# Impact of Community-Based Forest Restoration on stand structural attributes, aboveground biomass and carbon stock compared to State-Managed Forests in tropical ecosystems of Sri Lanka (#99692)



First submission

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# Impact of Community-Based Forest Restoration on stand structural attributes, aboveground biomass and carbon stock compared to State-Managed Forests in tropical ecosystems of Sri Lanka

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Estimation of plant community composition, aboveground biomass and carbon stock is crucial for understanding forest ecology, strengthening environmental management, and developing effective tools and policies for forest restoration. This study was conducted in nine different forest reserves in Sri Lanka from 2012 to 2018 to examine the impact of community-based forest restoration (CBFR) on stand structural attributes, aboveground biomass, and carbon stock. In total, 180 plots (90 plots in community-managed restoration blocks (CMRBs) and 90 plots assigned to state-managed restoration blocks (SMRBs)) were sampled at the study site. To conduct an inventory of standing trees, circular plots with a radius of 12.6 meters (equivalent to an area of 500 square meters) were established. The Shannon diversity index, Allometric equations and Difference in Differences (DID) estimation were used to assess the data. Our study provides evidence of the positive impact of the CBFR program on enriching trees diversity. Considering stand structural attributes of both blocks showed higher trees density in the smaller diameter at breast height (DBH) category, indicating growth in both CMRBs and SMRBs. The results showed that tree biomass and carbon density were disproportionally distributed across the nine different forest reserves, with high biomass (98.92 Mg $ha^{-1}$ and 106.64 Mg $ha^{-1}$) and carbon density (46.49 Mg C $ha^{-1}$ and 50.11 Mg C $ha^{-1}$) estimated in SMRBs in Bambarabedda Weliketiya Mukalana forest reserve (Figure 7), and low biomass (18.63 Mg $ha^{-1}$ and 21.44 Mg $ha^{-1}$) and carbon density (8.75 Mg C $ha^{-1}$ and 10.08 Mg C $ha^{-1}$) estimated in CMRBs in Gedaboyaya forest. However, CMRBs in Madigala reserve represent the highest biomass (56.53 Mg $ha^{-1}$ and 59.92 Mg $ha^{-1}$) and carbon (26.57 Mg C $ha^{-1}$ and 28.16 Mg C $ha^{-1}$) density. The results of biomass and carbon estimates were higher in all SMRBs in the nine different forest reserves compared to CMRBs. The findings suggest that future forest restoration programs in Sri Lanka should enhance participatory approaches to optimize tree species diversity, density and carbon storage; particularly, in community-controlled forests. Our findings could assist developing tropical nations in understanding how CBFR impacts forest restoration objectives and improves the provision of ecological services within forests.

# Impact of Community-Based Forest Restoration on stand structural attributes, aboveground biomass and carbon stock compared to State-Managed Forests in tropical ecosystems of Sri Lanka

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## Abstract

Estimation of plant community composition, aboveground biomass and carbon stock is crucial for understanding forest ecology, strengthening environmental management, and developing effective tools and policies for forest restoration. This study was conducted in nine different forest reserves in Sri Lanka from 2012 to 2018 to examine the impact of community-based forest restoration (CBFR) on stand structural attributes, aboveground biomass, and carbon stock. In total, 180 plots (90 plots in community-managed restoration blocks (CMRBs) and 90 plots assigned to state-managed restoration blocks (SMRBs)) were sampled at the study site. To conduct an inventory of standing trees, circular plots with a radius of 12.6 meters (equivalent to an area of 500 square meters) were established. The Shannon diversity index, Allometric equations and Difference in Differences (DID) estimation were used to assess the data. Our study provides evidence of the positive impact of the CBFR program on enriching trees diversity. Considering stand structural attributes of both blocks showed higher trees density in the smaller diameter at breast height (DBH) category, indicating growth in both CMRBs and SMRBs. The results showed that tree biomass and carbon density were disproportionally distributed across the nine different forest reserves, with high biomass (98.92 Mg ha$^{-1}$ and 106.64 Mg ha$^{-1}$) and carbon density (46.49 Mg C ha$^{-1}$ and 50.11 Mg C ha$^{-1}$) estimated in SMRBs in Bambarabedda Weliketiya Mukalana forest reserve (Figure 7), and low biomass (18.63 Mg ha$^{-1}$ and 21.44 Mg ha$^{-1}$) and carbon density (8.75 Mg C ha$^{-1}$ and 10.08 Mg C ha$^{-1}$) estimated in CMRBs in Gedaboyaya forest. However, CMRBs in Madigala reserve represent the highest biomass (56.53 Mg ha$^{-1}$ and 59.92 Mg ha$^{-1}$) and carbon (26.57 Mg C ha$^{-1}$ and 28.16 Mg C ha$^{-1}$) density. The results of biomass and carbon estimates were higher in all SMRBs in the nine different forest reserves compared to CMRBs. The findings suggest that future forest restoration programs in Sri Lanka should enhance participatory approaches to optimize tree species diversity, density and carbon storage; particularly, in community-controlled forests. Our findings could assist developing tropical nations in understanding how CBFR impacts forest restoration objectives and improves the provision of ecological services within forests.

**Keywords:** Community-based forest restoration, Woody species diversity and density, Biomass, Carbon stock, DID model.

## Introduction

Globally, forests are identified as one of the crucial ecological components for maintaining and supporting the rural social-ecological systems. Forestry serves as the primary land-use type in rural areas, playing a crucial role in managing the rural socio-ecological system and determining the rural landscape (Sunderland et al. 2017). One billion local people are responsible for managing 15.5% of the world's forests, and this number is rising (Rights & Initiative 2014). Tropical forests provide livelihoods for approximately 410 million people, including 60 million indigenous people dependent on forest resources (Bank 2004). Thus, the management of forestland without consideration of public opinion, particularly on land use and forest policies, is largely ineffective and suffers from insufficient scientific direction and weak enforcement (Rametsteiner & Whiteman 2014). In addition, studies found that the existing “command and control‟ approach of forest protection, or managed by the state without considering local people has not been effective in ensuring the sustainability of natural forests. Moreover, the fact that so many people depend on forest areas suggests that there is an intrinsic relationship between forests and local people. A study conducted by (Persha et al. 2011), found that the engagement of local people in forest-related decision-making and management could enhance forest conditions because they possess indigenous knowledge regarding the local environment, which can be used to develop and implement effective management strategies. Moreover, their easy accessibility to the forest provides them with a relatively great advantage for monitoring forest resource use. In addition to this, in several cultures, forests are consciously protected as sacred places due to their traditional, cultural, and spiritual beliefs. Moreover, local communities have an invested interest in conserving and utilizing forests to meet community needs (Béné et al. 2009; Brown et al. 1989). Therefore, community forestry is most widespread in Asia and Latin America, with the community controlling a substantial portion of the land covered by forests. For example, in the Asia-Pacific region, communities and indigenous people manage 25% of the forest land (Sunderlin et al. 2008).

The original idea behind CBFR was to improve forest conditions and support poor rural communities in the sustainable utilization of forest resources in their vicinity as a livelihood asset (Gurung et al. 2013). Several studies have highlighted the impact of CBFR on livelihoods as well as forest ecosystems. A study conducted by (Beauchamp & Ingram 2011; Pulhin & Dressler 2009; René Oyono 2005) highlighted the impact of community-based forest activities on rural livelihoods in terms of empowering women, reducing rural poverty, improving livelihoods, and promoting sustainable forest management. On the other hand, impact on increasing carbon sequestration (Luintel et al. 2018), reducing emissions (Pelletier et al. 2016), protecting and improving the forest ecosystem (Acharya 2003; Bijaya et al. 2016; Chinangwa et al. 2017; Chowdhury et al. 2018; Ekanayake et al. 2020; Gurung et al. 2013) also mentioned in the literature. In this context, CBFR programs have become an established component of international forest policy. Conversely, state-controlled forests impose control and restriction policies that mostly negatively affect forest dwellers' economies and livelihoods. In some cases, these policies also lead to the overexploitation of forests and their resources, drawing the conclusion that sometimes state-managed forest management approaches are ineffective (Agrawal et al. 2013; Buffum 2012; Ekanayake et al. 2018). For instance, a meta-study conducted by (Hayes 2006) comparing the relationship between vegetation density and the presence of rules in 76 state-managed park areas and 87 community-managed non-park areas found that in the community-managed non-park areas, 60% had identified rules for all forest products which is comparatively higher than in the state-managed park areas (30%). Also, this study found that in 30% of the state-managed parks, floral density was abundant, with an average of 36% and sparse of 44 %. At the same time, in the community-managed areas, tree cover was abundant at 29%, with an average of 43% and sparse cover of 28%. A similar result was found in another meta-study conducted by (Porter-Bolland et al. 2012) in the state protected area and community-managed areas. They observed that in the publicly protected area, the mean annual forest cover change was -1.47% and it was -0.24% in the community-managed area.

In comparison to other developing countries, the expansion of population size, political instability, and harsh economic conditions have resulted in endless pressure on forests and forest resources in Sri Lanka (Niesenbaum et al. 2005; Palo & Mery 1996). National figures show that between 1956 and 2010, the overall amount of forest cover decreased by 14.5%, and in 2010, 29.7% of the Sri Lankan land was covered by forest (Fernando 2017). Hence, in line with the concept of community forestry, Sri Lanka has greater potential for implementing and expanding a worthy CBFR program. Community-managed forests, together with community-established plantations and woodlots, are among the most important components of tropical ecosystems in Sri Lanka, in addition to natural forests and state-managed forest plantations (Béné et al. 2009). The Sri Lankan government has modified and revised its forest management policies since the late 1980s. So far, Sri Lanka has implemented CBFR programs, with expanding project sites, an enlarged rural population involved, and increasing research. Currently, 167 community-based forest restoration sites have been established in Sri Lanka, and approximately 23,500 hectares of forest land are managed by the community. Studies have highlighted that the majority of Sri Lanka CBFR sites are located in semi-mixed evergreen forests (Ekanayake et al. 2020; Ekanayake et al. 2022). Semi-mixed evergreen forests were found in the dry and intermediate zones of Sri Lanka. These forests are home to the richest biodiversity and contribute substantially to the global carbon budget (Chheng et al. 2016). Unfortunately, semi-mixed evergreen forests are affected more by shifting cultivation, human disturbance, and illegal logging (FAO 2010a; Robinson et al. 2014; Tripathi & Tripathi 2010). Therefore, the government established CBFR in semi-mixed evergreen forests to reduce anthropogenic pressure and enhance the livelihoods of forest-dependent people (Fernando 2017). Several historical studies (Bandaratillake et al. 1995; Ekanayake et al. 2022; Farooq et al. 2021; Gunatileke & Chakravorty 2003) have shown the impact of community-based forest activities on rural livelihoods and forest ecosystems. A study conducted by (Dissanayake 1998; Ekanayake et al. 2022; Zoysa & Inoue 2016) highlighted that CBFR increases household income. Moreover, (Ekanayake et al. 2022) also revealed that rural residents who participate into CBFR programs have more saving, more informal education opportunism, and access to state land holdings than other residents who do not participate in CBFR programs. Previous studies have also highlighted that the impact may vary with the pre-existing conditions of rural society and forest ecosystems (Ekanayake et al. 2020).

Consistent with previous studies of community-based forestry in Sri Lanka, the majority of them focused on the impact assessment of livelihood rather than on forest ecosystems. The most recent study (Ekanayake et al. 2020) on the impacts of community forestry on forest conditions highlighted the impact in terms of species diversity and evidence of the human disturbances. They found that the count of invasive species is considerably less in community managed forest blocks than state managed blocks. However, no study conducted on with the special emphasis on woody species composition, structure and carbon stocks. Therefore, this study on the impact assessment of CBFR on forest tree species diversity, density, biomass, and carbon stock is novel to Sri Lanka community-based research field. Despite accounting for a large proportion of the total vegetation (approximately four-fifths of the country's total vegetation), the semi-mixed evergreen forest type has received less research attention compared to other forest types (Dittus 1977; FD 2016), and no study related to the woody species composition, structure, and carbon stock of semi-mixed evergreen forests. This forest that are found not only in Sri Lanka, but also throughout the tropical and subtropical regions of the world. However, there is limited study related to the impact of community-based restoration activities on global semi-mixed evergreen forest (Chheng et al. 2016). Hence, this study provides data to fill the gap in knowledge related to the semi-mixed evergreen forest in Sri Lanka and globally (Mattei Faggin et al. 2017). Therefore, the present study aimed to: (i) assess the woody species diversity and density of selected semi-mixed evergreen forests, (ii) calculate tree biomass and carbon stocks, and (iii) analyse how these parameters differ between community-based forest sites and state-managed sites of Sri Lanka.

## Materials & Methods

### *2.1 Study area*

Sri Lanka is a tropical island with a land extent of approximately 65,610 square kilometers. The country is divided into three climatic zones based on seasonal rainfall, natural resources, and agricultural land use: dry, wet, and intermediate zones (Bank 2021). The intermediate zone is a climatic zone and that lies between the wet and dry zones, was selected for the study (Figure. 1). In the intermediate zone, there is a relatively short and mild dry season, with an average annual rainfall ranging from 1,750 to 2,500 mm and an annual average temperature of 30°C. The dominant soil types in the area were reddish-brown latosols and red-yellow podzolic soils, along with immature brown loams. The dominant vegetation type in the intermediate zone is semi-mixed evergreen forest, covering approximately 221,977 hectares of the land area. Evergreen species (e.g. *Manilkara hexandra Diospyros ebenum*, *Syzygium* spp.) dominate the forests within the intermediate zone, whereas the proportion of deciduous species (eg. *Chloroxylon swietenia*, *Vitex altissima*) is comparatively lower. Specifically, the southeastern and northwestern regions of the intermediate zone exhibited a higher prevalence of deciduous trees compared to the central and northern areas (Gunatilleke & Gunatilleke 1984). Semi-mixed evergreen forests occupy 20–30 plant families, 40–50 genera, and 40–60 species, with 17% of them endemic. *Euphorbiaceae, Moraceae, Anacardiaceae* and *Sapindaceae* are among the dominant vegetation composition observed in these forests (Illangasinghe et al. 1999). The semi-mixed evergreen forest covers the approximately four-fifths of country vegetation, and these forests provide a wide range of provisioning services in the shape of non-timber fruit products i.e. medicinal products, yams, bee honey, fruits, nuts, rattan, bamboo, flowers, leafy vegetable, fodder and agriculture products (roping materials, stalks, green manure). According to (Ekanayake et al. 2020), vegetable cultivation, paddy farming, and shifting (Chena) cultivation constitute the primary farming activities in the intermediate zone, while 65-75% of households in the area rely on forests for their everyday necessities (Liyanaarachchi 2004).

The intermediate zone extends to nine out of the 25 administrative districts in Sri Lanka. The area covered by this zone is estimated to be around 1.2 million hectares, which is 13.2% of the country. Four administrative districts were purposefully selected from the intermediate zone, namely Badulla, Monaragala, Kandy, and Kurunegala, and nine CBFR sites located in these districts were further purposefully selected.

**Figure 1. Location of the study area in a semi-mixed evergreen forest in Sri Lanka.**

The main reason these four districts and nine CBFR sites were chosen because they are located in the same eco-climatic zone and represent similar major woody species compositions, namely semi-mixed evergreen forests. Additionally, the forest sites had a substantial number of individuals who relied heavily on the forests for their daily needs. These regions play a vital role in fulfilling the day-to-day requirements of the local residents, given their strong dependence on forest resources (Liyanaarachchi 2004). Furthermore, these natural forests face various threats such as fires, grazing, illegal logging, and agricultural activities. Table 1 shows the forest location and forest cover of each CBFR site. All these nine CBFR sites, were established in nine natural forests (Table1). These natural forests are divided into two forest blocks namely SMRBs and CMRBs. In each forest, the land area which is in and near the boundary of the forest and degraded due to anthropogenic pressure are managed as CMRBs, and forest land in the core of each forest area is managed as SMRBs.

**Table 1.** Districts, Forest Names and Total Area of Nine CBFR Sites.

*2.2. Data collection*

The study followed a semi-experimental before-after control-impact (BACI) design (Greene 2003). According to (Bowler et al. 2012), the BACI design is the most effective study design for assessing the impact of forest community management programs. Thus, this study used BACI design to estimate the impact on woody species composition and structure, aboveground woody biomass (AGWB), and carbon stock (CS). In this framework, the forest areas currently under community management (CMRBs) were taken as treatment group while the areas managed by the Department of Forest Conservation (SMRBs) are regarded as the control group Furthermore, data collected in 2012 was classified as a before-CBFR program, while data gathered in 2018 was categorized as an after-CBFR program..

The total number of sample plots per tree stand depended on the stand's uniformity and size. At the research site, we sampled 180 individual plots in accordance with the operational guidelines for community forest management based on (Vianna & Fearnside 2014). These plots were evenly distributed, with 90 plots allocated to the community-managed restoration blocks (CMRBs) and the remaining 90 plots assigned to the state-managed restoration blocks (SMRBs). To conduct an inventory of standing trees with a diameter at breast height (DBH) greater than 5 cm, circular plots with a radius of 12.6 meters (equivalent to 500 square meters) were established as the primary sites (Figure 2). For carbon stock measurements, Global Forest Resources Assessment guidelines were used during data collection in the field (FAO 2010b).

During the study, forest field assistants and local people from the CBFR sites who possessed a deep understanding of the local flora played a vital role in identifying and documenting the common names of all plant species. During the study, data from 2012 was sourced from the documented inventory data of the Forest Department (FD). To collect 2018 data, we revisited the identical sample plots by utilizing the recorded GPS coordinates, ensuring consistency and comparability with the previous data collection.

**Figure 2. Forest plot layout sampling and data collection for woody species diversity, density, biomass and carbon stocks assessment.**

*2.3. Data Analysis*

STATA version 15.1 was used for descriptive and inferential statistical analysis of data. The data analysis involved the use of simple descriptive statistics, including measures such as averages and percentages, as well as econometric analysis to examine and evaluate the data. Woody species diversity, aboveground woody biomass, and carbon stock were determined using the following statistical methods: (a). The Shannon diversity index; (b) Allometric equations; and (c). Difference in Differences (DID).

### 2.3.1. Woody Species Diversity Analysis

Plant community variables such as tree stand density, basal area, and frequency were calculated. The Shannon diversity index was used to calculate the species diversity of woody plants (Eq. 1). The Shannon diversity index (H) is a widely employed metric for assessing the species diversity within a community. It incorporates both the abundance and distribution of species, thereby offering a comprehensive understanding of the overall diversity present (Spellerberg & Fedor 2003). These indices are commonly used in analyzing the woody species diversity in community-based forest management systems (Dhakal et al. 2011; Pandey et al. 2014).

Shannon diversity index (H) = $\sum_{i=1}^{s} -(Pi * ln Pi)$ (Eq. 1)

Where "$P_i$" represents the proportion of ith species in the entire population;
"S" denotes the total number of species recorded in the sites;
$\sum$ is the sum from species 1 to species "S";
"*ln*" is the natural logarithm.

### 2.3.2. Aboveground Woody Tree Biomass and Carbon Stock Analysis

Following the Global Forest Resources Assessment guidelines (FAO 2010b), aboveground biomass (AGB) is defined as the total living biomass above the soil, encompassing seeds, foliage, bark, branches, stumps and stems. The study calculated aboveground woody tree biomass. We estimated the aboveground biomass of individual trees using an allometric model published by (Brown et al. 1989) (Eq. 2) and then summed it to obtain the final estimate (Eq. 3).

$\hat{Y} = 34.4703 - 8.0671 (D) + 0.6586 (D^2)$ (Eq. 2)

Where, $\hat{Y}$ is the aboveground woody tree biomass (Individual tree biomass) (Kilogram Dry Matter/tree) and D is the diameter (cm). After calculating the aboveground biomass of individual trees, the total aboveground biomass is calculated in megagrams per hectare (Mg $ha^{-1}$), and the estimation is done on a per-hectare basis, as shown below (Eq 3). In this equation, we calculated the aboveground biomass (AGB) by summing the product of the unit biomass (AU) divided by 1000 and multiplying it by the factor 10,000 divided by the plot area.

AGB = ($\sum$ AU/1000) *(10,000/Plot area) (Eq. 3)

Where AGB represents the aboveground tree biomass, measured in megagrams of dry matter per hectare (Mg DM $ha^{-1}$);
AU represents the total tree biomass of all trees within the plot, measured in kilograms of dry matter per unit plot area (kg DM/plot area);

Factor 1000 equals the conversion of sample units from kilograms of dry matter per mega grams (kg DM/Mg);

The DM Factor 10,000 equals to conversion of the area from square meters ($m^2$) to hectares.

The Forest Resources Assessment guideline recommended a carbon conversion factor of 0.47 to estimate the carbon stock in aboveground biomass (FAO 2010b). Following; (Jew et al. 2016; Salas Macias et al. 2017), The carbon stock in aboveground biomass was calculated using the following equation (Eq. 4).

$$\Delta AGB = (AGB * CF) \qquad \text{(Eq. 4)}$$

Where ΔAGB represents the carbon content in the aboveground biomass measured in megagrams of carbon per hectare (Mg C $ha^{-1}$)

AGB refers to the aboveground tree biomass, measured in megagrams of dry matter per hectare (Mg DM $ha^{-1}$).

CF represents the carbon fraction expressed in megagrams of carbon per metric ton of dry matter (Mg C/t DM).

The default value is 0.47.

### 2.3.3. Difference in Differences (DID) analysis

The difference-in-differences (DID) approach was used to assess the impact of the CBFR program on woody species diversity, density, biomass, and carbon stock. The DID approach is an analytical method that assesses the differential effects of an intervention over time by comparing the outcomes between the treatment group and the control group (Bank 2023). The DID model estimates causal effects in non-experimental settings that involve two-time periods, where a group of treated units receives a treatment of interest starting in the second period, whereas a comparison group remains untreated in both periods (Roth et al. 2023). In this study, the DID analysis helps us answer the counterfactual question: To what extent does the CBFR policy intervention impact the biomass and carbon stock of the community-managed restoration blocks of forest and state-managed restoration blocks of semi-mixed evergreen forest over a period of time? Therefore, the DID-based model used in this study can be written as below (Eq. 5).

$$Y = \alpha_0 + \alpha_1 CBFR^{post} + \alpha_2 CBFR^{Tr} + \alpha_3 CBFR^{post} CBFR^{Tr} + \varepsilon \qquad \text{(Eq 5)}$$

Where the Y refers to the aboveground woody biomass/carbon stock, α is the DID coefficient estimate, $\alpha_1$ of $CBFR^{post}$ is the core coefficient equal to the time dummy (i.e. after introducing the program), $\alpha_2$ of $CBFR^{Tr}$ represents the treatment group (i.e. treatment sites), $\alpha_3$ of $CBFR^{post}CBFR^{Tr}$ is the time into treatment interaction, and ε is the random error term.

Data was gathered from both control and treatment groups during two-time periods (2012 and 2018). Subsequently, the net effect was determined using the difference-in-differences (DID) method, the mean gain in the control group from the mean gain in the treatment group. By employing this method, any inherent bias when comparing the control and treatment groups in the CBFR program is accounted for and removed. The DID estimate provided an indication of the impact of the CBFR program on aboveground woody biomass and carbon stock, revealing whether the program had a positive or negative effect.

## Results

### *3.1. Woody Species Diversity*

We identified 131 species of woody plants (103 trees, 21 shrubs, and 7 species of woody lianas) from 38 families (Figure 3), across nine semi-evergreen mixed forest habitats. In study sites, the five most abundant woody species were *Phyllanthus polyphyllus, Grewia damine, Bauhinia tomentosa, Mallotus philippensis* and *Glycosmis pentaphylla*. Economically valued woody trees where found as dominant species were *Cassia auriculata* (flower), *Terminalia bellirica* (medicine/fruits), *Manilkara hexandra* (fruits), *Drypetes sepiaria* (fruit), *Phyllanthus emblica* (fruits) and *Pterospertmum suberifolium* (timber). The SMRBs recorded practically all woody species, but the CMRBs recorded only 67. The results indicated that prior to the implementation of the CBFR program, SMRBs had 2 to 64 woody trees per plot with a mean of 24.8, whereas in CMRBs per plot, the number of trees ranged from 1 to 27 trees with a mean of 12.4. After CBFR, a single SMRBs plot had 2 to 66 trees with a mean of 25.7, and a single CMRBs plot had 2 to 30 trees with a mean of 14.1.

**Figure 3. Species distribution in semi-mixed evergreen forest.**

The Shannon diversity index for woody trees showed higher and relatively consistent values in the SMRBs (4.52 in both 2012 and 2018) compared to the CMRBs (3.80 in 2012 and 3.91 in 2018). The DID estimation of woody species diversity provides evidence of the positive impact of the CBFR program on enhancing woody plant diversity; however, it was not significant. Forest management data from Range Forest Offices (Kurunegala, Siyabalanduwa, Mahiyangana, Teldeniya, and Hunnasgiriya), where community forest sites were established, revealed that community members had a preference for species found in CMRBs. Economically valuable plants, such as *Pterospermum suberifolium* for timber, *Michelia champaca, Tectona grandis, and Phyllanthus emblica* (Indian gooseberry) for fruit, and *Khaya senegalensis,* emerged as the preferred commercial plantation species among community members because of high local market demand.

### *3.2. Woody species density and structure*

As shown in (Figure 4), the trees within the DBH class of 5-10 cm exhibited the highest density in the community-managed forest, increasing from 621 to 659 per 90 plots between 2012 and 2018. The density of trees within the DBH class of 11-20 cm also increased from 277 to 379, while the DBH class of 21-30 cm increased from 122 to 133, and the DBH class of 31-40 cm increased from 69 to 71. Additionally, the DBH class of 41-50 cm increased from 22 to 24. However, the last DBH class (>50 cm) showed no difference, remaining at 11 throughout the years 2012 to 2018. This shows that community-managed forests are dominated by newly grown trees after the implementation of the CBFR program. The basal area of trees in community-managed forest sites showed variations over the time periods of 2012 and 2018. In 2012, the highest basal area was observed in the 31-40 cm DBH class, whereas in 2018, the highest basal area was recorded in the 11-20 cm DBH class. Conversely, the lowest basal area was recorded in the 5-10 cm DBH class for both time periods (2012–2018).

**Figure 4. Trees density and basal area based on diameter distribution in the CMRBs.**

Similar to the CMRBs, trees of DBH class 5-10 cm which occurred in the state-managed forest blocks, had the highest density and increased from 1159 to 1363 per 90 plots from 2012 to 2018. The trees density of DBH class 11-20 cm increased from 549 to 652, while DBH class 21-30 cm increased from 201 to 233, and DBH class 31-40 cm decreased from 155 to 144. Additionally, the DBH class 41-50 cm showed a marginal change from 80 to 82. Finally, DBH class >50 cm had increased from 46 to 51 from the year 2012 to 2018. The basal area of trees was highest in the 31-40 cm DBH class in 2012 and the >50 cm DBH class in 2018, while it was lowest in the DBH class of 5-10 cm in both time periods (2012–2018) for state-managed forest sites (Figure 5).

**Figure 5. Trees density and basal area based on diameter distribution in the SMRBs.**

Consider the finding of DID estimation of the woody species density among the different DBH classes indicated that the CBFR program had a positive impact on woody species density. However, it was not significant.

*3.3. Aboveground Woody Tree Biomass and Carbon Stock*

Table 2 shows the biomass density and carbon density of woody trees in CMRBs and SMRBs in nine forest reserves in the semi-mixed evergreen forest. Tree biomass and carbon density were disproportionally distributed across the nine different forest reserves, with high biomass (98.92 Mg ha$^{-1}$ and 106.64 Mg ha$^{-1}$) and carbon density (46.49 Mg C ha$^{-1}$ and 50.11 Mg C ha$^{-1}$) estimated in SMRBs in Bambarabedda Weliketiya Mukalana forest reserve (Figure 7), and low biomass (18.63 Mg ha$^{-1}$ and 21.44 Mg ha$^{-1}$) and carbon density (8.75 Mg C ha$^{-1}$ and 10.08 Mg C ha$^{-1}$) estimated in CMRBs in Gedaboyaya forest.

**Table 3.** Total biomass density and carbon density of woody trees in nine forest reserves.

However, CMRBs in Madigala reserve represent the highest biomass (56.53 Mg ha$^{-1}$ and 59.92 Mg ha$^{-1}$) and carbon (26.57 Mg C ha$^{-1}$ and 28.16 Mg C ha$^{-1}$) density (Fig. 6). Moreover, the overall result of biomass and carbon estimates were higher in all SMRBs in the nine different forest reserves than in the CMRBs.

**Figure 6. Total biomass in the community-managed forest reserves.**

The DID coefficient estimate (Table 3) showed that the CBFR program itself did not have a significant impact on the biomass density and carbon density in the semi-mixed evergreen forest. The average aboveground woody tree biomass for the SMRBs in the semi-mixed evergreen forest was 76.6 Mg ha$^{-1}$ before CBFR and 83.30 Mg ha$^{-1}$ after CBFR. In SMRBs, the average carbon density was 36.02 Mg C ha$^{-1}$ before CBFR and 39.14 Mg C ha$^{-1}$ after CBFR. CMRBs show significantly less biomass and carbon density in both the before (31.84 Mg ha$^{-1}$ and 14.96 Mg C ha$^{-1}$) and after (35.18 Mg ha$^{-1}$ and 16.53 Mg C ha$^{-1}$) the CBFR program, respectively.

**Figure 7. Total biomass in the state-managed forest reserves.**

**Table 3.** The DID estimates of biomass density and carbon density of woody trees in the semi-mixed evergreen forest in Sri Lanka.

## Discussion

Examining the impact of CBFR on forest species diversity and carbon stocks provides insights into the carbon sequestration potential of the participatory approach with varying floral diversity, and sheds light on the underlying factors considered in further improvement of community-based forest management (Vance-Chalcraft et al. 2010). Several tropical forest studies have supported the significance of CBFR in promoting woody plant species diversity, structure, and aboveground carbon stock (Gregorio et al. 2020; Kumar et al. 2015; Mugwedi et al. 2017). This study result also provides the valuable funding to broaden the scope of community based forestry and fill the data gap in the semi-mixed evergreen forest.

Our results revealed greater woody species representation in SMRBs compared to CMRBs in year 2012 as well as 2018 but the species diversity did not change within the 5 years period. However, the DID estimate indicated that the CBFR program increased woody species diversity in the CMRBs. The reason for this is most of the CMRBs are degraded forest land with few numbers of scattered trees. Therefore, at the initial stage, the species diversity was considerably low. After implementing the CBFR program, community members planting different tree species in the CMRBs, and woody species diversity increased over time compared to the SMRBs. The diversity, distribution, and population structure of tree species provide fundamental information for forest conservation and management (Farooq et al. 2019b; Sahu et al. 2012). Lower values of species diversity indicate that one or a small number of species dominate a given area (Farooq et al. 2022a; Farooq et al. 2022b; Ifo et al. 2016). During the five-year sampling period of our study, the impact of CBFR on woody species diversity was found to be insignificant, which is similar to findings from a previous study conducted in Cambodia, where control sites exhibited a greater abundance of tree species, whereas CBFR sites were implemented two or five years prior to sampling (Lambrick et al. 2014). Our research also showed that CMRBs, in comparison to SMRBs, are typically situated in greater proximity to village areas. It is worth noting that several studies have shown that the distance between the forest and a nearby settlement can have a significant impact on forest composition, including density and diversity. For instance, a recent study conducted by (Hending et al. 2023) found that species diversity, tree size, and structural diversity were significantly reduced in the forest edges of Madagascar's transitional forests which are mainly influenced by human activities.

Trees density and basal area are vital woody species composition information that describe the structure of a forest (Farooq et al. 2019a; Farooq et al. 2020; Tarin et al. 2017). The analysis of diameter distributions showed smaller tree size and basal area in the CMRBs blocks than in the SMBRs which may be due to the younger age of the planted trees. The higher tree density and young age might affect the basal area of CMRBs, as site index and density are related to the basal area. In general, site index, crown size, stand age, and stand density influence the basal area of tree species (Deetlefs 1954). Similar to our study, a study conducted by (Paudyal et al. 2017) Nepal revealed that the number of pole-sized trees (small trees) increased in community managed sites while that of mature trees decreased due to harvesting for commercial purpose. Thus, overall basal area is less in those Community managed forest.

Several studies conducted worldwide revealed that the implications of CBFR programs have brought about positive changes in landscape restoration (Gregorio et al. 2020) and forest management (Gurung et al. 2013). A recent study by (Luintel et al. 2018) found that Nepal's community forestry had a significant positive impact on increasing the forest cover of degraded natural forests and biodiversity conservation compared to non-community forestry sites. In addition, (Bijaya et al. 2016; Pandit & Bevilacqua 2011) explored how CBFR improved forest tree density by planting economically and ecologically valuable trees at community management sites. Some studies have found that community forestry programs exhibit the capacity to improve and conserve the forest ecological system by increasing the structure and composition of the existing landscape (Chinangwa et al. 2017; De Jong et al. 2018; Ojha et al. 2022; Yadav et al. 2003).

CBFR sites located in Badulla (Gedaboyaya) and Monaaragala (Hawannarawa) districts are predominantly finger millet (*Eleusine coracana*) producing areas. Finger millet cultivations were observed as shifting cultivations (Chena) in natural forests since late 1980 (Marambe et al. 2020). As this crop requires more sunlight and is resistant to drought, people used to clear the forest land by removing larger shade trees. Usually, these Chena lands are located at the edge of the forest and are converted into CMRBs. Therefore, CMRBs in Gedaboyaya forest reported the lowest biomass and carbon density compared to the other forest.

The high biomass and high carbon density are attributed both to the large number of individuals and the presence of bigger trees (Wang et al. 2023). Large trees (high DBH) were scarce in the CMRBs due to removal through Chena cultivation and harvesting for wood for fuel, though they stock most of the estimated biomass. Conversely, low-biomass trees (less DBH) dominated in

CMRBs. The primary components of total biomass are the live tree and the dead wood component. The current study only focused on the woody tree biomass due to a shortage of data related to variables such as dead wood factors (dead trees, down litter). Therefore, the estimated result of our study on the carbon density of natural forests (36.02 Mg C $ha^{-1}$ before CBFR and 39.14 Mg C $ha^{-1}$ after CBFR) was relatively limited when compared to studies that reported the total aboveground carbon density of natural forests in various tropical countries, e.g. in the Philippines (86 Mg C $ha^{-1}$) Malaysia (100 Mg C $ha^{-1}$) and Thailand (98.76 Mg C $ha^{-1}$) (Pibumrung et al. 2008). Moreover, a study conducted in Sinharaja forest of Sri Lanka revealed that the total aboveground carbon content per hectare is 237.2 tons (Nissanka & Pathinayake 2009). However, a study conducted in Tankawati, a natural hill forest located in a moist tropical climate region of Bangladesh, reported a higher carbon density of woody tree biomass (110.94 Mg C $ha^{-1}$) than the findings in the current study (Ullah & Al-Amin 2012). These values are higher as a result of the greater richness of vegetation composition and a denser canopy structure than in semi-mixed evergreen forest. However, a study conducted in the Udawattakele Forest Reserve (UFR) in the Kandy District of Sri Lanka found that the total carbon density of the tree biomass was 36.55 Mg C $ha^{-1}$. This result is quite similar to our findings.

The DID coefficient estimation in this study revealed that the CBFR program did not have a significant influence on the carbon stock of aboveground woody tree biomass. Consistent with our findings, a study by (Luintel et al. 2018) also demonstrates a notable negative impact of community forestry on the aboveground carbon (AGC) of trees and saplings at a national level. However, the effect of community-based forestry on carbon stocks varies across different geographic and topographic contexts, as well as in forests with different canopy structures. Specifically, no significant effects of community-based forest on aboveground carbon were observed at lower elevations, in the Terai or hill regions, or beneath dense canopies. As mentioned above, a short sampling period (five years) is not enough to maintain a higher tree density (high biomass) in CMRBs. Also, in community-managed woodlots, farmers practice thinning operations to reduce crowding and competition among the trees and to maintain a steady growth rate. Therefore, tree density was less in the CMRBs. Similar to our findings, a study conducted in six different community forests in the Dolakha district, Nepal, found that, due to the exclusion of low-diameter trees, the community forest sites had lower biomass and carbon densities (Shrestha et al. 2013). Moreover, a study conducted in tropical dry deciduous forest ecosystems in northwestern Himalaya reported that reserve forest or the forest completely under control of state has maximum carbon density (69.15 Mg C ha−1), whereas the minimum was recorded in a co-operative society forest (CSF) (33.27 Mg C $ha^{-1}$) or the forest managed by the community (Kumar et al. 2022).

## Conclusions

To date, research on CBFR has mainly focused on its effects on forest people's livelihoods and the forest environment. The present study enriches the scope by integrating and assessing the effects of the CBFR program (2012–2018) on the plant community composition, biomass and carbon stock in a semi-mixed evergreen forest in Sri Lanka. Our research demonstrates that CBFR impacts tree diversity, density, total biomass, and carbon stock, depending on the pre-existing conditions of the forest. The trees diversity and density was significantly higher in SMRBs as compared to CMRBs due to the robust set of protective rules and regulations implemented by the Department of Forest to protect and conserve trees in state-managed forest reserves. Furthermore, most CMRBs were formerly degraded forest land used for shifting (Chena) cultivation, resulting in diminished tree populations owing to extensive clearing by farmers. As a result, the basal area of >50 cm DBH class trees was higher in SMRBs, whereas CMRBs were lowest in >50 cm DBH classes. Moreover, our results indicated that the average aboveground woody tree biomass in SMRBs was two times higher than that in CMRBs. Also, CMRBs exhibited lower biomass and carbon density before (31.84 Mg $ha^{-1}$ and 14.96 Mg C $ha^{-1}$) and after (35.18 Mg $ha^{-1}$ and 16.53 Mg C $ha^{-1}$) the CBFR program, respectively. Therefore, our findings show that the CBFR program does not significantly influence carbon density and woody tree biomass because it is implemented over a short period of time and lacks large trees. Moreover, this study does not use the data of long-term time series impact changes in below-ground biomass and soil organic carbon, so we recommend broadening the scope; additional empirical research in different time periods, locations, and at various scales is needed. We recommend that this community-based approach be replicated in other ecologically sensitive regions, such as degraded evergreen and mountain forests, which require immediate protection and can improve forest ecosystem services.

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## Table 1 (on next page)

Districts, Forest Names and Total Area of Nine CBFR Sites.

**Table 1.** Districts, Forest Names and Total Area of Nine CBFR Sites.

| **Districts** | **Coordinates** | **Natural forest name** | **CBFR site names** | **Total area of the forest (Hectares)** |
|---|---|---|---|---|
| Kurunegala | 7˚45′ N 80˚15′ E | Dolukanda natural forest | Seeradunna | 7,713 |
| Kurunegala | | Rakaula natural forest and plantation | Aludeniyaya | 900 |
| Badulla | 6˚59′05″ N 81˚ 03′23″ E | Madigala natural forest | Kinniyarawa | 300 |
| Badulla | | Dunukewala natural forest | Dunukewala | 237 |
| Badulla | | Walasgala aluyatawala natural forest | Walasgala | 70 |
| Badulla | | Gedaboyaya natural forest | Gedaboyaya | 50 |
| Kandy | 7˚15′N 80˚45′ E | Galkanda natural forest | Wegala | 60 |
| Kandy | | Bambarabedda Waliketiya Mukalana Forest | Bambarabedda | 69 |
| Monaragala | 6˚40′ N 8˚20′ E | Hawanarawa natural forest | Hawanarawa | 50 |

## Table 2(on next page)

Total biomass density and carbon density of woody trees in nine forest reserves.

**Table 2.** Total biomass density and carbon density of woody trees in nine forest reserves.

| **Name of forests** | **Biomass density (Mg ha$^{-1}$) (Carbon density (Mg C ha$^{-1}$))** | | | |
|---|---|---|---|---|
| | **Before/CMRBs** | **After/CMRBs** | **Before/SMRBs** | **After SMRBs** |
| Bambarabedda Weliketiya Mukalana | 27.10 (12.73) | 29.08 (13.66) | 98.92 (46.49) | 106.64 (50.11) |
| Galkanda | 33.76 (15.86) | 38.50 (18.09) | 72.85 (34.24) | 80.31 (37.74) |
| Hawanarawa | 20.73 (9.74) | 23.41 (11.00) | 81.38 (38.24) | 89.46 (42.04) |
| Rakaula | 43.24 (20.33) | 48.38 (22.74) | 70.76 (33.26) | 76.87 (36.13) |
| Dolukanda | 21.48 (10.09) | 24.61 (11.56) | 71.86 (33.77) | 79.76 (37.48) |
| Dunukewala | 36.11 (16.97) | 39.10 (18.38) | 71.88 (33.78) | 77.03 (36.20) |
| Gedaboyaya | 18.63 (8.75) | 21.44 (10.08) | 65.60 (30.83) | 69.32 (32.58) |
| Walasgala | 29.01 (13.63) | 32.18 (15.12) | 68.86 (32.36) | 76.58 (35.99) |
| Madigala | 56.53 (26.57) | 59.92 (28.16) | 87.79 (41.26) | 93.77 (44.07) |

Carbon density (Mg C ha$^{-1}$) are reported in parentheses.

## Table 3(on next page)

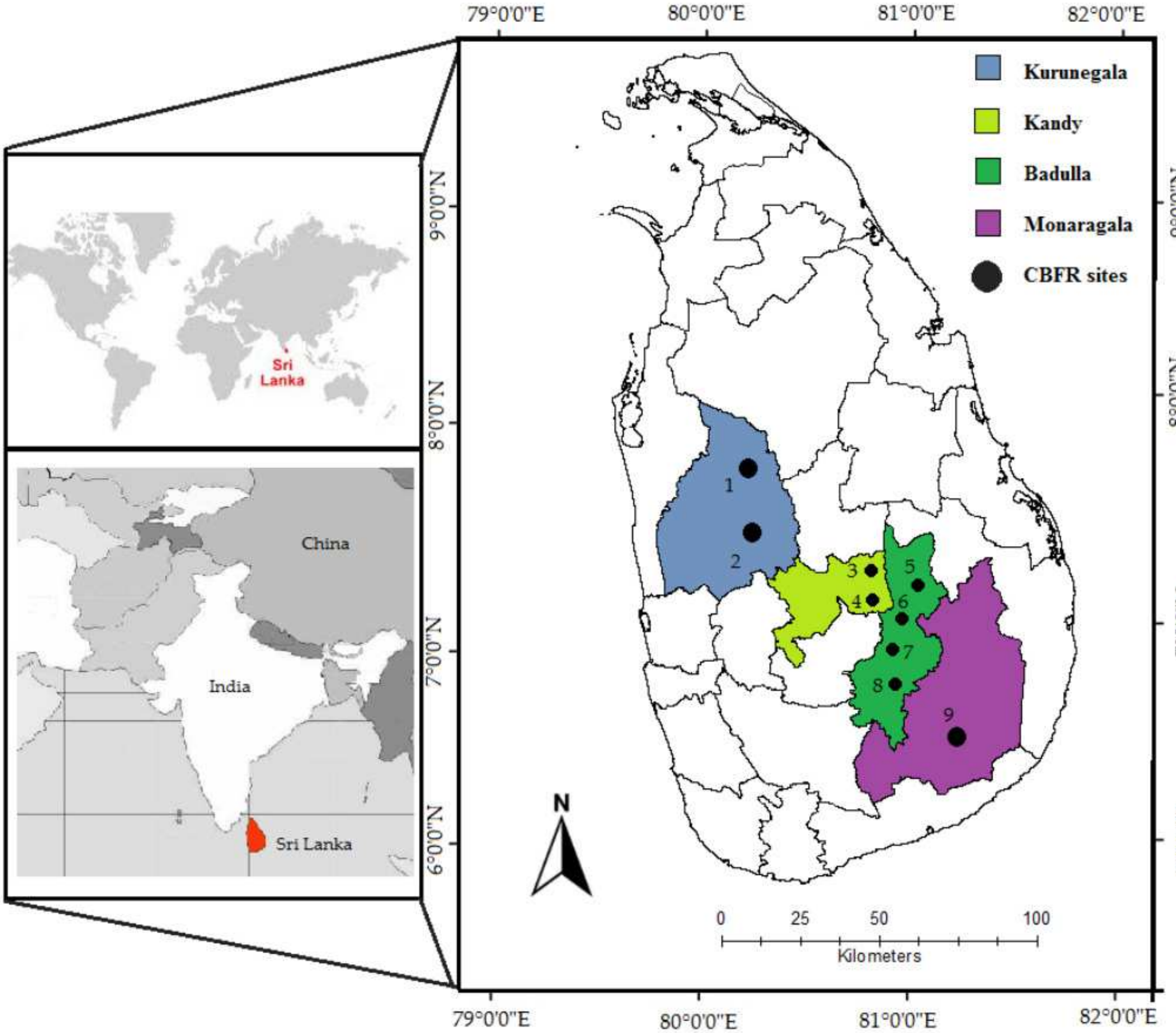
The DID estimates of biomass density and carbon density of woody trees in the semi-mixed evergreen forest in Sri Lanka.

**Table 3.** The DID estimates of biomass density and carbon density of woody trees in the semi-mixed evergreen forest in Sri Lanka.

| **Variable** | **CMRBs** | | **SMRBs** | | **DID estimation result** | |
|---|---|---|---|---|---|---|
| | Before the CBFR program | After the CBFR program | Before the CBFR program | After the CBFR program | Coefficient | p > (t) |
| Biomass density (Mg ha-1) | 31.84 | 35.18 | 76.6 | 83.30 | -3.32 | 0.675 |
| Carbon density (Mg C ha-1) | 14.96 | 16.53 | 36.02 | 39.14 | -1.55 | 0.676 |

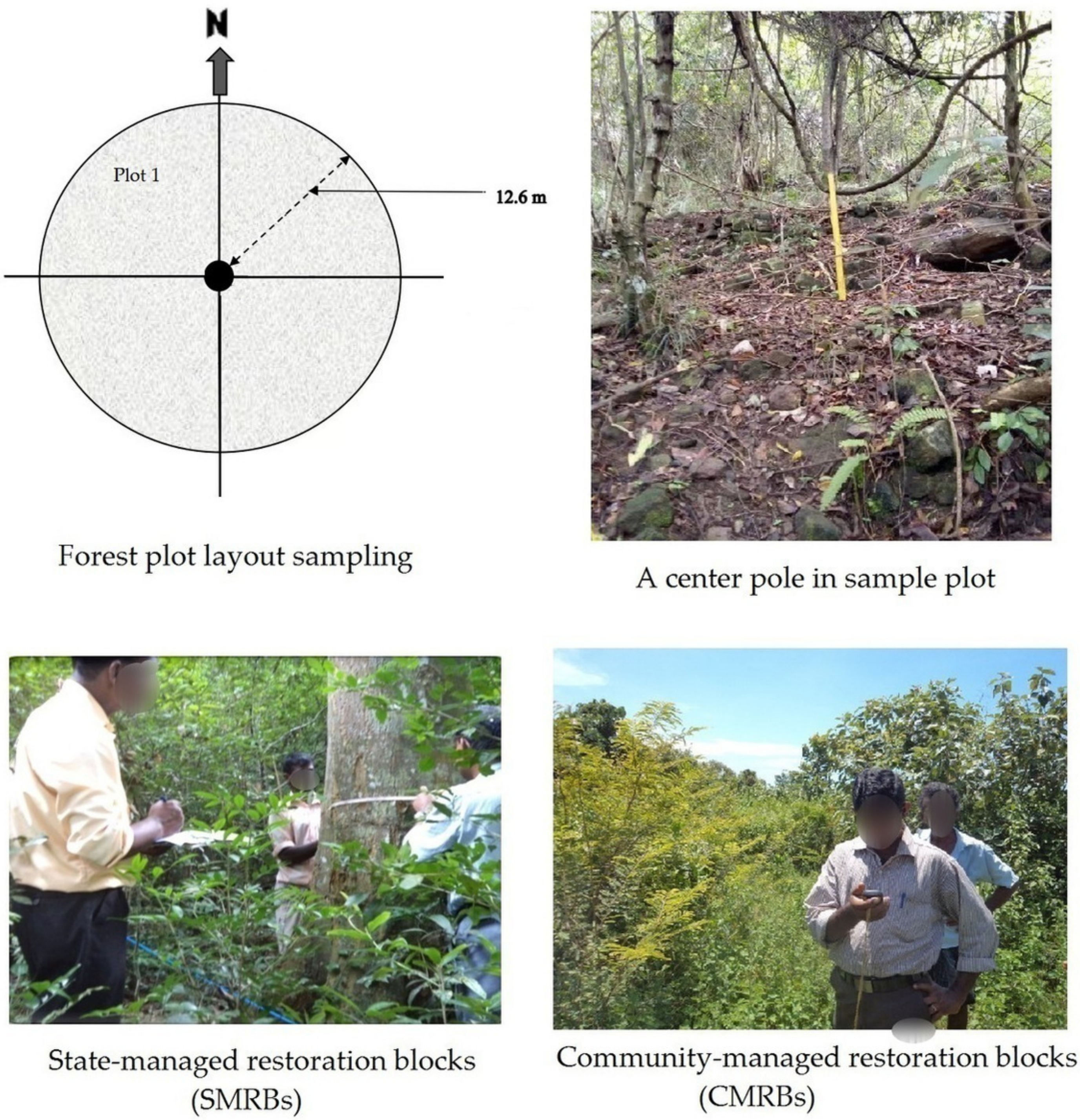
# Figure 1

Location of the study area in a semi-mixed evergreen forest in Sri Lanka.



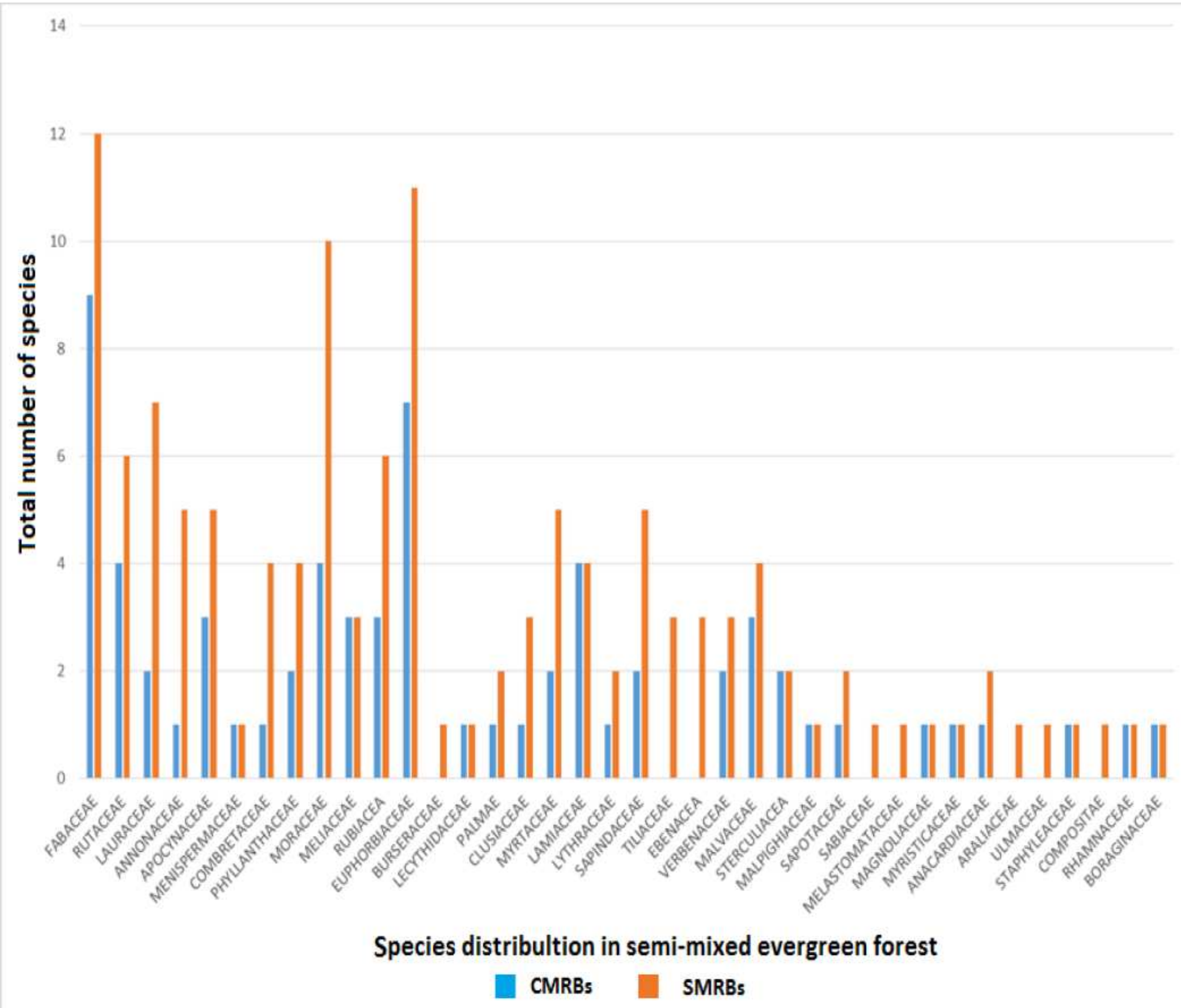
# Figure 2

Forest plot layout sampling and data collection for woody species diversity, density, biomass and carbon stocks assessment.



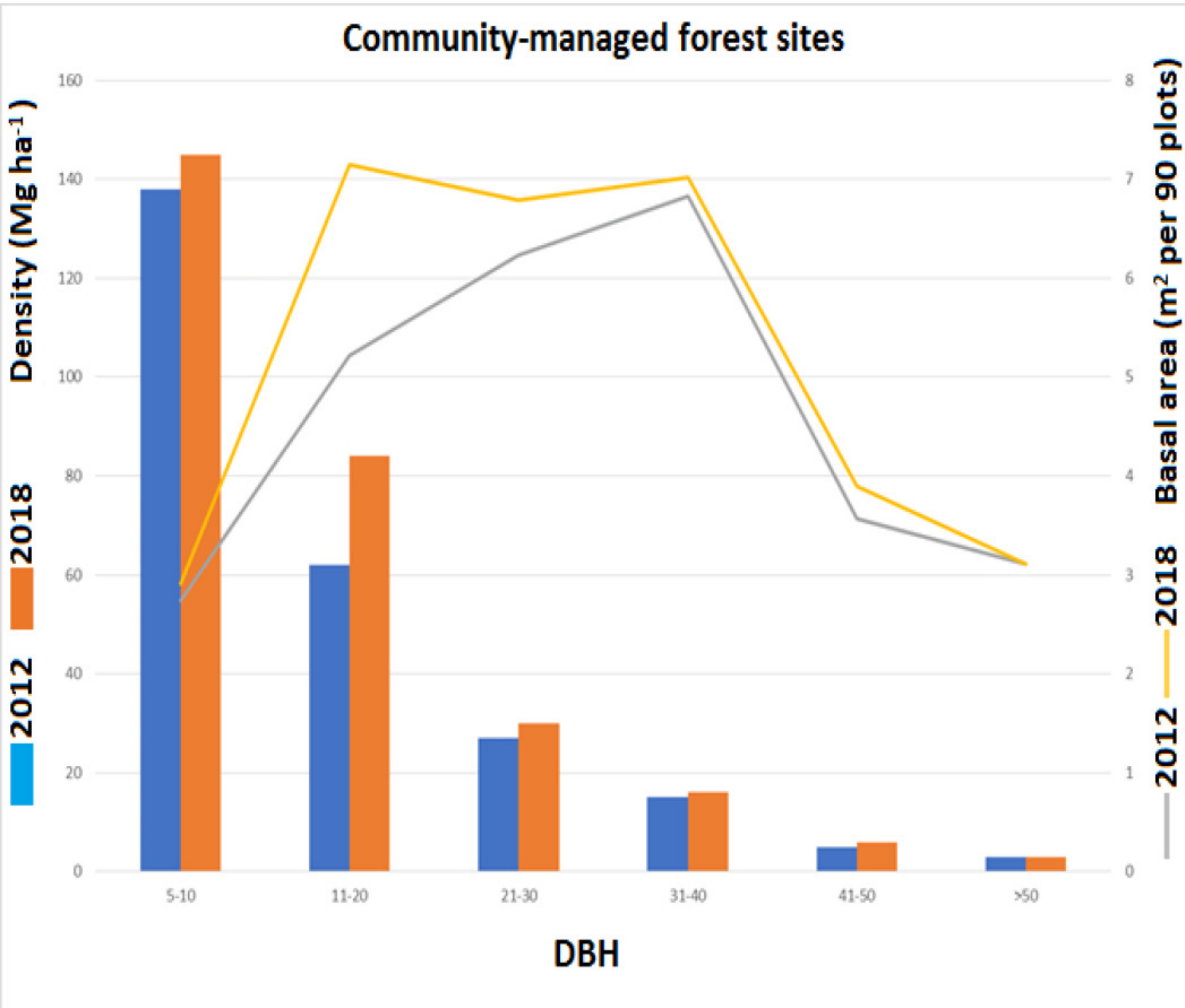
# Figure 3

Species distribution in semi-mixed evergreen forest.



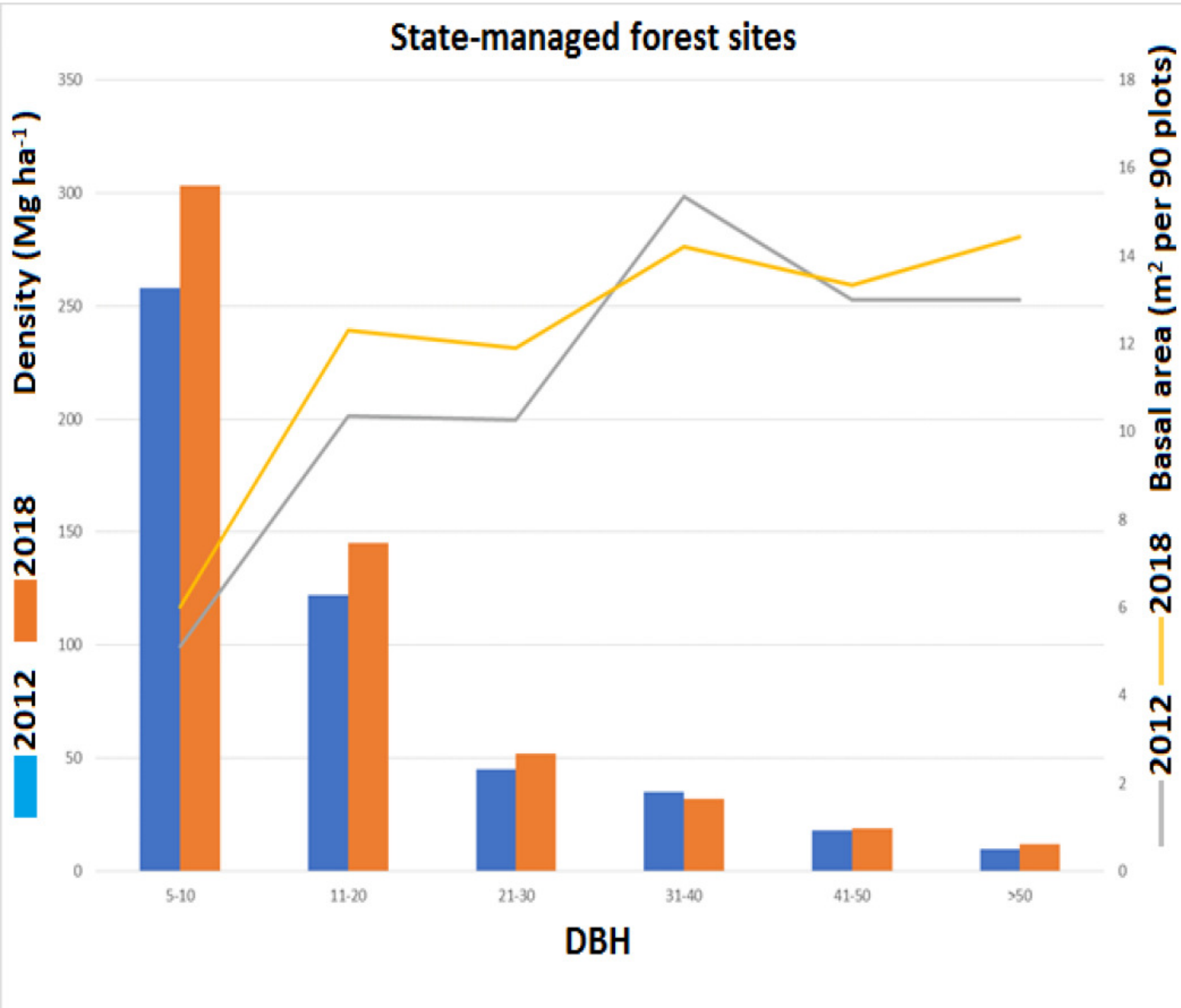
# Figure 4

Trees density and basal area based on diameter distribution in the CMRBs.



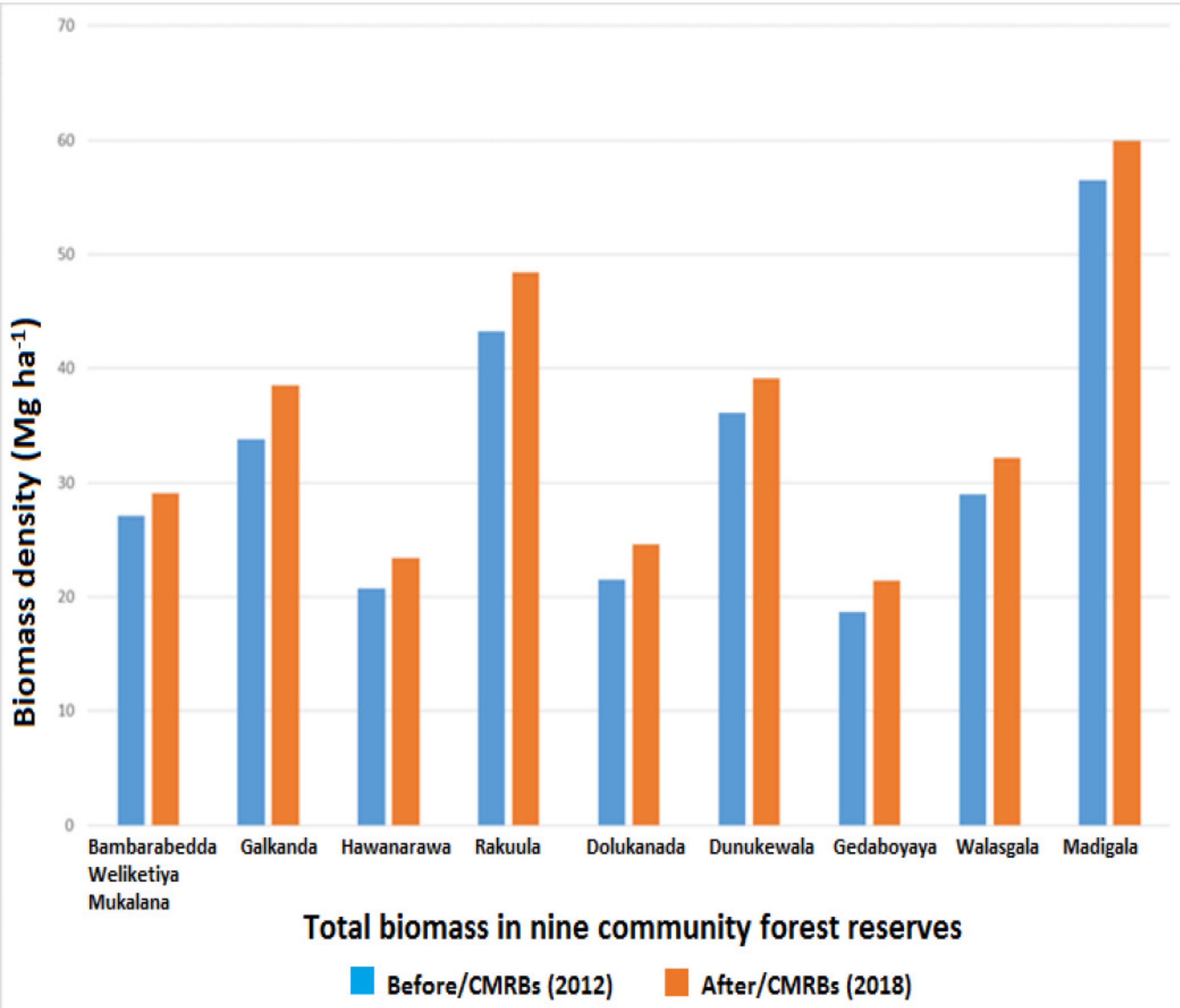
# Figure 5

Trees density and basal area based on diameter distribution in the SMRBs.



# Figure 6

Total biomass in the community-managed forest reserves.



# Figure 7

Total biomass in the state-managed forest reserves.