Species-wise Assessment of Above-Ground Biomass and Carbon Sequestration Potential in the Mangroves of Maharashtra, India

Satish Pardeshi [1], Manoj Chavan [1], Manish Kale [1], Manoj Khare [1], Nikhil Lele [2]

[1] *Centre for Development of Advanced Computing (C-DAC), Pune, Maharashtra, India*
[2] *Space Application Centre, Indian Space Research Organization (ISRO) Ahmedabad, India*

Abstract

Mangroves are highly productive ecosystems and are considered the largest potential sinks of atmospheric carbon. However, variability among species and communities significantly influences total carbon stock. This study evaluates the species-wise above-ground biomass (AGB) and carbon stock potential of mangrove species in Maharashtra, India, using primary field data from 44 geotagged plots. The available biomass equations were used to estimate the AGB and carbon at the plot level. Total carbon content was determined by multiplying per hectare AGB with the mangrove area for the 2018–19. Comparative assessment was carried out for the biomass and carbon between different mangrove species, class (dense and open) in the northern (Palghar, Thane, Mumbai, Raigarh districts) and southern zones of Maharashtra (Ratnagiri and Sindhudurg districts).

Out of 18 recorded species, *Avicennia marina* contributes the highest carbon stock per hectare (particularly in the dense plots of the northern zones) of more than 1500 t/ha, followed by *A. officinalis* and *Sonneratia apetala*. The lowest biomass was observed in Sonneratia alba (within open plots in the southern region) with values falling below 100 t/ha. The top 8 carbon-storing species together accounted for more than 90% of total estimated carbon.

Species contribution of the different mangrove species to the average carbon stock in the northern zone was in the order of. *Avicennia marina* > *Avicennia officinalis* > *Sonneratia apetala,* and in the southern zone it was broadly *Avicennia officinalis* > *Lumnitzera racemosa* > *Excoecaria agallocha*.

The biomass recorded was specific for each mangrove species, which may be attributed to adaptabilities of these species to environmental variables. The accumulation of biomass is primarily influenced by species, wood density, age of tree, climate, management regime, proximity to water channel, and nutrient sediment that supplement mangrove productivity (Kairo et al., 2008; Fatoyinbo et al., 2008).

This study confirms significant inter-species variability in carbon sequestration potential among mangrove species in Maharashtra. Species such as *Avicennia marina* and *A. officinalis* should be prioritized in restoration projects for maximizing carbon benefits.

Keywords: Mangrove, AGB, Biomass, Carbon stock, Maharashtra, Species-wise comparison, Remote sensing

1. Introduction

Mangrove forests are intertidal, salt-tolerant ecosystems distributed across tropical and subtropical coastlines. Occupying approximately 14 million hectares globally, they represent a small fraction of Earth's land area, yet play a disproportionately significant role in coastal stability, biodiversity support, and carbon sequestration (Wang et al., 2021a; Zhu & Yan, 2022). Mangroves are among the most carbon-dense natural systems, contributing to nearly 5% of global terrestrial carbon sequestration while covering only 0.1% of land area (Donato et al., 2011; Bouillon et al., 2008).

These ecosystems are key components of the "blue carbon" framework, which includes seagrasses and salt marshes, and are recognized for their capacity to sequester and store large quantities of atmospheric CO_2 in both biomass and sediments (Alongi, 2012; McLeod et al., 2011; Choudhary, 2024). Carbon is stored in living biomass (above- and below-ground), detrital material (e.g., deadwood, litter), and in long-term sediment pools, which can retain organic carbon over millennial timescales (Howard et al., 2017b). Among coastal ecosystems, mangroves are particularly effective carbon sinks, with sequestration rates exceeding those of many terrestrial biomes (Daniel et al., 2020; Duarte et al., 2013a).

Estimates suggest that mangroves may sequester up to 1,000 metric tons of carbon per hectare during peak growth periods (Zhu & Yan, 2022). Despite accounting for only 1% of the world's coastal areas, they store approximately 15% of the organic carbon in coastal sediments (Siikamäki et al., 2012a; Kandasamy et al., 2021). Globally, blue carbon ecosystems store approximately 11.5 billion tons of carbon, with mangroves contributing nearly 6.5 billion tons — the highest among blue carbon habitats (Siikamäki et al., 2012a).

India contributes approximately 3% of the global mangrove cover, with an estimated area of 4,639 km² (FAO, 2007; FSI, 2009). Despite this extent, comprehensive evaluations of ecosystem-level carbon stocks remain limited across Indian states. Maharashtra, with a 720 km-long coastline, supports one of the most ecologically diverse and spatially extensive mangrove systems along the west coast, covering nearly 320 km² (FSI, 2021). These mangroves are distributed across the districts of Mumbai, Raigad, Thane, Ratnagiri, and Sindhudurg, often occupying narrow estuarine corridors interspersed with mudflats and creeks.

Historical pressures from rapid urbanization, land reclamation, and industrial discharge have significantly altered mangrove landscapes, particularly in urban centres like Mumbai and Navi Mumbai. Nevertheless, Maharashtra still retains high species diversity, dominated by *Avicennia marina*, *Rhizophora mucronata*, and *Sonneratia alba*. These species exhibit differences in biomass accumulation and adaptability to salinity and tidal regimes, thereby influencing carbon sequestration potential at zonal scales. In recent years, mangrove conservation in Maharashtra has gained momentum through afforestation efforts, remote sensing–based monitoring by the Forest Department, and collaborations with scientific institutions such as ISRO and SAC. However, detailed information on species-specific biomass, carbon density, and disturbance-linked variability remains scarce, limiting the development of high-resolution blue carbon models for the region.

Aboveground biomass (AGB) is a critical variable for estimating carbon storage and evaluating the ecological function of mangrove forests (McLeod et al., 2011; Luo & Chui, 2020). However, biomass accumulation is highly variable and influenced by multiple factors including tree growth rates, diameter at breast height (DBH), age, and site-specific edaphic and climatic conditions (Sillanpää et al., 2017; Kamruzzaman, 2018; Bai et al., 2020). Soil nutrient status, particularly nitrogen availability, also contributes to site-level variation in biomass and carbon sequestration potential (Bai et al., 2020).

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Species composition and biodiversity further regulate ecosystem functioning. High-diversity systems have been linked to greater biomass and higher carbon storage, attributed to niche complementarity and enhanced productivity (Duffy, 2009; Isbell et al., 2015). Growth rates of mangrove species also vary with geomorphic settings, with riverine and interior zones often supporting faster-growing individuals than fringing areas (Krauss et al., 2007). At regional scales, climatic factors such as dry-season precipitation modulate growth and carbon storage, with larger individuals contributing disproportionately to biomass (Xiong et al., 2019). In addition to species-specific variation, anthropogenic drivers such as land use change can substantially impact mangrove carbon stocks and long-term sequestration potential (Murdiyarso, Sasmito, & Friess, 2020).

Despite the importance of species-specific responses, few studies have quantitatively compared biomass and carbon storage across different mangrove species. For instance, Kamruzzaman (2018) observed that *Rhizophora stylosa* accumulated more biomass than *Bruguiera gymnorrhiza* and *Kandelia obovata* in Okinawa's Manko Wetland. Similarly, Komiyama et al. (2008) found that *Rhizophora apiculata* exhibited higher aboveground biomass compared to *Sonneratia caseolaris* and *Bruguiera parviflora* in Thai mangrove stands. In another regional study, Wang et al. (2013) demonstrated species-based variation in carbon accumulation among dominant mangroves of *Kandelia*, *Avicennia*, and *Bruguiera* in southern China, with *Avicennia marina* showing lower biomass but higher adaptability under saline conditions. Such findings highlight the need for species-level evaluations to improve estimates of carbon potential and inform conservation and restoration strategies.

While field-based biomass assessments are fundamental for building accurate allometric models and understanding site-specific variation, they are often constrained by the logistical difficulties of working in intertidal zones. Mangrove fieldwork is physically demanding and time-intensive due to the presence of soft, muddy substrates, tidal fluctuations, and dense vegetation, all of which complicate access and data collection (Gao, 1999). Conventional quadrat sampling in such environments increases both labour and cost. In this context, remote sensing has emerged as a powerful tool for biomass estimation and forest monitoring. Its advantages—including wide spatial coverage, repeatability, and adaptability to inaccessible or degraded areas—make it particularly suitable for assessing mangrove structure and carbon storage across large scales (Navarro et al., 2019; Hamdan et al., 2014; Guo et al., 2021; Ibharim et al., 2015; Jayanthi et al., 2018; Kovacs et al., 2008; Le et al., 2020; Liao et al., 2019; Tian, 2022). The integration of remote sensing with field data enhances the efficiency and accuracy of biomass estimation, particularly in dynamic and heterogeneous landscapes such as mangroves.

A recent study in the mangrove forests of Maharashtra (Pardeshi et al., 2024) examined species zonation patterns and highlighted spatial variation in species dominance. These patterns are hypothesized to be key drivers of variability in aboveground biomass and carbon sequestration. The present study addresses this critical gap by evaluating species-level variations in aboveground biomass and carbon stock across northern and southern mangrove zones of Maharashtra. By integrating field-based observations from 44 georeferenced sample plots with ecological stratification (dense vs. open canopy), this study contributes to region-specific baselines for blue carbon accounting and ecosystem service valuation.

This study is part of a larger research effort on mangrove carbon dynamics in Maharashtra, India. While earlier work by Pardeshi et al. (2024) provided an ecosystem-scale assessment of above-ground carbon pools across major estuarine zones, the present study focuses on the species-level variation in biomass and carbon stock to identify dominant contributors and ecological patterns.

2. Study area

The present study was carried out along the west coast of Maharashtra, India, extending between 15°45′N and 20°00′N latitude and 68°00′E to 73°30′E longitude. This coastal belt spans approximately 720 kms and encompasses six maritime districts: Palghar, Thane, Mumbai, Raigad, Ratnagiri, and Sindhudurg (FSI, 2021; Pardeshi et al., 2024). These districts are home to a mosaic of estuarine systems, tidal creeks, and intertidal wetlands that support extensive yet fragmented mangrove habitats across 44 estuarine complexes.

The coastline is typified by both rocky and sediment-rich shores, with basaltic outcrops particularly evident in the southern districts. Mangrove vegetation in this region tends to occur in narrow corridors flanking creeks, estuaries, and backwaters, often bordering reclaimed land, aquaculture areas, or urban-industrial zones. This has made certain mangrove patches—especially those in and around Mumbai and Navi Mumbai—vulnerable to degradation due to encroachment, pollution, and altered hydrology.

The region experiences a tropical monsoon climate, with annual rainfall ranging between 2,000–3,500 mm and mean temperatures from 22°C to 32°C, creating suitable conditions for mangrove productivity (Harishma et al., 2020; IMD, 2018). However, the geomorphic and anthropogenic variations across zones result in distinct ecological settings that influence mangrove distribution and structure. Seasonal rainfall, salinity gradients, tidal flushing, and sedimentation rates play a key role in shaping biomass patterns and species composition along this coastal gradient.

3. Materials and methods

3.1 Remote Sensing and Mapping of Mangrove Extent

To assess mangrove extent and estimate above-ground carbon sequestration, a multi-source remote sensing approach was adopted, following the methodology outlined in Pardeshi et al. (2024). The primary dataset consisted of IRS P6 LISS IV imagery acquired during low tide conditions for the year 2018–19. These images included a synthetic shortwave infrared (SWIR) band, which helped enhance the spectral separation between mangrove and non-mangrove vegetation. Mangrove canopy classes—categorized as dense (>40% canopy cover) and open (10–40%) were delineated using on-screen visual interpretation at a 1:25,000 scale, based on tone, texture, shape, and spatial association (Lillesand et al., 2015).

Atmospherically corrected Sentinel-2 imagery (2018–19) at 10-meter resolution was used to develop spectral response models and derive an empirical per-pixel biomass estimation framework. For preprocessing of IRS imagery, the SACRS2 atmospheric correction software developed by the Space Applications Centre (ISRO) was used to convert raw digital numbers into surface reflectance and to integrate the synthetic SWIR band (Pandya et al., 2014; Rout et al., 2019).

In addition to these datasets, Landsat-8 OLI imagery (30 m resolution) from the same period was used for cross-validation of classified outputs. This allowed for consistency checks across spatial resolutions. To improve classification accuracy in visually complex or ambiguous areas, multi-date high-resolution Google Earth Pro images were referenced for the separation of closely associated land cover types, such as salt marshes, orchards, and degraded zones (Google, 2022).

Ground-truth data from field investigations, along with visual interpretation from satellite images, supported the identification of mangrove communities. In total, 20 true mangrove species and 95 associated plant taxa were recorded (Supplementary Material 1, Pardeshi et al. (2024)). These were organized into 32 distinct mangrove communities based on dominant species composition, which were then homogenized into two canopy density categories viz. dense and open, for the final 2018–19 mangrove extent map.

3.2 Field Investigation and Ground Truth

Field investigations were conducted between October 2019 and October 2022 to support ground truthing, classification validation, and species-level biomass estimation. A total of 44 fixed-area sample plots, each measuring 0.1 hectares (30 m x 30 m), were laid across the mangrove zones of Maharashtra. This corresponded to approximately 0.01% of the total mangrove area (376 km²), surpassing the minimum requirement of 38 plots for representative sampling.

The selection of ground plots was guided by image-based parameters such as tonal and textural variability, proximity to the coast, salinity gradients, freshwater availability, and geomorphological diversity. Plot locations were deliberately chosen to represent the full range of spectral and ecological variability, including species associations, canopy conditions, and landscape features.

At each site, the centre tree (C1) was marked with a metal tag with the help of galvanized string, and the plot corners were labelled as C2 through C5. A complete floristic inventory of all mangrove trees, shrubs, and herbs within each plot was undertaken. In cases of taxonomic uncertainty, high-resolution photographs were taken and species identification was confirmed in the laboratory.

All mangrove trees ≥10cm in girth within the plots were identified to species level and measured for height (m) and circumference at breast height (CBH in cm) using a measuring tape to the nearest centimetre. Visual indicators of disturbance such as grazing, lopping, or fire were recorded. Observations on vegetation type and structure, density were also documented in situ.

The preliminary mangrove extent map was field-validated across both dense and open canopy classes. More than 500 waypoints were collected throughout the mangrove landscapes using GPS, with associated attributes on vegetation condition, class, and land use. These waypoints were later used for post-classification accuracy assessment and final map correction, ensuring consistency between remote sensing interpretation and field observations.

3.3 Biomass and Carbon Pool Estimation

Aboveground biomass (AGB) estimation was conducted using field data collected from 44 georeferenced sample plots. Circumference at breast height (CBH), measured at 1.37 meters above ground, was converted to diameter at breast height (DBH) using the formula: $DBH = CBH/\pi$

Tree Above-ground biomass (AGB) was estimated following the approach of Pardeshi et al. (2024), where species-specific allometric equations compiled from the literature were applied (Table 1 in Pardeshi et al., 2024).

In cases, where species-specific equations were not available, generalized available equations were used for the estimation of carbon stocks across diverse mangrove species. Wood density values (ρ) for individual species were sourced from the World Agroforestry Centre's Global Wood Density Database (Chave et al., 2009).

The biomass per tree was estimated and then summed for each plot to calculate total biomass per plot. These values were converted to tons per hectare and averaged across all plots to obtain the mean aboveground biomass (AGB) for the study area. In line with the IPCC (2006) guidelines, aboveground carbon stock (Cag) was estimated by applying a standard carbon conversion factor of 0.5, assuming that 50% of the dry biomass constitutes carbon. The final carbon stock estimates are reported in units of tons of carbon per hectare (t C ha^{-1}).

The carbon stock was estimated using the equation $Cag = 0.50\ Wag$ (where Cag is the above-ground carbon stock, and Wag is the AGB) (Brown, 1997; Petersson et al., 2012).

Belowground biomass was not included in the present analysis, as the study focused solely on species-specific aboveground carbon pools. Understory components such as seedlings, herbs, and litter were also excluded due to their minimal contribution in mature mangrove systems and their spatial discontinuity (Kauffman & Donato, 2012; Vinod et al., 2018).

3.4 Data analysis

Data processing and analysis were conducted to quantify aboveground biomass (AGB) and carbon stock at the species level. Field data from 44 georeferenced sample plots were first compiled and cleaned. For each tree, AGB was calculated using species-specific or generalized allometric equations, and then converted to aboveground carbon stock using the factor 0.5 (IPCC, 2006; Brown, 1997).

Species-wise aggregations were computed to obtain:

a. Total and mean AGB (t /ha),
b. Corresponding carbon stock (t C/ ha),
c. Number of individuals per species,
d. Biomass and carbon (t/ ha) in Dense and Open canopy classes
e. Biomass and carbon (t/ ha) in Northern zone (Palghar, Thane, Mumbai, Raigarh districts) and Southern zone (Ratnagiri and Sindhudurg districts

To normalize biomass and carbon estimates per unit area, plot-level values were scaled to hectares and averaged. This allowed comparison of species-specific carbon contributions across the entire study area.

Each sample plot was assigned to a zone (North or South) and canopy class (Dense or Open), allowing comparative analysis of species-wise biomass and carbon stock across ecological gradients. Descriptive statistics and spatial summaries were computed using Microsoft Excel.

Descriptive statistics and exploratory visualizations were used to evaluate patterns in species dominance and carbon potential. Species were ranked by total carbon stock per hectare to highlight the most efficient carbon-sequestering taxa.

Species contributing >80% of the total carbon pool were flagged for further ecological interpretation. Carbon-rich species identified from this analysis informed the zonation-based biomass mapping and potential conservation priorities.

4. Results and Discussions

The interpretation of derived map revealed that total mangrove area in the Maharashtra state in the year 2018–19 was 376.13 km^2. Total mangrove area under dense (density > 40%) and open mangroves (density < 10–40%) forests in the year 2018–19 was 210.50 km^2 and 165.71 km^2, respectively (Pardeshi et al., 2024)

To further understand spatial variability, biodiversity metrics were also evaluated for study area and separately for the northern and southern zones. These zone-wise indices—such as species richness, Shannon diversity, Simpson dominance, and evenness—are useful for comparing habitat quality and species distribution across the latitudinal gradient. This approach confirms significant ecological contrasts between zones, influenced by site conditions, species assemblages, and canopy composition.

4.1 Species Composition and Tree Abundance

A total of 15 true mangrove species were recorded across 44 georeferenced sample plots**,** representing a wide range of floristic diversity. Species Composition of Mangrove Forests in Maharashtra (%) are presented in Table 1.
The most frequently encountered species was *Avicennia marina*, accounting for approximately 39% of all recorded individuals (n = 1,716). Other commonly observed species included *Excoecaria agallocha* (n = 556), *Sonneratia alba* (n = 532**)**, and *Rhizophora mucronata* (n = 529), indicating their widespread occurrence across the sampling plots.
The largest girth was recorded for *Avicennia officinalis*, with a maximum girth at breast height (GBH) of 256 cm, and a mean GBH of 56.69 cm across 207 individuals. This was followed by *Sonneratia apetala*, which exhibited a maximum GBH of 251 cm and an average of 58.17 cm across 228 individuals.
Although *Heritiera littoralis* was restricted to a few plots in the southern zones, some individuals exhibited substantial stem girth, with a maximum GBH of 176 cm. However, the average girth for this species remained relatively low at 18.86 cm, based on measurements from 56 individuals.

4.2 Species Structure and Importance Value Index (IVI)

The species composition of mangrove forests in the study area revealed notable dominance patterns across the sampled plots. Structural metrics including density (trees per hectare), frequency, basal area, and the composite Importance Value Index (IVI) were calculated for each species to assess their ecological significance (Table 2).

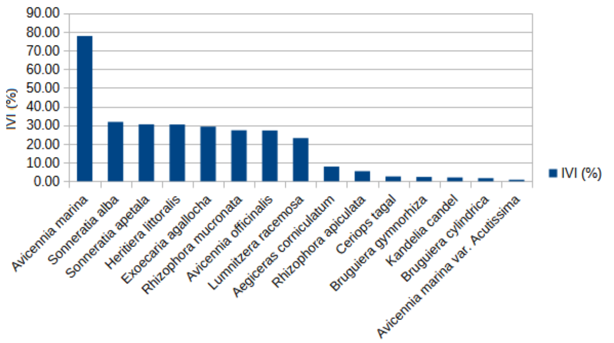

Figure 1: Importance Value Index (IVI) ranking of Mangrove species in Maharshtra

Among the recorded species, *Avicennia marina* emerged as the most structurally dominant, with the highest density of approximately 681 trees/ha, and an IVI score exceeding 77%. It was present in 28 out of 44 plots, indicating both widespread distribution and high abundance. Its dominance was also reflected in a substantial share of the total basal area, contributing significantly to stand-level carbon stock (Figure 1).
Sonneratia alba ranked second, showing high IVI value with 32% and occurring in 13 plots with 532 individuals having relative density of 12%, lower than *A. marina*. On other hand *Rhizophora mucronata* and *Avicennia officinalis* with relative frequency of 13% and 12 % were present in 17 and 16 plots respectively and IVI of 27% each.
Sonneratia apetala also exhibited strong relative dominance, particularly in the southern estuarine sites, where it contributed large individual basal areas despite being recorded in fewer plots. Other species such as *Heritiera littoralis* and *Lumnitzera racemosa* displayed more localized dominance patterns occurring in few plots in south zone only. In particular, *Heritiera littoralis*, despite its limited occurrence, contributes significantly to basal area and dominance due owing to its large stem girth and mature tree structure.
Excoecaria agallocha and *Avicennia officinalis* show balanced structure and presence, with IVIs above 25%, marking them as ecologically important.
The analysis of species diversity using the dataset from 44 mangrove plots revealed that the Shannon diversity index (H') was calculated at **1.85**, indicating moderate diversity, while the Simpson index (D) was **0.786**, suggesting high species heterogeneity and low dominance. The Evenness value of **0.685** implies a moderately equitable distribution of individuals among species. The most frequently occurring species was *Avicennia marina* (1716 individuals), followed by *Excoecaria agallocha, Sonneratia alba and Rhizophora mucronata.* These metrics provide the structural complexity of Maharashtra's mangrove ecosystems and serve as ecological indicators of habitat quality.

4.3 Mangrove Species by Above-Ground Biomass and Carbon Stock

Table 3 shows the total and average Biomass, total and average Carbon with per t/ ha Biomass and Carbon values for mangrove species observed in all 44 plots in both zones across both classes of canopy (Table 3).
Although *Heritiera littolaris* showed highest biomass of 119.53 t/ha, it was observed only at one location in a limited area during field investigations. *Avicennia marina* showed biomass of 62.93 t/ha and was predominantly observed in the study area appearing in 28 plots. *Avicennia officinalis* and *Sonneratia apetala* with 56.58 t/ha and 32.86 t/ha were observed distributed in the study area. *Lumnitzera racemosa* found with numerous individuals (n = 492) was mostly observed in shrubby form with average girth of 21.45 cm, hence exhibit biomass of 18.06 t/ha.
Out of 15 recorded species, *Avicennia marina* dominated with 1716 individuals and an average biomass of 92.41 kg/tree, resulting in a carbon density of 31.46 t C/ha. *Avicennia officinalis* followed with 28.29 t C/ha, and *Sonneratia apetala* with 16.43 t C/ha. The top 8 carbon-storing species together accounted for more than 90% of total estimated carbon.

4.4 Zonal comparison of biomass and carbon estimation by mangroves species

4.4.1 Biomass and carbon estimation in North and South zone

The total and average Biomass, total and average Carbon with per t/ ha Biomass and t/ ha Carbon values for mangrove species were compared with respect to North and south zones of Maharashtra (Table 4 & 5).
Among the different mangrove species highest biomass of 78.5 t/ ha was observed for *Avicennia marina* in the North zone followed by *Avicennia officinalis* (36.89 t/ ha) and *Sonneratia apetala* (35.61 t/ ha) In the southern zone *Heritiera littoralis* showed highest biomass of 119.56 t/ ha followed by *Avicennia officinalis* (63.15 t/ ha) and *Lumnitzera racemosa* (20.30 t/ ha). *Rhizophora apiculata* showed least biomass of 0.23 t/ ha in northern zone and *Bruguiera gymnorhiza* with 1.33 t/ ha in southern zone.

4.4.2 Canopy class comparison

The total and average Biomass, total and average Carbon with per t/ ha Biomass and t/ ha Carbon values for mangrove species were compared with respect to Dense and Open canopy classes of North and south zones of Maharashtra (Figure 2).

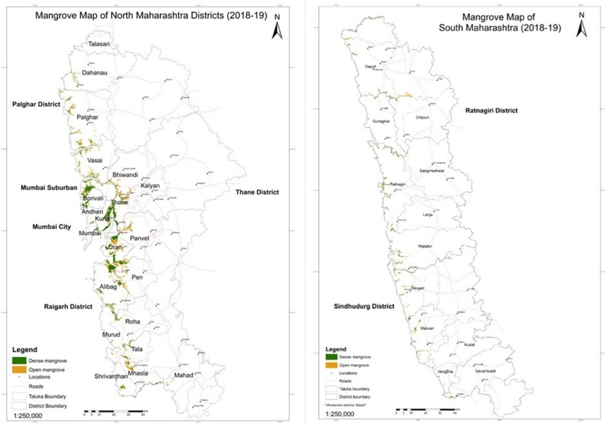

Figure 2: Dense and Open class of Mangrove in the North and South zones of Maharashtra

Table 6 exhibit species wise average and sum biomass (kg), average and sum Carbon (kg) and per t/ ha Biomass and Carbon values for North zone with Dense canopy plots (Table 6).
In the Dense canopy class of North zone, *Avicennia marina* was the largest contributor with biomass of 85.38 t/ ha, followed by *Avicennia officinalis* and *Sonneratia apetala* with 47.62 t/ ha and 30.18 t/ ha respectively.
Table 7 exhibit species wise average and sum biomass (kg), average and sum Carbon(kg) and per t/ ha Biomass and Carbon values for North zone with Open canopy plots (Table 7).
Major contributor in the Open class in the North zone was *Sonneratia apetala* with 60.04 t/ ha followed by Avicennia marina with 34.94 t/ ha. *Sonneratia apetala* is major contributor due to the presence of large population of it in the Raigarh district and along the open narrow riverine patches. Contribution of other species are negligible in the open forest of north zone.
Table 8 exhibit species wise average and sum biomass (kg), average and sum Carbon(kg) and per t/ ha Biomass and Carbon values for South zone with Dense canopy plots (Table 8).
The Dense canopy class of South zone of Maharashtra shows much diversity with *Avicennia officinalis* dominating in most areas. The recorded biomass of *A. officinalis* 68.90 t/ ha. *Heritiera littolaris* with 119.56 t/ ha has the highest per ha contribution. Other species includes *Lumnitzera racemosa* and *Excoecaria agallocha* recorded moderate biomass with 13.22 t/ ha and 12.68 t/ ha respectively.
Table 9 exhibit species wise average and sum biomass (kg), average and sum Carbon(kg) and per t/ ha Biomass and Carbon values for South zone with open canopy plots (Table 9).
The open canopy class of South zone of Maharashtra is dominated by *Avicennia officinalis* and *Lumnitzera racemosa* with recorded biomass of 51.62 t/ ha and 48.64 t/ ha respectively. *Excoecaria agallocha* recorded moderate biomass contribution of 16.47 t/ ha. *Avicennia marina* which is dominant in the northern zone has negligible contribution along with *Sonneratia alba* and *Rhizophora apiculata* and *R. mucronata.*
The southern zone plots—especially those classified as open—had noticeably lower biomass per hectare, typically below 55 t/ha, indicating regional variation influenced by environmental and anthropogenic factors. These patterns highlight the species- and zone-specific biomass dynamics that are essential for carbon modelling, restoration prioritization, and climate mitigation policies.
Among the mangrove species assessed, the highest biomass of 85.38 t/ha was recorded for *Avicennia marina*, particularly in the dense plots of the northern zone of Maharashtra. This species contributed significantly to the above-ground carbon pool due to its high abundance and favourable site conditions. In contrast, the lowest biomass was observed in *Sonneratia alba* within open plots in the southern region, with values falling below 1 t/ha.
Plots categorized as dense consistently recorded higher biomass and carbon values than their open canopy counterparts. In the northern zone, *Avicennia marina* and *Sonneratia apetala* showed the highest productivity, while in the southern zone, *Avicennia officinalis* remained dominant. The lowest species-level biomass was observed for *Avicennia marina* and *Sonneratia alba*, particularly in open southern plots.
Heritiera littoralis exhibited the highest average biomass per individual, despite having low density, suggesting its high structural mass and wood density. Similarly, *Excoecaria agallocha* and *Rhizophora mucronata* had moderate biomass per tree but contributed substantially to zone-level totals due to their consistent occurrence.

4.5 Comparison with Other Regional Studies

Several international studies align with the findings of the present work. For example, Donato et al. (2011) observed mature Indo-Pacific mangroves to frequently exceed 140 t/ha of aboveground biomass, while Kauffman et al. (2011) documented values ranging from 75 to over 250 t/ha in Micronesian mangrove forests. The species *Avicennia marina* is consistently identified as major carbon contributor across Southeast Asia, similar to the species dominance observed in Maharashtra.
The results of this study are consistent with other regional mangrove biomass and carbon assessments conducted across India. For instance, Harishma et al. (2020) in Kerala reported *Avicennia marina* with a maximum biomass of 162.18 t/ha and a carbon stock of approximately 81.09 t C/ha, In the present study, the biomass of *Avicennia marina* reached as high as 85.38 t/ha in dense northern plots, reflecting high structural maturity and favorable growth conditions.
The current species-specific analysis reveals significantly higher contributions by a few dominant taxa in localized zones. This suggests that while broader assessments provide landscape-level averages, species-level studies are essential to capture high-performing taxa and ecological outliers.
The observed diversity indices in this study (Shannon: 1.877; Simpson: 0.212) are also aligned with findings from Kerala and Sundarbans, confirming moderate to high biodiversity and low dominance. This ecological consistency across coastal zones underscores the reliability and robustness of the applied field and analytical protocols.

5. Conclusion

This study provides a detailed evaluation of species-level contributions to above-ground biomass and carbon stocks within the mangrove ecosystems of Maharashtra. By integrating field-based inventories with ecological stratification, we observed clear patterns in species dominance, structural biomass distribution, and carbon storage potential.
Avicennia marina emerged as the most dominant and productive species across the study area, followed by notable contributors such as *Avicennia officinalis*, *Sonneratia apetala*, and *Heritiera littoralis*. Plots with dense canopy cover—especially in the northern estuarine zones—showed consistently higher biomass and carbon values, underscoring the importance of forest structure in regulating carbon dynamics.
The calculated Importance Value Index (IVI), which combines relative density, frequency, and dominance, revealed a skewed community composition, with *A. marina***,** *Sonneratia alba*, and *Sonneratia apetala* together accounting for over 140% of the total IVI. This dominance pattern highlights the ecological

plasticity and adaptability of a few key taxa in shaping the structure and function of Maharashtra's mangrove forests.

Moderate to high species richness and evenness were also observed across several estuarine zones, reflecting relatively balanced community structures in parts of the landscape. These results reinforce the dual ecological and climate-regulating value of Maharashtra's mangroves, particularly in the context of targeted restoration, conservation, and blue carbon initiatives.

Species-specific carbon contributions also revealed some unexpected insights. *Heritiera littoralis*, though less abundant, demonstrated high per-tree biomass, pointing to its potential role in long-term carbon accumulation. Despite its limited use in large-scale restoration due to propagation challenges, its high biomass suggests value in strategic plantation efforts aimed at maximizing carbon sequestration.

Zonal comparisons indicated that northern districts such as Raigad and Thane retain greater structural integrity and biomass density than the more fragmented mangroves in the southern coast. These differences likely reflect a combination of disturbance regimes, sediment dynamics, and creek morphology. Hence, restoration and management strategies should be spatially differentiated to address zone-specific ecological pressures.

The species-level biomass and carbon estimates presented in this study align with the range reported in earlier ecosystem-scale assessments for Maharashtra. The high per-hectare carbon density observed for *Avicennia marina*—especially in dense plots—is consistent with those findings, reaffirming the reliability of field-based methods and species-specific biomass models.

Overall, this study underscores the importance of incorporating species-level data into blue carbon accounting and mangrove management frameworks. A deeper understanding of species-specific growth patterns and carbon potential not only strengthens ecological baselines but also informs more effective, targeted conservation and restoration planning.

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Appendix

Table 1 Species Composition of Mangrove Forests in Maharashtra (%)

Row Labels	Percentage by no. of individual
Acivennia marina	38.95
Excoecaria agallocha	12.62
Sonneratia alba	12.07
Rhizophora mucronata	11.78
Lumnitzera racemosa	11.17
Sonneratia apetala	5.17
Avicennia officinalis	4.70
Heritiera littoralis	1.27
Aegiceras corniculatum	0.93
Rhizophora apiculata	0.52
Bruguiera gymnorhiza	0.30
Kandelia candel	0.25
Ceriops tagal	0.20
Bruguiera cylindrica	0.05
Avicennia marina var. Acutissima	0.02

Table 2 Species Structure and Importance Value Index (IVI)

Species name	Density trees/ha	Relative Density (%)	Frequency	Relative Frequency (%)	Basal Aream^2	Dominance (m^2/ha)	Relative Dominance (%)	IVI (%)
Avicennia marina	680.95	38.95	0.64	21.05	24.47	9.71	17.77	77.77
Sonneratia alba	454.70	12.07	0.30	9.77	6.35	5.43	9.94	31.79
Sonneratia apetala	211.11	5.17	0.27	9.02	9.61	8.90	16.29	30.49
Heritiera littoralis	622.22	1.27	0.02	0.75	1.40	15.50	28.38	30.40
Excoecaria agallocha	441.27	12.62	0.32	10.53	4.21	3.34	6.12	29.26
Rhizophora mucronata	339.22	11.78	0.39	12.78	2.30	1.51	2.76	27.32
Avicennia officinalis	143.75	4.70	0.36	12.03	8.24	5.73	10.48	27.21
Lumnitzera racemosa	780.95	11.17	0.16	5.26	2.30	3.66	6.69	23.12
Aegiceras corniculatum	50.62	0.93	0.20	6.77	0.07	0.09	0.16	7.86
Rhizophora apiculata	42.59	0.52	0.14	4.51	0.11	0.21	0.38	5.41
Ceriops tagal	33.33	0.20	0.07	2.26	0.02	0.06	0.10	2.56
Bruguiera gymnorhiza	72.22	0.30	0.05	1.50	0.05	0.28	0.52	2.32
Kandelia candel	61.11	0.25	0.05	1.50	0.03	0.15	0.27	2.02
Bruguiera cylindrica	11.11	0.05	0.05	1.50	0.01	0.05	0.10	1.65
Avicennia marina var. Acutissima	11.11	0.02	0.02	0.75	0.00	0.02	0.04	0.81

Table 3 Species-wise Above ground biomass and carbon estimation in study area

Species name	**Average Biomass (kg)**	**Total biomass (kg)**	**Mean carbon (kg)**	**Total carbon (kg)**	**Biomass t/ ha**	**Carbon t/ ha**
Heritiera littoralis	192.16	10760.69	96.08	5380.34	119.56	59.78
Acivennia marina	92.41	158571.45	46.20	79285.73	62.93	31.46
Avicennia officinalis	393.62	81479.47	196.81	40739.74	56.58	28.29
Sonneratia apetala	155.68	35495.18	77.84	17747.59	32.87	16.43
Lumnitzera racemosa	23.13	11381.94	11.57	5690.97	18.07	9.03
Excoecaria agallocha	21.38	11889.57	10.69	5944.79	9.44	4.72
Sonneratia alba	17.04	9063.46	8.52	4531.73	7.75	3.87
Rhizophora mucronata	16.72	8677.09	8.36	4338.55	5.67	2.84
Rhizophora apiculata	35.88	825.13	17.94	412.56	1.53	0.76
Bruguiera gymnorhiza	18.36	238.63	9.18	119.32	1.33	0.66
Kandelia candel	10.30	113.32	5.15	56.66	0.63	0.31
Bruguiera cylindrica	30.02	60.04	15.01	30.02	0.33	0.17
Aegiceras corniculatum	4.87	199.53	2.43	99.77	0.25	0.12
Ceriops tagal	7.23	65.06	3.61	32.53	0.24	0.12
Avicennia marina var. Acutissima	7.32	7.32	3.66	3.66	0.08	0.04
Grand Total	**74.63**	**328827.89**	**37.32**	**164413.94**	**317.24**	**158.62**

Table 4 Species-wise biomass and carbon estimation in North zone

Species name	**Average of Biomass (kg)**	**Sum of Biomass (kg)**	**Average of Carbon (kg)**	**Sum of Carbon (kg)**	**Biomass t/ ha**	**Carbon t/ ha**
Acivennia marina	92.85	155431.79	46.43	77715.90	78.50	39.25
Avicennia officinalis	204.33	13281.61	102.17	6640.80	36.89	18.45
Sonneratia apetala	155.31	35254.80	77.65	17627.40	35.61	17.81
Lumnitzera racemosa	8.32	2246.01	4.16	1123.00	12.48	6.24
Sonneratia alba	15.13	3192.62	7.57	1596.31	8.87	4.43
Exoecaria agallocha	3.70	596.10	1.85	298.05	1.32	0.66
Bruguiera cylindrica	30.02	60.04	15.01	30.02	0.33	0.17
Rhizophora mucronata	5.31	111.41	2.65	55.71	0.25	0.12
Ceriops tagal	7.23	65.06	3.61	32.53	0.24	0.12
Rhizophora apiculata	20.75	20.75	10.37	10.37	0.23	0.12
Aegiceras corniculatum	2.21	63.96	1.10	31.98	0.14	0.07
Avicennia marina var. Acutissima	N/A	N/A	N/A	N/A	N/A	N/A
Bruguiera gymnorhiza	N/A	N/A	N/A	N/A	N/A	N/A
Heritiera littoralis	N/A	N/A	N/A	N/A	N/A	N/A
Kandelia candel	N/A	N/A	N/A	N/A	N/A	N/A
Grand Total	**78.77**	**210324.16**	**39.39**	**105162.08**	**174.87**	**87.44**

Table 5 Species-wise biomass and carbon estimation in South zone

Species name	Average of Biomass (kg)	Sum of Biomass (kg)	Average of Carbon (kg)	Sum of Carbon (kg)	Biomass t/ ha	Carbon t/ ha
Heritiera littoralis	192.16	10760.69	96.08	5380.34	119.56	59.78
Avicennia officinalis	480.27	68197.86	240.13	34098.93	63.15	31.57
Lumnitzera racemosa	41.15	9135.93	20.58	4567.96	20.30	10.15
Exoecaria agallocha	28.59	11293.47	14.30	5646.74	13.94	6.97
Rhizophora mucronata	17.20	8565.68	8.60	4282.84	7.93	3.97
Sonneratia alba	18.29	5870.84	9.14	2935.42	7.25	3.62
Acivennia marina	74.75	3139.66	37.38	1569.83	5.81	2.91
Sonneratia apetala	240.38	240.38	120.19	120.19	2.67	1.34
Rhizophora apiculata	36.56	804.38	18.28	402.19	1.79	0.89
Bruguiera gymnorhiza	18.36	238.63	9.18	119.32	1.33	0.66
Kandelia candel	10.30	113.32	5.15	56.66	0.63	0.31
Aegiceras corniculatum	11.30	135.57	5.65	67.79	0.38	0.19
Avicennia marina var. Acutissima	7.32	7.32	3.66	3.66	0.08	0.04
Bruguiera cylindrica	0.00	0.00	0.00	0.00	0.00	0.00
Ceriops tagal	0.00	0.00	0.00	0.00	0.00	0.00
Grand Total	**68.26**	**118503.73**	**34.13**	**59251.87**	**244.82**	**122.41**

Table 6 Species-wise Above ground biomass and carbon estimation in North Zone-Dense canopy class

North -Dense Class Species name	Average of Biomass (kg)	Sum of Biomass (kg)	Average of Carbon (kg)	Sum of Carbon (kg)	Biomass t/ ha	Carbon t/ ha
Acivennia marina	94.31	145996.69	47.16	72998.34	85.38	42.69
Avicennia officinalis	204.09	12857.46	102.04	6428.73	47.62	23.81
Sonneratia apetala	157.72	24446.96	78.86	12223.48	30.18	15.09
Lumnitzera racemosa	8.34	2244.51	4.17	1122.26	24.94	12.47
Sonneratia alba	15.13	3192.62	7.57	1596.31	8.87	4.43
Excoecaria agallocha	3.67	575.92	1.83	287.96	2.13	1.07
Ceriops tagal	9.17	64.18	4.58	32.09	0.71	0.36
Bruguiera cylindrica	30.02	60.04	15.01	30.02	0.33	0.17
Rhizophora mucronata	11.63	104.68	5.82	52.34	0.29	0.15
Rhizophora apiculata	20.75	20.75	10.37	10.37	0.23	0.12
Aegiceras corniculatum	2.28	63.88	1.14	31.94	0.18	0.09
Grand total	**77.40**	**189627.70**	**38.70**	**94813.85**	**200.87**	**100.43**

Table 7 Species-wise Above ground biomass and carbon estimation in North Zone-Open canopy class

North -Open Class Species name	Average of Biomass (kg)	Sum of Biomass (kg)	Average of Carbon (kg)	Sum of Carbon (kg)	Biomass t/ ha	Carbon t/ ha
Sonneratia apetala	150.11	10807.84	75.05	5403.92	60.04	30.02
Acivennia marina	74.88	9435.10	37.44	4717.55	34.94	17.47
Avicennia officinalis	212.07	424.14	106.04	212.07	4.71	2.36
Excoecaria agallocha	5.05	20.18	2.52	10.09	0.11	0.06
Rhizophora mucronata	0.56	6.73	0.28	3.36	0.07	0.04
Lumnitzera racemosa	1.50	1.50	0.75	0.75	0.02	0.01
Aegiceras corniculatum	0.08	0.08	0.04	0.04	0.00	0.00
Ceriops tagal	0.44	0.88	0.22	0.44	0.00	0.00
Grand total	**94.07**	**20696.45**	**47.04**	**10348.23**	**99.91**	**49.96**

Table 8 Species-wise Above ground biomass and carbon estimation in South Zone-Dense canopy class

South-Dense Class Species name	Average of Biomass (kg)	Sum of Biomass (kg)	Average of Carbon (kg)	Sum of Carbon (kg)	Biomass t/ ha	Carbon t/ ha
Heritiera littoralis	192.16	10760.69	96.08	5380.34	119.56	59.78
Avicennia officinalis	527.76	49609.70	263.88	24804.85	68.90	34.45
Lumnitzera racemosa	69.98	4758.66	34.99	2379.33	13.22	6.61
Excoecaria agallocha	33.57	6847.87	16.78	3423.94	12.68	6.34
Sonneratia alba	18.49	5844.04	9.25	2922.02	9.28	4.64
Rhizophora mucronata	16.40	7201.75	8.20	3600.88	8.89	4.45
Acivennia marina	76.14	3121.65	38.07	1560.82	6.94	3.47
Sonneratia apetala	240.38	240.38	120.19	120.19	2.67	1.34
Rhizophora apiculata	37.67	678.01	18.83	339.00	1.88	0.94
Bruguiera gymnorhiza	18.36	238.63	9.18	119.32	1.33	0.66
Kandelia candel	17.66	70.63	8.83	35.32	0.78	0.39
Aegiceras corniculatum	11.30	135.57	5.65	67.79	0.38	0.19
Avicennia marina var. Acutissima	7.32	7.32	3.66	3.66	0.08	0.04
Grand total	**70.65**	**89514.89**	**35.33**	**44757.45**	**246.59**	**123.30**

Table 9 Species-wise Above ground biomass and carbon estimation in South Zone-Open canopy class

South-Open Class Species name	Average of Biomass (kg)	Sum of Biomass (kg)	Average of Carbon (kg)	Sum of Carbon (kg)	Biomass t/ ha	Carbon t/ ha
Avicennia officinalis	387.25	18588.17	193.63	9294.08	51.63	25.82
Lumnitzera racemosa	28.42	4377.26	14.21	2188.63	48.64	24.32
Excoecaria agallocha	23.28	4445.60	11.64	2222.80	16.47	8.23
Rhizophora mucronata	23.12	1363.93	11.56	681.96	5.05	2.53
Rhizophora apiculata	31.59	126.37	15.80	63.19	1.40	0.70
Kandelia candel	6.10	42.69	3.05	21.34	0.47	0.24
Acivennia marina	18.02	18.02	9.01	9.01	0.20	0.10
Sonneratia alba	5.36	26.80	2.68	13.40	0.15	0.07
Grand total	**61.81**	**28988.84**	**30.90**	**14494.42**	**124.01**	**62.01**