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# Restoring a dry tropical forest through assisted natural regeneration: enhancing tree diversity, structure, and carbon stock

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ABSTRACT

Deforestation is a key factor in global climate change, severely impacting ecosystem services. Effective implementation of reducing emissions from deforestation and forest degradation (REDD+) initiatives is essential for mitigating this change. Reforestation is a sustainable way to mitigate deforestation effects. We studied the impact of assisted natural regeneration (ANR) on restoring dry forest land, increasing biodiversity, structure, and carbon stock. Reforestation units were established at a multiple row planting system in a dry tropic region. We selected 63 plots, each 20 m × 20 m, categorized into multiple row–mixed plantation (MRMP) and multiple row–unmixed plantation (MRUP). We measured tree height and diameter at breast height (DBH) and evaluated biodiversity indices, including the Shannon–Weiner Index (SWI), species richness, evenness, and Important Value Index (IVI). Carbon stock was estimated using allometric equations. We identified 931 individual trees representing 27 species, 24 genera, and 14 families. MRMP showed significantly higher biodiversity, species richness, and evenness than MRUP. *Terminalia arjuna* was the most dominant species (IVI=124.45), followed by *Khaya senegalensis* (53.84). Survival rates exceeded 90 % for *T. arjuna, K. senegalensis, Madhuca longifolia*, and *Pongamia pinnata* ($p<0.001$). No significant differences were observed in tree DBH, tree height, tree density, basal area, and carbon stock among the plantation categories. The species *Albizia saman* exhibited a high diameter increment rate (4.07 ± 1.55 cm/year), followed by *K. senegalensis* (3.83 ± 0.43 cm/year). A mean value of 5.63 ± 1.13 MgC/ha of carbon stock was stored, while 20.66 ± 4.13 Mg/ha of atmospheric $CO_2$ was sequestered. The results highlight that promoting mixed tree species in multiple rows to enhance biodiversity and optimize carbon regulation. This technique should be popularized to restore the dry forest landscape across the region.

## 1. Introduction

The continuous reduction of forest cover globally affects all living beings and causes many environmental challenges (Huo and Peng, 2023). Around 31 % of the land area is covered by forest, amounting to 4.06 billion hectares. From 1990 to the present, about 420 million hectares of forests have been depleted for human consumption. The rate of forest cover reduction was 10 million hectares per year from 2015 to 2020 (FAO, 2005; Kaviani Rad et al., 2022). Deforestation leads to global warming and, consequently, climate change, impacting the ecology, society, and economy (Nguyen et al., 2023). Therefore, the world has united to increase forest cover through the REDD+ program, which aims to reduce emissions from deforestation. However, the REDD+ mechanism has moderate effectiveness in Sri Lanka, leading to several challenges in climate mitigation (Vijitharan et al., 2024). Forest cover in Sri Lanka decreased from 85 % to 70 % from 1881 to 1900. Deforestation occurred abruptly from 1956 to 2010. In 1956, 44.2 % forest cover was estimated. However, forest cover continuously decreased, and it was 37.5 % in 1983, 31.2 % in 1992, 29.6 % in 1999, and 29.7 % in 2010 (De Zoysa, 2001; FAO, 2020). Forest cover depleted largely in the dry zone due to urbanization, human resettlements, agricultural encroachments, with several areas marked as deforestation sites (Marambe et al., 2015).

Reforestation stands out as a promising method to enhance forest coverage in landscapes, forming a crucial component of green infrastructure whose dynamics are shaped by the behavioral traits of plant

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species within the environment (FAO, 2019). Tree planting for landscape reforestation offers numerous benefits, including the restoration of abandoned or degraded lands, carbon regulation, biodiversity enrichment, and provision of microclimatic conditions, and other ecosystem services. Natural regeneration methods can mitigate the costs of restoration activities while providing a range of ecosystem services, yielding benefits at local and global scales (FAO, 2019). Natural regeneration spans from unassisted to actively managed approaches. Unassisted natural regeneration involves protecting areas from degradation to facilitate regeneration through ecological processes such as secondary succession (Zahawi et al., 2014). Conversely, assisted natural regeneration (ANR) involves the management of regeneration processes to hasten restoration toward predefined targets (Shono et al., 2007).

ANR stands out as a leading practice for forest restoration, accelerating the natural succession process in abandoned or cleared lands (Galatumbage et al., 2021; Lohbeck et al., 2021). It serves as another method aimed at fostering site conditions conducive to natural regeneration through targeted management practices (McCreary et al., 2011). ANR serves as an adaptive forest management approach for the restoration of valuable species within natural forests (Abella et al., 2020; FAO, 2019). ANR represents a straightforward and cost–effective method for restoring forest ecosystems by converting degraded areas into more productive forests. Moreover, restored forest provides timber, biodiversity, and non–timber forest products (Shono et al., 2007). The distinction between ANR and natural regeneration lies in the application of silvicultural operations (Khaine et al., 2018). ANR achieves success through employing methods of desirable species regeneration (Simonsen, 2013). While applying ANR in drylands presents both challenges and opportunities, potential limitations should be addressed to ensure success (McCreary et al., 2011), such as wildlife and domestic animals damages, lack of soil fertility and water availability, selection of suitable tree species, type of planting materials used for enrichment planting, labour availability, and limited post planting monitoring (Rivero-Villar et al., 2022; FAO., 2019). At the local scale, ANR can be supported through land and silvicultural operations, including high density planting and suitable tree species (Chomba et al., 2020; Schmidt et al., 2021).

ANR fosters the creation of a mixed–species forest, mimicking the conditions found in natural forests where diverse trees and plants of various ages coexist. Conversely, forest plantation is often consisted of one or a few species. The diverse array of species and age groups in ANR forest restoration mitigates the risks associated with mono plantation, alleviating soil erosion and facilitating rainfall infiltration (FAO, 2019). There is an urgent need for a comprehensive, selection of suitable local species for promotion in both pure and mixed plantings, contributing to restoration efforts globally (Hérault et al., 2020). In our study, tree species were planted using a multiple–row system, where species were either mixed or unmixed.

In tropical regions, assisted natural regeneration surpass tree planting in effectively restoring biodiversity and forest structure (Wheeler et al., 2016). This approach can be complemented with enrichment planting of valuable species (FAO, 2019). Despite numerous tree planting programs in Sri Lanka by both government and private sectors, reforestation efforts face challenges in management and monitoring, hindering success. Assisted natural regeneration remains underutilized for restoring dry forest tree species due to limited knowledge and experience. Effective monitoring is crucial for any forest restoration project (FAO, 2019). Post–planting assessments in Sri Lanka are insufficiently conducted, neglecting suitable tree species with multipurpose benefits. The selection of appropriate species is vital for forest restoration, particularly native trees, which are well–suited to local conditions. Although native species often regenerate naturally with minimal intervention, some may require advanced regeneration techniques (Kassaye et al., 2023). In contrast, dry tropical forests have received less attention from the scientific community and the public compared to wet tropical forests for restoration activities (Aronson et al., 2005; Hardwick et al., 2004). Additionally, there is a lack of evidence regarding the success of assisted natural reforestation (ANR) in the tropics. Therefore, the purpose of this study is to investigate how reforestation can be successful in dry tropical forests using the ANR method. To evaluate restoring ability, species suitability, growth conditions, and ecosystem regulation for future planning, a study was conducted to assess tree species diversity, growth conditions, and carbon regulation in ANR sites of a dry tropical region. Overall aim of the study was to determine whether ANR can restore biodiversity, tree structure, and carbon stock in a dry tropical forest. To achieve this aim, the study had the following specific objectives: can MRMP planting system restore biodiversity, tree structure, and carbon stock more effectively than the MRUP planting system in a dry tropical forest, and how management activities assist the restoration success in a dry tropical forest. Finally, we hypothesized that ANR techniques, including the selection of suitable tree species, planting systems, and post–planting management, can successfully restore a dry tropical forest.

## 2. Materials and methods

### 2.1. Study area

This study was conducted in a dry tropics' region of the Sri Lanka. Fig. 1 shows the location of the study area, which is in the Kilinochchi district of northern province, Sri Lanka. The area is predominating dry mixed ever green forest. Reforestation units of the Faculty of Agriculture, University of Jaffna were selected as a study site which fell the coordinates of 80° 24 E' 61° 6 N'. Tree planting was started in the premises since 2014. The reforestation units are considered as young plantations, with all the trees being less than or equal 9 years old. The study area comes under the agroecological zone of dry zone low county ($DL_3$) with flat topography. The climate conditions during the experiment were characterized as dry and hot based on the agroecological zone of the country. The average elevation of the study area is about 67 m above mean sea level. This location's average annual air temperature ranged from 28 °C to 33 °C, and the average annual precipitation ranged from 1040 mm to 1560 mm (Punyawardena, 2007).

### 2.2. Sampling designs

A total of 63 plots, covering an area of 2.52 hectares, were established with dimensions of 20 m × 20 m across the study area. The plots were demarcated using purposive sampling methods according to the planting system and pattern practiced in the reforestation units. Five plots with irregular sizes (20 × 12, 18 × 32, 20 × 11.5, 20 × 18, 20 × 12) were excluded from the analysis. Based on the planting patterns, the sampling plots were categorized into two groups of plantations: multiple row–mixed plantation (MRMP) and multiple row–unmixed plantation (MRUP) (Table 1). 33 plots were selected for MRMP, while 30 plots were allocated for MRUP.

### 2.3. Data collection

Tree height was measured using a Suunto clinometer (Suunto PM–5/360 PC, Suunto, Vantaa, Finland) for all trees within the sample plot. The clinometer readings for the top, bottom, and head level were recorded at a distance of 20 m away from each tree (Lotfalian et al., 2007). For smaller trees, height measurements were taken using a meter tape and calibrated pole. Tree diameter at breast height (DBH), measured at 1.3 m above the ground surface, was recorded using a diameter tape (d–tape) (Model 283D, Forestry Suppliers, Jackson, MS, USA) (Hairiah et al., 2001). The number of individuals per plot and their respective species were recorded using a datasheet. The geographic location of each tree was determined using a handheld Garmin GPS device (Garmin GPSMAP 64 s, Garmin, Olathe, KS, USA).

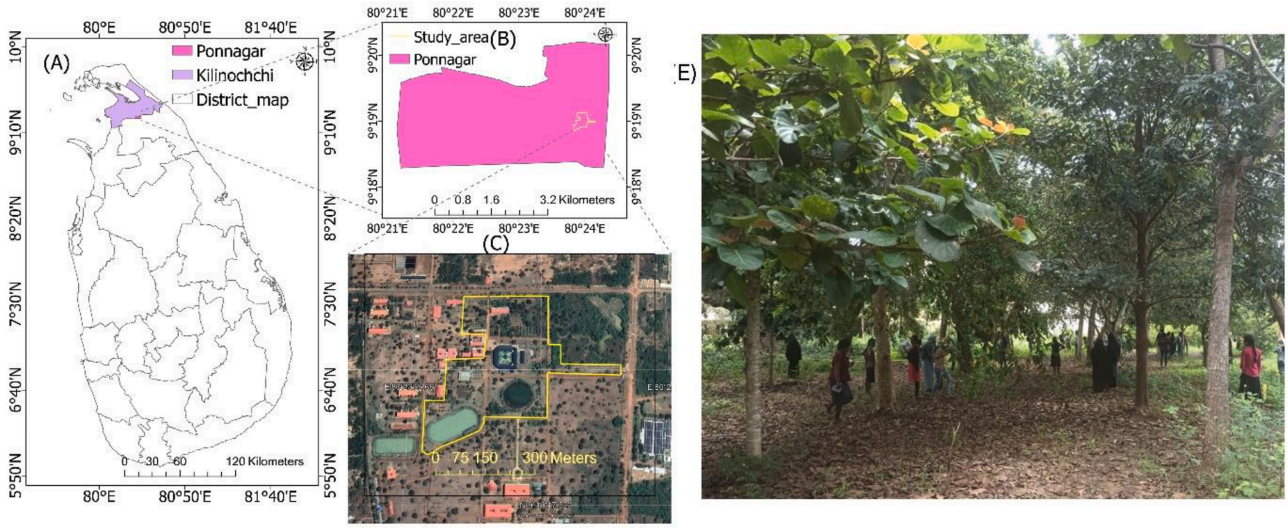
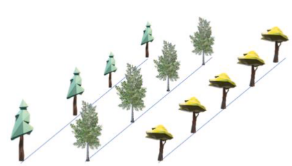



**Fig. 1.** Study site: A) study area in Sri Lanka map; B) study location in Ponnagar division; C) study area boundary (yellow boarder) with Google Earth Pro map, Faculty of Agriculture at Georeferenced Kandawala system; E) an example of reforestation unit, multiple row – mixed planting system.

**Table 1**
Model of mixed and unmixed plantations with description.

| Plantation category | Model | Descriptions |
|---|---|---|
| Multiple Row–Mixed Plantation |  | Different species were planted in a block. In a row, species were mixed. Some tree species in a row differ from another row. |
| Multiple Row–Unmixed Plantation |  | Different species were planted in a block. But, in a row, the same species were planted. Tree species in a row differ from another row or the same species are planted as double/ triple rows continuously next to other row with different species. |

### 2.4. Tree species diversity and dominant

Shannon–Wiener index (SWI) was used to estimate tree species diversity and its value ranges from 0 to In (S). Shannon–Wiener index (Shannon and Weaver, 1949) denoted by Eq. 1,

$$H = -[(Pi)\ln(Pi)] \quad (1)$$

$\Sigma$ = summation

Pi = proportion of total sample represented by species i (divide number of individuals of species i by total number of samples

Species richness was estimated using Eq. 2.

$$S = \frac{Number\ of\ species}{Number\ of\ individual\ species} \quad (2)$$

Maximum diversity was measured using Eq. 3

$$Hmax = ln\ (S) \quad (3)$$

Evenness of the tree species was estimated using Eq. 4.

$$E = \frac{H}{Hmax} \quad (4)$$

Dominant of tree species was estimated using Important Value Index (IVI). The IVI is computed using abundance, dominance, and frequency. Species abundance was calculated based on number of individuals in species and relative frequency. Occurrence of species in the sampling plots was used to estimate the relative density. Basal area was used to estimate the dominance (Misra, 1969).

Relative density (ReDen) was calculated by using Eq. 5

$$\text{ReDen} = \frac{Number\ of\ individuals\ of\ a\ species}{Total\ number\ of\ individuals\ of\ all\ species} \text{x } 100 \quad (5)$$

Relative dominance (ReDom) was calculated by using Eq. (6).

$$\text{ReDom} = \frac{Basal\ area\ of\ a\ species}{Total\ basal\ area\ of\ all\ species} \times 100 \quad (6)$$

Eq. 7 was used to measure Relative frequency (ReFre)

$$\text{ReFre} = \frac{Frequency\ of\ a\ species}{Total\ frequency\ of\ all\ species} \times 100 \quad (7)$$

Importance value index was measured by using Eq. 8

$$\text{IVI} = \text{ReDen} + \text{ReDom} + \text{ReFre} \quad (8)$$

### 2.5. Estimation of tree biomass and carbon stock

First individual tree biomass (kg/tree) was calculated. Above ground biomass was calculated by using following allometric equation (Eq. (9)) (Chave et al., 2014).

$$AGB = 0.0673 \times \left(\rho\ D^2 H\right)^{0.976} \quad (9)$$

Where,

AGB – above ground biomass (kg / tree)

$\rho$ – wood density (g / $cm^3$)

D – diameter at breast height in cm

H – Tree height (m)

Allometric equation (Eq. (10)) for tropical forest was used to estimate the below ground biomass (BGB) (Cairns et al., 1997).

$$BGB = -\exp(-1.0587 + 0.8836\ln(AGB)) \quad (10)$$

Where,

BGB = below ground biomss or root biomass in kg / tree, ln= natural logarithm,

Exp = "e to the power ".

AGB = above ground biomass in kg / tree.

$$TBM = AGB + BGB \tag{11}$$

Where,

TBM – total biomass in kg / tree,

AGB – above ground biomass in kg / tree,

BGB – below ground biomass in kg / tree

The carbon conversion factor 0.47 is used for carbon stock estimation (IPCC, 2006). Individual tree total biomass (TBM) (Eq. (11)) was then sum up per plot. Carbon stock was estimated into mega gram carbon content per ha (Mg C/ha). The carbon stock which estimated only from tree species excluding the carbon stored in plant litter materials, dead trees, lianas, saplings and soil carbon stock.

### 2.6. Data analysis

Different analytical methods were approached to estimate the significance of the data using Excel (Microsoft Corporation, Redmond, WA, USA) and Minitab version 17 (Minitab Inc., State College, PA, USA). A Kruskal–Wallis test was performed to determine the median of two or more groups significantly differ due to the number of plots differed in mixed and unmixed plantation categories. Mann Whitney U Test (Wilcoxon Rank Sum Test) was performed to determine the median of a sample differs significantly from a specified value.

**Table 2**
Identified species with English or common, scientific and family name in the reforestation units.

| No | English / Common Name | Scientific name | Family |
|---|---|---|---|
| 1 | African mahogany/Khaya | *Khaya senegalensis* | Meliaceae |
| 2 | Beach almond/Kathaapu/ Kottamba | *Terminalia catappa* | Meliaceae |
| 3 | Billing/Bilin | *Averrhoa bilimbi* | Oxalidaceae |
| 4 | Bulu | *Terminalia bellirica* | Combretaceae |
| 5 | Cashew | *Anacardium occidentale* | Anacardiaceae |
| 6 | Gliricidia | *Gliricidia sepium* | Fabaceae |
| 7 | Golden Shower/Kontrai/Ehela | *Cassia fistula* | Fabaceae |
| 8 | Guava | *Psidium guajava* | Myrtaceae |
| 9 | Indian beech/Pungai/Karanda | *Pongamia pinnata* | Fabaceae |
| 10 | Indian gooseberry/Nelli | *Phyllanthus emblica* | Phyllanthaceae |
| 11 | Jack | *Artocarpus heterophyllus* | Moraceae |
| 12 | Jamun/Jamblon/Naval/Dan | *Syzygium cumini* | Myrtaceae |
| 13 | Kumbuk/Maruthu | *Terminalia arjuna* | Combretaceae |
| 14 | Maha–Nuga | *Ficus benghalensis* | Moraceae |
| 15 | Mahogany | *Swietenia macrophylla* | Meliaceae |
| 16 | Manchaadi/Madatiya | *Adenanthera pavonina* | Fabaceae |
| 17 | Mango | *Mangifera indica* | Anacardiaceae |
| 18 | Mara | *Albizia lebbeck* | Fabaceae |
| 19 | Mee/Illuppai | *Madhuca longifolia* | Sapotaceae |
| 20 | Neem/Kohomba | *Azadirachta indica* | Meliaceae |
| 21 | Palu | *Manilkara hexandra* | Sapotaceae |
| 22 | Pare Mara | *Albizia saman* | Fabaceae |
| 23 | Pink rosea | *Tabebuia rosea* | Bignoniaceae |
| 24 | Pomegranate | *Punica granatum* | Lythraceae |
| 25 | Seetha fruit/Ahu | *Morinda citrifolia* | Rubiaceae |
| 26 | Sithiravempu/Pihimbiya | *Filicium decipiens* | Sapindaceae |
| 27 | Trincomalee wood/ Samandalai/ Halmilla | *Berrya cordifolia* | Tiliaceae |

## 3. Results

### 3.1. Tree species diversity

#### 3.1.1. Identification of tree species

The identified tree species are listed in Table 2. A total of 931 individual trees, representing 27 species, 24 genera, and 14 families, were identified. Among these, 17 species were plantation forestry species, while the remaining species were fruit plants. The dominant family was Fabaceae, with 6 identified species, followed by Meliaceae, which had 4 species.

#### 3.1.2. Diversity of tree species

Table 3 represents the tree biodiversity in the study area. Tree diversity was significantly higher in MRMP (SWI: 1.34±0.07) compared to MRUP (SWI: 0.45±0.05) (p=0.0001). Similarly, species richness was significantly greater in MRMP (5.09±0.34) than MRUP (2.17±0.14). The mean value of evenness was also significantly higher in MRMP (0.86 ±0.02) compared to MRUP (0.43±0.05). These findings indicate that MRMP exhibited higher tree species diversity and richness with a more even distribution compared to MRUP. However, tree density did not significantly differ between the plantation categories.

#### 3.1.3. Species dominance

Important value index (IVI) with relative density (ReDen), relative frequency (ReFre) and relative dominance (ReDom) is given in Table 4. Based on the IVI, dominant species was *Terminalia arjuna* (124.45) followed by *Khaya senegalensis* (53.84), *Mangifera indica* (41.51), *Gliricidia sepium* (41.4), *Albizia lebbeck* (30.54), *Syzygium cumini* (27.76), and *Tabebuia rosea* (22.26).

#### 3.1.4. Survival percentage

Table 5 presents the survival percentage of tree species. A Wilcoxon Signed Rank test revealed a significant difference (p=0.000) in the survival percentage among the tree species. Species such as Dan, Kumbuk, Mara, Khaya, Mee, and Karanda exhibited survival percentages exceeding 90 % in the study area. However, the survival percentage of Mahogany was significantly lower, at 60 %.

### 3.2. Forest structure

#### 3.2.1. Tree diameter, height, and basal area distributions

The total number of individuals within each diameter class is illustrated in Fig. 2. In Fig. 2a), it is evident that most trees significantly (p=0.001) fell within the ≤10 cm diameter class, followed by the 11–20 cm class, while a smaller number of trees fell within the 21–30 cm and 31–40 cm diameter classes. Similarly, Fig. 2b) demonstrates that most trees significantly fell (p=0.001) within the 6–10 m height class, followed by the ≤5 m class. Overall, mean DBH and height in the study area was 7.94±0.21 (40.13–3) and 5.89±0.11 (21.3–1.1), respectively.

The number of individuals within diameter classes for each species is illustrated in Fig. 3. Species such as Kumbuk, Khaya, and Dan exhibited significantly higher numbers within the 11–20 cm DBH class, whereas Mango, Gliricidia, Mara, Pink rosea, Cashew, and Mee fell within the

**Table 3**
Tree species diversity in multiple rows mixed and unmixed plantation.

| Parameters | Mean values | | Total values | | P–value |
|---|---|---|---|---|---|
| | MRMP | MRUP | MRMP | MRUP | |
| Population | 10.94±0.6 | 19±2.13 | 361 | 570 | 0.213 |
| SWI | 1.34±0.07 | 0.45±0.05 | 2.96 | 1.8 | 0.000* |
| Species richness | 5.09±0.34 | 2.17±0.14 | 27 | 16 | 0.000* |
| Evenness | 0.86±0.02 | 0.43±0.05 | 0.88 | 0.65 | 0.000* |
| Density/ha | 0.3±0.04 | 1.07±0.13 | 274 | 475 | 0.213 |

Mean values were given with ± Standard error at α = 0.05.

**Table 4**
Value of relative density (ReDen), relative frequency (ReFre), relative dominance (ReDom), and IVI for tree species.

| Species | ReDen | ReFre | ReDom | IVI |
|---|---|---|---|---|
| Kumbuk | 29.11 | 57.81 | 37.53 | 124.45 |
| Khaya | 5.69 | 34.38 | 13.77 | 53.84 |
| Mango | 6.02 | 31.25 | 4.24 | 41.51 |
| Gliricidia | 17.51 | 14.06 | 9.83 | 41.40 |
| Mara | 4.30 | 21.88 | 4.37 | 30.54 |
| Dan | 3.44 | 20.31 | 4.01 | 27.76 |
| Pink rosea | 2.69 | 17.19 | 2.39 | 22.26 |
| Cashew | 4.30 | 10.94 | 4.45 | 19.68 |
| Mee | 1.61 | 12.50 | 1.55 | 15.66 |
| Guava | 4.19 | 10.94 | 0.17 | 15.29 |
| Mahogany | 1.29 | 10.94 | 2.63 | 14.86 |
| Karanda | 2.15 | 9.38 | 2.70 | 14.23 |
| Neem | 1.29 | 12.50 | 0.16 | 13.95 |
| Pare Mara | 0.86 | 9.38 | 1.80 | 12.03 |
| Nuga | 0.75 | 9.38 | 0.68 | 10.80 |
| Nelli | 0.86 | 7.81 | 1.97 | 10.64 |
| Madatiya | 0.75 | 7.81 | 1.73 | 10.29 |
| Ehela | 1.61 | 7.81 | 0.43 | 9.86 |
| Pihimbiya | 1.07 | 7.81 | 0.44 | 9.33 |
| Kottamba | 1.18 | 7.81 | 0.22 | 9.22 |
| Albizia | 0.97 | 6.25 | 1.82 | 9.04 |
| Pomegranate | 5.26 | 3.13 | 0.00 | 8.39 |
| Halmilla | 0.64 | 6.25 | 0.55 | 7.44 |
| Palu | 0.43 | 6.25 | 0.75 | 7.43 |
| Bulu | 0.54 | 4.69 | 1.21 | 6.44 |
| Jack | 0.64 | 4.69 | 0.29 | 5.62 |
| Acacia | 0.11 | 1.56 | 0.19 | 1.86 |
| Billing | 0.11 | 1.56 | 0.14 | 1.80 |

**Table 5**
Number of planted and existing tree species with survival percentage.

| Tree species | Existing | Planted | Survival % |
|---|---|---|---|
| Dan | 32 | 33 | 96.97 |
| Kumbuk | 271 | 280 | 96.79 |
| Mara | 40 | 42 | 95.24 |
| Khaya | 53 | 56 | 94.64 |
| Mee | 15 | 16 | 93.75 |
| Karanda | 20 | 22 | 90.91 |
| Cashew | 40 | 45 | 88.89 |
| Pare Mara | 8 | 9 | 88.89 |
| Madatiya | 7 | 8 | 87.50 |
| Nuga | 7 | 8 | 87.50 |
| Guava | 39 | 45 | 86.67 |
| Pink rosea | 25 | 30 | 83.33 |
| Ehela | 15 | 18 | 83.33 |
| Bulu | 5 | 6 | 83.33 |
| Pomegranate | 49 | 60 | 81.67 |
| Gliricidia | 163 | 200 | 81.50 |
| Mango | 56 | 70 | 80.00 |
| Neem | 12 | 15 | 80.00 |
| Pihimbiya | 10 | 13 | 76.92 |
| Albizia | 9 | 12 | 75.00 |
| Halmilla | 6 | 8 | 75.00 |
| Jack | 6 | 8 | 75.00 |
| Kottamba | 11 | 15 | 73.33 |
| Nelli | 8 | 11 | 72.73 |
| Mahogany | 12 | 20 | 60.00 |

≤10 cm DBH class.

The DBH and height for each species is depicted in Fig. 4. Khaya and Bulu exhibited significantly higher mean DBH values compared to Mahogany, Manchaadi, and Albizia. Similarly, Khaya, Albizia, and Manchaadi had significantly greater mean heights compared to other tree species. Overall, the Khaya species demonstrated relatively high mean DBH and height values.

Mean DBH, height, and basal area across plantation categories are presented in Fig. 5. In Fig. 5a), it is observed that mean DBH ($p = 0.645$) and height ($p = 0.186$) did not significantly differ among the plantation categories. The mean values of DBH and height in the study area were 10.82±0.22 cm (1 –33) cm and 6.34±0.11 (1 – 21) m, respectively. In Fig. 5b), it is shown that mean basal area did not significantly differ ($p = 0.259$) among the plantation categories. The mean basal area of the study area was 2.996±0.46 $m^2$ $ha^{-1}$ (0.05 –24.61 $m^2$ $ha^{-1}$).

The mean values of basal area and tree density with species rank are depicted in Fig. 6. Basal area and tree density exhibited a positive correlation with species dominance. Basal area demonstrated a significantly stronger relationship with species dominance compared to tree density (Wilcoxon Signed Rank Test, $p=0.0001$).

### 3.2.2. *Tree growth*

Table 6 presents the growth rates of DBH and height. The species Pare Mara exhibited a high DBH increment rate (4.07±1.55 cm/year), followed by Khaya (3.83±0.43 cm/year), Madatiya (3.56±0.31 cm/year), and Dan (3.41±0.19 cm/year). For tree height growth rate, Madatiya showed the highest rate (1.89±0.29 m/year), followed by Pare Mara (1.82±0.19 m/year), Dan (1.78±0.26 m/year), and Khaya (1.74±0.13 m/year) at MRMP sites. In MRUP sites, the DBH increment, and height growth rate of Khaya were higher (4.37±0.25 cm/year) than in MRMP. However, data were insufficient for other species.

## 3.3. *Forest biomass and carbon stock*

The mean values of tree biomass and carbon stock across plantation categories are illustrated in Fig. 7. There was no significant difference ($p=0.378$) observed in tree biomass and carbon stock among the plantation categories. The mean biomass and carbon stock were 11.74 ± 2.35 and 5.63 ± 1.13, respectively. Table 7 provides the total and mean values of biomass, carbon stock, and carbon sequestration. A total of 14.2 MgC was accumulated, while 52.06 Mg of carbon dioxide were sequestered in the study area. The mean carbon stock was 5.63 ± 1.13 (0.04–62.3) MgC/ha, and the mean carbon sequestration was 20.66 ± 4.13 (0.15–228.3) Mg/ha.

The mean values of carbon stock and carbon sequestration for tree species are depicted in Fig. 8. A similar trend was observed for both carbon stock and carbon sequestration. In Fig. 8a), it is shown that mean carbon stock among the species significantly differed ($p=0.001$). The tree species Pera Mara exhibited the highest carbon stock (66±36.78 kg/tree), followed by Madatiya (49±19.85 kg/tree), Bulu (43±10.19 kg/tree), Mahogany (42±12.35 kg/tree), and Khaya (40±5.05 kg/tree) in the study area. Fig. 8b) demonstrates that mean carbon sequestration among the species significantly differed ($p=0.001$). Pera Mara sequestered the highest amount of carbon dioxide (34.6±19.76 kg/year), followed by Madatiya (25.71±9.65 kg/year), Bulu (22.4±5.34 kg/year), Mahogany (21.78±6.47 kg/year), and Khaya (20.78±2.65 kg/year)

# 4. Discussion

## 4.1. *Tree management and monitoring in ANR sites*

In the span of a decade, the study area has been opening with prolonged dry spells from March to August, attributed to climate change. Situated in an elevated location, the area faces challenges in water availability for newly planted trees during this period. To address this, we utilized a tractor–mounted bowser for watering purposes for up to three years post–planting. Our tree planting endeavors commenced during the rainy season at the onset of September, aligning with observations indicating higher regeneration success when planting occurs under optimal soil moisture conditions (Bekele-Tesemma and Tengnäs, 2007). Selecting tree seedlings with heights ranging from 60–90 cm for regeneration proved advantageous, as planted seedlings outperformed exposed or buried seeds (Palma et al., 2020), contributing significantly to the regeneration success witnessed in the study sites. In addition, the soil composition in the area predominantly consists of gravel, indicating marginal land. To ensure successful tree planting, we adopted a strategy

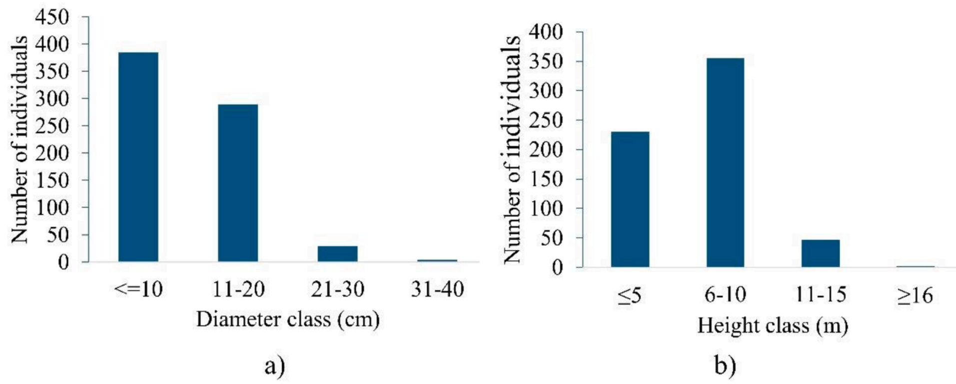



**Fig. 2.** Number of trees with diameter class (a) and height class (b) in the study area.

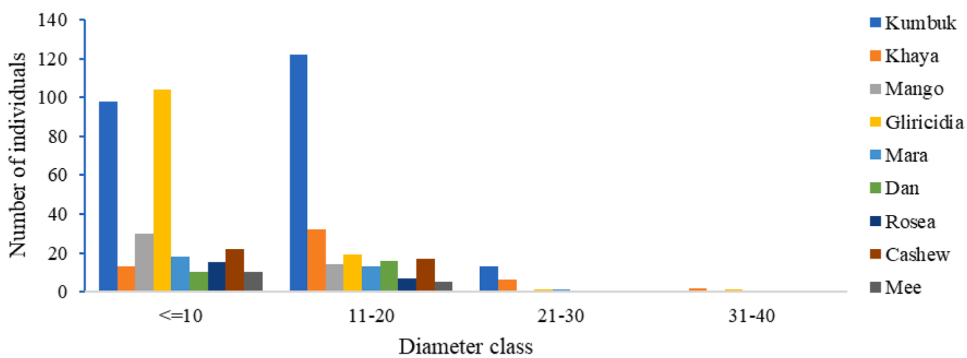



**Fig. 3.** Number of individuals diameter class distribution for dominant species.

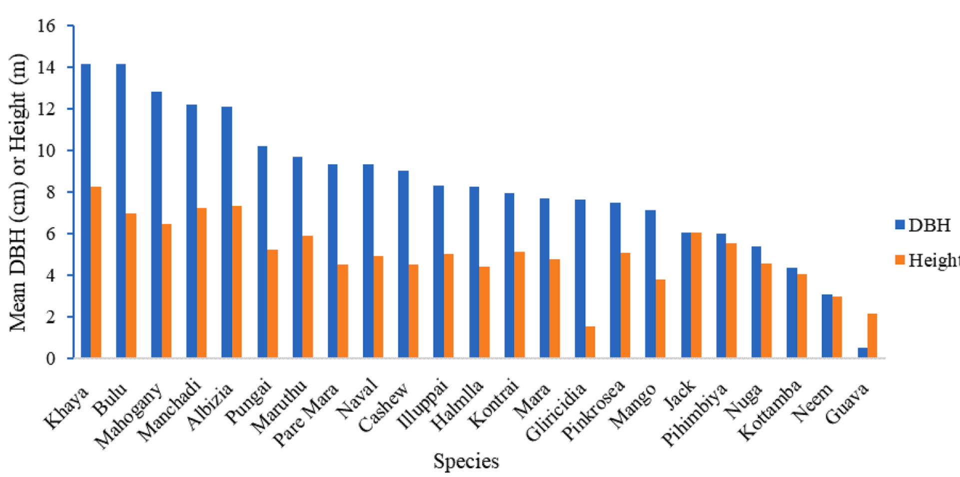



**Fig. 4.** Mean DBH and Height of tree species.

of creating planting holes measuring 90 cm × 90 cm × 90 cm in excessively gravelly soils and 60 cm × 60 cm × 60 cm in moderately gravelly soils for length, width, and depth, respectively. These holes were filled with a mixture of jungle forest soil, cow dung, and leaf litter before planting (Fig. 9). Additionally, the reforestation unit was safeguarded by an administrative boundary wall, providing protection against wildlife and stray animals, a factor proven to enhance regeneration success (Kassaye et al., 2023). Native species well–suited to the dry tropics were predominantly selected for planting. However, we introduced some non-native species from other regions to diversify the ecosystem, particularly for seasonal flowering and fast growth. The management of tree planting operations and continuous monitoring efforts contributed significantly to the higher percentage of reforestation success observed in the study sites. Moreover, the promotion of natural regeneration through silvicultural treatments emerged as a pivotal strategy in expediting the restoration and productivity of degraded forest ecosystems (Shoo and Catterall, 2013). Practices such as assisted natural regeneration, which involve minimizing human and grazing disturbances while implementing specific silvicultural treatments, have demonstrated efficacy in forest restoration efforts (Shoo and Catterall, 2013).

### 4.2. *Tree species and diversity in ANR sites*

The selection of appropriate tree species is paramount for the success of ANR techniques. In a study conducted in the dry tropics of Sri Lanka's

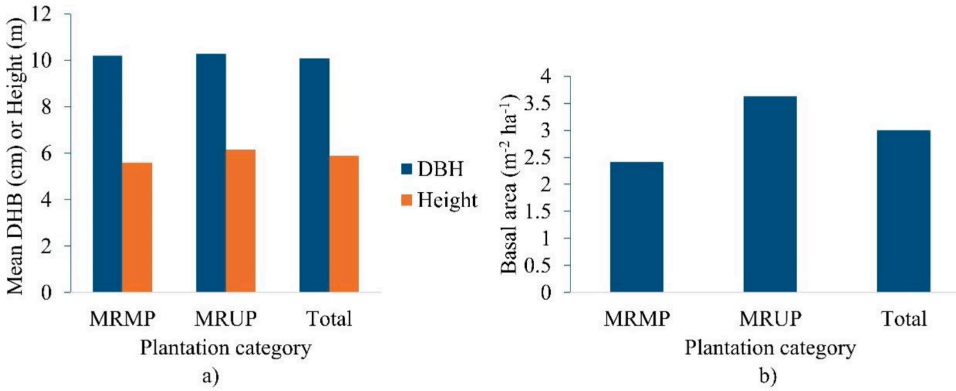



**Fig. 5.** Mean DBH or height (a), and basal area (b) with plantation categories.

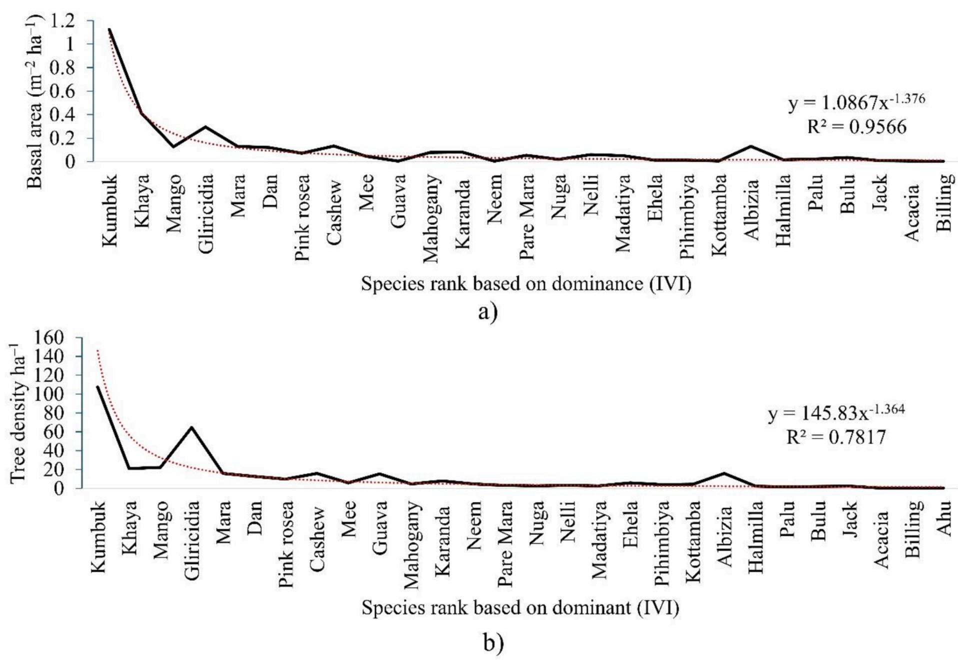



**Fig. 6.** Relationship of basal area (a) and tree density (b) with species dominance.

**Table 6**
Growth rate of species in selected plots the study area.

| | MRMP DBH (cm/ year) | Height (m/ year) | MRUP DBH (cm/ year) | Height (m/ year) |
|---|---|---|---|---|
| Pare Mara | 4.07±1.55 | 1.82±0.19 | – | – |
| Khaya | 3.83±0.43 | 1.74±0.13 | 4.37±0.25 | 2.785±0.16 |
| Madatiya | 3.56±0.31 | 1.89±0.29 | – | – |
| Dan | 3.41±0.19 | 1.78±0.26 | – | – |
| Pink rosea | – | – | 2.91±0.45 | 1.50±0.19 |
| Kumbuk | 2.88±0.3 | 1.53±0.12 | – | – |
| Mara | 2.70±0.39 | 1.41±0.14 | – | – |

Anuradhapura district, Galatumbage et al. (2021) identified a total of 32 tree species at ANR sites. Our findings regarding the Shannon–Wiener Index (SWI) in mixed plantation sites align with previous research, where SWI ranged from 0.88 to 0.89 (Anuraj et al., 2019), indicating consistency across studies. In mature mixed plantation sites, teak emerged as the dominant species, with an Important Value Index (IVI) of 111.34, followed by Eucalyptus (49.91) (Anuraj et al., 2019). In contrast, our study recorded higher survival percentages for tree species compared to Galatumbage et al. (2021), who reported high survival rates for *M. longifolia* (Mee) (72 %), *S. revolutum* (Danba) (78.4 %), and *T. arjuna* (Kumbuk) (53.2 %). This disparity in survival rates can be attributed to the management practices implemented post–planting in our study, which mitigated challenges such as water scarcity and wildlife damage, resulting in higher tree density compared to the ANR site studied by Galatumbage et al. (2021) (55 stems ha$^{-1}$). Further, *S.revolutum* and *M.longifolia* were adaptive species for ANR activities in Anuradhapura district. According to FAO (2019), a minimum density of approximately 800 natural seedlings per hectare is required for effective ANR, with canopy closure expected within two to three years with densities up to 3000 seedlings per hectare. However, our study observed a lower density than the recommended threshold, leading to canopy closure occurring after seven years of planting.

### 4.3. Carbon stock and sequestration

The amount of $CO_2$ sequestered by trees is influenced by various factors such as growth rate, age, and species. Young, rapidly growing trees have been observed to uptake significantly more carbon than mature trees. It's noteworthy that newly established rainforests on degraded land, termed secondary forests, can store up to 11 times more

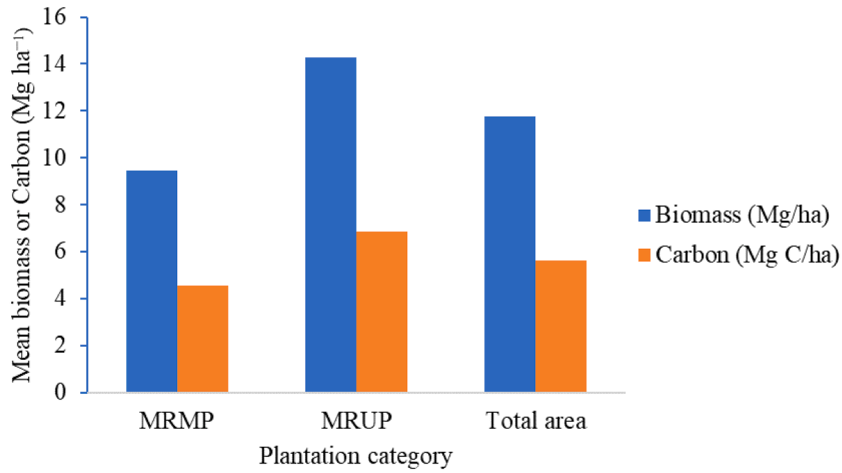



**Fig. 7.** Tree biomass and carbon stock with plantation categories.

**Table 7**
Total and mean value of biomass, caron stock, and carbon sequestration.

| Biomass/Carbon | Value |
|---|---|
| Total biomass in the study area (Mg) | 29.58 |
| Mean biomass (Mg/ha) | 11.74±2.35 (129.7–0.09) |
| Total carbon in the study area (Mg) | 14.20 |
| Mean carbon (Mg/ha) | 5.63±1.13 (62.3–0.04) |
| Carbon sequestration in the study area (Mg) | 52.06 |
| Carbon sequestration (Mg/ha) | 20.66±4.13 (228.3–0.15) |

carbon than old–growth rainforests (Köhl et al., 2017). For instance, research by Myers and Goreau (1992) indicated that tropical tree plantations consisting of pine and eucalyptus species can sequester an average of 10 tons of carbon per hectare per year, totaling approximately 33.26 tons of $CO_2$/ha/year. Moreover, average of 2.22 kg biomass was increased annually per tree, while exceeded amount of 6 Mg C /ha was recoded for species *Anogeissus leïocarpa, K. senegalensis, Pterocarpus erinaceus* (Hérault et al., 2020).

Our study's findings align with existing research in tropical climates, suggesting that a single tree can sequester a minimum of around 25 kg of $CO_2$ per year over a useful life span of 40 years. Similarly, newly planted trees in tropical regions may remove up to 50 kg of $CO_2$ annually during their growth period of 20–50 years with an average of 25 kg of carbon sequestered per tree per year (Köhl et al., 2017). Myers and Goreau (1992) also showed that tropical tree plantations of pine and eucalyptus can sequester, 33.33 kg $CO_2$/tree/year at 1000 trees per hectare.

Research on mixed tree species plantations has shown favorable outcomes in tropical regions, including reduced incidence of pests and diseases, optimal land utilization, higher percentage of survival rates, and risk diversification (López-Sampson et al., 2021; Montagnini et al., 1995). Such mixed species plantations typically aim for homogenous mixtures of two or more species or the promotion of principal species in double–layered or single–layered stands (Pancel, 2016). While monocultures offer significant economic benefits and have been favored in large–scale plantation development, there has been a shift towards smallholder operations in many tropical regions, often necessitating the use of mixed species to diversify risks, especially involving native species with limited information available (Liu et al., 2018).

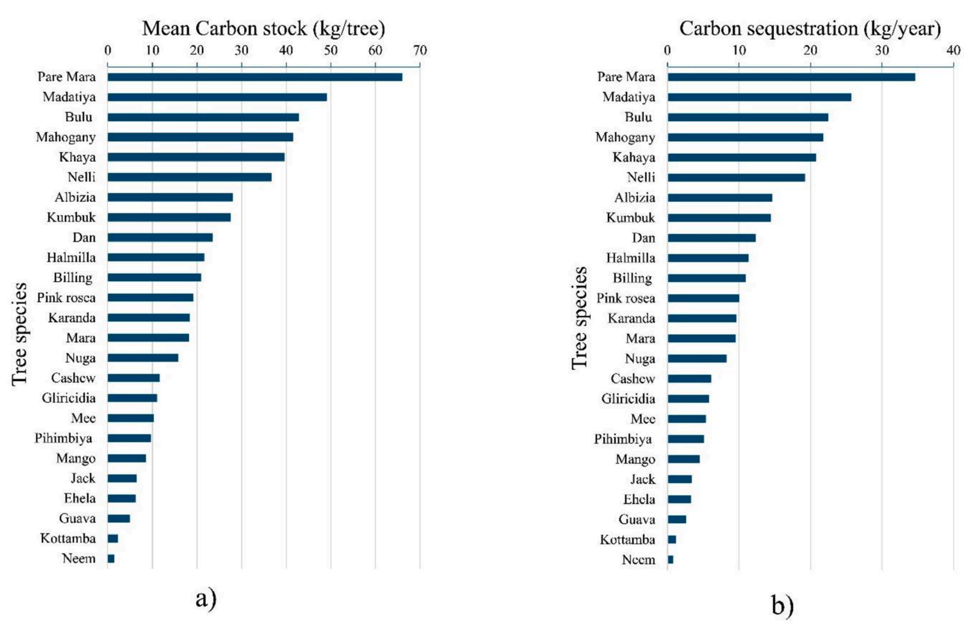



**Fig. 8.** Mean value of the carbon stock in kg/ tree (a) and carbon sequestration in kg/year (b) with tree species

**Fig. 9.** a) Tree planting preparation by technical staff and field workers; b) Filling of a planting hole using cow dung and topsoil; b) Tree growth success in a ANR site – MRUP (species Khaya); d) Tree growth success in a ANR site – MRMP.

## 5. Conclusions

In conclusion, our study underscores the critical role of ANR in restoring dry forest landscapes, enhancing biodiversity, and optimizing carbon regulation. The findings reveal that multiple row–mixed plantation (MRMP) sites exhibited significantly higher tree biodiversity, species richness, and evenness compared to multiple row–unmixed plantation (MRUP) sites. *Terminalia arjuna* emerged as the most dominant species, followed by *Khaya senegalensis,* indicating the suitability of these species for ANR activities in the dry tropics. Moreover, survival rates exceeding 90 % were observed for several key species, highlighting the effectiveness of ANR in fostering tree establishment and growth. Forest structure analysis revealed no significant differences in tree diameter, height, basal area, and carbon stock between MRMP and MRUP categories, suggesting that both plantation types contribute similarly to carbon sequestration efforts. Mean carbon stock was estimated at 5.63 ± 1.13 MgC/ha, with a total of 14.2 MgC stored in the study area, equivalent to sequestering 52.06 Mg $CO_2$. These results emphasize the potential of ANR as a cost–effective and environmentally sustainable approach to forest restoration and carbon sequestration in dryland ecosystems.

Furthermore, effective tree management practices, including appropriate species selection, site preparation, and post–planting care, were crucial in ensuring the success of ANR activities. Continuous monitoring and adaptive management strategies are essential for optimizing regeneration success and maintaining ecosystem health. Overall, our study highlights the importance of promoting mixed tree species in ANR projects to enhance biodiversity, optimize carbon regulation. These findings contribute valuable insights to forest restoration efforts in the context of climate change mitigation and biodiversity conservation.

### Implications, suggestions, and recommendations

Planting trees in multiple rows as mixed planting (MRMP) restores biodiversity, tree structure, and carbon stock more effectively than planting in multiple rows as an unmixed planting system (MRUP). While multiple rows facilitate post–tree management practices, a mixed planting system promotes tree species diversity. From this study, we could recommend that implementing the MRMP system in deforested areas of dry tropical forests is a viable option for landscape restoration. In this study, ANR successfully restored biodiversity, tree structure, and carbon stock, with a high tree survival rate. Given the challenges faced by dry tropical forests, including water scarcity, poor soil fertility, and damage from wildlife and domestic animals, further recommend the following measures to enhance restoration success: protected fencing – plant seedlings with protected fencing to prevent damage from wildlife and domestic animals, water management – ensure water availability during hot periods to support tree growth and survival, and selection of tree species– carefully select suitable tree species, especially fast-–growing ones, for a quick restoration process. Further, ANR holds the potential to rejuvenate soil quality and improve microclimatic conditions within ecosystems. It was observed that the higher litterfall from trees post–reforestation efforts. However, further investigation is needed to investigate soil fertility enhancement within the restored units.

Additionally, identifying deforestation hotspots will facilitate targeted restoration activities nationwide. The government and private sectors should take necessary actions to restore dry forest ecosystems, including policy changes or amendments to support restoration efforts. Adequate funding should be allocated to support these activities. A systematic national survey is needed to evaluate restoration areas, identifying strengths and weaknesses in restoration activities for future improvements. These measures will contribute to the effective restoration of dry tropical forests, enhancing biodiversity, and optimizing carbon sequestration.

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### Informed consent statement

All persons in the photographs cited in the article constated for the publication of the faces in the Journal.

### CRediT authorship contribution statement

**Rajive Rajapakshe:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jeyavanan Karthigesu:** Writing – review & editing, Supervision, Methodology. **Sivananthawerl Thavananthan:** Writing – review & editing, Supervision, Conceptualization. **Sivamathy Sivachandiran:** Writing – review & editing, Supervision. **Venukopan Navaneetham:** Methodology, Conceptualization. **Sritharan Sinnamani:** Methodology, Conceptualization.

### Declaration of competing interest

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

### Data availability

Data will be made available on request.

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