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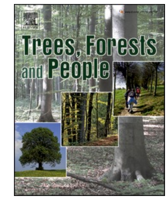


# Assessing carbon sequestration in urban Miyawaki forests of south India: Implications for climate mitigation planning and land suitability

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ABSTRACT

Globally, plantation forests are widely recognized as an effective solution to combat land degradation. One such approach of creating plantation forest is the Miyawaki method of afforestation and reforestation, which involves dense planting of native species. This study investigates the carbon sequestration potential of three Miyawaki forests aged 2, 4, and 5 years in the south Indian cities of Bengaluru and Palakkad. We conducted field sampling to measure tree attributes, including Diameter at Breast Height (DBH) and height, which were used to calculate the above-ground biomass (AGB) using species-specific equations. Carbon storage and sequestration rates were then estimated using the same allometric approach, combined with the age of the Miyawaki forest stands. Our findings reveal that the annual growth rate of forest biomass increases significantly with age, resulting in a total biomass accumulation of 165.7 Mg C/ha within five years of planting. Additionally, carbon sequestration rates showed a rapid increase with forest age, with the 2-year-old forest sequestering 5.284 Mg C/ha-yr, the 4-year-old forest sequestering 20.042 Mg C/ ha-yr, and the 5-year-old forest sequestering 33.084 Mg C/ha-yr. We also identified over 200,000 km$^2$ of underutilized marginal land with climatic conditions similar to those of the study sites, offering vast potential for expanding Miyawaki forest interventions. In this context, the Miyawaki method could be positioned within policy interventions aimed at climate mitigation in India and beyond, considering the relevant biophysical and ecological factors.

## 1. Introduction

The Global Carbon Budget (2023) estimates that approximately 40 billion metric tons of $CO_2$ are released annually, with 36–37 billion metric tons from fossil fuel use and 3–4 billion metric tons from land-use changes (Friedlingstein et al., 2023). Of this, oceans and terrestrial ecosystems absorb around 9–10 and 11–12 billion metric tons respectively, while the remaining $CO_2$ accumulates in the atmosphere, intensifying climate change (Friedlingstein et al., 2023). The 2023 UN Climate Conference highlighted nature-based solutions such as halting deforestation, restoring wetlands, and enhancing green cover as critical to carbon sequestration and climate resilience (Bulkeley et al., 2023).

In the context of increasing green cover as a potential climate solution, the Miyawaki method has emerged as a promising afforestation approach to support biodiversity and provide ecosystem services alike (Singh and Saini, 2019; Jaiswal et al., 2025). Developed in the 1990s by Japanese botanist Prof. *Akira Miyawaki*, this technique involves creating dense, native forests that grow rapidly, achieving full canopy closure within 2–3 years (Miyawaki and Golley, 1993). Today, Miyawaki forest stands (MwFSs) are primarily established to improve local microclimates— like reducing heat and improving air quality— and to provide green spaces for residents, mostly in urban areas (Manuel, 2020; Kurian, 2020). They are also widely adopted in corporate social responsibility (CSR) initiatives, often to showcase climate-conscious efforts and generate carbon offsets.

Against this backdrop, it is important to critically examine how

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effective these forests truly are at sequestering carbon (C). The assumption that tree planting always leads to rapid C storage is not necessarily accurate (Roy and Bhan, 2024). Factors such as species selection, human intervention, and land-use history considerably influence C sequestration outcomes (Rodrigues et al., 2023). Although MwFSs are known for rapid growth and dense canopies— potentially suggesting faster carbon uptake— their actual effectiveness remains debated. This is especially relevant in India, where empirical data on post-plantation growth and carbon accumulation are largely inadequate. A systematic evaluation of C sequestration across MwFSs of varying ages is, therefore, essential to generate context-specific insights.

Forest stands created using the Miyawaki technique are often promoted in policy and popular literature as sequestering carbon up to 15–30 times faster than natural forests— primarily due to their high planting density and rapid early-stage growth (ICLEI South Asia, 2022; Riyas, 2022; Waddington, 2022; Times of India, 2025). However, such claims are largely context-dependent and remain unverified by systematic, long-term empirical studies (Daniels and Vencatesan, 2021). If validated, this would position them among the most effective nature-based solutions for climate change. Moreover, biodiversity conservation— an essential component of climate mitigation— can also benefit from MwFSs (Schirone et al., 2011). Eco-forests established using this method in Thailand's Khlong Luang district, for example, showed rapid growth and enhanced C sequestration (Hanpattanakit et al., 2022). Similarly, a study in Malaysia's Sarawak region found that a 19-year-old MwFS had C stock comparable to that of a naturally regenerating secondary forest. However, overall C stock in MwFSs has generally been reported as lower than other Southeast Asian forests (Kueh et al., 2016). The limited existing research thus presents mixed evidence on their C sequestration and storage potential.

To address this gap, our study evaluates how C sequestration potential changes in Miyawaki forests during the early years after plantation. We estimated above-ground biomass using species-specific allometric equations and tree dimension data from three forests of different ages located in the southern Indian states of Kerala and Karnataka. We focused on two key questions: (1) How do C sequestration rates change in Miyawaki forests as they age? (2) Where in India can more MwFSs, with comparable C sequestration rates, be developed to prevent land degradation?

According to Miyawaki forestry principles, such forests are considered ecologically self-sustaining after three years and are thereafter left to grow without further human intervention (Ahirwal and Maiti, 2021). Based on this, our study was designed with two main objectives: (1) to quantify and compare above-ground carbon accumulation across three Miyawaki forest stands of different ages (2, 4, and 5 years) in south India; and (2) to identify ecologically suitable areas across peninsular India where similar Miyawaki forests could potentially be developed using spatial analysis. These objectives help address both the ecological dynamics of post-maturity growth and the practical considerations for future scaling of this afforestation approach.

This study presents what is likely the first empirical assessment of age-wise carbon accumulation in Miyawaki forests in India. Although widely promoted as fast-growing, high-impact models for urban afforestation, their carbon sequestration potential has remained largely unverified in the Indian context. Drawing on field-based measurements across an early growth gradient, we provide critical data to inform policy, planning, and implementation of urban nature-based solutions. By addressing both geographic and methodological gaps, this study contributes to the growing literature on small-scale, rapid afforestation and supports more evidence-based integration of Miyawaki forests into climate mitigation and CSR strategies.

## 2. Methods

### 2.1. Study site description

The study was conducted at two sites in Bengaluru, Karnataka, and one site in Palakkad, Kerala, in southern India (Fig. 1). According to the Köppen climate classification, both Bengaluru and Palakkad are classified under the Aw climate class, defined by tropical climatic conditions (Prasad et al., 2021; Rajashekara, 2020).

Palakkad, located in the southern Indian state of Kerala at an altitude of approximately 84 m above sea level, experiences a warm and humid climate influenced by the Palakkad Gap (Ray et al., 2017). The region receives an average annual rainfall of around 2400 mm, with the majority occurring during the southwest monsoon (June to September) and additional rainfall during the northeast monsoon (October to November). The climatic conditions are characterized by pronounced seasonal variation, with hotter summers (28 °C–38 °C) from March to May and comparatively milder winters (22 °C–32 °C) from November to February, with a mean annual temperature of 25.9 °C (Dhanya et al., 2023). The main land cover includes about 46.5 % agriculture, 31 % forest, 10.3 % buildings, and 5.5–6 % fallow lands. The remaining land is barren or uncultivatable areas, tree crops, and cultivable wastes (Premakumar and Vinothkanna, 2015).

The younger Miyawaki site examined in this study, hereafter referred to as MwFS 1, is situated within the Indian Institute of Technology (IIT) Palakkad campus, approximately 20 km from the city of Palakkad. Established in 2020, MwFS 1 covers an area of 1600 $m^2$ and was initially planted with 4800 saplings representing 19 native species, at a density of three saplings per $m^2$. At the time of assessment, 1200 individuals had survived (Table 1). The reduction in survival is primarily attributed to recurrent herbivory and trampling by wild fauna such as chital (*Axis axis*), Asian elephants (*Elephas maximus*), and wild boars (*Sus scrofa*), which regularly access the site from the adjoining forest department-controlled area (Shaji, 2024). Palakkad district records some of the highest instances of human–elephant conflict in Kerala, and this MwFS is located close to the ecologically sensitive Malampuzha–Kanjikode–Walayar–Madukkarai forest belt— a recognized elephant corridor under the jurisdiction of the Walayar Forest Range within the Palakkad Forest Division (Sengupta et al., 2020; Thiyagaraj, 2015). Prior to the plantation, the site was predominantly covered by *Pennisetum setaceum* (fountain grass), a known invasive species in the region.

Bengaluru, located in the southern Indian state of Karnataka, lies at an altitude of 915 to 960 m above sea level, which contributes to its moderate and pleasant climate. The city receives an annual average rainfall of approximately 970 mm, primarily during the southwest monsoon (June to September) with additional contributions from the northeast monsoon (October to November). The mean annual temperature stands at 24.1 °C with summer months (March to May) reaching 20 °C to 36 °C and winter months (November to February) experiencing 15 °C to 28 °C (Rajashekara, 2020). This favorable climatic condition has earned Bengaluru its reputation as a city with a salubrious environment, complementing its status as a major hub for information technology and innovation in India. The main land cover includes about 38 % built-up areas, 44 % croplands in semi-arid or dry sub-humid regions, 4 % fallow lands, and 0.5–5 % seasonally fluctuating wetlands (Buchhorn et al., 2020). Only 7–9 % of Bengaluru is classified as some type of forest or non-forest tree cover, with 90 % of these being open forest types with unclassified vegetation (Buchhorn et al., 2020).

The older Miyawaki forest stands examined in this study are located in Bengaluru. These two forest stands, referred to as MwFS 2 and MwFS 3, are similar in size (Table 1). MwFS 2 is the 4-year-old forest stand, and MwFS 3 is the 5-year-old stand. Each site contained 2000 saplings planted at a density of three saplings per $m^2$. Both sites exhibit a survival rate of approximately 55 % at the time of measurement. MwFS 2 consists of 24 native species while MwFS 3 contains 20 native species. The two stands are located adjacent to each other within the Indian Railways

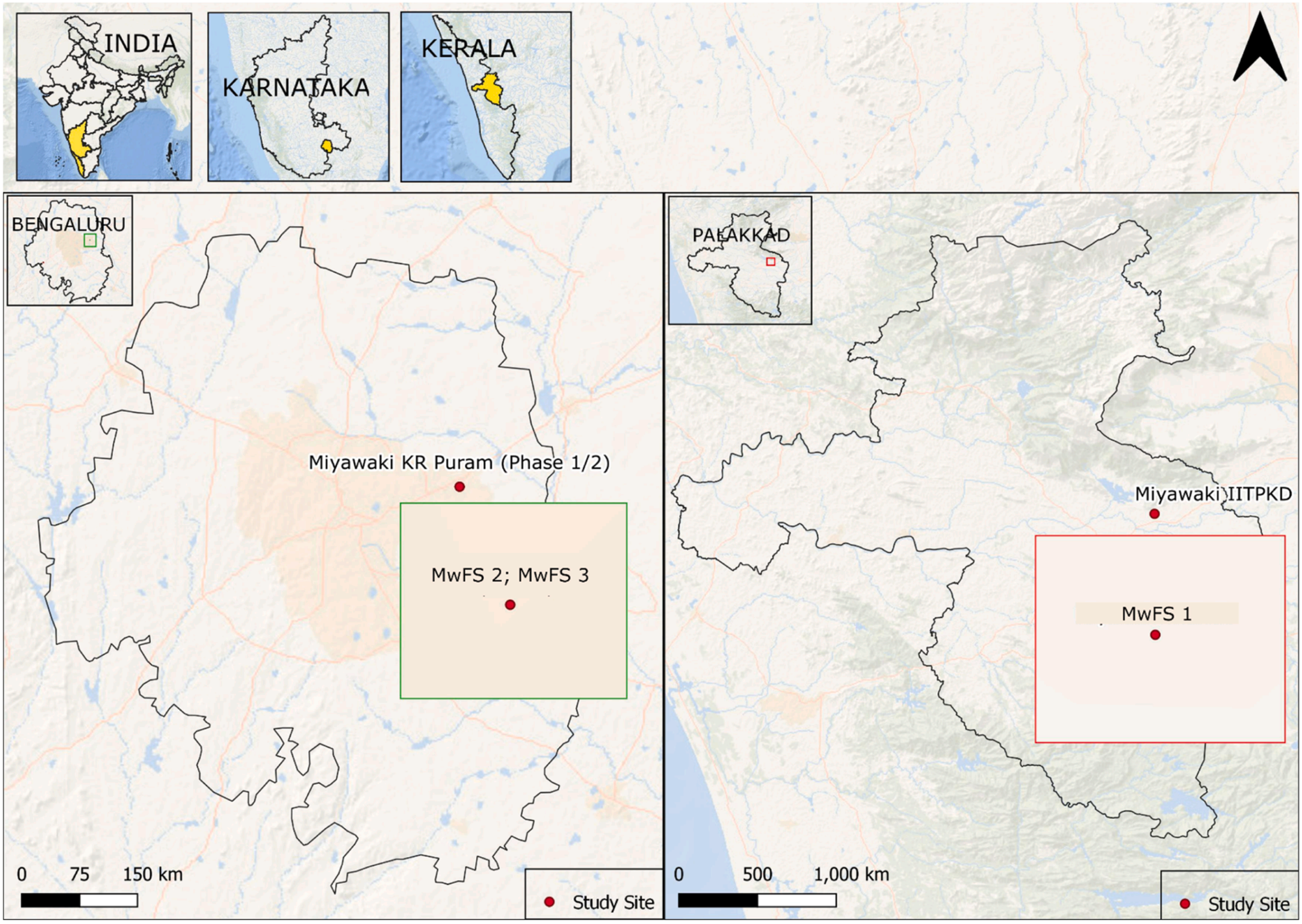


**Fig. 1.** Map depicting locations of study sites.

**Table 1**
Description of the study sites.

| Details | MwFS 1 | MwFS 2 | MwFS 3 |
|---|---|---|---|
| Location | Palakkad (Kerala) | Bengaluru (Karnataka) | Bengaluru (Karnataka) |
| Area ($m^2$) | 1600 (0.16 ha) | 600 (0.06 ha) | 600 (0.06 ha) |
| Planting date (yyyy-mm) | 2021–03 | 2017–12 | 2016–09 |
| Sampling date (yyyy-mm) | 2022–12 | 2021–09 | 2021–08 |
| Plantation age (months) | 21 | 45 | 59 |
| Sapling count (planted) | 4800 | 2000 | 2000 |

Diesel Loco Shed campus in the northeastern Bengaluru area of Krishnarajapuram (KR Puram), and the campus is under the protection of Indian Railways security. Prior to the establishment of the Miyawaki forests, a traditional row plantation with 70 trees existed in the northeastern corner of the site, dating back to before 2013. To the northwest of the site lies a marshy water body, which occasionally fills with local runoff. In late February 2016, a significant fire occurred in the area, as reported by local residents and the NGO responsible for the establishment of the two Miyawaki forests.

All three forest sites assessed in this study were explicitly developed following the Miyawaki afforestation method. This included steps such as soil preparation with organic amendments, selection of diverse native species based on local ecological zones, high-density planting (3–5 saplings per $m^2$), excavation of planting pits to a depth of 0.5–1 m, mulching, and minimal post-establishment intervention following an initial maintenance period of approximately three years (Miyawaki, 1999; Miyawaki, 2004). Although the area of each plantation is relatively small (~ 600 $m^2$), such compact plots are characteristic of Miyawaki forests, particularly in urban settings where land availability is limited (Miyawaki, 2008; Moore, 2024). In fact, the Miyawaki method is uniquely suited to small-scale, high-density urban plantations and has been widely adopted in urban contexts across the globe for precisely this reason (Qi et al., 2024). These features distinguish the studied plots from conventional plantations and support their classification as Miyawaki forest stands, as also confirmed by the implementing actors who verified that standard Miyawaki protocols were followed.

### *2.2. Field data collection and measurement protocols*

#### *2.2.1. Soil sample collection*

In addition to collecting primary vegetation data in the forest sites, we conducted soil analyses to establish baseline information on current soil conditions, focusing on organic carbon, total nitrogen, and soil texture. Three soil samples were randomly collected from within each MwFS and three from adjacent non-forested areas, at two depths: 0–15 cm and 15–30 cm. The samples within each land-use types were thoroughly mixed to form composite samples. Field weights were recorded, following which the samples were air-dried and sieved through a 2 mm mesh to remove debris and roots.

#### *2.2.2. Tree structural data collection*

We documented tree structural data from the three MwFS locations in 2021 (Bengaluru) and 2022 (Palakkad). For both MwFSs in Bengaluru, we used 10 randomly placed 1 $m^2$ quadrats to record the diameter at breast height (DBH), height, and frequency (i.e., number of individuals) of each tree within the quadrats. The use of 1 $m^2$ quadrats was appropriate given the high density and structural complexity characteristic of these small-sized MwFSs. We ensured that all tree species present in the MwFS were represented in our measurements (Fig. 2). For the MwFS in Palakkad, trees were selected randomly, with at least five replicates per species for DBH and height measurements. A complete list of species is provided in *supplementary file S1*. Additionally, we recorded the total number of individuals per species across all three MwFS sites.

We measured the circumference of trees at breast height (~1.3 m above the ground) using a standard measuring tape, and tree height was recorded using a levelling staff. DBH was then calculated from the measured circumference values using simple circle formula (refer to Eq. (1)).

$$\text{DBH} = \text{Circumference at breast height}/\pi \tag{1}$$

### 2.3. Estimation of soil parameters, biomass, carbon storage and rates of carbon sequestration

To assess the current condition of soil organic carbon (SOC), we employed the Walkley-Black method (FAO, 2019), which involves the wet oxidation of organic matter using a dichromate solution. The percent SOC was calculated using the following formula (refer to Eq. (2)):

$$\text{SOC}(\%) = [(B - S) \times N \times 0.003 \times 1.33 \times 100]/\ \text{W} \tag{2}$$


**Fig. 2.** A summary of common species observed across the three Miyawaki forest sites in Kerala and Karnataka, India.

where:

$B$= Volume of ferrous ammonium sulfate used for blank (mL)
$S$= Volume of ferrous ammonium sulfate used for sample (mL)
$N$= Normality of ferrous ammonium sulfate
$W$= Weight of soil sample (g)
1.33= correction factor for incomplete oxidation of organic C

Nitrogen content was determined using the Kjeldahl method (Sáez-Plaza et al., 2013), which measures total nitrogen through acid digestion and distillation. Soil texture was analyzed using the Bouyoucos hydrometer method (Beretta et al., 2014), which estimates particle size distribution based on sedimentation rates in a suspension.

Tree dimensions (DBH and height)— recorded through field data— were used in species-specific allometric equations to estimate the AGB of each measured tree. These equations were sourced from published literature and the *GlobAllomeTree* database. When species-specific equations were unavailable, genus-level allometric equations were applied (refer to S1). Belowground biomass (BGB) was derived from AGB estimates using root-to-shoot ratios (RSR). Given the limited availability of species-specific RSR values, we adopted the standard RSR value of 0.5 (refer to Eq. (3)). This value corresponds to woodland/ savanna vegetation type as recommended by the IPCC's Good Practice Guidance for Land Use, Land-Use Change, and Forestry 2003 (Penman et al., 2003).

Accordingly, BGB was calculated using the formula:

$$\mathrm{BGB} = \mathrm{AGB} \times 0.5 \tag{3}$$

Total biomass (TB) was determined by summing AGB and BGB (refer to Eq. (4)):

$$\mathrm{TB} = \mathrm{AGB} + \mathrm{BGB} \tag{4}$$

Herbaceous vegetation is highly absent in Miyawaki sites, therefore, only tree species were considered in calculation. Further, we used bootstrapping to estimate total forest biomass (TFB) within each MwFS (refer to Eq. (5)):

$$TFB = \sum_{i=1}^{i=N} N_i \times B_i \tag{5}$$

Where $N$ is total number of unique tree species in a MwFS site, $N_i$ is number of trees belonging to i$^{th}$ species, and $B_i$ is biomass of a tree belonging to i$^{th}$ species coming from a bootstrap sample.

Bootstrapping is a statistical technique that involves repeatedly resampling a dataset to create many simulated samples— known as bootstrap samples— and is particularly useful when working with small sample sizes or unknown data distributions (Kreiss and Lahiri, 2012). The data for each of the three MwFS was then randomly resampled with replacement to generate new samples to calculate TFB as per Eq. (5). We repeated this process with 20,000 iterations to create a distribution of the confidence intervals, mean, median, and standard deviation of TFB for each of the three MwFS. By computational experiments with varying number of iterations, we finalized the number of iterations to be 20,000 because statistical estimates did not change by further increasing number of iterations.

TB is typically about 50 % carbon by dry weight (refer to Eq. (6)). This percentage can vary slightly based on the species and type of vegetation, but 50 % is a common approximation (Houghton et al., 2009). Therefore,

$$\mathrm{Carbon(Mg)} = \mathrm{TB} \times 0.5 \tag{6}$$

From TB, we first calculate carbon storage and then the carbon sequestration rate is calculated after dividing the above value with the age of the MwFS in Mg C/ha-yr. We used R (version 4.2.3; R Core Team) for statistical analyses and graphical representations.

### 2.4. Unlocking marginal lands: expanding Miyawaki forest development in India

This study analyzes land use and land cover (LULC) data from the National Remote Sensing Centre (NRSC) 2015 dataset (NRSC 2019 LULC report) to identify marginal lands across India based on LULC class characteristics. We estimated the potential marginal land suitable for future Miyawaki forest projects in areas with climatic conditions similar to those of our study sites (Sharma and Goyal, 2018). High-resolution Köppen-Geiger climate data from Beck et al. (2023) was used, with a 1 km resolution covering the period from 1991 to 2020. The data was clipped to focus on India, utilizing the India shapefile. The LULC and Köppen climate classification data were overlaid to identify marginal lands with potential for Miyawaki forest growth, exhibiting characteristics similar to those observed in the three study sites. Additionally, protected areas were excluded from the analysis using the protected area shapefile from Ghosh-Harihar et al. (2019) to determine the total available area for expanding Miyawaki forests.

## 3. Results

### 3.1. Baseline soil information for the three Miyawaki forest sites

Soil testing revealed that organic carbon levels were 1.3 % both inside and outside MwFS 1 in Palakkad. In Bengaluru, the organic carbon content was 1 % inside MwFS 2 and MwFS 3, compared to 0.8 % outside these forest sites (Table 2). In Bengaluru, nitrogen levels ranged from 0.09 % to 0.13 % inside the MwFSs 2 and 3 and were 0.07 % outside. In Palakkad, nitrogen levels were similar inside and outside the MwFS 1 but slightly higher (0.16 %) compared to the sites in Bengaluru (Table 2). Soil texture analysis revealed that the soils of MwFSs 2 and 3 in Bengaluru are predominantly sandy, with minimal silt and (higher than silt) clay content. In contrast, the soil of MwFS 1 in Palakkad is less sandy and contains higher proportions of clay and silt compared to the soils of MwFSs 2 and 3 in Bengaluru (Table 2).

### 3.2. Total biomass estimation in the Miyawaki forest sites

In this study, we estimated total forest biomass (TFB) for three MwFS sites of varying ages. The average TFB in Bengaluru's MwFS 3 (5 years old) was 19,850.42 kg (median= 19,850.08 kg; SD= 168.70 kg). For MwFS 2 (4 years old), the mean was 9619.95 kg (median= 9621.75 kg; SD= 174.26 kg). Palakkad's MwFS 1 (2 years old) had a mean TFB of 3381.76 kg (median= 3383.99 kg; SD= 107.78 kg) (Fig. 3).

Biomass accumulation showed a clear positive association with forest age. MwFS 3 had nearly six times the TFB of MwFS 1 and roughly

**Table 2**
Results of soil testing- Organic Carbon (OC), Nitrogen (N), and texture analysis.

| Site name | Average bulk density (g/cm$^3$) | Average organic carbon (%) | Average nitrogen (%) | Texture (Average values) | | |
|---|---|---|---|---|---|---|
| | | | | Clay (%) | Sand (%) | Silt (%) |
| *Palakkad*-MwFS 1 | 1.57 ± 0.02 | 1.327 ± 0.09 | 0.164 ± 0.02 | 24 ± 1.96 | 3.33 ± 1.16 | 72.67 ± 2.3 |
| *Palakkad*-outside MwFS 1 | 1.57 ± 0.02 | 1.317 ± 0.09 | 0.159 ± 0.02 | 24.67 ± 1.16 | 4 | 71.33 ± 1.16 |
| *Bengaluru*-MwFS 2 | 1.584 ± 0.27 | 1.08 ± 0.2 | 0.108 ± 0.03 | 18.67 ± 1.16 | 2 | 79.33 ± 1.16 |
| *Bengaluru*-MwFS 3 | 1.57 ± 0.64 | 1 ± 0.12 | 0.1 ± 0.09 | 16.67 ± 1.16 | 2 | 81.33 ± 1.16 |
| *Bengaluru*-outside MwFSs 2 and 3 | 1.68 ± 0.14 | 0.793 ± 0.07 | 0.072 ± 0.03 | 16 | 0.67 ± 1.16 | 83.33 ± 1.16 |

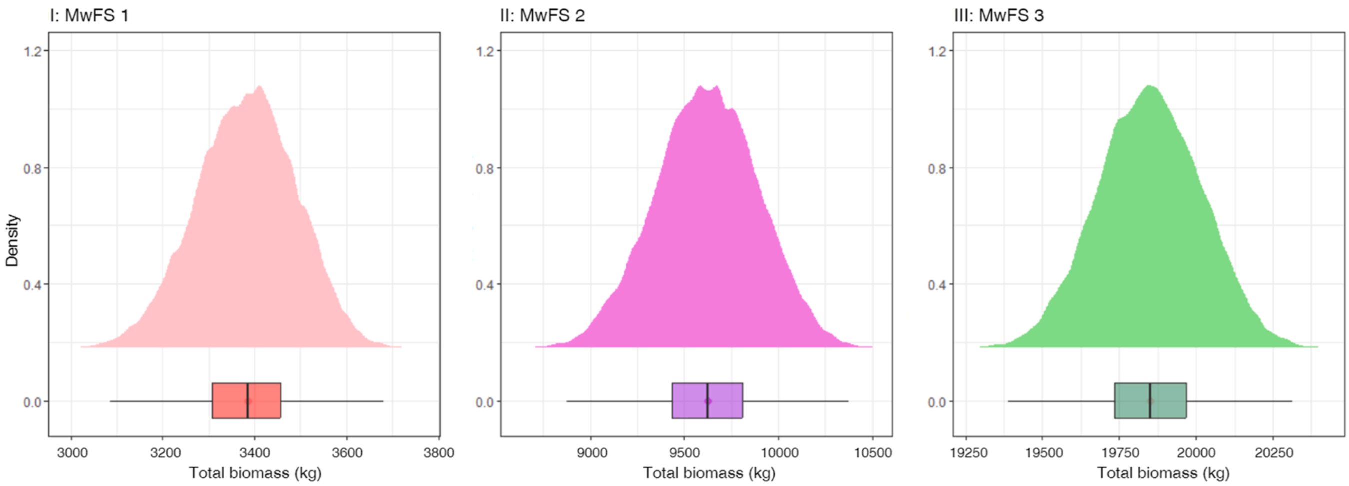


**Fig. 3.** Bootstrapped estimates of total forest biomass across three Miyawaki forest sites. Density curves (unitless) represent the distribution, with boxplots showing central tendencies.

double that of MwFS 2. These trends reflect the expected increase in biomass as forest stands mature and tree growth advances over time.

### *3.3. Carbon sequestration rates in Miyawaki forest sites across an age spectrum*

We estimated the current C stock and annual C sequestration rates in the standing biomass across the three MwFSs using TB calculations. This analysis focuses solely on aboveground biomass, as the short monitoring duration does not permit reliable assessment of changes in SOC, which typically require longer-term observation.

In the oldest site (MwFS 3; 5 years), the estimated C stock is 165.4 Mg C/ha. For MwFS 2 (4 years), the stock is 80.16 Mg C/ha, and in the youngest site (MwFS 1; 2 years), it is 10.57 Mg C/ha (Fig. 4A). This mirrors the trend observed in TFB, with C stock increasing markedly across the age gradient. Notably, MwFS 3 has more than twice the C stock of MwFS 2 and nearly 16 times that of MwFS 1. These differences suggest that substantial C accumulation occurs after the third year, likely due to accelerated growth and structural development as ecological succession progresses. The C stock in MwFS 2 is almost eight times higher than in the youngest site (MwFS 1), demonstrating that even a one-year difference in age results in a significant increase in C stock (Fig. 4A).

C sequestration rates, derived from C stock values, follow a similar trend (Fig. 4B). MwFS 3 sequesters carbon at 33.08 Mg C/ha-yr, approximately six times higher than MwFS 1 (5.28 Mg C/ha-yr), and about 1.6 times that of MwFS 2 (20.04 Mg C/ha-yr). MwFS 2, at 4 years, sequesters carbon at 20.04 Mg C/ha-yr— nearly four times that of the youngest site, MwFS 1. This indicates that as Miyawaki forests mature, C uptake accelerates, with a particularly steep increase occurring just after the early establishment phase.

### *3.4. Mapping potential areas for developing Miyawaki forests in India*

Building on the results on C stock and sequestration rates in MwFS, it can be rightly inferred that MwFS could be a potential nature-based solution to improve green cover in the light of climate change and land degradation.

We estimated that approximately 258,857.2 km$^2$ of marginal land, classified under a climate category similar to that of our MwFSs in Bengaluru and Kerala (as per the Köppen climate classification; Fig. 5), is available. This vast area of marginal land is either less productive or degraded and could potentially be utilized for the implementation of Miyawaki forests, without impacting natural ecosystems or land currently used for food production. Given the similarity in climatic conditions to the study sites, we anticipate that the temporal trends of biomass growth and C sequestration in biomass will mirror those observed in the MwFSs, making these areas suitable for Miyawaki forest plantations. However, it is important to note that site-specific ecological and edaphic factors—such as soil composition, nutrient availability,

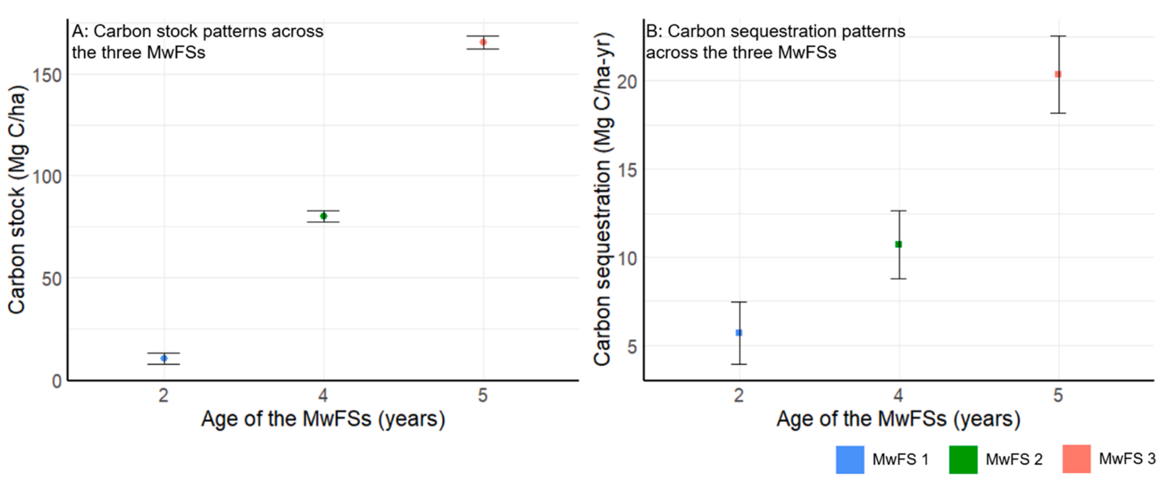


**Fig. 4.** Carbon stock and carbon sequestration rates across different age groups of Miyawaki forest sites (MwFS 1, MwFS 2, and MwFS 3).

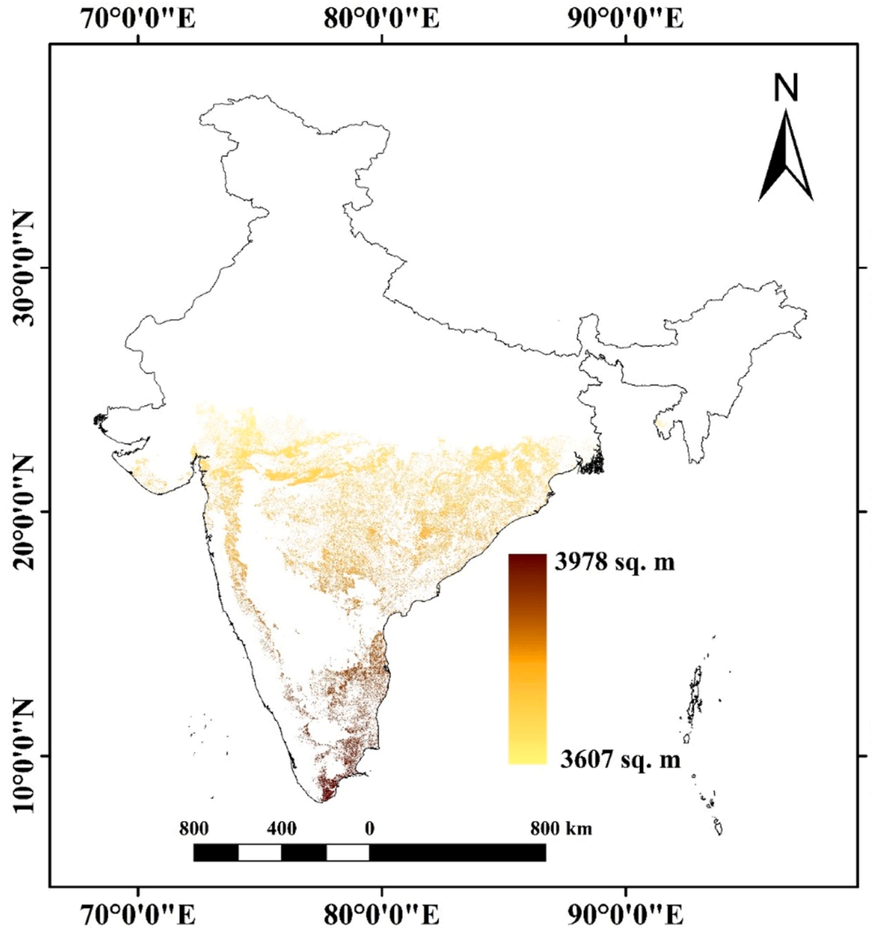


**Fig. 5.** Map of India showing potential marginal areas with Aw climate classification (Köppen system) suitable for Miyawaki projects—
The legend of map shows the area of pixels in which the bigger pixel the most south one has area 3967 square meter and the smallest 3607 square meter in that map.

water retention, local biodiversity, and even historic land use practices— can significantly influence the growth and success of these plantations. Therefore, a thorough assessment of these factors is essential before considering the implementation of Miyawaki forests in other areas. Expanding on this estimation, assuming that the C accumulation in biomass over a five-year period on the marginal land depicted in Fig. 5 would be comparable to our estimates (165.4 Mg C/ha), we project that approximately 4.28 billion Mg C could be sequestered in biomass alone over five years following the establishment of Miyawaki plantations. This estimate is derived from the calculation $165.4 \times 258{,}857 \times 100 = 4.28 \times 10\hat{}9$ (the factor of 100 is used to convert the area to ha).

## 4. Discussion

This study provides what is likely the first integrated quantitative assessment of biomass and C storage in three Miyawaki forest systems in peninsular India. By applying AGB-based allometric equations— a mathematically robust method for estimating C stored in tree biomass (Das et al., 2021; Habib and Al-Ghamdi, 2021; Gesta et al., 2023; Nyamukuru et al., 2023)—our results show that carbon stocks and sequestration rates increase substantially with forest age. This finding aligns with established patterns in other afforestation and reforestation efforts globally. For example, rapid C accumulation has been reported in early successional native species plantations in China's natural forests (Chen et al., 2013) and in similar tropical restoration efforts in other regions (Silver et al., 2000). Such parallels suggest that Miyawaki forests, though small in area, can perform comparably to larger afforestation models in terms of early-stage carbon gains. This underscores their potential as viable tools for enhancing carbon sinks, especially in fragmented or degraded urban and peri-urban landscapes in India and beyond.

The soil analysis suggests that site-specific edaphic conditions and pre-existing vegetation strongly influence early-stage soil responses in MwFS. In Palakkad, where grasses dominated prior to planting, comparable SOC levels inside and outside the forest plot point to legacy effects— grasses are recognized for their efficient carbon storage in root systems and upper soil layers (Jobbágy and Jackson, 2000). Conversely, in Bengaluru, the slight SOC enrichment within the MwFS may reflect nascent improvements in soil quality linked to afforestation, consistent with trends observed in other small-scale reforestation initiatives in degraded urban lands in China (Li et al., 2024). However, SOC changes tend to manifest slowly and often require a decade or more of monitoring to detect statistically robust trends (Poeplau et al., 2011). Similarly, nitrogen levels, a key determinant of plant productivity (Zheng, 2009), did not differ significantly between forested and non-forested patches, indicating that short-term plantation age or species composition has yet to significantly influence soil nutrient dynamics— an outcome reported in other Miyawaki forest plantations as well (Guo, 2018). These patterns were further shaped by soil texture: the sandy soils of Bengaluru likely limited organic matter retention, whereas the relatively higher clay and silt content in Palakkad may have supported greater microbial activity and nutrient stabilization (Six et al., 2002). Together, these results affirm that the initial site context can mediate early ecological benefits from Miyawaki forests.

In our study, all three MwFSs showed a positive correlation between forest age and carbon storage, though the rate of increase varied across locations. Notably, the 5-year-old Bengaluru site (MwFS 3) stored 165.4 Mg C/ha— nearly double that of the 4-year-old site (80.16 Mg C/ha) and markedly higher than the 2-year-old Palakkad site (10.57 Mg C/ha). These differences highlight the Miyawaki method's potential for rapid C sequestration within short timeframes. When contextualized within Indian forest types, our estimates closely align with tropical dry deciduous forests— the dominant type in our study regions. For instance, the C stock of the 4-year-old MwFS (80.16 Mg C/ha) is comparable to the 93.8 Mg C/ha reported for dry deciduous forests by Salunkhe et al. (2018). While considerably lower than the 607.7 Mg C/ha typical of tropical wet evergreen forests (Salunkhe et al., 2018), the stocks achieved within five years remain noteworthy, especially given the plantations' limited size and degraded starting conditions. The observed age-related increase in carbon storage mirrors global patterns, such as those seen in U.S. forests and the Chakaria Sundarbans in Bangladesh (Hoover and Smith, 2023; Ismail et al., 2025). These findings suggest that incorporating Miyawaki forests into degraded Indian landscapes could substantially contribute to national afforestation and ecological restoration goals.

In southeastern Vietnam, *Acacia mangium* plantations— an introduced species in that region (CABI, 2017)— exhibited a peak C sequestration rate of 11.56 Mg C/ha-yr in 7-year-old stands (Levan et al., 2020), whereas the 5-year-old MwFS 3 examined in this study reported a markedly higher rate of 33.08 Mg C/ha-yr. Even the 2-year-old MwFS 1 (5.28 Mg C/ha $yr^{-1}$) exceeds the rates observed in a 6-year-old tropical mixed-species plantation in Costa Rica (2.4–6.5 Mg C/ha-yr) (Shepherd and Montagnini, 2001). Such discrepancies may stem from differences in planting densities, site productivity, prior land-use histories, and bioclimatic conditions (Nave et al., 2019). Nevertheless, it is plausible that the defining characteristics of the Miyawaki method— particularly its emphasis on high-density, multi-layered, and native species assemblages— play a significant role in facilitating rapid early-stage biomass and C accumulation, likely through enhanced resource-use efficiency and complementary species interactions (Tilman et al., 1996).

The adaptability of Miyawaki forests to various ecological conditions has been demonstrated across Japan (Miyawaki, 1998), the Mediterranean (Schirone et al., 2011), and Belgium (de Brabandère and Malengreau, 2023). Building on this versatility, our spatial analysis identifies over 200,000 $km^2$ of marginal land in India that shares climatic parameters with our study sites, suggesting substantial potential for scaling this afforestation model nationally. This potential gain becomes more urgent when considered in the context of India's climate commitments— namely, the pledge to achieve net-zero carbon emissions by 2070 and reduce projected emissions by 1 billion Mg C by 2030 (Chaturvedi et al., 2024; Singh, 2022). Based on our estimates, if Miyawaki forests were deployed across these suitable marginal lands, they could sequester roughly 4280 million Mg C over five years, offering a significant contribution to national climate goals (Kurian and Vinodan, 2022). This aligns with ongoing national initiatives like the *Green India Mission* and the *Nagar Van Yojana*, which prioritize degraded land restoration and urban greening (Press Information Bureau, 2023a, 2023b). Moreover, India's commitment under the UNCCD to restore 26 million ha of degraded land and create 2.5–3 billion tonnes of additional carbon sinks by 2030 further supports the integration of Miyawaki afforestation into relevant policy frameworks (Press Information Bureau, 2024).

Although the findings are informative, the limited number of study sites ($n = 3$) may restrict the extent to which these results hold across other contexts. We did not include belowground or soil carbon measurements, due to their slower accumulation and the absence of baseline data. Additionally, biomass estimations based on a limited number of sampled trees per species and reliance on allometric models introduce uncertainty. Future research should expand site representation and include long-term monitoring of both above- and belowground carbon dynamics. Taken together, our findings offer compelling evidence that Miyawaki forests can be powerful tools for enhancing C sequestration in urban and degraded ecosystems. Their ability to sequester significant C within just 3–5 years, even with modest land areas, makes them especially attractive for climate mitigation and biodiversity enhancement in land-scarce contexts. The inclusion of native species also supports local ecological networks, making this approach not only carbon-efficient but also sensitive to local biodiversity.

From a practical standpoint, implementing Miyawaki forests requires substantial initial investment for seedling preparation and intensive early-stage maintenance (Miyawaki and Golley, 1993). However, these forests tend to become largely self-sustaining after the first two to three years and require minimal maintenance thereafter (Kurian, 2020; Akram et al., 2025). Based on insights from our study, we suggest several ways to optimize resource use and enhance ecological outcomes in Miyawaki forest projects, particularly in urban settings. For instance, the common practice of planting species of uniform age may constrain natural herbaceous recruitment and ecological succession. Introducing tree seedlings of varied ages could enhance vertical structure and microhabitat diversity, improving light and moisture distribution for understory vegetation. Selective pruning of branches in dense stands may further support ground-level biodiversity by increasing sunlight penetration, aiding seedling regeneration, and promoting litter decomposition. Enrichment with native herbaceous species, identified through surveys of nearby undisturbed habitats, can accelerate vegetative complexity by strengthening ground cover. When combined with pruning to improve light availability, such interventions can significantly enhance the establishment and persistence of understory layers. These enrichment efforts should prioritize species capable of self-propagation to promote long-term resilience. In addition, involving local communities in planting, early care, and monitoring can reduce costs while fostering stewardship. Together, such targeted strategies— when guided by site-specific baseline studies like ours— can help develop Miyawaki forests that are more biodiverse, adaptive, and cost-effective.

## 5. Conclusion

This study provides empirical evidence that Miyawaki forests, even at early stages of growth, can support considerable biomass accumulation and carbon sequestration. These results highlight their potential contribution to afforestation and climate mitigation efforts, particularly in ecologically degraded or underutilized lands. As such, the approach merits consideration within national and sub-national planning frameworks aimed at enhancing green cover and ecosystem services. However, the deployment of Miyawaki forests must be context-sensitive. Past experiences, such as tree planting in natural grasslands, underscore the risks of ecologically misaligned interventions. We therefore emphasize the importance of careful site selection, ecological assessment, and long-term monitoring in scaling such models responsibly.

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## Availability of data statements

The data is provided in the supplementary file S1.

## CRediT authorship contribution statement

**Anirban Roy:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Merlin Lopus:**

Writing – review & editing, Project administration, Methodology, Investigation, Data curation. **Sruthi Surendran:** Writing – review & editing, Software, Investigation, Formal analysis, Data curation. **Amit Kushwaha:** Writing – review & editing, Software, Resources, Investigation, Formal analysis, Data curation. **K.A. Sreejith:** Writing – review & editing, Resources, Project administration, Methodology, Investigation, Conceptualization. **K.C. Akhila:** Investigation, Data curation. **G. Anna:** Investigation, Data curation. **P. Saranga:** Investigation, Data curation. **N. Sethulakhsmi:** Investigation, Data curation. **Deepak Jaiswal:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Formal analysis, Data curation, Conceptualization.

## Declaration of competing interest

This study received partial funding from SayTrees NGO, and the fieldwork in Bengaluru was conducted in forest areas developed by them. The authors declare that the study's design, data analysis, and interpretation were carried out independently, without any involvement or influence from the funding organization.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2025.100925.

## Data availability

Data will be made available on request.

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