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RESEARCH ARTICLE

Tree Cover Assessment

Assessment of tree cover density of Sri Lanka using visual interpretation of open-source high-resolution imagery and geographic information system interface mapping

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Abstract: Trees are found in various formations, ranging from individual trees to randomly occurring tree clusters and systematically established tree plantations, as well as natural forests. Accurate information about trees, their distribution and density is crucial for the development of national policies, strategies, and management decisions related to tree planting, and environmental management. While some organizations and individuals have mapped forests, home gardens, and trees outside forests at different scales, the lack of comprehensive and systematic spatial distribution data on trees and tree cover density in Sri Lanka has been a significant challenge for policymakers. To address this issue, this study utilized the tree cover mapping (TCM) tool developed by U.S. Geological Survey. High-resolution images were visually interpreted within a geographic information system interface to map tree cover. The TCM tool employed a systematic sample grid, with a sampling interval of 200 m. The study encompassed 1.64 million sampling units, and mapping and interpretation were conducted at a scale of 1:3000. The resulting tree density map had a resolution of 200 m. Results show that 78% of the country's land area has a tree cover density exceeding 10%, resembling open and sparse forests, while 64% of the country exhibits a tree cover density exceeding 40%, comparable to dense forest areas. The study found that although forest cover was limited in districts such as Colombo, Gampaha, and Jaffna, these areas still displayed a significant level of tree cover density, offering services and functions similar to those provided by forests.

Keywords: Canopy density, Sri Lanka, tree cover, tree density.

INTRODUCTION

The world's forests have undergone significant modifications due to human activities, resulting in the conversion of large forest areas into smaller, fragmented patches (Haddad *et al*., 2015). This transformation is primarily driven by population growth (FAO, 2015), leading to the creation of diverse landscapes where trees can be found in various situations and spatial patterns (de Foresta *et al*., 2013). They comprise tree formations ranging from individual trees in various places to systematically managed tree plantations and natural forest areas (Kleinn, 2000; de Foresta *et al*., 2013). In this context, Sri Lanka is not an exceptional country as the country's forest cover has been depleted to 29.2% (Premakantha *et al*., 2021), and exhibits fragmented forests interspaced within agricultural, urban, and built-up areas. This trend of diminishing forest extent and increasing tree presence in non-forest areas is observed throughout the tropics (FAO, 2005). A 'tree' can be defined as a woody perennial with a single self-supporting

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main stem, with a minimum height of 5 m (Nicholson & Clapham, 1975; Thomas, 2000). Trees, including bamboo and palms, provide various environmental services categorized as provisioning, regulating, cultural, and supporting services (MEA, 2005). The products and services offered by trees are generally consistent across different land use types, although their abundance and intensity can vary depending on the specific land use (de Foresta *et al.*, 2013). Hence, while conserving the existing limited extent of natural forests in the country, it is essential to obtain products and services which are provided by forests from trees outside forests also.

Tree canopy cover density is a primary structural characteristic (Coulston *et al*., 2012) that is important for forest landscapes including forest plantations as well as non-forest landscapes such as urban lands, home gardens, tea (*Camellia sinensis*), rubber (*Hevea brasiliensis*), coconut (*Cocos nucifera*), and other agricultural lands. Tree cover density, referred to as tree canopy coverage or crown cover, is defined as the proportion of the forest or land-use floor covered by the vertical projection of the tree crowns, which is a critical aspect of forest management activities (Jennings *et al*., 1999). Tree cover density products represent the level of tree canopy density coverage on a scale of 0 (no trees) to 100% (full canopy coverage) (EARSC, 2015; Cotillon & Mathis, 2016). The amount of tree cover is a fundamental component of the landscape, which is directly related to environmental services provided, including carbon sequestration (Kellndorfer *et al*., 2006; Suganuma *et al*., 2006), atmospheric cooling (Shashua-Bar & Hoffman, 2000; Shashua-Bar *et al*., 2011), maintaining stream water temperatures (Webb & Crisp, 2006), stormwater mitigation and erosion control (Bartens *et al*., 2009), air pollution mitigation (Nowak *et al*., 2008; 2018; John *et al*., 2012), reduced energy use (Hsieh *et al*., 2018), habitat provision (Burghardt *et al*., 2009), increased property values (Escobedo *et al*., 2015), and reduced mental fatigue (Houlden *et al*., 2018).

Despite the significance of trees and their products and services, comprehensive global documentation of their spatial distribution, volume, and value remains inadequate in official statistics (Warner, 2000; Thomas *et al*., 2021). However, obtaining reliable information on the spatial distribution, density, species composition, quality, and temporal changes of trees is essential for developing national policies, strategies, and management decisions, as well as monitoring their impacts (Bradshaw, 2012; Hansen *et al*., 2013; Thomas *et al*., 2021).

Accurately mapping and monitoring tree cover across extensive areas poses a significant challenge (Fisher *et al*., 2016). While ground surveying provides the most precise method, its use is limited due to cost and time constraints (Kleinn, 2000). Even though several remote sensing-based methodologies have been developed to generate information on tree cover across large spatial extents, most data are based on satellite sensors with resolutions too coarse to observe isolated trees or regeneration of trees, or both (Cotillon & Mathis, 2016).

For instance, in dry land regions like the Sahel in Africa, where trees are scarce, traditional satellite-derived methods struggle to accurately map tree cover (Cotillon & Mathis, 2016). However, the application of the Support Vector Machine (SVM) approach using Sentinel-2 satellite images has shown great promise in accurately mapping tree cover and assessing their potential, achieving over 96% accuracy (Mirończuk & Hościło, 2017). Comparative studies have demonstrated SVM's superiority over other classifiers, such as conventional k-Nearest Neighbour (kNN) and radial basis neural network (Melgani & Bruzzone, 2004).

Although Sri Lanka has produced land use maps that include forest cover and home garden areas (LUPPD, 2020; Premakantha *et al*., 2021; Gunawardena & Fernando, 2022), as well as certain systems of trees outside forests (Premakantha *et al*., 2008), comprehensive information on tree cover density and its distribution across different land use types and the stream network is currently unavailable. This knowledge gap is a fundamental requirement for sustainable planning, implementation, and monitoring of tree planting programmes to maximize ecological, economic, and social benefits. Therefore, the objective of this study is to estimate the extent and spatial distribution of tree cover density in Sri Lanka, considering forest cover, various land use types, and the stream network. High-resolution satellite imagery will be utilized to map tree cover density and identify potential areas for tree planting and management beyond forest areas.

MATERIALS AND METHODS

Accurately mapping the extent of tree cover in large areas presents challenges due to the limitations of satellite-derived data with coarse resolutions. However, the Tree Cover Mapping (TCM) tool (Figure 1), developed by the U.S. Geological Survey Earth Resources Observation and Science Centre (Cotillon & Mathis, 2016), offers the facility to estimate tree cover. The TCM tool usually (1) facilitates the process of panning and zooming into each sample; (2) facilitates estimation of the amount of tree cover within a specific sampling frame by placing a grid of calibration points on each sample; (3) makes it compatible with Google Earth, and (4) generates a map based on the sample points (Cotillon & Mathis, 2016). This ArcGIS add-on utilizes high-resolution imagery and visual interpretation to facilitate large-scale tree cover mapping. The TCM tool enables the estimation of tree cover within a defined sampling frame by placing a grid of calibration points on each sample. It also integrates with Google Earth to synchronize location and extent information for mapping purposes.

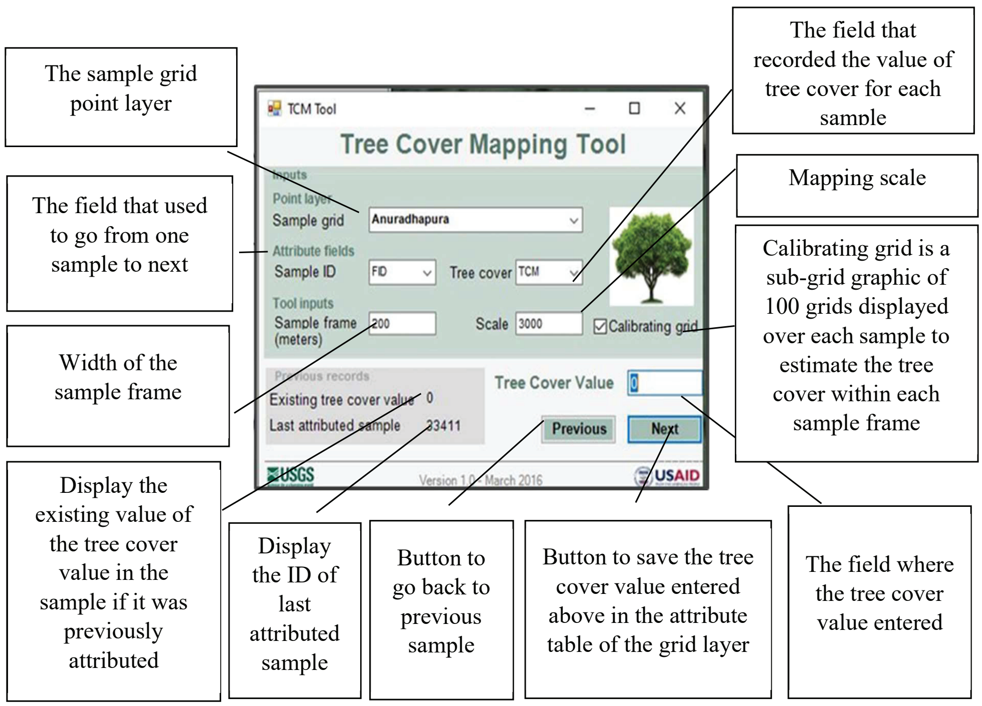

Figure 1: Tree cover density mapping parameters in Tree Cover Mapping Tool

To map tree cover using the TCM tool, a systematic sampling grid was established over the study area. This grid, created using the 'Create Fishnet' Arc Toolbox, consists of regularly spaced intervals and defines the resolution and precision of the output map. The two layers were created over the study area: a point layer, which was the sample grid, and a polygon or polyline layer that can be deleted. The sample frame's area is 4 ha and its width is 200 m. Hence, the resolution of the tree density map is 200 m. High-resolution imagery is used for tree cover mapping, typically at a scale ranging from 1:6000 to 1:2000, depending on the desired level of precision, confidence, and effort dedicated to the mapping exercise.

In this study, a sample grid layer comprising more than 1.6 million grids covering the entire island of Sri Lanka was visually interpreted to estimate tree cover density. Skilled remote sensing technicians conducted this interpretation. A Tree Cover field was created in the attribute table of the sample grid layer to record the tree cover value for each sample. The value was estimated based on the number of dots touching the canopy of a tree within the sample frame as shown in Figure 2.

Once all the sample grid points were attributed, the systematic sample grid was converted to a raster format. This conversion allows for further analysis using geographic information system (GIS) techniques such as Zonal Statistics and Heatmaps using Kernel Density or Point Density functions. The accuracy of mapping was assessed through manual validation using Google Earth Street view images for ground truthing purposes, resulting in an accuracy rate exceeding 90%.

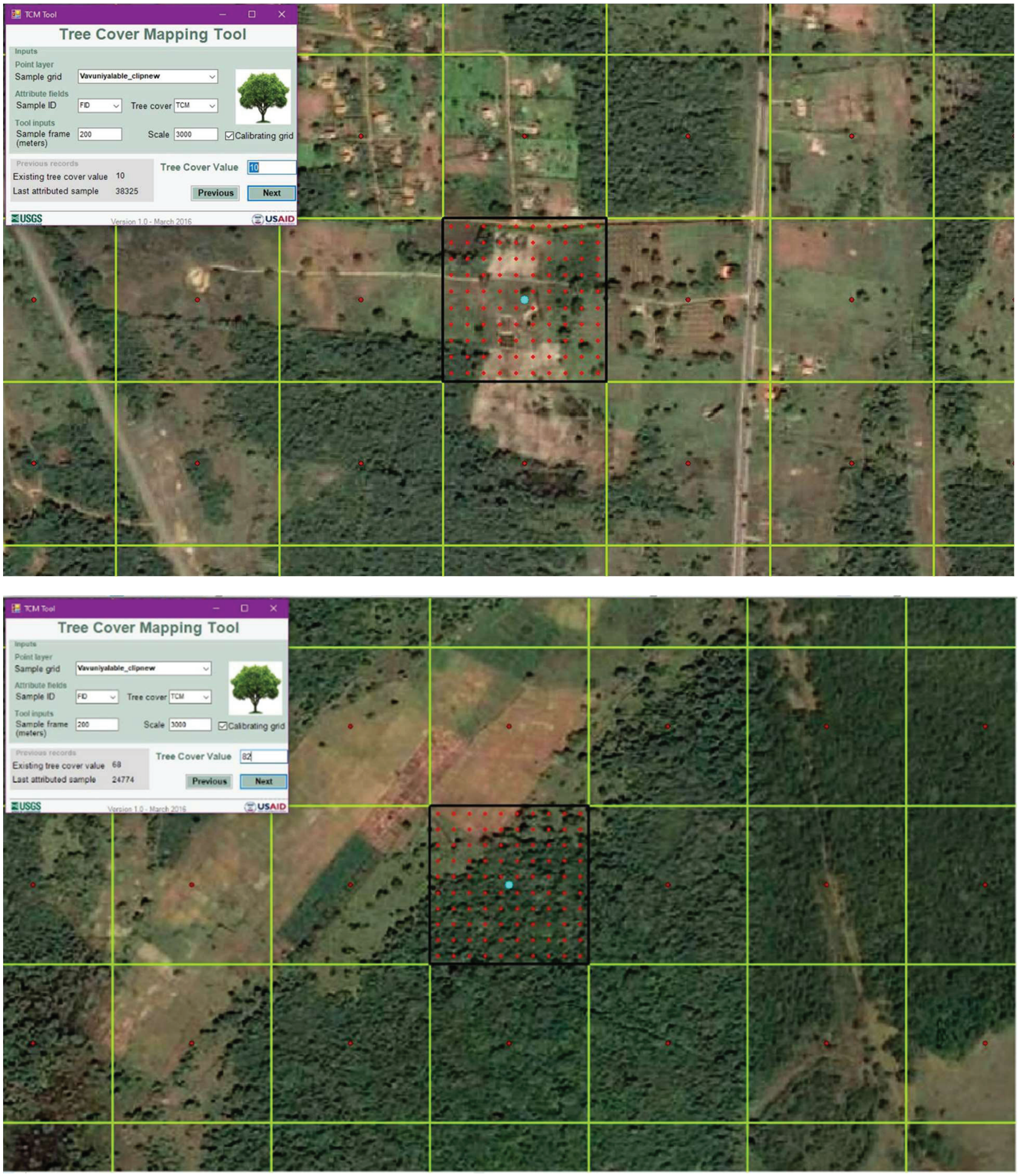

Figure 2: The method of assessing percent of tree canopy cover within each sample frame

To create tree cover density maps for different land use types, widely used categories that include significant tree components were selected. These categories were based on the land use classifications of the Survey Department of Sri Lanka and the Land Use Policy Planning Department (LUPPD). The selected land use categories included tea, coconut, and rubber plantations, agricultural areas, grasslands, home gardens, forests, and built-up areas, each contributing varying tree cover densities that support different ecosystem functions.

RESULTS AND DISCUSSION

The tree cover density map of Sri Lanka produced using the Tree Cover Mapping Tool based on administrative districts of the country is given in Figure 3. As of the assessment, 78% of the land area of the country has more than 10% tree cover density, which is similar to the open and sparse forests category, while 64% of the country has more than 40% tree cover density, which is similar to the dense forest category. This study reveals that the tree cover density in Sri Lanka is high (64%) compared to Nepal (44.9% in 2016; Fox *et al*., 2019), India (36.18% in 2021; ISFR, 2021), Bangladesh (21% in 2014; Potapov *et al*., 2017) and New South Wales, Australia (27.11% in 2016; Fisher *et al*., 2016). The spatial distribution of the tree cover density map indicates that it is well-distributed throughout Sri Lanka, and may be offering goods and services spreading equally through the entire country, especially in areas with limited natural forest cover (Figures 3).

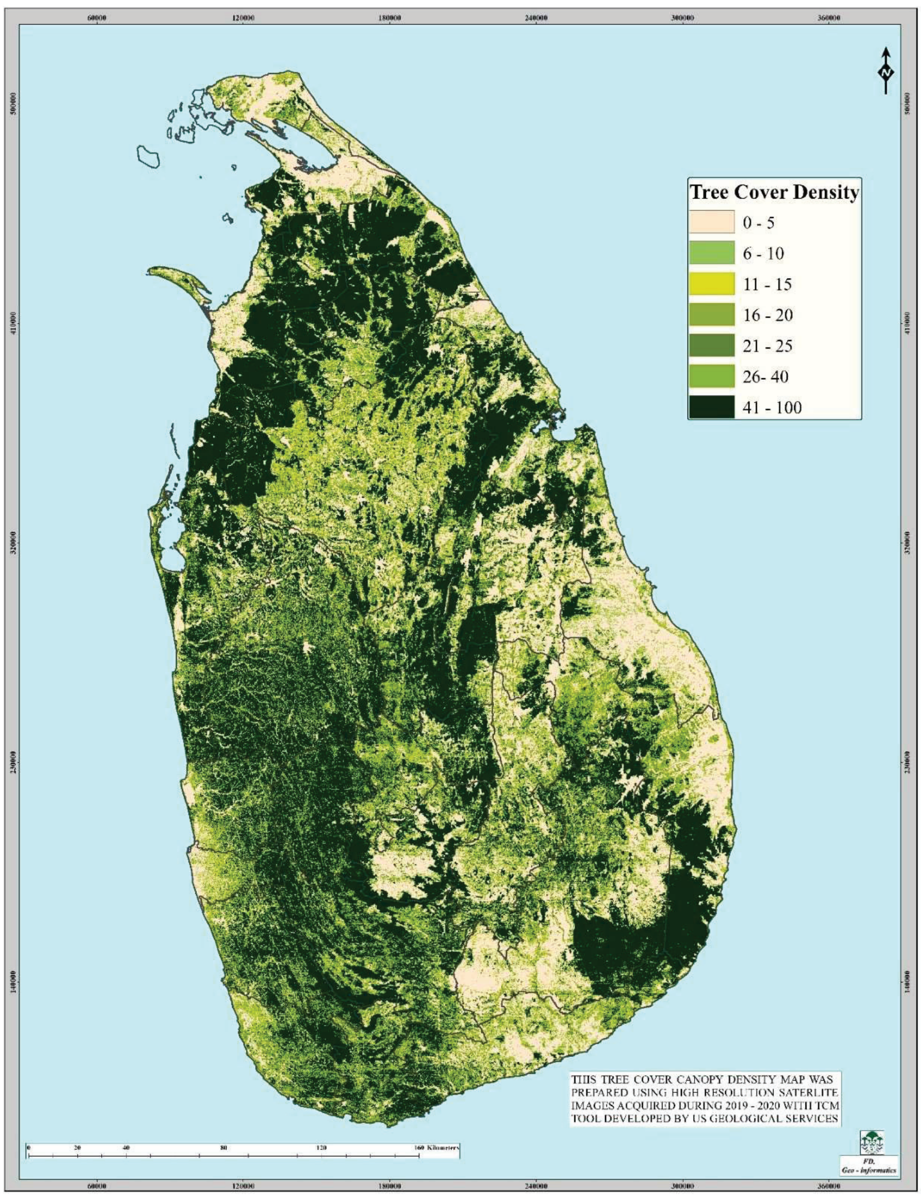

Figure 3: Tree cover density map based on administrative districts of Sri Lanka

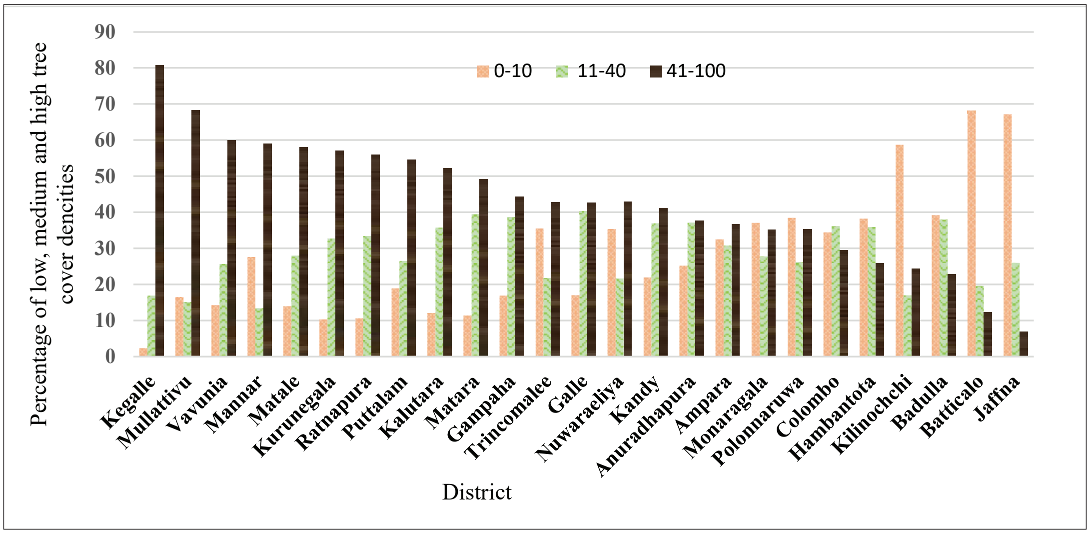

Figure 4: District level distribution of low (0-10%), medium (11-40%) and high tree cover densities (41-100%) of Sri Lanka

Figure 4 illustrates the distribution of areas with tree density similar to non- or low forest areas (0–10%) and those similar to forests (11–40% and 41–100%) in each district, as of FAO (2012) definition used to define a forest. This information highlights the significant roles of tree cover in providing ecosystem services comparable to forests in districts where natural forest cover is limited. For example, in Gampaha, Colombo, Kurunegala, and Jaffna, the natural forest cover is limited to 1.6%, 2.9%, 4.5%, and 4.7%, respectively (Premakantha *et al*., 2021), but tree cover density is substantial (Figure 4). Additionally, Kegalle (97%), Kurunegala (90%), Matara (89%), and Ratnapura (89%) districts have larger areas with relatively high tree cover densities (11–100%), while Batticaloa (68%), Jaffna (66%), and Kilinochchi (59%) districts have relatively large areas with low tree cover density (0–10%) (Figure 4). These data emphasize the importance of assessing different land use categories and their tree utilization in each district and province for effective planning of tree planting and environmental conservation proposals.

Figure 5 provides the spatial distribution of tree densities in different land-use systems that include trees as a major component. The results of the study revealed that the tree cover density varies significantly among land-use systems. Areas where rubber is grown on a commercial scale exhibit high tree cover density (41–100%) similar to that of forests, justifying the inclusion of it into forest cover in the FAO definition (FAO, 2005). Similarly, coconut plantations too have a higher tree density. Agricultural areas, grasslands, and built-up areas have over 50% their land area with low tree densities (0-10%). As indicated by MEA (2005), Premakantha (2015), and Tassera *et al.* (2020), different land use type performs different functions at varying magnitudes that are important for human well-being and environmental conservation. Therefore, all land use types have a certain value in terms of provisioning ecosystem services and goods under the current land use system of the country. By changing the special composition and structure of the tree components, their capacity can be greatly improved. Hence, correct interventions should be chosen or else they might hinder the performance of any land use type in terms of environmental services.

The Food and Agriculture Organization (FAO) defines 'forest' as a portion of land bigger than 0.5 ha with trees higher than 5 m and a tree canopy cover of more than 10%, or with trees that will be able to meet these criteria. It does not include land that is predominantly under agricultural or urban land use. However, Trees Outside the Forests (TOFs) which includes agricultural (tea, coconut and rubber plantations, home gardens, and other agroforestry systems) and urban lands play a major role in providing ecosystem services under the present land use system of the country. This is important for the districts such as Kurunegala, Gampaha, Kalutara, and Colombo, where natural forest cover is limited and tree cover is high in performing major functions similar to forests.

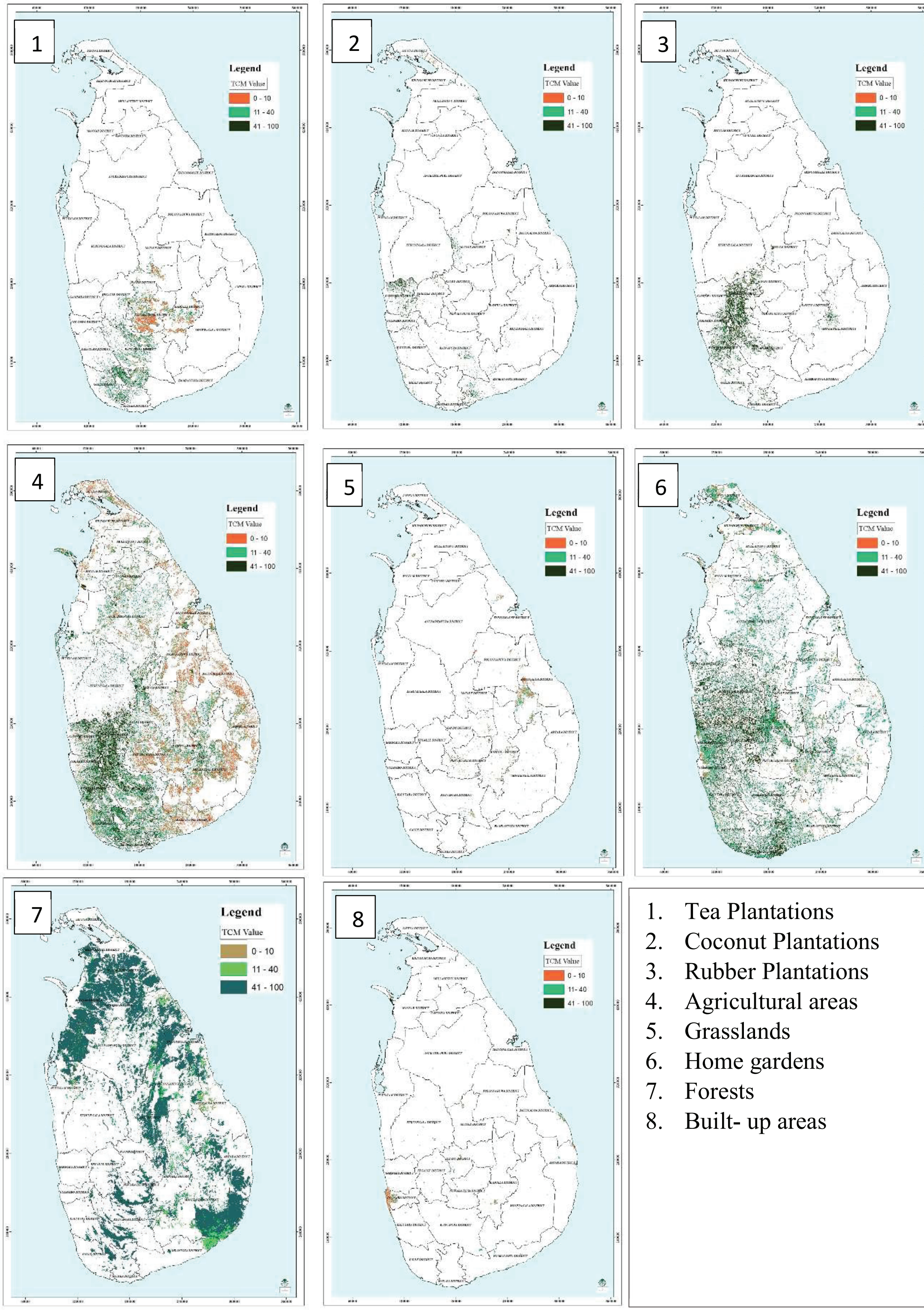

Figure 5: Distribution of tree cover densities in main land use classes in Sri Lanka.
Note: Scale of an A4 size map is 1:1,800,000

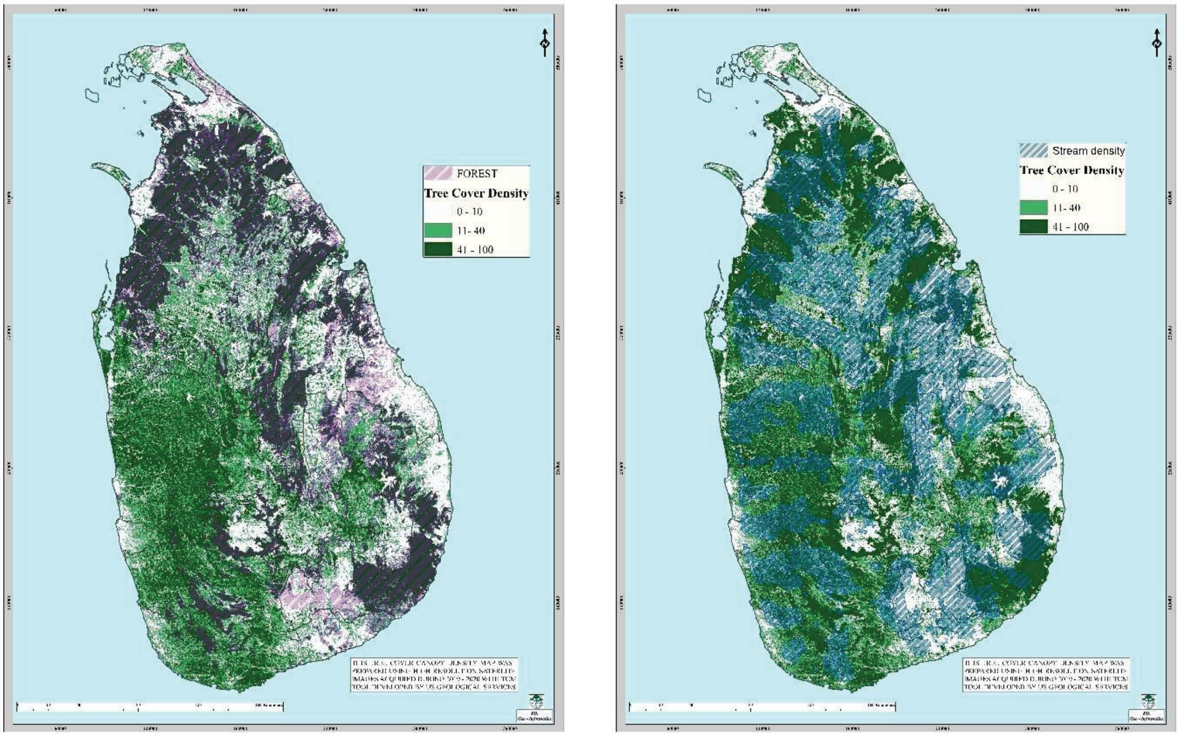

Figure 6: The maps of forest cover overlaid on tree cover density (left) and stream densities overlaid on tree cover density map (right) of Sri Lanka

Figure 6 displays the forest cover map overlaid on the tree cover density map, as well as the stream density map overlaid on the tree cover density map in Sri Lanka. The forest cover map shows that the forest area is only 29.2% (Premakantha *et al*., 2021). However, there are other types of land use with tree cover densities greater than 10%, but they do not qualify as forests because they do not meet the other criteria of the FAO. Deforestation due to various drivers takes place continuously leading to the fragmentation of forests in Sri Lanka and elsewhere. In this regard, the tree cover density map helps to determine the best suitable area for connecting fragmented forests taking into account the proximity and type of land use and their tree cover density. The stream network map shows high tree cover density in most areas but low density in certain areas that require interventions to increase tree cover (Figure 6). Hence, attention should be given to such areas in tree planting campaigns. Sri Lanka is blessed with a network of over 100 streams, which is distributed across all land use categories. Stream bank vegetation, called riparian, is an ecosystem situated between aquatic and terrestrial environments, and is a relatively narrow strip of land along the bank of a river. The riparian systems along the river/stream banks function to reduce soil erosion by trapping sediments and minimizing bank erosion, to filter nutrients and pollutants, to stabilize surrounding ecosystems by shading, reducing temperature, and adding organic matter, to recharge groundwater and reduce floods (Debano & Schmidt, 1990; Naiman & Decamps, 1997; Pusey & Arthington, 2003). Further, healthy riparian vegetation can also provide significant habitats for flora and fauna and aesthetic value to the environment. Thus, proper planning and implementation of tree planting with suitable species for a given environment can be facilitated and monitored with maps of tree density along the stream network of Sri Lanka.

Planting trees in forests as well as outside forests is a major topic of discussion today as the impact of climate change can be seen and felt around the world. Historically, numerous tree-planting programmes by various organizations have been implemented, but their success is questionable. Planting trees without a clear objective, lack of proper planning and coordination among institutions, use of unsuitable species, and lack of follow-up activities and maintenance programmes have been identified as the main reasons for the failure of tree-planting programmes in Sri Lanka. Thus, increasing tree cover and tree density has to be planned and implemented wisely, otherwise resources could be wasted without achieving expected targets. Therefore, the tree component of each land use type needs to be identified, before deciding on interventions to change species composition, structure, density, and tree management, hence functions. Such kinds of planning and intervention will enhance the tree cover further, achieving ecological, economic, and social benefits. As demonstrated by examples from various locations, such as the successful case in Nepal (Fox *et al*., 2019), proper planning and implementation of tree planting campaigns can result in a doubling of tree cover within a period of 24 years.

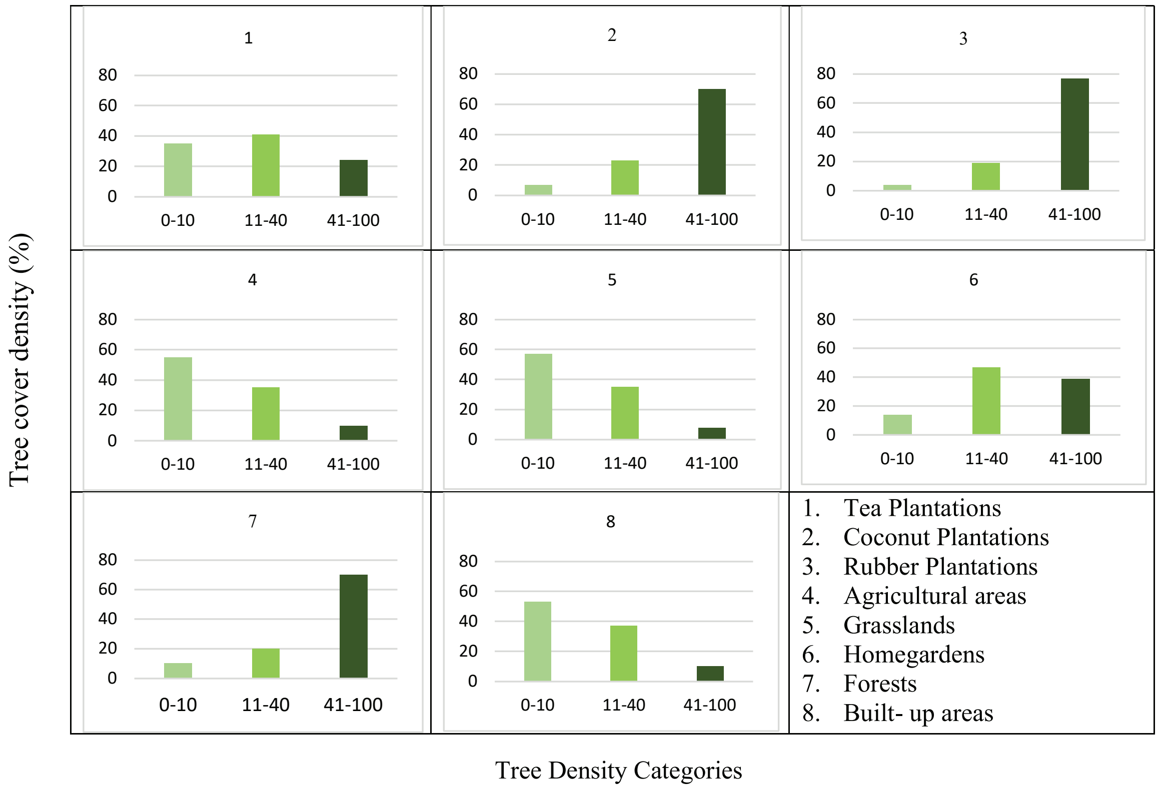

Figure 7: Distribution of tree cover density categories of major land use types in Sri Lanka

Tree cover density and its implication on land use planning and policy decisions

Different land use types have several tree components and their functionality varies greatly depending on their location, composition, and management (Premakantha, 2015). The tree cover density of major land use types used in this study is presented in Figure 7. To maximize the ecological, economic, and social benefits of trees and land use types, it is crucial to investigate the spatial distribution of each land-use type along with tree density distribution, social structure, and strategies for increasing tree presence in the system. This may involve adding more trees to the system, replacing or substituting trees based on community or national goals, and providing appropriate guidelines to align with the existing system. Moreover, the perception of tree resources outside forests varies among stakeholders representing agriculture, forestry, irrigation, urban, and suburban land uses. Consequently, planning tree inventories outside forests poses several challenges compared to forest inventories (Schnell *et al*., 2015). As suggested by Crowther *et al*. (2015), establishing tree planting targets and assessing the proportionate contribution of such projects require a solid baseline understanding of current and potential tree populations at sub national, national, regional, and global scales. In Sri Lanka, this baseline assessment based on different land use categories, where objectives of tree planting and stakeholders' interest align closely, is yet to be determined.

Tea plantations

The tea-growing districts of Sri Lanka include Nuwara Eliya, Kandy, Badulla, Matale, Kegalle, Galle, Matara, and Ratnapura. Figure 5 illustrates the distribution of tree cover density in these tea plantation areas. Within tea plantations, various tree components serve different purposes: shade trees within tea cultivation, riparian vegetation along streams, natural forest patches, forest plantations, and trees planted along roadsides and around offices and resident areas of workers. This study reveals that the tree cover density in tea plantations is lower compared to other major plantation crops such as coconut and rubber (Figure 7), despite the presence of visible tree components in certain areas of tea plantations. However, incorporating multi-purpose trees and fruit trees like apples (*Malus domestica*) and pears (*Pyrus communis*) in the upcountry region and jackfruit (*Artocarpus heterophyllus*) in low country areas, as shade trees or planted along borders, offices, and residential areas can contribute to food and environmental securities. In some cases, tea plantations also contain isolated forest patches, requiring a forest management plans for the Regional Plantation Companies when natural forest patches or forest plantations coexist within tea plantations. Selecting suitable areas and seed sources for establishing forest plantations, along with appropriate silvicultural practices, can enhance timber production and carbon sequestrating. Additionally, degraded areas can be utilized for establishing fuelwood or biomass blocks, as tea plantations heavily rely on fuelwood for tea drying and cooking by the plantation community. Furthermore, in tea plantations where riparian or stream banks directly adjoin tea fields without a buffer strip, incorporating appropriate shrubs, trees and other species such as wild sugarcane as a buffer strip can prevent stream bank erosion and washing of nutrients, conserving biodiversity while supporting tea production.

Coconut plantations

Currently, coconuts are grown in the coconut triangle, which comprises Colombo, Puttalam, and Kurunegala but spatially extends beyond these districts and also in the dry zone of Sri Lanka. Figure 5 illustrates the distribution of tree cover density of these coconut plantation areas. Although coconut cultivations generally have a high tree density, their function as a habitat is limited due to monoculture practices. Nonetheless, certain areas within coconut plantations exhibit visible tree components, including intercropped perennial trees, patches of natural forests, forest plantations, roadside plantings, and trees surrounding office premises and residential areas for workers. Increasing tree density is crucial to optimize the lands under coconut more efficiently in a way that creates more economic, social, and environmental benefits. Kurunegala Plantation Limited has successfully demonstrated the feasibility of incorporating additional tree species into coconut cultivation. They have introduced trees such as durian (*Durio zebethensis*), jackfruit, rambutan (*Nephelium lappaceum*), mango (*Mangifera indica*), and gliricidia (*Gliricidia sepium*), with pepper (*Piper nigrum*), cloves (*Syzygium aromaticum*), cinnamon (*Cinamomum zeylanicum*), and annuals such as turmeric (*Curcuma longa*) in various mixtures. This approach, including roadside plantations, has proven to be successful, resulting in increased revenue for the company and generating additional employment opportunities (Samarakoon *et al*., 2023). The company plans to further expand the agroforestry area by incorporating more tree species into coconut plantations. Augmenting tree cover density in coconut plantations will not only contribute to increased agricultural productivity but also yield environmental benefits. These include carbon sequestration and establishment of biological corridors to connect fragmented forests.

Rubber plantations

The districts where rubber is grown in Sri Lanka are Colombo, Galle, Gampaha, Kalutara, Kandy, Kegalle, Matale, Matara and Ratnapura, and recently in Moneragala (Figure 5). Although rubber plantations are not officially classified as forests in Sri Lanka, they meet the definition of forest according to the FAO (FAO, 2005) because their structure is similar to forests, albeit cultivated as monoculture stands. Consequently, they fulfil most functions of forests. Rubber cultivation plays a significant role in the Sri Lankan economy, contributing to foreign exchange earnings, employment generation, and environmental protection. However, there are limited opportunities to increase the tree cover in rubber plantations, except during the early years when intercropping with certain tree crop species is possible. Nevertheless, opportunities exist to enhance tree density along stream banks, around office premises, residential areas of workers, forest plantations, and natural forest patches (Figure 7).

Home gardens

The expansion of home gardens in Sri Lanka has been driven by population growth, resulting in approximately 18% of the country's coverage being occupied by home gardens (Figure 5; Pushpakumara *et al*., 2012; LUPPD, 2020). Home gardens are a crucial element of the rural community, offering functions similar to forests. In home gardens, variations in species composition of trees and their structure can be observed based on their location, including the front yard, back yard, fence, and around the water sources. Increasing tree density in home gardens can be achieved through scientific approaches, such as adding more trees to the system. Additionally, management of existing trees involves pruning unwanted and diseased branches, while thinning helps remove weak trees (those that are dying, diseased, decayed, damaged, or have broken tops), allowing healthier trees to grow faster and reducing competition for growth. When timber volume ceases to increase due to maturity or death, replacement of trees with the same species can be carried out, especially for economically valuable trees. Furthermore, non-economic trees can be removed and replaced with high-yielding tree species. In areas with low tree density, tree introduction can also be practiced (Pushpakumara *et al*., 2012). Increasing trees in home gardens contributes to improved food security, dietary diversity, micro-climate, and income for rural communities while enhancing environmental security and resilience in the region (Pushpakumara *et al*., 2012; Weerahewa *et al*., 2012; Lowe *et al*., 2021). There is significant potential to expand tree density in home gardens, as recent assessments indicate that approximately 52% of home gardens in the country are underutilized (LUPPD, 2020). By analyzing the total number of home gardens and identifying those with available space for tree crops in each district or AGA division, it becomes possible to address issues related to food and nutritional security. Suitable species such as jackfruit, coconut, leafy vegetable species, fruit trees, etc. can be included in the system or dedicated tree crop villages (*e.g.*, jackfruit village, durian village) can be established for commercial production, as previously practiced by the Department of Agriculture. Due to its extensive high-canopy home gardens and its high biodiversity per unit area, Sri Lanka is exceptional in South Asia concerning tree cover density.

Grasslands

There are several types of grasslands, including *patana* (montane), savannah, and lowland grasslands. The composition of trees in these grassland types varies significantly based on the climate zone and the presence of biotic and abiotic disturbances (Figure 5; Figure 7). When increasing tree cover density in grasslands, careful planning is essential. Naturally occurring grasslands serve as habitats for birds and small animal species, as well as crucial feeding grounds for migratory birds and large animals such as elephants, deer, and buffaloes. Therefore, before preparing a plan to enhance tree density in the grassland system, it is crucial to identify the underlying causes that have led to concerns regarding the grasslands. In some cases, increasing tree density may require no interventions beyond addressing the driving forces that impact the grasslands. The Forest Department of Sri Lanka implements interventions such as assisting natural regeneration and planting trees where they are absent, or a combination of both, to increase the tree density in grasslands. Additionally, it is also possible to protect stream banks in grasslands by planting appropriate trees.

Agricultural areas

The agricultural sector plays a vital role in the economy of Sri Lanka, as over 70% of the rural population relies on agriculture for their livelihoods. Being an agricultural country, the cultivation of trees and crops is prevalent in almost all districts of Sri Lanka (Figure 5). Trees grown on agricultural lands serve important purposes such as facilitating nutrient recycling, controlling soil erosion, enhancing the micro-climate, and providing agricultural inputs such as green manure. In agricultural lands, it is essential to increase tree density in a manner that does not lead to competition with crops for vital resources such as sunlight, water, and nutrients. To achieve the optimal level of agricultural production and tree-based products, it is necessary to test various tree-crop models and introduce new species. Increasing tree density in agricultural areas is critical as it helps to connect isolated forest patches, thereby expanding the habitat range of numerous plant and animal species. This requires a comprehensive analysis of different agricultural systems, such as paddy-based systems, maize and other field crop-based systems, fruit orchards, chena system, including their spatial distribution and the level of underutilization of lands (Figure 7). Additionally, planting trees along stream banks, tanks, and water bodies can offer further benefits. This holds particular significance in the village tank systems of Sri Lanka, where the traditional system operates with various tree-dominated sub-ecosystems such as catchment forests, tree belts, interceptors, and homesteads. Originally, human settlement was restricted to designated areas within these systems, but currently, settlements have expanded to multiple areas. Consequently, trees must play a crucial role in these expanded settlements.

Built-up areas

Built-up areas cover permanent buildings in urban and semi-urban regions, trees along streets, roads, and canals, as well as isolated trees within urban areas and a few forest patches left for recreation activities or as urban parks (Figure 5), and are exposed to a high level of CO_2 emissions. Trees play a crucial role in urban areas by improving the micro-climate, mitigating the urban heat island effect, reducing dust particles and alleviating noise pollution. Increasing tree density in urban areas may pose challenges beyond certain levels. However, through proper planning, areas such as urban parks, city roadsides, vehicle parking lots, sidewalks, street tree planting and space around water bodies have been identified as suitable for increasing tree density. It is important to emphasize that proper planning, including selection of the right trees for the right locations, and effective management practices such as the removal of weak and dead branches, and pruning of excess branches are essential for sustainability. These measures also help to minimize potential damage caused by trees during strong winds and heavy rain events.

Forests

As of 2021, Sri Lanka's natural forest cover is at 29.2%, and although the rate of depletion and degradation has slowed compared to previous periods, it continues to decrease. Sri Lanka's natural forest cover comprises a range of ecosystems, including savanna, mangroves, and forests of varying openness and density. This natural vegetation types exhibit diversity and are dispersed across the wet, dry and intermediate climate zones of the country. However, forest cover is predominantly concentrated in the Northern and Eastern provinces and the central hills (Figure 5). In order to fulfill its Nationally Determined Contribution (NDC) to the United Nations Framework Convention on Climate Change (UNFCCC), Sri Lanka places great importance on planned and organized activities within its forest landscape. One of the targets outlined in the NDC is to increase the national forest cover from the current level to 32% by 2030 (MoE, 2023). To achieve this target, several key areas of focus have been identified, including sustainable management of natural forests, improving the quality of growing stocks in natural forests, demarcating forest boundaries, establishing protected areas and environmentally sensitive zones, restoring and rehabilitating degraded forests (including mangrove vegetation), enhancing catchment protection for major rivers and cascade systems, and establishing plantation forests (MoE, 2023). Additionally, reforestation efforts on non-forest lands, accompanied by proper land use planning, as well as restoration and reforestation of degraded and marginal agricultural lands, are essential for increasing the country's forest cover. To effectively carry out these activities, it is crucial to have an understanding of the current level of tree density and anticipate future changes resulting from proposed interventions. This information can be obtained from tree cover density maps specifically designed for identified forests and non-forest lands.

We have developed the first country-scale map depicting tree canopy cover density in Sri Lanka by utilizing high-resolution imagery within a geographic information system interface mapping. This map also incorporates the distribution of tree cover density across different land use categories, along with forest cover and stream density. Despite the country's forest cover being 29.2%, the tree cover density of 64% indicates that more than half of the total tree cover in Sri Lanka originates from trees outside forests. In some areas, these trees outside forests represent the sole available resource for local populations. They encompass various types of trees, which the Sri Lankan government, Forest Department, Department of Agriculture, and Department of Export Agriculture have actively promoted through initiatives such as home garden improvement programmes, participatory forestry, social and community forestry, urban woodlots and parks, and agroforestry among others. These trees outside forests serve as the second-best options for natural forests, highlighting their significance.

The information presented in this paper serves as baseline information for monitoring tree cover density in the future, as well as tracking tree-planting programmes across different land use types. These monitoring efforts can be implemented at various administrative levels, including *Grama Niladari* (GN) division, Assistant Government Agents (AGA) division, district, provincial, and national levels, to achieve respective environmental, food, and nutritional security goals.

CONCLUSIONS

The tree cover density map of Sri Lanka provides valuable insights into the distribution and density of trees across different land-use categories in the country, hence providing valuable information for land-use planning and policy decisions. The findings reveal that a significant portion of the land area, approximately 78%, has more than 10% tree cover density, similar to the open and sparse forests, while 64% of the country has more than 40% tree cover density, similar to the dense forests. These findings also highlight the important role of tree cover in providing ecosystem services, particularly in districts with low forest cover. The map also highlights the variation in tree cover density across different land-use systems and the potential for increasing tree cover in such land-use systems. However, there are challenges and shortcomings in tree-planting programmes in Sri Lanka in different land use systems. Hence, proper planning and implementation is needed to maximize the benefits of tree cover within each land-use type and enhance their environmental performance.

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