mean annual rainfall (mm)
DL_3	Chili, onion and ground nut cultivation. Scrubbed forests	>800 mm
DL_4	Paddy and field crops. Scrubbed forests	>750 mm

2.3. Method of collection of data

The homegarden survey was conducted in January–March 2019 using a pre-tested questionnaire using an online platform. Face to face interviews were conducted with the head of the household or a key decision-maker of the household. Identification of floral species was done through observations. Woody and non-woody tree species in the garden along with tree stand measurements (DBH measured in 'cm' and height estimated in 'm') of each woody tree were the key information gathered to estimate the AGB of homegardens. All the individual woody trees found in homegardens with a DBH > 5 cm were inventoried to estimate AGB, as described by Baishya et al. (2009), Brakas and Aune (2011), Gedefaw et al. (2014). Non-woody trees (*Musa spp.* and *Carica papaya*) were also recorded as they represented the tree community of the homegardens. Presence of livestock animals in surveyed homegardens was noted as a binary data (yes/no) along with the diversity of animals in terms of different species.

Monthly income of the households, family size and dependency ratio were recorded as the primary socioeconomic data. The respondents were asked whether they utilize non-timer materials within or outside the homegarden. Information on general practices of different agronomic activities and other involvement in the homegarden were also gathered.

Information on homegarden and the interventions made through the household were identified by directing questions on time allocated by the households for homegarden related activities, utilization of timber and non-timber materials, fertilizer management, and practice of various agronomic activities. Altogether 139 homegardens and households were included in the survey. Since four outliers were identified after adopting the Grubbs' test, the final sample consisted of 135 homegardens.

2.4. Methods of analysis of data

Demographic characteristics of the households of each homegarden were presented using descriptive statistics. Species richness was recorded as the total number of woody tree species observed in a homegarden and the abundance was presented as the total number of individual trees.

Due to the lack of properly validated methods on calculating the biomass of tropical tree species, including the species prevailing in Sri Lankan homegardens, most commonly used general allometric models which are developed with critical validation process of an extensive datasets were applied in the study. Hence, the Pantropical allometric equations which have been developed for tropical natural forests by Brown (1997), Chave et al. (2005) and, Hairiah et al. (2010) were used

Table 2
Equations used to calculate above-ground carbon Y = AGB (Mg/ha), D=DBH (cm), H=Height (m), S=Wood density (g/cm^3).

	Biomass category	Equations	References
a	Individual trees (dry forest)	$Y = exp[-2.187 + 0.916 \times ln(D^2 \times H \times S)]$	Chave et al., 2005
b	Individual trees (moist forest)	$Y = exp[-2.977 + ln(D^2 \times H \times S)]$	Chave et al., 2005
c	Palm trees	$Y = exp[-2.134 + 2.530 \times ln(D)]$	Brown, 1997
d	Banana	$Y = 0.030\ D^{2.13}$	Hairiah et al., 2010

to calculate AGB (Table 2). For an instance, among many other recent studies which had a similar interest, Kassa et al. (2022) and Susanto and Kartawinata (2021) have also used the same equations to estimate the AGB, while emphasizing the validity of these equations. These equations were applied to each tree separately to estimate the AGB of individual trees and summed up to estimate the total AGB of the respective homegarden. The computed AGB was then transformed to aboveground carbon stock considering that carbon accounted for 50% of the total AGB of the studied system (Brown, 1997).

The tree diversity data which were recorded during the survey by means of species richness and abundance of each species, were used to calculate the Shannon Wiener index (SWI) (Eq. (1)) (Shannon et al., 1950; Spellerberg and Fedor, 2003)

$$H\ (SWI) = -\sum (p_i) \times ln(pi) \tag{1}$$

where, H=SWI, p_i = proportion of total sample represented by species, i = proportion of species relative to total number of species.

Summed Dominance Ratio (SDR) was calculated (Eq. 2) using relative density (RD) and relative frequency (RF) of perennial species to identify the most dominant species in a homegarden (Chen et al., 2014; Rahman et al., 2017a, 2017b; Whitney et al., 2018). The SDR value can be used to identify the most valuable and useful species for a given cluster or an area (Whitney et al., 2018).

$$SDR = (RD + RF)/2 \tag{2}$$

Where, SDR = Summed Dominance Ratio, RD = Relative Density (total number of individuals of a crop/Total number of individuals of all crops) RF = Relative Frequency (total count of homegardens in which a crop occurred/sum of counts of all crop occurrences in all homegardens surveyed).

To determine the importance value of a species relative importance value (RIV) was calculated as stated in Eq. (3), using relative frequency (RF) and relative dominance (RD'; Eq. (4)) of perennial species.

$$RIV = RF + RD^{'} \tag{3}$$

$$RD^{'} = \frac{Total\ basal\ area\ of\ all\ individuals\ of\ a\ certain\ species}{Total\ basal\ area\ of\ all\ individuals\ of\ all\ species} \tag{4}$$

Independent variables which were hypothesized to possess an effect on the AGB of homegardens are listed in Table 3. Selection of determinant factors on AGB of homegardens along with the sources of references. The AGB was regressed with those variables.

The variable named 'technical knowledge' was constructed to illustrate commitments of the household for technology-based practices namely, changing planting dates, introducing high-yielding, pest and disease-resistant varieties, changing agronomic practices, fertilizer management, utilization of timber and non-timber materials within and outside the homegarden, and application of soil and water conservation methods (mulching, building terraces, and shading). A binary score (one and zero for presence and absence, respectively) was assigned to each activity. Thus, the composite score was calculated by aggregating the value of individual scores obtained from each question. The effect of presence of livestock animals on tree diversity and AGB was assessed by applying a *t*-test.

Table 3
Selection of determinant factors on AGB of homegardens.

Variable	Unit	Sources adopted from
SWI of homegardens	No unit	Korale-Gedara et al., 2012
Frequency of time allocation per hectare	Hours per ha per week	Santhoshkumar and Ichikawa, 2010 Soemarwoto, 1987;Ninez, 1985; Ruthenberg, 1971
Technical knowledge of farming	Composite score	Daulagala et al., 2013; Galhena et al., 2013; Kumar and Nair, 2004; Teklehaimanot and Hall, 2012; Weerahewa et al., 2012; Soemarwoto, 1987
Non-timber usage inside the homegarden (binary)	No unit	Santhoshkumar and Ichikawa, 2010; Landon-Lane, 2011

3. Results

3.1. General description of the homegardens

The average family size of the households surveyed was four members with a dependency ratio of 0.85. Of the respondents, 78% were males and the average age was 53 years. A regular homegarden had an average land extent of 0.1 ha which comprised of different floral species that help in income generation and in supplying domestic food necessities. Fifty percent of the households had livestock (cattle, goat, poultry, or any combination of the mentioned animals). The homegardens represented a standard perennial tree-based agroforestry system, with poor tree diversity.

A large majority of the homegardens were small-scale with an average extent of 0.07 ha. An average household income was around 28,000 LKR per month and agriculture related activities were also contributing to that (Table 4).

The two AERs in Jaffna peninsula; DL_3 and DL_4 are illustrated in Fig. 1. The majority of the homegardens surveyed (84%) were located in DL_3 which is dispersed on the main island. There's an intermediate common area between DL_3 and DL_4, which has mixed features and ecological conditions of the two regions, but could not be classified as a new AER. The common region is named DL_3&DL_4.

3.2. Tree diversity, composition, SWI and presence of livestock animals

During the homegarden survey, a total of 1286 perennial individual trees belonging to 38 species were inventoried along with tree stand measurements (height and DBH). These perennial species belonged to 32 genera and 17 families. Other than the recorded perennials, banana (*Musa spp.*) and papaw (*Carica papaya* L.) were also observed in homegardens, which were categorized into non-woody perennial species. In this study, homegardens in the Jaffna peninsula were described using perennial trees and tree diversity which consists on average of nine individual trees with a mean richness of four and SWI value of 1.10 ± 0.58. The total land extent of homegardens covered in the study was 13.72 ha where the mean perennial species found per ha of homegarden was 65 and the mean individual trees per ha of homegarden was 136.

Most of the homegardens had a land extent of <0.2 ha (small scale) (Table 5). Only 11 and 02 homegardens were identified as medium (0.2–0.8 ha) and large scale (>0.8 ha), respectively. The calculated floristic diversity indices such as richness, abundance and SWI, and AGB among the small, medium, and large scale homegardens were similar. Thus, large-scale homegardens were considered a rare observation in the study site. (See Table 6.)

As depicted in Fig. 2, >90% of the recorded species were captured within 106 homegardens (78.5% of the total). In addition to that, the same trend was observed in the species-area curve, by capturing 90% of

Table 4
Brief summary of the study sample of homegardens.

Parameter	Small scale	Medium scale	Large scale	Overall
Sample size (n)	122	11	2	135
Family size	4 ± 1	3 ± 2	3 ± 1	4 ± 2
Dependency ratio*	0.88 ± 0.86	0.64 ± 0.67	0.50 ± 0.71	0.85 ± 0.84
Household monthly income (LKR)	29,616 ± 25,976	21,518 ± 14,528	19,500 ± 27,577	28,806 ± 25,238

[*] The dependency ratio was calculated by dividing the number of dependent members in the family by the number of independent members in the family.

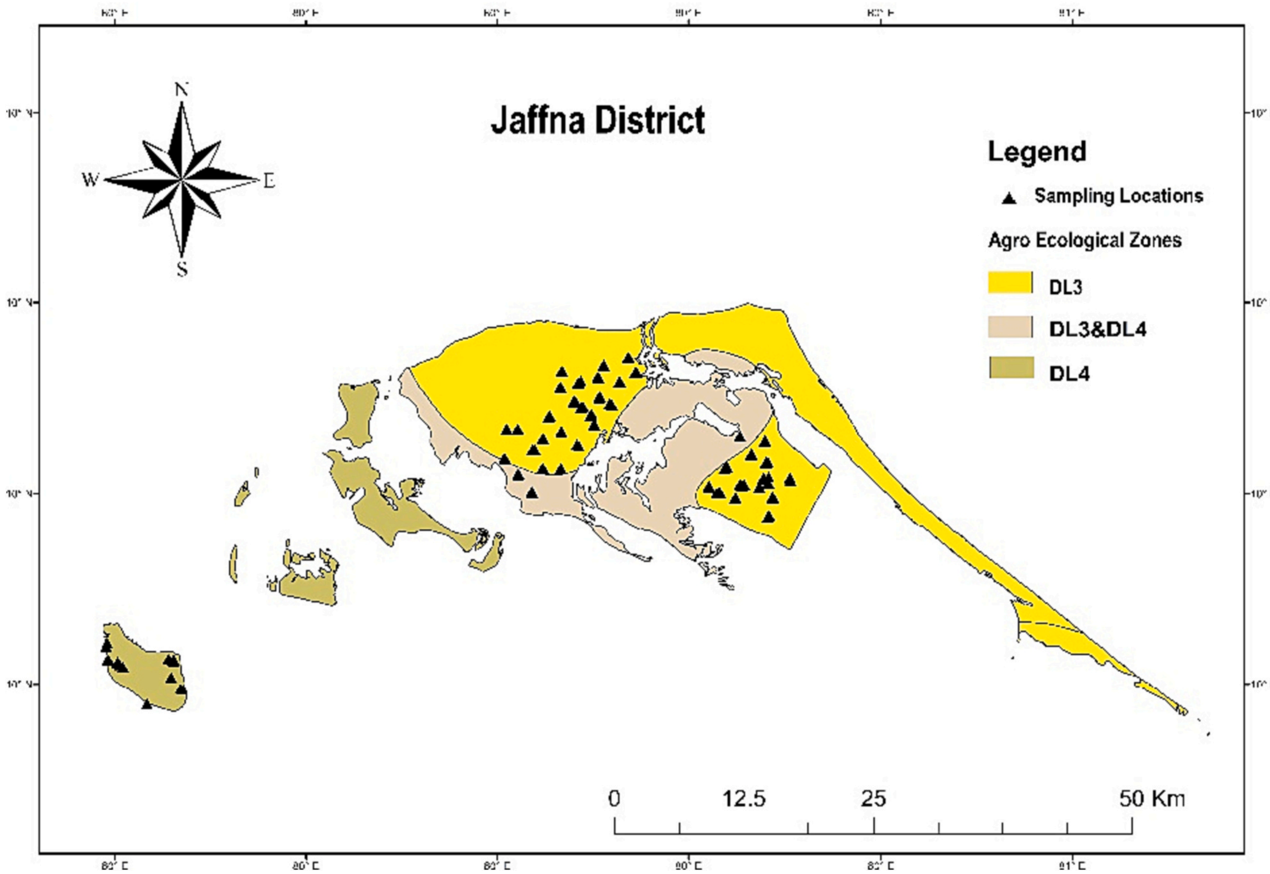


Fig. 1. Distribution of the survey sample across the captured agro-ecological regions; DL3, DL3&DL4, and DL4.

Table 5
Summary of floristic data and AGB of the homegardens (n = 135).

Parameter	Small scale	Medium scale	Large scale	Overall
Sample size (n)	122	11	2	135
Mean richness	4 ± 2	3 ± 2	6 ± 3	4 ± 2
Mean abundance	9 ± 7	14 ± 11	19 ± 21	10 ± 7
SWI	1.12 ± 0.58	0.80 ± 0.49	1.69 ± 0.12	1.10 ± 0.58
Mean extent/HG (ha)	0.0671 ± 0.0295	0.3196 ± 0.1581	1.0116 ± 0.2861	0.1017 ± 0.1436
Species per ha	71 ± 45	11 ± 7	6 ± 1	65 ± 47
Trees per ha	146 ± 104	48 ± 40	16 ± 16	136 ± 104
Mean AGB (Mg C/ha)	25.24 ± 21.23	11.52 ± 11.25	3.23 ± 2.88	23.80 ± 20.91

HG: Homegarden, ±Standard deviation.

Table 6
Multiple linear regression analysis on determinants of AGB.

Variable	Mean(±SE)	Coefficient	p
AGB (C Mg/ha): *Dependent variable*	23.80 ± 1.80		
Independent variables			
Constant		1.340	0.000
SWI	1.11 ± 0.05	6.120	0.036
Time allocation for homegarden (hours/ week/ha)	184.37 ± 13.90	0.020	0.053
Technical knowledge of farming (Score)	5.64 ± 0.28	1.381	0.020
Non-timber usage inside the homegarden	Yes = 71 (53%)	7.910	0.038
	No = 64	N/A	N/A

(R^2 = 14.77, p = 0.000, F = 6.81)

the recorded species with 85% (11.64 ha) of the total land extent surveyed.

Tree diversity, species richness, and abundance between the two AERs were similar ($P > 0.05$). Still, in Jaffna, there's a combined AER (DL_3&DL_4) identified that deliberately possesses characteristics of both DL_3 and DL_4 (Punyawardena, 2009). However, despite having a small sample size, (n = 06) DL_3&DL_4 region appeared to be having a higher number of trees as well as species per hectare compared to the other two regions, resulting in a higher SWI.

C. nucifera (*Cocos nucifera* L.*)* was the most dominant and abundant perennial crop recorded in homegardens in Jaffna, followed by mango (*Mangifera indica* L.), neem (*Azadirachta indica* A. Juss.), arecanut (*Areca catechu* L.) and jackfruit (*Artocarpus heterophyllus* Lam.). A total of 556 *C. nucifera* trees were recorded, which explained 43% of the total recorded individual trees, in 87% of the homegardens in the study sample. The summed dominance ratio (SDR) which combined both frequency and abundance of a given species showed that *C. nucifera* was dominating the tree community by 32%, followed by mango, neem, and jackfruit. Similarly, according to the relative importance value (RIV), *C. nucifera*, *M. indica*, *A. indica*, *A. heterophyllus*, and palmyra (*Borassus flabellifer* L.) were noted as the top five most important tree species in an average homegarden in Jaffna (Fig. 3). Both SDR and RIV were represented by the same set of perennial species with minor deviations in their rank of importance or dominance.

People in the *Jaffna* district had shown a significant interest on rearing domesticated livestock animals as an animal based food source at subsistence levels and also as an additional income source. About 50% of the homegardens assessed in *Jaffna* had livestock (Jeyavanan et al., 2017; Lowe et al., 2021), where the most common animal species was chicken (*Gallus gallus domesticus*), while cattle (*Bos spp.*) and goat (*Capra aegagrus hircus*) were found in lesser numbers. In *Jaffna,* 06 (4%)

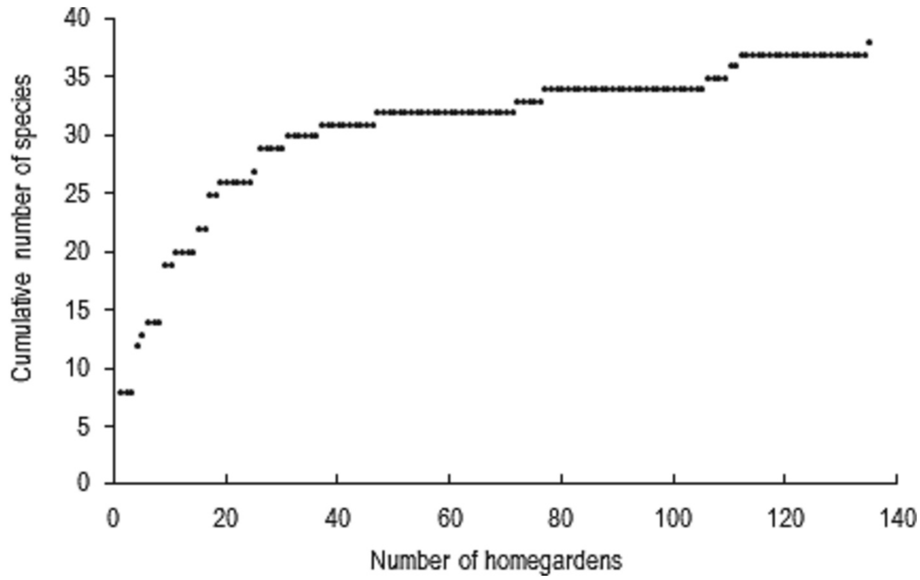


Fig. 2. Perennial species accumulation curve of the study sample.

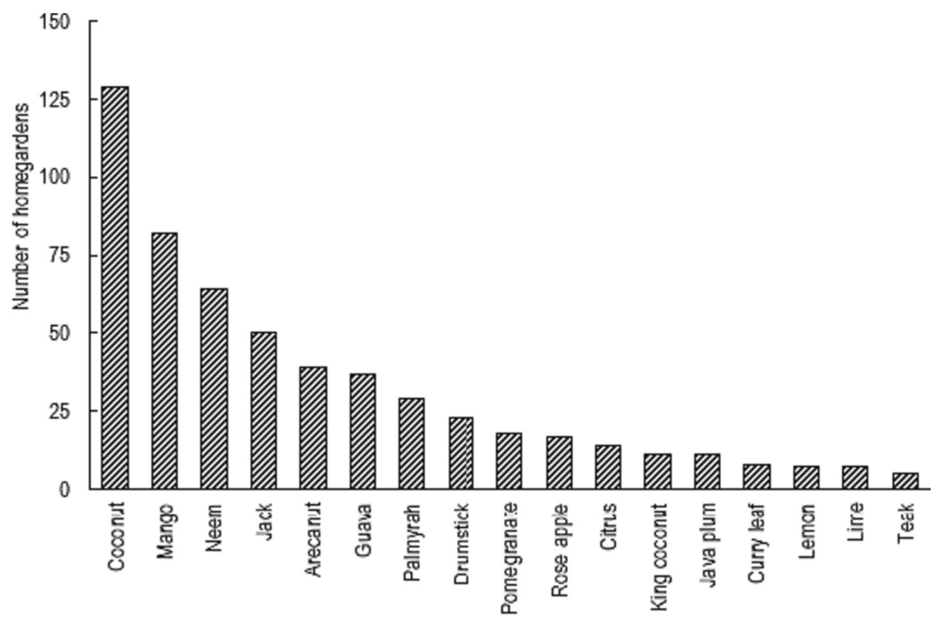


Fig. 3. Most commonly observed perennial species in Homegardens of Jaffna peninsula.

homegardens had combination of livestock; cattle and goats with poultry, and 34 (23%), 26 (18%) and 22 (15%) homegardens had only poultry, goats and cattle, respectively (Lowe et al., 2021).

However, raring livestock stated no significant effect on the total household income which implies that the livestock are being kept for other values such as; aesthetic value, nutritional value, ready to trade property *etc.*, rather than regular income generation activity. It was interesting to note that the households which produced livestock products, tend to share the excess produce in some situations (Fig. 4). However, understandably the primary act was to consume and sell the excess produce to earn an extra income.

Being one of the easily managed backyard animal species, keeping poultry in homegardens could be highly beneficial. However, raring cattle and goats in homegardens indicated no effect on milk and milk based food consumption in Jaffna homegardens indicating that consumption of milk based products do not get affected by the availability of dairy animals in homegardens in the study area.

3.3. Contribution from perennial crops and livestock to the household in terms of income

Both perennial trees and livestocks act as food and income sources that increase the livelihood diversity of the households. Around 33%, 27%, 12% and, 19% of households have obtained income from coconut, fruits, egg and animals and >30% of households were able to get income from the other sources as well (Fig. 5). The household income gained from the homegarden ranged from zero to 1,320,000 (22,435 ± 11,7629) LKR.

3.4. Above-ground biomass carbon (AGB)

The mean AGB of an average homegarden in Jaffna was 23.80 Mg C/ha with a wide variation (range: 0.06–105.06 Mg C/ha and the coefficient of variation was 88%). The lowest mean AGB was recorded in DL_3 while the highest was recorded in DL_3&DL_4. This high variation was

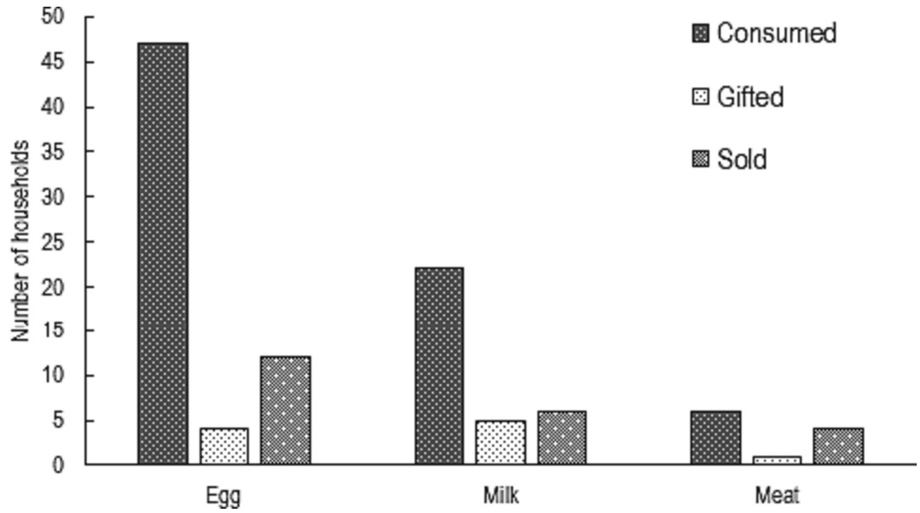


Fig. 4. *Three main ways of utilizing livestock products originated from homegardens in Jaffna (Lowe et al., 2021).*

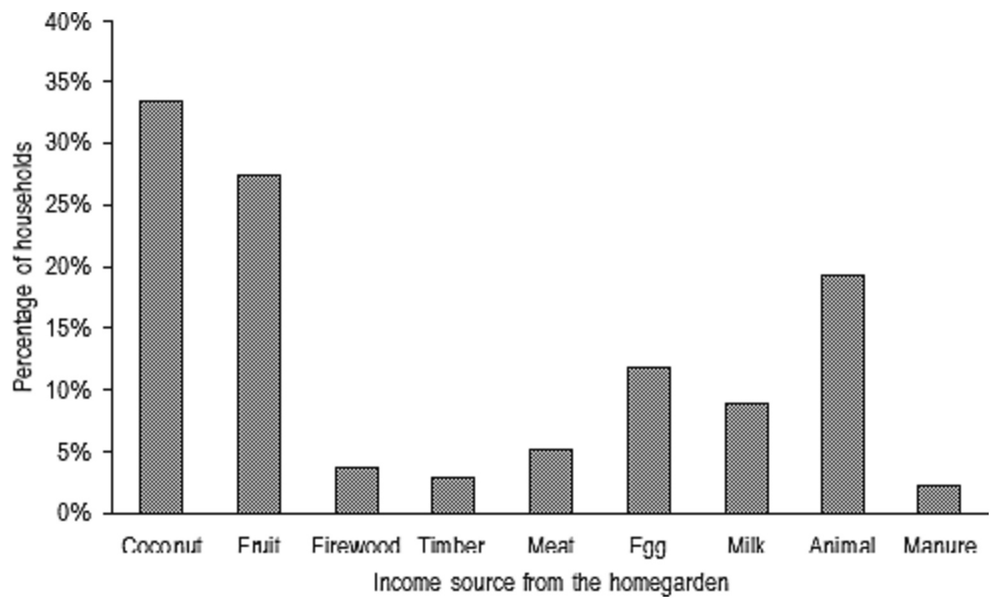


Fig. 5. Different income sources recorded from homegardens in Jaffna.

observed owing to the highly diverse nature of homegardens under various levels of supervision. Combining the dominance and abundance, the top contributors to the overall AGB were observed as *C. nucifera*, *M. indica,* and *B. flabellifer*, followed by *A. indica*, *A. heterophyllus*, and guava (*Psidium guajava* L.). >90% of the total AGB recorded was described by the top three dominant species (*C. nucifera*, *M. indica*, and *B. flabellifer*).

AGB of a small-scale homegarden (25.2 Mg C/ha) was more than twice that of a medium-scale homegarden (11.5 Mg C/ha). The AGB among DL_3, DL_3 & DL_4 (this is the area exists in between the two AERs, which obviously retain mixed characteristics of both other regions and generally indicated in AER maps of Sri Lanka) and DL_4 was similar ($P > 0.05$). The land extent of the homegardens and AGB were significantly negatively correlated ($p < 0.05$) having the low strength of correlation (0.277).

3.5. *Effects of tree diversity and other determinant factors on AGB*

The SWI ($R^2 = 0.0344$) and species richness ($R^2 = 0.0926$) showed a significant ($P < 0.05$) weak positive correlation with AGB (Fig. 6). However, the species per ha ($R^2 = 0.237$) and trees per ha ($R^2 = 0.5885$) explained a higher proportion of the variation of AGB in homegardens in Jaffna.

When the AGB was regressed with SWI, it was found that time allocation for the homegarden per week/ha, technical knowledge of farming, and non-timber usage within the homegarden have positive and significant effects on AGB (Table 1).

3.6. *Relationship between AGB and its determinant factors*

The time allocated for homegardens was measured by number of hours per ha. It was observed that the involvement in the garden activities and interventions by the household in larger homegardens were relatively poor and the mean time allocation was 184.37 ± 13.90 h/week/ha which ranged from 0 to 764 h/week/ha. The mean AGB could be enhanced by 0.02C Mg/ha, with a slight effort of adding one hour/week/ha associated with garden activities. The households studied in Jaffna peninsula have mainly used their technical knowledge in utilizing timber and non-timber materials produced within homegardens, applying appropriate soil and water conservation methods, pest and

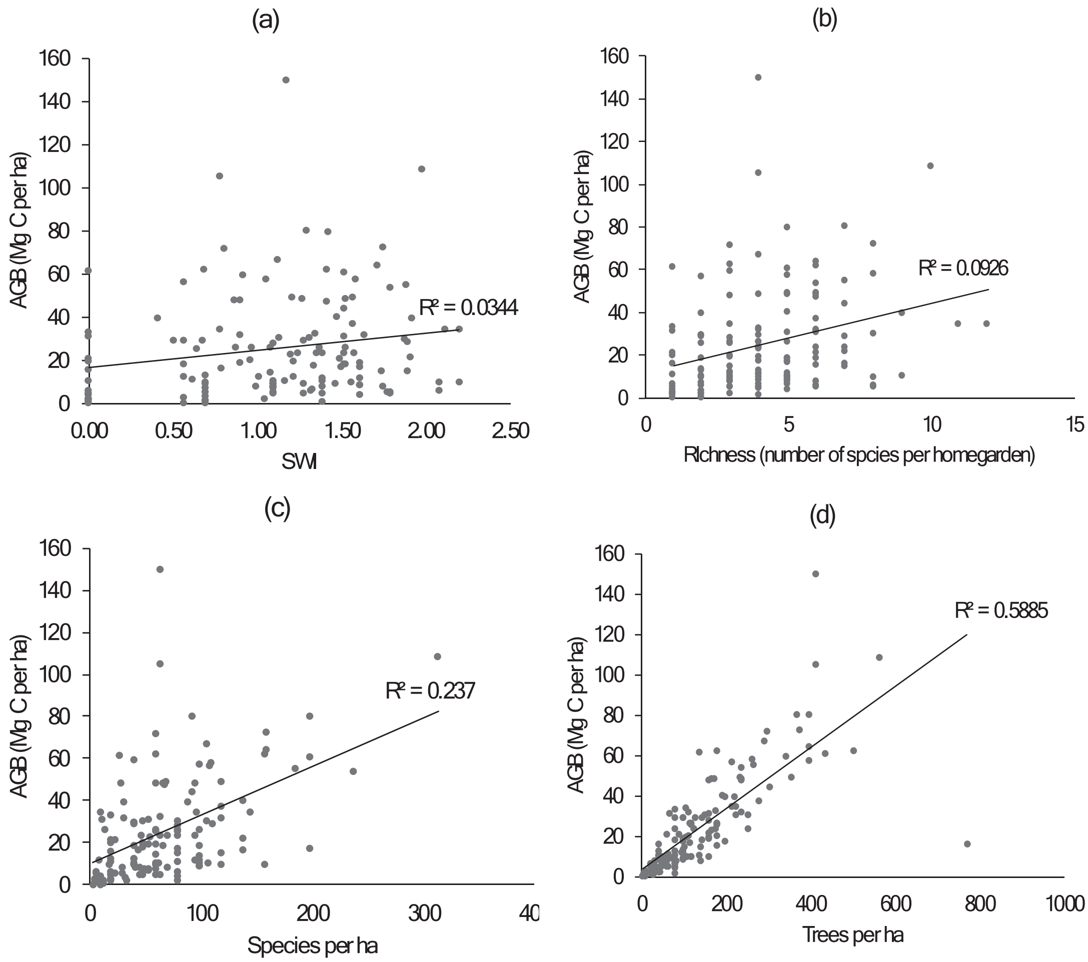


Fig. 6. Impact of tree diversity on AGB of homegardens in Jaffna. (a). AGB vs SWI, (b). AGB vs species richness, (c). AGB vs species density, (d). AGB vs tree density.

disease management, and other agronomic practices. The mean value for the calculated score was 5.64 ± 0.28 ($\beta = 1.381$). The households which were utilizing non-timber materials within the homegarden perceived the potential to increase the mean AGB by 7.91C Mg/ha compared to the households which were not utilizing non-timber materials within the homegarden. They have utilized non-timber materials such as cadjan leaves and litter material for different purposes within the homegarden itself, and those will ultimately end up adding organic matter to garden soil.

In the study sample, 67 homegardens out of 135 homegardens had livestock. Homegardens which had livestock as an active component in their homegardens had a significantly lower SWI value (SWI = 0.995, $p < 0.05$) compared to the opposite of that (SWI = 1.215). However, the mean AGB was significantly higher when livestock animals are present (AGB = 28.4 Mg C/ha, $p < 0.05$) in a particular homegarden, than the opposite of that (AGB = 19.3 Mg C/ha). The number of trees/ ha and number of tree species/ ha had no association with the presence of livestock animals in the homegarden.

4. Discussion

4.1. Characteristics of the study site and sampled homegardens

An agro-ecological region (AER) is the advancement of agro-climatic zones, which deliberately consider climatic conditions, soil type, topography, and land use, in addition to the traditional concern on elevation, rainfall, and temperature in the differentiation of agro-climatic zones. Although there are no sub-regions found in Jaffna, in general, the annual rainfall and rainfall distribution are considered to divide AERs into sub-regions (Punyawardena, 2009). According to Punyawardena (2009), DL_3 and DL_4 are two of the three regions which receive the least recorded annual rainfall in Sri Lanka. Small-scale homegardens were observed as the representative characteristic of homegardens in Jaffna, where the same observation was reported by Jeyavanan et al. (2017) and Lowe et al. (2021). According to the report on Land Use and Land Cover of Sri Lanka (2019), Jaffna consists of 31.58% homegardens, 28.85% of agricultural lands, and 8.44% of forest cover, 4.05% of built-up land, 1.40% of abandoned paddy, 4.96% of wet lands, 6.39% of rocky, sandy, bare lands and 14.34% water bodies, in terms of overall land cover. As per the report of Land Use Policy Planning Department of Sri Lanka (2019), there are 168,084 homegardens in the Jaffna peninsula, which covers 27,570 ha of arable land in total (0.16 ha per homegarden on average). However, only 1.40% of the land was recorded as bare land, implicating that land utilization is highly optimized.

4.2. Tree diversity, composition, and ecological variation

Referring to the species accumulation curve, it was evident that the study sample could be attributed as a representative sample of the study site, in terms of tree diversity. The current study recorded 38 different perennial species for the study area. This value represents around 10% of the total perennial species (400) recorded in Sri Lankan homegardens (Pushpakumara et al., 2012). Jeyavanan et al. (2017) recorded 135 floral species in homegardens in the Jaffna peninsula. However, their study included both perennial trees and annual field crops, which account for a high number of recorded species. Nevertheless, the current study was focused on the perennial tree community of the garden which determines the permanent structure of homegardens attributing the sustainability and maintenance (Lowe et al., 2022; Gajaseni and Gajaseni, 1999). The functional diversity of the homegarden changes according to the seasonality of major cash crops cultivated in the study region. For instance, when it is the paddy cultivated season, the attention and man-power which have been directed on annual crops in homegardens get diverted to the paddy fields, resulting in a considerable change in the production level within the homegarden (Gliessman, 1990).

Due to the unique ecological conditions of the study site, the tree species diversity in terms of species per ha and trees per ha was lower than the average values reported for Sri Lankan homegardens (Pushpakumara et al., 2012). This finding supports the report of Korale-Gedara et al. (2012) who observed a limited diversity of 2 floral species per an average homegarden in the Dry zone homegardens in Batticaloa district. A recent study conducted in Hambantota district (with DL_5 as the main AER) recorded a diversity index value of 2.09 with an average richness of 25 species per homegarden. This could be attributed to the larger land extent of homegardens in Hambantota area (>0.5 ha) compared to the Jaffna peninsula (Williams et al., 2018). In general, available land extent has a direct positive influence on the species richness of the garden (Korale-Gedara et al., 2012; Melvani et al., 2020; Williams et al., 2018). However, as agroforestry systems, homegardens possess the capacity to accommodate a high floral diversity resembling natural forest structures with concern for the benefits of different species at different canopy layers (Gliessman, 1990; Sahoo, 2009).

Among the most important and dominant species estimated (SDR and RIV), *C. nucifera* and arecanut were observed in majority of the homegardens in Sri Lanka. Previous studies identified homegardens as palm-based agroforestry systems (Kumar, 2011; Dey et al., 2014). In addition to that, Palmyra was recorded as a multipurpose perennial palm species owing to the favorable climatic and soil conditions in Jaffna peninsula. In general, the northern part of the island is well known for having a Palmyra as a key species. Besides Palmyra, the species such as *C. nucifera*, *M. indica*, *A. indica*, *A. heterophyllus*, and guava *P. guajava*, *A. catechu* and moringa (*Moringa oleifera* Lam.) were recorded as the most important species cultivated in homegardens in Jaffna, where the majority were fruit baring multipurpose species. Households tend to utilize these plant-based food items to fulfill the nutrient requirement which is a key aspect in assuring domestic food security (Marsh, 1998; Rahman et al., 2017a, 2017b; Mellisse et al., 2018; Panyadee et al., 2018). Thus, well-managed homegardens possess the capacity to offer a year-round yet subsistence level plant-based food production to the household, as a remedy to suppress domestic food insecurity (Ferdous et al., 2016; Mitchell and Hanstad, 2004; Pandey et al., 2017; Sahoo, 2009; Talukder et al., 2000).

4.3. Estimation of AGB

The estimated mean AGB of 23.80 Mg C/ha consisted of only the biomass carbon contribution from the perennial tree community. Recent studies confirm that >98% of the AGB was attributed to the woody perennial tree community of the respective ecosystem, which is homegarden in the given situation (Birhane et al., 2020; Lowe et al., 2022). Therefore, since the woody tree community was the key contributor to AGB, small shrubs, herbs, and plants were not considered in estimating the AGB in the current study owing to their insignificant input. Mattsson et al. (2013) estimated the mean AGB carbon stock of 35 Mg C/ha for a Dry zone homegarden in DL_5 (Hambantota district) and DL_1 (Anuradhapura district) AERs. However, they estimated the AGB of an average Dry zone homegarden in DL_1 as 12.7 Mg C/ha, which was comparatively lower than the current estimations. Jeyavanan et al. (2017) estimated the mean AGB of a Dry zone homegarden in Jaffna as 40.51 Mg C/ha, using 125 homegardens, which was higher than the projected values of the current study. These variations could be attributed to the variability in tree diversity, the number of trees per ha, ecological variations, and compositional differences among sampled homegardens (Henry et al., 2009; Montagnini and Nair, 2012). In addition, the sampling method and selection criteria of homegardens in the current study have resulted in a highly diverse set of homegardens, which could be acknowledged as the predominant reason for these differences.

In the current study, estimated AGB of a small-scale homegarden (25.2 Mg C/ha) was higher than that of a medium-scale homegarden (11.5 Mg C/ha). The same observation was recorded by similar studies conducted recently. For instance, Mattsson et al. (2015) stated that the AGB carbon stocks in small-scale and medium-scale homegardens in Dry zone region are 26 Mg C/ha and 09 Mg C/ha, respectively. A study in Bangladesh recorded the same trend of AGB carbon stocks of 58.46 Mg C/ha in a small-scale and 40.50 Mg C/ha in medium-scale homegardens (Jaman et al., 2016). Lowe et al. (2022) estimated that 38.8 ± 29.7 Mg C/ha and 28.0 ± 14.9 Mg C/ha stocks in small-scale and medium scale homegardens in Sri Lanka, respectively. These observations confirm that a higher number of trees per ha and tree diversity are maintained in small-scale homegardens than the medium and large-scale counter partners.

4.4. Factors affecting AGB; tree diversity vs human intervention

According to the results of the regression model, AGB tends to possess a positive correlation with the SWI, family labor hours, technical knowledge, and non-timber usage within the homegarden. As mentioned in the previous section, the perennial tree community is well-established as the primary and major contributor to AGB. According to Korale-Gedara et al. (2012) SWI is known as the 'proportional abundance or evenness, accounting for the land shares allocated to each crop as well as the number of crops'. Further, several studies conducted recently also found that tree diversity is a crucial factor to be considered when addressing AGB. The impact of high tree diversity has been concluded as a positive induce to nurture the AGB of a homegarden ecosystem (Lowe et al., 2022; Baul et al., 2021; Brakas and Aune, 2011; Jaman et al., 2016; Mattsson et al., 2015; Rahman et al., 2021; Siyum and Tassew, 2019). Hence, it is obvious that SWI could essentially be considered one of the major driving forces that determine the AGB. However, with the present study, the scattered distribution of AGB was visualized with the given SWI. The AGB values of <40 Mg C/ha were reported in each level of SWI even when diversity was not stated (SWI = 0). Further, high values of AGB were stated at moderate levels of SWI. The reason may be that the explained variability by SWI is low.

As per the findings of Santhoshkumar and Ichikawa (2010), Soemarwoto (1987), Ninez (1985), and Ruthenberg (1971), the diversity and accessibility of the garden are governed by the household members, who deliberately manage the homegarden by providing full-time or part-time labor. According to Rooduijn et al. (2018) the species richness of a homegarden is controlled by the landscape structure while the household governs the abundance of each species within the garden. Further, Mattsson et al. (2015) have stated that the tree composition, tree density and richness are influenced by the preferences of the household which is reflected in diverse spatial arrangements within the garden. However, allocated time for garden work depends on the availability and convenience of the family members, the number of households in the homegarden and the extent of the homegarden (Santhoshkumar and Ichikawa, 2010; Soemarwoto, 1987). According to Stoler (1975), a higher perennial tree community in a homegarden is reflected by the absence of family labor for garden work, since mature perennial trees demand the least supervision in terms of their growth and maintenance, compared to annual crops. Perennials are allowed to succeed a progressive growth by occasional management practices such as pruning. Comparably, as perceived in the current study the AGB is extremely low in the homegardens where the allocated time by the households is low since those households have not concerned about improving their homegardens. The households who allocated excessive time to their homegardens, could obtain more share of consumption from the homegarden in terms of outputs of both annual and perennial plants than the households who have spent lesser time. They could achieve high benefits by properly managing annual and perennial plants.

Even though scientific knowledge and skills are not fundamentally required to maintain a regular homegarden (Kumar and Nair, 2004), a lack of knowledge in agronomic practices might suppress the potential for maximum utilization of the resources within a homegarden. Thus, if the households have a specific set of skills and local knowledge on gardening, it could be used effectively to assist in enhancing the performance of the homegarden (Galhena et al., 2013). For instance, the tree community gets managed well by utilizing the available space more efficiently while maintaining an appropriate tree density within the garden. According to Gajaseni and Gajaseni (1999), proper management of the tree community was the key to the establishment of a homegarden; removal of mature timber for construction, pruning of selected species, and selection of trees to be left and grow in the garden. The same study concluded that the owner of the homegarden should ensure the proper establishment and endurance of the outstanding perennial species, before introducing other crops. Therefore, the trees may reach a proper DBH at maturity with enhanced fruiting capacities and stand qualities. Hence, traditional knowledge and skills play an important role in enduring proper agronomic practices in a well-utilized homegarden (Gajaseni and Gajaseni, 1999; Galhena et al., 2013; Kumar and Nair, 2004). In addition, households tend to add more trees as a practice concerning soil and water conservation with minimal removal of large and mature trees from the homegarden, which ultimately increases the total AGB carbon stock of the system.

The homegardens which consisted of livestock animals tend to have a significantly lower tree diversity index, which hints that the particular set of homegardens had a lower number of tree species and individual trees. It was noted that to maintain a livestock farm, even with a fewer number of animals, an open and spacious land was required. This allows the owners to get rid of some of the trees to maintain the space requirement, which might be the situation in these homegardens with a lower tree diversity. Still, the owners have kept some of the trees, which possess a significant value to the household with minimum inputs and maintenance, and a multipurpose asset in the long-run. Therefore, these homegardens comprised of a less number of perennial trees, which were obviously mature and older; *e.g. C. nucifera*, *M. indica*, *A. indica* and *A. heterophyllus*. In general, these species are known as prominent biomass stocks in homegardens, which ultimately accumulate an extensive amount of carbon biomass within the homegarden compared to the homegardens which had no livestock.

According to Blanckaert et al. (2004) and Cleveland and Soleri (1987), environmental sustainability can be achieved by the proper application of local knowledge in the conservation of resources; soil, and water. Further, when it is combined with scientific knowledge, it essentially increases the productivity of the homegarden while reducing environmental degradation (Teklehaimanot, and Hall, 2012; Tefera et al., 2019). Thus, the households become capable of maintaining perennial species community more productive and optimal, while enhancing the annual crop production and livestock within the homegarden ecosystem (Soemarwoto, 1987; Landon-Lane, 2011). Similarly, as per the present study, AGB is low within the homegardens where the households had a low level of technical knowledge. Having a high level of technical knowledge, such households could occupy comparatively high AGB in their homegarden. Most of them have used their technical knowledge especially on pest and disease management, utilizing materials in the homegarden and integrated farming practices.

Santhoshkumar and Ichikawa (2010) and Landon-Lane (2011) have pointed out the importance of material utilization in the homegarden. Non-timber materials such as cadjan leaves, dead leaves, tree branches, and other litter materials accumulated within the homegarden play a significant role in this concept. The litter fall is considered the major reservoir for nutrient cycling in tropical terrestrial systems, which in this case, homegardens (Gajaseni and Gajaseni, 1999). Relatively high AGB was reported in the homegardens where the non-timber material was accumulated, even though low and moderate amounts of AGB were observed in the homegardens where non-timber materials were not utilized inside the homegardens by the households. Generally, households either use them within the homegarden as a compostable organic fertilizer or get rid of them without utilizing them. Moreover, when litter fall from the multiple canopy layered trees are allowed to get accumulated and composted within the homegarden, the soil fertility and organic matter content are gradually increased while amplifying the nutrient availability of the garden soil (Gajaseni and Gajaseni, 1999; Soemarwoto, 1987). This recycling process improves the soil nutrient availability which is there to be up-taken by the tree community of the garden. According to Gajaseni and Gajaseni (1999), owing to the minimal export of harvested products from the homegardens, nutrient loss from the system is considered moderately less. Thus, homegardens possess the tendency to maintain an extensive production capacity with the assistance of appropriate, timely human involvement.

5. Conclusions

Following the same trend of smallholder agriculture, which is prominent in the Jaffna peninsula, a significant majority of the study sample of homegardens was also recognized under small-scale operation. Although the study site was one of the areas with the least annual rainfall, a substantial tree diversity was observed as indicated by species richness, abundance, and SWI. However, the findings were comparable to similar studies conducted in the Dry zone homegardens in different sites in Sri Lanka. The most dominant perennial species were recorded as *C. nucifera*, followed by *M. indica, A. catechu,* and *A. heterophyllus*, which are distinctive species commonly found in Sri Lankan homegardens. Homegardens which had livestock animals tend to utilize them as food sources to diversify the household food basket, in addition to the perennial originated plant based food items. Estimated AGB of the study sample showed a significant variation owing to the diversity of homegardens ranging from urban, sub-urban to rural parts of the district. Since the tree community was the primary contributor to AGB, SWI showed a positive significant correlation with increasing AGB. Rearing livestock animals within homegardens in Jaffna, has led those homegardens towards a poorly diversified ecosystem in terms of trees, yet with a higher AGB stock compared to the ones which had no livestock. In addition, time allocation in homegarden activities, technical knowledge of agronomic practices, and non-timber utilization within the garden also positively correlated with AGB. According to the suggested model, by increasing the number of tree species and individual trees per ha and proper usage of non-timber matter such as litter-fall, the AGB of dry zone homegardens can be amplified. Further, it suggests that the efficient guidance of the family labor force along with appropriate technical knowledge is an important requirement in enhancing the AGB accumulation in homegardens. Overall, the human interventions play a vital role in mediating the functional diversity and endurance of homegarden system amidst all naturally mediated environmental services it offers. Moreover, the government should intervene within this progression to come up with a sound mechanism to identify, categorize and monitor different clusters of homegardens having various potentials and capacities. Still, if a vital impact from homegardens are to be expected, a rigorous extension service and following up is vital in the given context. Thus, it is recommended to clearly identify the potential of human involvement in making the contribution of homegardens strong and sustainable to deliver the expected ecological services.

Funding

The study was funded by the National Science Foundation. Sri Lanka. Grant Number; NTRP/217/CC&ND/TA-04/P-02/01.

Ethical approval

Not required.

Consent to participate

Informed consent was obtained from all individual participants included in the study.

Consent for publication

The authors affirm that human research participants provided informed consent for publication of their data.

CRediT authorship contribution statement

Ayesh Lowe: Writing – original draft. **Niluka Kuruppuarachchi:** Writing – original draft. **Pradeepa Silva:** Funding acquisition, Writing – review & editing, Supervision. **Gamini Pushpakumara:** Writing – review & editing, Supervision. **Lalith Suriyagoda:** Supervision, Writing – review & editing. **Jeevika Weerahewa:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Acknowledgement

This paper was presented during the Asian Development Bank Institute (ABDI) Conference titled 'The Agriculture-Livestock-Forestry Nexus in Asia: Contributions and Potential for Improving Farmers' Livelihoods, Soil Health, and Climate Change Adaptation and Mitigation', held on November 2–3, 2023 at Lobesa, Bhutan. The authors would like to express their gratitude for the valuable feedback provided by the conference discussant, participants, and anonymous reviewers, which significantly enhanced the article's quality and presentation. Additionally, the authors extend their sincere thanks to ADBI and the guest editors for initiating this special issue.

References

Abere, F., Belete, Y., Kefalew, A., Soromessa, T., 2017. Carbon stock of Banja forest in Banja district, Amhara region, Ethiopia: an implication for climate change mitigation. J. Sustain. For. 36 (6), 604–622. https://doi.org/10.1080/10549811.2017.1332646.

Baishya, R., Barik, S.K., Upadhaya, K., 2009. Distribution pattern of aboveground biomass in natural and plantation forests of humid tropics in Northeast India. Trop. Ecol. 50 (2), 295–304.

Bargali, K., Bargali, S.S., 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.

Baul, T.K., Peuly, T.A., Nandi, R., Schmidt, L.H., Karmakar, S., 2021. Carbon stocks of homestead forests have a mitigation potential to climate change in Bangladesh. Sci. Rep. 11 (1), 1–11. https://doi.org/10.1038/s41598-021-88775-7.

Birhane, E., Ahmed, S., Hailemariam, M., Negash, M., Rannestad, M.M., Norgrove, L., 2020. Carbon stock and woody species diversity in homegarden agroforestry along an elevation gradient in southern Ethiopia. Agrofor. Syst. 94 (3), 1099–1110. https://doi.org/10.1007/s10457-019-00475-4.

Blanckaert, I., Swennen, R.L., Flores, M.P., López, R.R., Saade, R.L., 2004. Floristic composition, plant uses and management practices in homegardens of San Rafael Coxcatlán, Valley of Tehuacán-Cuicatlán, Mexico. J. Arid Environ. 57 (2), 179–202.

Brakas, S.G., Aune, J.B., 2011. Biomass and Carbon Accumulation in Land Use Systems of Claveria, the Philippines. C, 163–175. https://doi.org/10.1007/978-94-007-1630-8_9.

Brown, S., 1997. Estimating biomass and biomass change of tropical forests: a primer. FAO For. Pap. 134 (August), 55. http://www.fao.org/docrep/W4095E/W4095E00.htm.

Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Fölster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.P., Nelson, B.W., Ogawa, H., Puig, H., Riéra, B., Yamakura, T., 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145 (1), 87–99. https://doi.org/10.1007/s00442-005-0100-x.

Chen, Y.C., Wu, C.F., Lin, S.H., 2014. Mechanisms of forest restoration in landslide treatment areas. Sustainability (Switzerland) 6 (10), 6766–6780. https://doi.org/10.3390/su6106766.

Cleveland, D.A., Soleri, D., 1987. Household gardens as a development strategy. Hum. Organ. 46 (3), 259–270.

Daulagala, C., Weerahewa, J., Marambe, B., Pushpakumara, G., Silva, P., Punyawardena, R., Premalal, S., Miah, G., Roy, J., Jana, S., 2013. Socio - economic characteristics of farmers influencing adaptation to climate change: empirical results from selected Homegardens in South Asia with emphasis on commercial orientation. Sri Lanka J. Adv. Soc. Stud. 2 (2) https://doi.org/10.4038/sljass.v2i2.6208.

Dey, A., Islam, M., Masum, K.M., 2014. Above ground carbon stock through palm tree in the Homegarden of Sylhet City in Bangladesh. J. For. Environ. Sci. 30 (3), 293–300. https://doi.org/10.7747/jfs.2014.30.3.293.

Ferdous, Z., Datta, A., Anal, A.K., Anwar, M., Khan, A.S.M.M.R., 2016. Development of home garden model for year round production and consumption for improving resource-poor household food security in Bangladesh. NJAS - Wagening. J. Life Sci. 78, 103–110. https://doi.org/10.1016/j.njas.2016.05.006.

Gajaseni, J., Gajaseni, N., 1999. Ecological rationalities of the traditional homegarden system in the Chao Phraya Basin, Thailand. Agrofor. Syst. 46 (1), 3–23. https://doi.org/10.1023/A:1006188504677.

Galhena, D.H., Freed, R., Maredia, K.M., 2013. Promising Aproach, 1–13. BioMed Central. https://doi.org/10.1186/2048-7010-2-8.

Gedefaw, M., Soromessa, T., Belliethathan, S., 2014. Forest carbon stocks in woody plants of Tara Gedam Forest: implication for climate change mitigation. Sci. Technol. Arts Res. J. 3 (1), 101. https://doi.org/10.4314/star.v3i1.16.

Gifawesen, S.T., Tola, F.K., Duguma, M.S., 2020. Review on role of home garden agroforestry practices to improve livelihood of small scale farmers and climate change adaptation and mitigation, 8 (5), 134–145. https://doi.org/10.11648/j.jps.20200805.15.

Gliessman, S.R., 1990. Integrating Trees into Agriculture: The Home Garden Agroecosystem as an Example of Agroforestry in the Tropics, 1983, pp. 160–168. https://doi.org/10.1007/978-1-4612-3252-0_11.

Hairiah, K., Dewi, S., Agus, F., Velarde, S., Ekadinata, A., Rahayu, S., van Noordwijk, M., 2010. Measuring carbon stocks across land use systems: a manual. World Agroforestry Centre (ICRAF), SEA Regional Office, Bogor, Indonesia, p 155.

Henry, M., Tittonell, P., Manlay, R.J., Bernoux, 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. https://doi.org/10.1016/j.agee.2008.09.006.

Jaman, M.S., Hossain, M.F., Shariful, I., Helal, J., G, M., Jamil, M., Mizanur, R., 2016. Quantification of carbon stock and tree diversity of Homegardens in Rangpur District, Bangladesh. Int. J. Agric. For. 6 (5), 169–180. https://doi.org/10.5923/j.ijaf.20160605.01.

Jeyavanan, K., Sivachandiran, S., Pushpakumara, D.K.N.G., 2017. Ecosystem services of homegarden agroforestry in Jaffna Peninsula. J. Dry Zone Agric. 3 (November), 56–68. http://repo.lib.jfn.ac.lk/xmlui/handle/123456789/1458.

Karki, H., Bargali, K., Bargali, S.S., 2021. Spatial and temporal trends in soil N-mineralization rates under the agroforestry systems in Bhabhar belt of Kumaun Himalaya, India. Agrofor. Syst. 95 (8), 1603–1617.

Kassa, G., Bekele, T., Demissew, S., Abebe, T., 2022. Above-and belowground biomass and biomass carbon stocks in homegarden agroforestry systems of different age groups at three sites of southern and southwestern Ethiopia. Carbon Manag. 13 (1), 531–549.

Korale-Gedara, P., Weerahewa, J., Pushpakumara, G., Kodithuwakku, S., S., 2012. Commercial orientation and its effects on plant diversity in homegardens: an empirical investigation of rural households in Sri Lanka. Sri Lankan J. Agric. Econ. 14 (0), 17. https://doi.org/10.4038/sjae.v14i0.4600.

Kumar, B.M., 2006. Carbon sequestration potential of tropical homegardens, 1, 185–204. https://doi.org/10.1007/978-1-4020-4948-4_11.

Kumar, B. Mohan, 2011. Species richness and aboveground carbon stocks in the homegardens of Central Kerala, India. Agric. Ecosyst. Environ. 140 (3–4), 430–440. https://doi.org/10.1016/j.agee.2011.01.006.

Kumar, B.M., Nair, P.K.R., 2004. The enigma of tropical homegardens. Torquebiau 1992, 135–152. https://doi.org/10.1007/978-94-017-2424-1_10.

Land Use and Land Cover of Sri Lanka, 2019. Land Use Policy Planning Department, 663 Colombo, Sri Lanka. ISBN 978-955-4708-09-7.

Landon-Lane, C., 2011. Livelihoods Grow in Gardens. Diversity Booklet Number-2, 2nd ed. Rural Infrastructure and Agro-Industries Division, Food and Agriculture Organization of the United Nations, Rome.
Lope-Alzina, Diana G., Howard, Patricia L., 2012. The structure, composition, and functions of homegardens: focus on the Yucatán Peninsula. Revista Etnoecologica 9 (1), 17–41.
Lowe, W.A.M., Sinniah, J., Jeyavanan, K., Silva, G.L.L.P., Pushpakumara, D.K.N.G., 2021. ' Can homegardens assist in enhancing the domestic food security?' A study in Jaffna Peninsula, Sri lanka. Agrofor. Syst. 1 https://doi.org/10.1007/s10457-021-00647-1.
Lowe, W.A.M., Silva, G.L.L.P., Pushpakumara, D.K.N.G., 2022. Homegardens as a modern carbon storage: assessment of tree diversity and above-ground biomass of homegardens in Matale district, Sri Lanka. Urban For. Urban Green. 74, 127671.
Marsh, R., 1998. Building on traditional gardening to improve household food security. Sustain. Dev. 4–14.
Mattsson, E., Ostwald, M., Nissanka, S.P., Marambe, B., 2013. Homegardens as a multi-functional land-use strategy in Sri Lanka with focus on carbon sequestration. Ambio 42 (7), 892–902. https://doi.org/10.1007/s13280-013-0390-x.
Mattsson, E., Ostwald, M., Nissanka, S.P., Pushpakumara, D.K.N.G., 2015. Quantification of carbon stock and tree diversity of homegardens in a dry zone area of Moneragala district, Sri Lanka. Agrofor. Syst. 89 (3), 435–445. https://doi.org/10.1007/s10457-014-9780-8.
Mellisse, B.T., Descheemaeker, K., Giller, K.E., Abebe, T., van de Ven, G.W.J., 2018. Are traditional home gardens in southern Ethiopia heading for extinction? Implications for productivity, plant species richness and food security. Agric. Ecosyst. Environ. 252 (September 2017), 1–13. https://doi.org/10.1016/j.agee.2017.09.026.
Melvani, K., Bristow, M., Moles, J., Crase, B., Kaestli, M., 2020. Multiple livelihood strategies and high floristic diversity increase the adaptive capacity and resilience of Sri Lankan farming enterprises. Sci. Total Environ. 739 https://doi.org/10.1016/j.scitotenv.2020.139120.
Minasny, B., McBratney, A.B., 2006. A conditioned Latin hypercube method for sampling in the presence of ancillary information. Comput. Geosci. 32 (9), 1378–1388. https://doi.org/10.1016/j.cageo.2005.12.009.
Mitchell, R., Hanstad, T., 2004. Small Homegarden Plots and Sustainable Livelihoods for the Poor Food and Agriculture Organization of the United Nations Livelihood Support Programme (LSP) an Inter-Departmental Programme for Improving Support for Enhancing Livelihoods of THE Rural Poor. Food and Agriculture Organization of the United Nations. March.
Montagnini, F., Nair, P.K.R., 2012. Carbon sequestration: An underexploited environmental benefit of agroforestry systems. In: New Vistas in Agroforestry. Springer, Dordrecht, pp. 281–295.
Mulugeta, Getachew, 2014. Evergreen agriculture: agroforestry for food security and climate change resilience. Journal of Natural Sciences Research 4 (11), 80–90.
Ninez, V., 1985. Introduction: household gardens and small-scale food production. Food Nutr. Bull. 7 (3), 1–5. https://doi.org/10.1177/156482658500700303.
Pandey, R., Aretano, R., Gupta, A.K., Meena, D., Kumar, B., Alatalo, J.M., 2017. Agroecology as a climate change adaptation strategy for smallholders of Tehri-Garhwal in the Indian Himalayan region. Small-Scale For. 16 (1), 53–63. https://doi.org/10.1007/s11842-016-9342-1.
Panyadee, P., Balslev, H., Wangpakapattanawong, P., Inta, A., 2018. Karen Homegardens: characteristics, functions, and species diversity. Econ. Bot. 72 (1), 1–19. https://doi.org/10.1007/s12231-018-9404-8.
Punyawardena, B.V.R., 2009. Sri Lankawe Warshapathanaya Ha Krushi-Parisarika Kalapa (Rainfall and Agroecological Regions of Sri Lanka). Agriculture Press, Department of Agriculture, Peradeniya, Sri Lanka. J102–2012/6 1500 (S)(Rp).
Pushpakumara, D.K.N.G., Marambe, B., Silva, G.L.L.P., Weerahewa, J., Punyawardena, B.V.R., 2012. A review of research on homegardens in Sri Lanka:the status, importance and future perspective. Trop. Agric. 160 (June 2014), 55–125.
Rahman, A.N.M.A., Islam, A.K.M.M., Arefin, M.A., Rahman, M.R., Anwar, M.P., 2017a. Competitiveness of winter rice varieties against weed under dry direct seeded conditions. Agric. Sci. 08 (12), 1415–1438. https://doi.org/10.4236/as.2017.812101.
Rahman, M.A., Tani, M., Asahiro, K., Asik Ullah, S.M., 2017b. Species composition, diversity and productivity of homesteads in southeastern Bangladesh. Small-Scale For. 16 (3), 295–309. https://doi.org/10.1007/s11842-016-9356-8.
Rahman, M.M., Kundu, G.K., Kabir, M.E., Ahmed, H., Xu, M., 2021. Opposing ecological strategies together promote biomass carbon storage in homegardens agroforestry of southern Bangladesh. Forests 12 (12). https://doi.org/10.3390/f12121669.
Rooduijn, B., Bongers, F., van der Wal, H., 2018. Wild native trees in tropical homegardens of Southeast Mexico: fostered by fragmentation, mediated by management. Agric. Ecosyst. Environ. 254 (June 2017), 149–161. https://doi.org/10.1016/j.agee.2017.10.015.
Roshetko, J.M., Delaney, M., Hairiah, K., Purnomosidhi, P., 2002. Carbon stocks in Indonesian homegarden systems: can smallholder systems be targeted for increased carbon storage? Am. J. Altern. Agric. 17 (3), 138–148. https://doi.org/10.1079/AJAA200116.
Ruthenberg, H., 1971. Farming Systems in the Tropics By Ruthenberg Hans. https://doi.org/10.1017/s0014479700005494.
Sahoo, U.K., 2009. Traditional home gardens and livelihood security in North-East India. J. Food Agric. Environ. 7 (2), 665–670.
Santhoshkumar, A.V., Ichikawa, K., 2010. Homegardens: Sustainable Land Use Systems in Wayanad, Kerala, India (n.d.).
Shahi, C., Bargali, S.S., Bargali, K., Vibhuti., 2023. Dry matter dynamics and CO2 mitigation in the herb layer of Central Himalayan agroecosystems along an altitudinal gradient, India. Trop. Ecol. 64 (1), 180–192.
Shannon, C.E., Weaver, W., Wiener, N., 1950. The mathematical theory of communication. Phys. Today 3 (9), 31–32.
Siyum, G.E., Tassew, T., 2019. The use of homegarden agroforestry systems for climate change mitigation in lowlands of southern Tigray, Northern Ethiopia. Asian Soil Res. J. 2 (2), 1–13. https://doi.org/10.9734/asrj/2019/v2i230049.
Soemarwoto, Otto, 1987. Homegardens: a traditional agroforestry system with a promising future. Agroforestry 157–170.
Spellerberg, I.A.N.F., Fedor, P.J., 2003. Ecological Sounding a Tribute to Claude Shannon (1916–2001) and a Plea for more Rigorous use of Species Richness, Species Diversity and the ' Shannon – Wiener ' Index, pp. 177–179.
Stoler, A., 1975. Garden Use and Household Consumption Patterns in a Javanese Village.
Susanto, D.A., Kartawinata, K., 2021. Carbon potentials in biomass of fruit trees in home gardens in the Bogor Regency, West Java. J. Trop. Ethnobiol. 4 (2), 118–129.
Susanto, D.A., Kartawinata, K., Nisyawati., 2021. Carbon potentials in biomass of fruit trees in home gardens in the Bogor Regency, West Java. J. Trop. Ethnobiol. IV (2), 118–129. https://doi.org/10.46359/jte.v4i2.100.
Talukder, A., Kiess, L., Huq, N., De Pee, S., Darnton-Hill, I., Bloem, M.W., 2000. Increasing the production and consumption of vitamin A-rich fruits and vegetables: lessons learned in taking the Bangladesh homestead gardening programme to a national scale. Food Nutr. Bull. 21 (2), 165–172. https://doi.org/10.1177/156482650002100210.
Tefera, Y., Babu, A., Bizuayehu, B., 2019. Homegarden plant use and their traditional management practice in Bule Hora district, West Guji Zone, Southern Ethiopia. Agric. Res. Technol. 21, 556168.
Teklehaimanot, Z., Hall, J.B., 2012. Farmers ' ecological knowledge about homegarden production systems in bangladesh, p. 8028. https://doi.org/10.1080/14728028.2001.9752372.
Weerahewa, J., Pushpakumara, G., Silva, P., Daulagala, C., Punyawardena, R., Premalal, S., Miah, G., Roy, J., Jana, S., Marambe, B., 2012. Are homegarden ecosystems resilient to climate change? An analysis of the adaptation strategies of homegardeners in Sri Lanka. APN Sci. Bull. 2, 22–27.
Whitney, C.W., Luedeling, E., Hensel, O., Tabuti, J.R.S., Krawinkel, M., Gebauer, J., Kehlenbeck, K., 2018. The role of homegardens for food and nutrition security in Uganda. Hum. Ecol. 46 (4), 497–514. https://doi.org/10.1007/s10745-018-0008-9.
Williams, N.E., Carrico, A.R., Edirisinghe, I., Jayamini Champika, P.A., 2018. Assessing the impacts of agrobiodiversity maintenance on food security among farming households in Sri Lanka's dry zone. Econ. Bot. 72 (2), 196–206. https://doi.org/10.1007/s12231-018-9418-2.
Yohannes, H., 2015. Carbon stock analysis along altitudinal gradient in Gedo Forest: implications for forest management and climate change mitigation. Am. J. Environ. Protect. 4 (5), 237. https://doi.org/10.11648/j.ajep.20150405.14.