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A Geospatial and Socio-economic Assessment of Tree Density in Home Gardens as Trees Outside Forests Sources in Agro-ecological Regions: Upper Mahaweli Catchment, Sri Lanka

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ABSTRACT

Homegardens (HGs) serve as crucial 'Trees Outside Forest Sources' (TOFS) systems, offsetting tree cover loss resulting from extensive deforestation in the Upper Mahaweli Catchment (UMC) over the past two centuries. This study examined the temporal and spatial distribution of HGs in relation to agro-ecological regions (AERs) within the UMC boundary, assessed the tree density of HGs, and analyzed the biophysical and socio-economic factors influencing tree density. Geospatial assessment utilized Landsat Images and tree density estimation was based on a random sample of 500 HGs in the UMC with a minimum diameter at breast height (dbh) of >10cm. Regression analysis was employed to identify factors affecting tree density. The spatial assessment revealed that in 2017, the AER of IM3a covered the highest percentage area (66.5%) whereas IM1a recorded the greatest incremental percentage change (22.8%) from 1992-2017, while the lowest change was observed in IL2 (0.03%). The highest tree density was observed in IU2 (858 trees/ha), and the average density in WM2a (505 trees/ha), comparable to that of South-Asian tropical rainforests. However, there is a concerning trend of rapid spread of exotic species contributing to the high tree density observed in IU2, WM2a, and IU3d. The multiple linear regression model ($p<0.01$, R2 = 58.62%) indicated spatial, agronomic and institutional factors positively influenced tree density. Conversely, the HG area square, and demographic factors had a significant negative impact on tree diversity ($p<0.01$). To ensure the ecological sustainability of the UMC, the study proposes to introduce an appropriate incentive package to enhance tree density in HGs, with native species.

INTRODUCTION

Trees Outside Forests Sources (TOFS) provide numerous environmental, social, cultural, aesthetic, and economic services, as well as vital products such as fruits, oils, gum, resin, fodder, medicine, timber and fuelwood that are essential for the livelihood of people (De Foresta et al., 2013; Jhariya et al., 2019). Trees are predominantly found in agroforestry systems and urban land uses, and they play an integral role in non-forest environments, as well as in the socio-economic well-being of communities. Despite the abundance of tree resources in outside forest areas across countries, they have often been overlooked, with the focus primarily on forests. However, in recent years, the ecological and societal benefits of TOFS have gained recognition (Schnell et al., 2015). There is a wealth of historical and contemporary literature on agroforestry and urban planning that emphasizes the significant role of TOFS (Sharma et al., 2007; Chakravarty et al., 2019).

Homegardens (HGs) are agroforestry systems that represent one of the most common forms of TOFS in tropical regions. They are characterized by their rich species diversity and composition, as well as the dense distribution of faunal species and floral strata, highlighting the exceptional ecological features of HGs (Kumar and Nair, 2004; Kumar and Tiwari, 2017). HGs have the potential to revitalize degraded landscapes (Shastri et al., 2002; Albuquerque et al., 2005).

The Upper Mahaweli Catchment (UMC) landscape has suffered from land degradation as a result of large-scale deforestation over the past two centuries (Wickramagamage, 1990). HGs, being one of the primary land uses in the UMC and has a long history of providing a wide range of ecosystem services to its inhabitants, contribute to various catchment protection functions, including soil erosion control, enhancement of soil nutrients, water regulation, and climate regulation (Chakravarthy et al., 2019; Laura et al., 2012). Therefore, HGs with a high density of trees have significant potential for catchment protection, particularly in areas with insufficient forest cover. Krishnarajah and Sumanarathne (1988) reported that well-managed HGs have an estimated soil erosion rate (0.05 t/ha) that is comparable to the annual loss experienced in natural forests.

Climatic, edaphic, and landform-related factors directly influence the spatial and temporal distribution of land uses, including HGs (Kumar et al., 2014). An agro-ecological region (AER) is a land resource-mapping unit that possesses a unique combination of landform, soil, climatic characteristics, and/or land cover, with specific potentials and constraints for land use (FAO, 1996). Therefore, it is crucial to analyze the temporal and spatial distribution of HGs within a given landscape or catchment area in relation to the characteristics of the AERs.

Deforestation disrupts the local hydrological cycle and alters the heat release pattern due to changes in land cover (Werth and Avissar, 2005). General Circular Models (GCM) suggest that deforested regions can experience up to an 80% reduction in annual rainfall, and the impact extends beyond the deforested area, affecting rainfall patterns in surrounding regions (Hasler et al., 2009). Changes in rainfall patterns can lead to droughts, particularly during the dry season, which negatively impacts agriculture and water availability. Wickramagamage (1990) reported that the natural vegetation, which had protected and improved the river catchment in the central highlands of Sri Lanka for thousands of years, has been nearly completely destroyed, making it realistically impossible to restore these areas to forests. In such circumstances, HGs with a rich tree density in the Upper Mahaweli Catchment (UMC) can play a significant role in compensating for the lost vegetation cover and the ecosystem services resulting from large-scale deforestation. Additionally, tree-rich HGs possess a high resilience capacity to absorb environmental stresses caused by deforestation, given their high tree density and diversity. Furthermore, tree-rich HGs are recognized as one of the best options for the *in situ* conservation of genetic resources (Watson et al., 2001; Schroth et al., 2004).

The capacity of HGs to provide ecosystem services is determined by both their extent and the quality in terms of tree diversity. Since the qualitative characteristics of HGs largely depend on the agro-ecological conditions in which they are located, it is vital to assess the temporal and spatial distribution of HGs in the UMC in relation to AERs. The definition of AER enables comparisons among similar biophysical situations that are subjected to a wide range of socio-economic and land use conditions (Sivakumar and Valentine, 1997). An AER represents a particular combination of natural characteristics such as climate, soil, and relief (Panabokke, 1996). Each AER corresponds to uniform agro-climate, soil, and terrain conditions that support a specific farming system. Based on the 75% expectancy of mean annual rainfall, Sri Lanka can be divided into three major climatic zones: the Wet Zone (>2500mm), Intermediate Zone (1750-2500mm), and Dry Zone (<1750mm). Additionally, three major elevation zones exist: Up-Country (above 900m), Mid-Country (300-900m), and Low-Country (below 300m). Based on climate, topography, and major soil groups, Sri Lanka is subdivided into 46 AERs (Punyawardhene, 2008).

There is a lack of literature regarding AER-based analysis that covers heterogeneous and large-scale landscapes such as catchments. The distribution and qualitative characteristics of HGs are influenced by various socio-economic factors, which necessitate further analysis. Conducting such an analysis would provide valuable information for policy formulation aimed at enhancing the potential of HGs to provide ecosystem services that are crucial for catchment sustainability. Consequently, a study was designed to address the following research questions: (a) What is the distribution of HGs, as the major TOFS, in the Upper Mahaweli Catchment (UMC) in terms of AERs? (b) What are the qualitative characteristics of HGs in terms of tree density? and (c) What factors influence the tree density of HGs? The main objective of this study was to assess the temporal and spatial distribution of HGs in the UMC in relation to AERs, tree density within HGs, and to estimate the factors affecting the tree density of HGs.

METHODOLOGY

Study area

The Upper Mahaweli Catchment (UMC) served as the study area for this research. The UMC's absolute location ranges between longitude 80° 25' to 81° 01' E and latitude 6° 45' to 7° 30' N, encompassing areas in the Central, Uva, and Sabaragamuwa provinces (De Silva, 1997). Due to its environmental and socio-economic significance to the country, it is known as the heart of Sri Lanka. Within the UMC, there are five sub-catchments: Kotmale, Victoria, Randenigala, Rantembe, and Uma Oya (Figure 1). The study area's elevation varies from 2,717 m at Pidurutalagala (Gibbon, 1990), the country's highest summit, to 150 m at Rantembe. The majority of the UMC is located in the Wet Zone (annual rainfall >2,500 mm), with only a small patch belonging to the Intermediate Zone (annual rainfall 1,750 – 2,500 mm). Precipitation is seasonal and heavy, ranging from 1,000 mm/year to 5,500 mm/year. The total surface area of the catchment is 3,110.81 km2, characterized by rugged topography and a mean slope gradient ranging from 5° to 30°. Within the catchment, five main soil types have been identified, with Red Yellow Podzolic soil being the dominant type, covering approximately 60% of the area (Hevawasam, 2010).

A geospatial assessment was conducted to identify the distribution of high-growth areas (HGs) in 2017 and to track changes in these areas over a 25-year period from 1992 to 2017 within the boundaries of the UMC (Department of Agriculture, 2003). The AER map was overlaid with the UMC, and Landsat data acquired in 1992 and 2017 were utilized for the geospatial analysis (Table 1) as the most accurate and available data for the study.

The image data underwent pre-processing using ERDAS Imagine 2014 software for geo-referencing. Mosaicking and sub-setting of the images were performed based on the Area of Interest (AOI). To enhance the contrast and improve the precision of information extraction, layer stacking was conducted to create a color composite for each year's image. The selected land use classes included forests and scrubs, HGs, tea, paddy, other agriculture crops, bare land and grasses, water bodies, and urban areas (Table 2). Supervised classification was employed using training samples. Due to similar misclassification errors encountered with forest patches and home garden clusters, screen digitization was adopted for these classes after the pixel-based classification, aiming to enhance the accuracy of the information (Wang et al., 2015; Madarasinghe et al., 2020). Ancillary data utilized in the analysis included Google images acquired in 2017, land use maps prepared by the Mahaweli Authority of Sri Lanka (MASL), and 1:50,000 topographic maps.

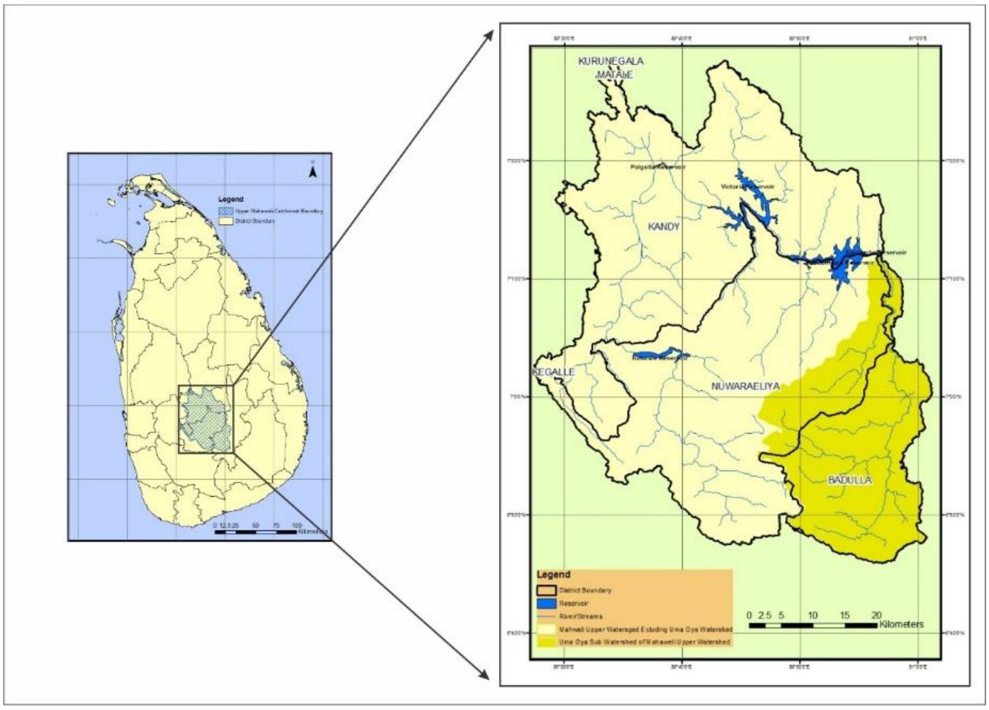

Figure 1: Study area map of Upper Mahaweli Catchment of Sri Lanka Geo-Spatial assessment

Table 1. Satellite data specification used in the study.

Data	Year of Acquisition	Bands	Resolution (m)	Source
Landsat TM	1992	Multispectral	30 m x 30 m	USGS
Landsat TM	2017	Multispectral	30 m x 30 m	USGS
Google image	2017	-	1 m x 1 m	Google Earth

Table 2. Description of land use/ land cover classes.

Land use classes	Description
Forest & shrubs	Dense forests, spars forests, forest plantations and shrubs
Homegardens	Homegarden clusters with tree components
Tea	Tea plantations
Paddy	Paddy fields
Other Agricultural lands	Agricultural areas with annual cash crops and vegetables including *chena* cultivation
Bare land and Grass	Bare ground, vacant lands, open area, and fallow lands including grasslands
Water bodies	Reservoirs, rivers, streams and lakes
Urban	Urban, residential, commercial, industrial, transportation, roads, sub-urbs and mixed urban settings.

Visual image interpretation of remote sensing imagery provides a reasonably accurate method for classifying complex and heterogeneous landscapes and spatial units with distinct image pattern characteristics (Borkar, 2018; Arveti, 2016). The interpretation elements utilized included tone, texture, size, shape, pattern, and association. Due to the unavailability of Google images in 1992, topographic maps were used as an alternative. For on-screen digitizing and land use map preparation for 1992 and 2017, ArcGIS-10 software was employed. Spatial data analysis was conducted to identify changes, and an accuracy assessment was performed using a total of 280 random sample points from the entire catchment, representing each of the above-mentioned land cover classes, along with ground verification using GPS points.

Following the aforementioned procedure, land use maps were prepared for 1992 and 2017 to determine the spatial distribution of HGs along with other land uses within the UMC. The UMC encompasses 22 AERs within its boundaries. The percentage of the AER area covered by HGs was estimated for both 1992 and 2017, relative to all the AERs covered by the UMC. Based on these estimates, the percentage change in the area occupied by HGs from 1992 to 2017 was also calculated.

Assessment of tree density

Tree density is an important quantitative measure of tree cover, as it determines the quality of a TOFS (Perera and Rajapakse, 1991; Kumar and Tiwari, 2017; Zomer et al., 2016). The horizontal distribution of trees in a landscape can be expressed in terms of tree density, such as trees per acre or basal area per acre (Deyong, 2016). Therefore, all trees with a diameter at breast height (DBH) greater than 10 cm were enumerated. The species name, genera, and family names were recorded and confirmed using literature sources. The expertise of a botanist, the knowledge and experience of HG owners, and the researcher's familiarity with the study area were utilized to identify the tree species. Tree height was measured using a clinometer, and DBH measurements were obtained using a standard measuring tape.

A stratified and randomized sampling technique was employed to obtain 500 samples from eight Divisional Secretariat Divisions (DSDs) located within the catchment area, spanning the Kandy District and the Badulla District. The selection of Kandy and Badulla districts was primarily driven by the representation of most of the land area in the UMC, the widespread distribution of HGs, and the aim to capture a wide variation in biophysical and socio-economic factors. The DSDs were considered as strata, and random samples were taken from villages within each DSD. In the Badulla District, samples were taken from Hali-Ela (N=55), Kandakatiya (N=56), Bandarawela (N=57), and Walimanda (N=56). Similarly, samples were taken from DSDs in Kandy to represent Gangawatakorale (N=67), Pathahewahata (N=64), Doluwa (N=47), and Kundasale (N=98). The selection criteria were based on several factors, including the size, age, location, and socio-economic background of the owners, in order to capture a wide variation within and between HGs. To compare the tree density of HGs belonging to different AERs, the Kruskal-Wallis test (Conover, 1999) was used.

Factors effect on tree density of agro-ecological regions in UMC

The vegetative characteristics and functions of traditional HGs are influenced by various interconnected factors, including the characteristics of HGs themselves, demographic, spatial, and institutional factors, as well as biophysical factors (Peyre et al., 2006; Abebe et al., 2006; Shrestha, 2018; Karunarathna & Gunathilaka, 2002). Building upon existing literature, this study formulated a hypothesis that several factors, such as HG characteristics, spatial attributes related to HG location, agronomy-related variables, demographic characteristics, and institutional support received by HG owners (e.g., planting materials, incentives, and subsidies), would impact tree density. To examine the relationship between these factors and tree density, a multiple linear regression model (Equation 1) was developed.

$$Y = \alpha + \beta 1X1 + \beta 2X2 + \beta 3X3 + \dots\dots\dots\dots\dots\dots + \varepsilon \quad \text{(Eq. 1)}$$

Where;

Y: Tree density of home garden, X_i : Factors influencing on tree density (as stated previously) and βi: Coefficients.

Data and data sources

Primary data were collected from HG owners using a structured questionnaire, while secondary data were obtained from relevant sources. The explanatory variables and their respective sources for both primary and secondary data are listed in Table 2. Data analysis was conducted using STATA 12.1 software. To assess multicollinearity among the explanatory variables, the Variance Inflation Factor (VIF) was employed.

RESULTS AND DISCUSSION

Spatial distribution of homegardens in agro-ecological regions of the UMC

The distribution of HGs in AERs of UMC in 1992 and 2017 is depicted in Figures 2 and 3, respectively. These land use maps illustrate the distribution of HGs alongside other land uses. The percentage of the AER area occupied by HGs in 1992 and 2017 is shown in Figures 4. In 1992, quantitative estimates revealed that the highest percentage of HG distribution was observed in the AER of WM3b (52.7%). IU3 exhibited an average distribution of 18%, while IL2 had the lowest distribution of 0.01%. The high distribution in WM3b can be attributed to the presence of ideal agro-climatic conditions as well as the high residential population density in this AER. Conversely, the low distribution in IL2 is primarily due to the extensive forest cover in this AER.

Figures 3 and 4 illustrate that in 2017, the highest distribution of HGs was observed in IM3a (66.5%). Additionally, AERs WM2b (62.0%), WM3b (61.5%), and WM3a (55.1%) displayed a higher distribution of HGs, accounting for more than 50% of the AER area. IU3c exhibited an average distribution of 28.0%, while IL2 (0.03%) and WU3 (2.7%) had the lowest distribution. While the majority of the WU3 region is covered by forests, there is a relatively smaller extent occupied by tea plantations.

Table 2. Data and sources for explanatory variables

Data	Data source
Characteristics of homegardens	
Area of the homegarden	homegarden-based household survey.
Age of the homegarden	homegarden-based household survey
Spatial data	
Distance to the nearest town from homegarden	Proximity analysis was done using GIS. Road shape file and GN division shape were used
Distance to the sub catchment where homegarden is located	Proximity analysis was done using GIS. Urban council and Municipal council, shape file and GN division shape were used
Agro Ecological region that GN division located.	Agro-ecological region map and GN division map
Agronomic Practices	
Pepper cultivated area	homegarden-based Household survey
Vegetable cultivated area	homegarden-based Household survey
Demographic variables	
Population Density of GN Division where homegarden is located	Department of Census and Statistics
Institutional support related data	Opinion Survey with homegarden owners

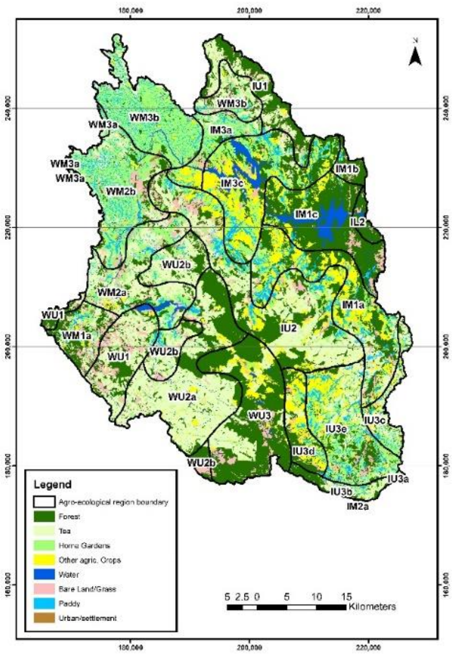

Figure 2: Distribution of homegardens along with other land uses in the agro-ecological regions of UMC in 1992

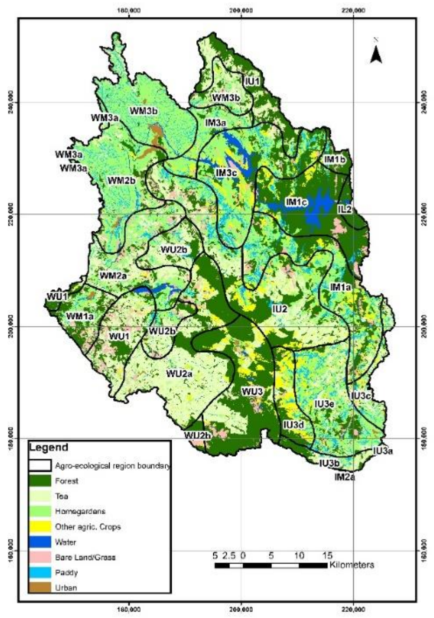

Figure 3: Distribution of homegardens along with other land uses in the agro-ecological regions of UMC in 2017

The percentage change in the area of HGs in AERs from 1992 to 2017 is depicted in Figure 5. Interestingly, the percentage of HGs increased in several AERs during this period. The highest increase was observed in IM1a (22.9%) and IM3a (20.7%), followed by a moderate increase in IM2a and WM2b (average increase of 8.3%). The lowest changes were recorded in IL2 (0.001%), IU1 (1.4%), and WU3 (1.3%). Field surveys revealed that new settlements have been established in IM1a over the past two to three decades. In the Kandakatiya DSD of the Badulla district and Walapane DSD of the Nuwara Eliya district in the IM1a region, unproductive barren lands owned by the Land Reclamation Commission of Sri Lanka have been distributed among landless families. These new settlers have converted grasslands into HGs with a diverse tree cover, leading to increased ecosystem services derived from the catchment landscape (Herath et al., 2021). Furthermore, the negligible change or stable forest cover observed in IL2 is beneficial for the sustainability of the catchment.

Tree density of homegardens in agro-ecological regions

A total of 64,163 trees were enumerated in 500 HGs as part of this study. These trees belonged to 118 different species, distributed among 38 families. Carter (1992) reported 101 tree species in privately-owned agroforestry in Nepal, with tree density in HGs ranging from 95 to 2,170 trees/ha.

Figure 6 illustrates the tree density of HGs in AERs of UMC. The Kruskal-Wallis test indicated a significant difference in tree densities among the AERs ($p<0.01$). The average tree density of HGs was determined to be 524 trees/ha. This finding aligns with previous studies conducted on Kandyan forest gardens in Sri Lanka (Perera and Rajapakse, 1991; Pushpakumara et al., 2016), where the number of trees with a diameter of 5 cm and above ranged from 92 to 3,736 trees/ha, with 70% of the gardens containing 500 to 1,500 trees/ha. Abebe et al. (2013) reported a tree density ranging from 86 to 1,082 trees/ha, with an average value of 475, in agroforestry HGs in Southern Ethiopia. Similarly, Kassa et al. (2015) found an average woody tree density of 589 trees/ha in household agroforestry systems in southern Ethiopia, which received a mean annual rainfall of 900–2,200 mm.

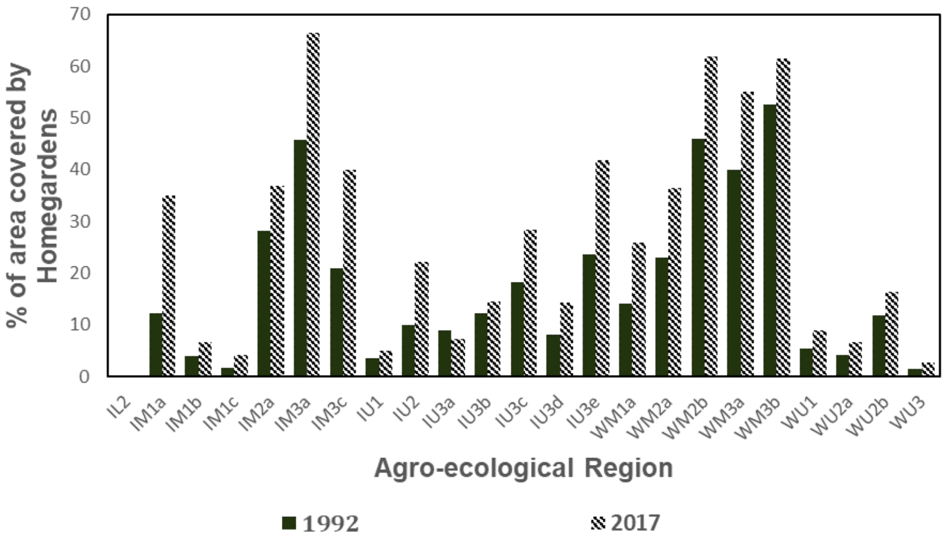

Figure 4: Percentage area of homegardens in the agro-ecological regions of UMC in 1992 and 2017

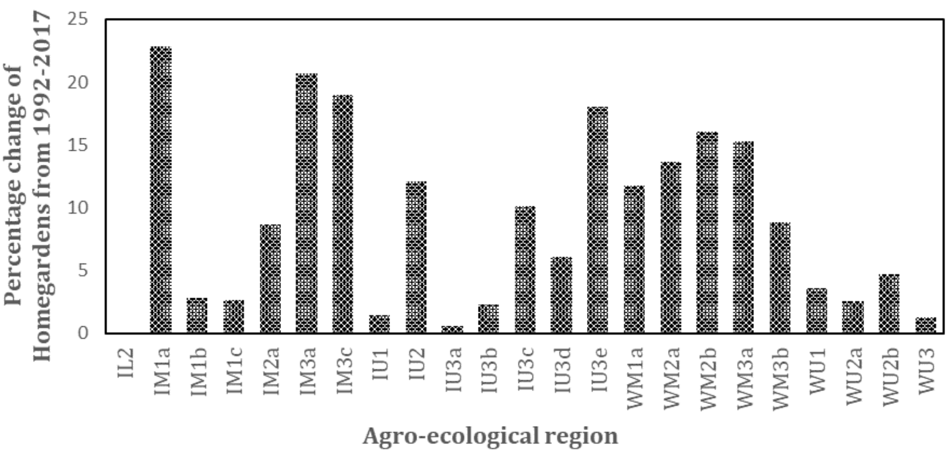

Figure 5: Percentage change on area of homegardens of UMC from 1992- 2017

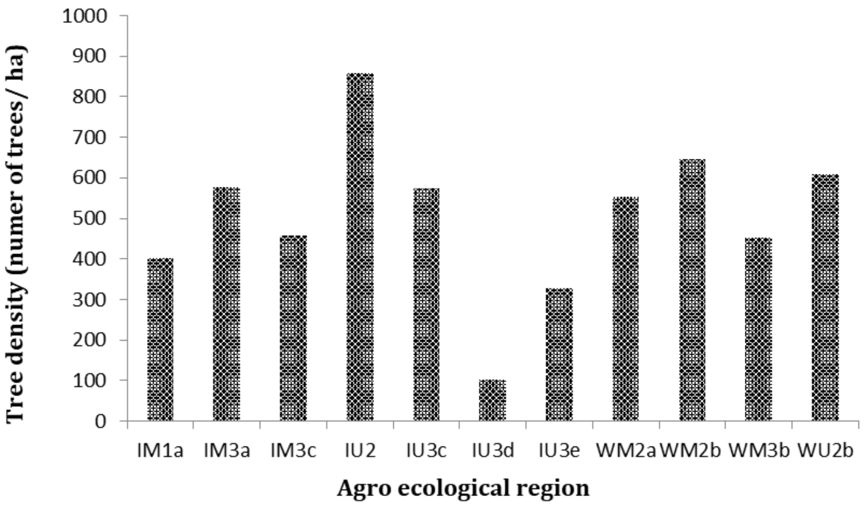

Figure 6: Tree density of homegardens in agro-ecological regions of UMC

The average tree density of the Eastern Ghats of India ranged from 435 to 767 trees/ha (Naidu and Kumar, 2016). Uttam et al. (2021) reported mean tree densities of 539, 554, and 638 trees/ha in tropical, subtropical, and temperate regions, respectively. In the present study, the average tree density of HGs in UMC falls within the range of natural forests in the tropics. This suggests that HGs in UMC have the potential to compensate for forest cover loss in areas where deforestation has occurred.

As shown in Figure 7, the highest tree density of 859 trees/ha was recorded in the AER IU2, followed by WM2b (645 trees/ha) and WU2b (608 trees/ha). The average tree density was observed in IU3c (573 trees/ha), IM3a (577 trees/ha), and WM2a (559 trees/ha), with the lowest density recorded in IU3d (103 trees/ha). During the field survey, it was noted that the IU2 region had typical Kandyan HGs with a higher tree density. Despite having a lower distribution of HGs compared to the average among AERs, IU2 exhibited HGs with a dense tree cover. The region's agro-climatic conditions are optimal for tree growth.

Among the top ten individual tree species, *Gliricidia sapium* (350 trees/ha), *Artocarpus heterophyllus* (21 trees/ha), Mangifera indica (11 trees/ha), *Magnolia champaca* (8 trees/ha), *Areca catechu* (103 trees/ha), and *Cocos nucifera* (15 trees/ha) were the most abundant in the highly-dense HGs of the IU2 region. *Areca catechu* and *Cocos nucifera* are multipurpose tree species. However, exotic species such as *Toona sinensis* (28 trees/ha), *Grevillea robusta* (25 trees/ha), *Alstonia macrophylla* (25 trees/ha), *Swietenia macrophylla* (21 trees/ha), and *Eucalyptus grandis* (1 tree/ha) also contributed to the species composition and tree density of HGs in this AER. *Alstonia macrophylla* has become an invasive tree species in WM2a, WM2b, and IU3c. These findings indicate a tendency of exotic species, such as *Alstonia macrophylla* and *Eucalyptus torelliana*, to spread in HGs in IU2, which is well-known for the presence of typical Kandyan forest gardens. Similarly, the spread of *Eucalyptus spp*. in IU3d is common. However, these exotic species primarily contribute to the timber supply of the country and spread rapidly when the agro-climatic conditions are highly favorable for them (Ariyadasa, 2002).

The lowest tree density was recorded in the AER IU3d (105 trees/ha). The main reason revealed during the resource assessment survey was the maximum allocation of cultivable areas of the HGs for intensive vegetable cultivation, which is a lucrative income-generating livelihood for the majority of HG owners in this region. *Eucalyptus grandis* (20 trees/ha) and *Eucalyptus torelliana* (5 trees/ha) were the most abundant tree species in the HGs. The agro-climatic conditions, such as rainfall and temperature, in this region are highly favourable for the rapid growth of exotic species. It was also found that such species are intentionally planted to control the high wind speeds prevalent in this region, in addition to their use as timber. Therefore, these exotic species are common in the majority of HGs in this region. This implies that there is a propensity for the rapid spread of such exotic species in IU3d, posing a threat to the already diminishing native or local species in this region (Ariyadasa, 2002).

Factors affecting the tree density.

The multiple linear regression model used to identify the influence of socio-economic, agronomic, demographic, spatial, and institutional factors on tree diversity in HGs was statistically significant ($p<0.01$), with an R-squared value of 58%. The multicollinearity test for the explanatory variables showed that all variables had a VIF value of less than 10, indicating the absence of multicollinearity.

The results of the multiple linear regression model are presented in Table 2. They revealed that some factors had a positive influence on the tree density of HGs, while others had negative effects. Among the socio-economic factors, the area of HGs had a negative correlation with tree density ($p<0.01$). This implies that tree diversity increases with the area of HGs up to a certain extent but tends to decrease with further expansion. Similar results have been reported for plant diversity in HGs in Sri Lanka (Korala-Gedara et al., 2012). One of the main reasons for this relationship is that owners convert a part of the HGs area into agricultural crops or other commercial purposes to generate additional income since maintaining only a tree cover is not economically viable for short-term or seasonal earnings.

The field survey revealed that a considerable portion of large-scale HGs in several AERs, such as IU2, WM2a, IU3c, IM3a, and IU3e, has been converted to tea, coconut, vegetable, or banana cultivation. Under such circumstances, trees in the HGs may be thinned out to reduce competition for light with income-generating agricultural crops, resulting in reduced tree density. Previous studies have also reported higher species density in small HGs compared to large HGs (McConnell and Dharmapala, 1973; McConnell, 1992).

The percentage change in the HG area from 1992 to 2017 showed a negative relationship with tree density in HGs (p<0.01). This relationship was particularly observed in the IM1a region, where the highest percentage change in HG extent was reported. The distribution of unproductive government-owned lands to landless individuals is a common practice in this region. The settlers generally prioritize the cultivation of conventional crops rather than maintaining a high tree density in their HGs. Additionally, the agro-climatic conditions, such as rainfall and temperature, are not ideal for a dense tree cover in the IM1a region.

Agronomic factors, such as pepper (*Piper nigrum*) cultivation, positively contributed to tree density (p<0.01). This is mainly due to the extensive cultivation of *G. sepium* to support pepper vines. Similar situations were observed in many AERs, including IU2, IU3c, and WM2b. However, a negative correlation was observed between vegetable cultivation and tree density (p<0.05). This relationship was primarily observed in AERs IU3d and IU3e, where intensive vegetable cultivation was practised.

Table 2: The results of the multiple linear regression model

Variable	Estimates of the regression Model			
Dependent variable	**Tree density of homegarden**			
	Coefficient estimate	**Standard Error**	**t value**	**Probability**
Scio- economic factors				
Area of the homegarden	1589.85	178.554	8.9	0.293
Area square of the homegarden	***-153.32	117.504	-1.3	0.000
Percentage area changed of the homegarden	***-7505694	0.243	-3.09	0.002
Agronomic factors				
Pepper cultivation area of the homegarden	*4.43	0.356	12.42	0.082
Vegetable Cultivation area of the home garden	*-548.10	314.350	1.74	0.082
Demographic factors				
Population Density	***-0.15	0.0262	-6.76	0.000
Spatial factors				
Distance to the main road	***10.46	2.821	3.71	0.000
Sub catchment where homegarden is located	***703.85	134.076	5.25	0.000
Institutional variables				
Support of Department of the Agriculture	-51.78	46.499	-1.11	0.266
Support of the Department of Export Agriculture	***295.81	56.455	5.24	0.000
Support of the Forest Department	***169.37	64.599	2.62	0.009
Support of the Mahaweli Authority of Sri Lanka	54.27	34.203	1.59	0.113
Support of the NGO	-6.72	51.340	-0.13	0.896
Agro-ecological region effect				
Agro ecological region fixed effect	Yes			
Coefficient	219.83	116.423	1.89	0.06
No. of observations	500			
Test	F Value: 26.86			
Probability value	0.000***			
R-squared	0.5862			
Adjusted R-squared	0.5644			

*** p<0.01, ** p<0.05, * p<0.1

Regarding demographic factors, population density showed a negative relationship with tree density (p<0.01). Zomer et al. (2009) explained that the relationship between tree cover and population density varies depending on the region. However, field observations indicated that in highly populated areas in AERs such as WM3b and IM1a, there is limited space to accommodate trees in HGs due to growing demands for housing and other commercial purposes in the limited available land area. Xia et al. (2020) also revealed that an increasing population leads to the conversion of productive agricultural lands for more complex uses.

Among the spatial factors, the distance to the main roads has positively influenced the tree density of HGs (p<0.01). This relationship has also been observed in HGs in Southern Ethiopia, as revealed by Abebe et al. (2013). During field observations, it was evident that HGs located farther away from the main roads had higher tree density in almost all AERs. The higher land value and increased demand for residential and commercial purposes may have led to the fragmentation and conversion of HGs located near main roads into other land uses. These factors contribute to a lower number of trees and tree density in HGs.

The sub-catchment where HGs are situated also had a positive influence on the tree density of HGs (p<0.01). The UMC can be divided into two major sub-catchments: the Victoria Upper Watershed, which is the primary sub-catchment (excluding the Uma-Oya sub-catchment), and the Uma Oya sub-catchment (Figure 1). HGs with higher tree density were commonly found in the AERs located in the Victoria sub-catchment, where a significant portion of the catchment is in the wet zone and receives ample rainfall suitable for tree growth. In comparison, HGs with lower tree density were more common in the Uma Oya sub-catchment. Apart from agro-climatic factors, socio-economic factors such as intensive vegetable and tea cultivation have also contributed to lower tree density in the Uma Oya sub-catchment area.

Institutional policies have had a significant influence on farmers' decision-making regarding tree planting in agroforestry systems (Parwada et al., 2019). The present study revealed that institutional support from the Department of Export Agriculture and the Forest Department has had a highly positive influence on increasing tree density in HGs. The promotion of pepper cultivation by the Department of Export Agriculture has had a greater impact on enhancing tree density in WM2a, WM2b, WU2b, and IU3c, where pepper cultivation is extensively supported through the cultivation of *G. sepium*. Additionally, the Forest Department promotes tree planting in HGs as part of forest policies to increase tree cover. Karunarathna & Gunathilaka (2002) reported that environmental awareness programs have positively influenced tree cultivation in HGs.

CONCLUSIONS

The scientific information regarding the spatial and temporal distribution of Tree Resources Outside Forests Sources (TROFS) in the Upper Mahaweli Catchment (UMC) and their qualitative characteristics is crucial for formulating policies and strategies to restore tree cover in the catchment area. This is primarily due to the inadequate forest cover resulting from severe deforestation over the past two centuries. The study revealed significant differences in the distribution of HGs and their tree density among the AERs of the UMC. In addition to agro-ecological factors, various socio-economic, agronomic, demographic, spatial, and institutional factors influence the tree density of HGs.

There has been a significant variation in the distribution of HGs among the AERs of the UMC between 1992 and 2017. The majority of the AERs exhibited an increasing percentage change in the extent of homegardens during this period. This change is favorable for the sustainability of the catchment, as it has the potential to enhance the extent of tree cover in the catchment. The average tree density of HGs in AERs such as IU2, WM2b, WU2b, IU3c, IM3a, and WM2a falls within the range observed in natural forests in the tropics. This indicates that HGs in most AERs of the

UMC have a high potential for compensating for the inadequate forest cover in the region. However, there is a tendency for the spread of exotic species, which has resulted in higher individual tree species density which exceeds the individual tree species density of native species in AERs such as IU2, WM2a, and IU3d. These exotic species in HGs also contribute to the timber supply of the country. However, their rapid spread under favorable agro-climatic conditions can have detrimental effects on species diversity. Additionally, agro-climatic regions with the lowest tree density (IU3d) have a majority of exotic species. This indicates a threat to the endemic and native species, such as *Haldinia cardifolia, Pterocarpus santalimus, Diospyrus ebenum*, *Ficus collosa, Cryptocarya membranacea,* and *Ligustrum robustum*, in these regions. Since HGs serve as an alternative for the *in situ* conservation of genetic resources in areas with limited forest cover, special consideration should be given to maintaining a balance between native and exotic species in tree planting programs conducted by relevant authorities. The study also revealed an inverted parabolic relationship between tree density and the size of HGs, highlighting an increasing trend in tree density with increasing extent of the HGs. However, it is worth noting that tree density tends to decrease after reaching a maximum extent of the HGs. The conversion of large-size HGs into agriculture for income generation, such as tea, pepper, and vegetable cultivation, was observed in most AERs.

This study can serve as a model for large-scale catchment landscapes, focusing on macro-scale assessments that examine temporal and spatial changes and the reasons behind such changes, particularly in relation to TOFS as there is a limited availability of such studies in Sri Lanka. This area of study requires more attention to generate scientific information for policy formulation aimed at enhancing the quantity and quality of TOFS. Therefore, the study proposes the introduction of special incentive packages for HG owners who maintain large-scale HGs with high tree density and a greater presence of native species. This approach would also discourage the conversion of HGs into other land uses and help restore ecosystem services for the sustainability of the UMC.

Limitation of the study: The temporal analysis in this study covered the period from 1992 to 2017, as it fell within the study period and utilized the available data at the start of the research. However, it is crucial to apply the same methodology to analyze the dynamics of HGs continuously over a similar time scale, not only in the study area but also across the entire country.

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