Estimation of Carbon Stock in Mangrove Ecosystem

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Estimation of Carbon Stock in Mangrove Eco-system

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Maps are based on the Survey of India maps with the permission of the Surveyor General of India. The territorial waters of India extend into the sea to a distance of twelve nautical miles measured form the appropriate baseline.

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Preface

Climate change is serious threat to nature and life on the earth. Recent past years witnessed several natural calamities in different corners of the world and may have disturbed human life. Forests play an important role in mitigation and adaptation of climate change phenomenon. Carbon sequestration by forest has attracted much interest as a mitigation approach as it has been considered a relatively inexpensive means of addressing climate change, in short period. Mangrove Forests help stabilizing the environment by removing and storing more carbon, than any other ecosystems on Earth.

UNFCCC monitors the Green House gases through the process of National Communication (NATCOM). India is a Party to the United Nations Framework Convention on Climate Change and report the GHG inventory on a regular basis. Forest Survey of India has been providing the information of forests sub-sector for preparation of GHG inventory of LULUCF sector to the Ministry for reporting to various NATCOM, BUR. The forest carbon stock is estimated by FSI from two regular activities of FSI *viz.* Forest Cover Mapping and National Forest inventory. FSI reports the carbon stock for all the five carbon pools namely AGB, BGB, Deadwood, Litter and Soil Organic Carbon (SOC) in different forest types in the country.

In India, Mangroves are spread over an area of 4,992 km^2, which is nearly 3.37% of world's mangroves vegetation. Considering the high potential of carbon sequestration in the mangrove forest, FSI has been given a project by the NATCOM cell of the Ministry of Environment Forest and Climate Change to estimate the carbon stock in all five pools of carbon for all the 12 States having Mangrove Forest in India. Accordingly, FSI has carried out a study based on Lidar and field inventory data for estimation of carbon stock in all the 12 States. It is hoped that the results of the study will be useful for readers.

Anoop Singh

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Important contributions of FGD and TFI staff members are instrumental in bringing the report to a successful end.



Executive Summary

Coastal vegetation is an important biological carbon sink, capable of sequestering greater amounts of carbon per unit area than terrestrial forests. The greatest proportion of carbon in coastal systems, commonly referred to as "blue carbon", is stored below ground in the sediment, with a smaller proportion stored in the above-ground biomass. Among the three key blue carbon ecosystems (mangroves, seagrasses and saltmarshes), mangroves have the greatest above ground biomass and carbon storage, due to their larger, woody growth forms. With the increasing need to quantify carbon stored within forests for national carbon accounts, as required under the United Nations Framework Convention on Climate Change (UNFCCC), Reducing Emissions from Deforestation and Degradation (REDD+) and voluntary carbon markets, precise estimation of carbon sequestered in mangroves forest areas is essential.

Remote sensing technology has proved to be a promising tool for forest monitoring and carbon stock estimation at local as well as global level. This study focussed on estimation of mangrove carbon stock in India using advanced space- borne based LiDAR technology. The application of LiDAR data may offer enhanced accuracy when estimating mangrove AGB and will be powerful tool for quantifying the carbon sequestered by mangrove forests. National Aeronautics and Space Administration's (NASA's) Ice, Cloud and land Elevation Satellite-2 (IceSat-2) (launched in Year 2018) ALT08 (Land Water Vegetation Elevation) products have been used in the present study.

LiDAR is a laser scanner that uses a pulsed laser to measure distances to the Earth's surface and provides absolute x, y and z values for returned pulses. For the purpose of this study, LiDAR data has been downloaded and processed for all the mangrove dominated States/UTs in the country. Mean canopy height and canopy openness parameters from LiDAR data have been found efficient for modelling above ground biomass. T-test revealed that there is no statistical difference between LiDAR derived mean canopy height and ground data collected for tree height. It provides strength to use mean canopy height parameter from LiDAR for AGB modelling. For AGB modelling, regression analysis has been performed using LiDAR derived mean canopy height and canopy openness as independent variables and AGB calculated for all 50 sample points as dependent variable. Regression analysis resulted in a model for AGB estimation i.e.

AGB = -4.0218* Mean canopy LiDAR height + 46.2604* Canopy Openness

Multiple R value of 0.95, R square = 0.91, adjusted R square = 0.89 & SE = 19.78 t/ha.

Ground data has been collected in three mangrove dominating States in India i.e. Maharashtra, Odisha and West Bengal. These three States are having large area under mangroves and having variety of mangrove species composition in almost all three canopy density classes' i.e. very dense, moderately dense and open forest. Maharashtra mangroves are dominated by Avicennia marina mangroves along with Rhizophora mucronata, Sonneratia apetala and Sonneratia alba. In West Bengal mangrove forest, 13 mangrove species were reported during field visit namely Avicennia alba, Avicennia marina, Avicennia officinalis, Aegiceras corniculatum, Bruguiera gymnorrhiza, Ceriops decandra, Excoecaria agallocha, Heritiera fomes, Rhizophora apiculata, Sonneratia apetala, Sonneratia caseolaris, Xylocarpus mekongenesis and Xylocarpus granatum. In Odisha, 14 mangrove species were reported during field visit namely Avicennia alba, Avicennia marina, Avicennia officinalis, Aegiceras corniculatum, Aglaia cucullata, Ceriops decandra, Excoecaria agallocha, Heritiera fomes, Kandelia candel, Rhizophora apiculata, Rhizophora mucronata, Sonneratia apetala and Sonneratia alba. Ground data has been collected for all 5 carbon pools i.e. AGB, BGB, Dead wood, litter and SOC in all the three canopy density classes and calculation has been done for all carbon pools.

The model developed on the basis of the ground and LiDAR data for the three States has been used for the AGB estimation of all States/UTs mangroves separately in all three canopy density classes. One-way ANOVA test has been performed to check the significance of model for different canopy density classes. ANOVA results revealed that the so computed AGB per ha for very dense, moderately dense and open forest canopy density classes are significantly different from each other. BGB estimation has been done using root to shoot ratio available in the literature. Dead wood carbon, litter carbon and SOC has been estimated for rest of the mangrove States taking average of calculated carbon multiplied by area of mangroves in respective States/UTs in different canopy density classes.

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ACRONYMS AND ABBREVIATIONS

AGB	Above Ground Biomass
ATLAS	Advanced Topographic Laser Altimeter System
BGB	Below Ground Biomass
BUR	Biennial Update Report
CRZ	Coastal Regulation Zone
DBH	Diameter at Breast Height
FAO	Food and Agriculture Organization
FGD	Forest Geo-informatics Division
FRA	Forest Rights Act
GIS	Geographic Information System
GHG	Green House Gases
GPG	Good Practice Guidance
IceSAT-2	Ice, Cloud, and land Elevation Satellite 2
InSAR	Interferometric Synthetic Aperture Radar
IPCC	Intergovernmental Panel on Climate Change
ISFR	India State of Forest Report
LiDAR	Light Detection and Ranging
MAP	Management Action Plan
MDF	Moderately Dense Forest
NATCOM	National Communication (to UNFCCC)
NDVI	Normalized Difference Vegetation Index
OF	Open Forest
PolSAR	Polarimetric Synthetic Aperture Radar
REDD+	Reducing Emissions from Deforestation and Degradation
SAR	Synthetic Aperture Radar
SOC	Soil Organic Carbon
TFI	Training & Forest Inventory
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
UTs	Union Territories
VDF	Very Dense Forest
WWF	World Wide Fund for Nature

GLOSSARY

Above-ground biomass	The AGB carbon pool consists of all living vegetation above the soil, inclusive of stems, stumps, branches, bark, seeds and foliage.
ANOVA	Analysis of variances (ANOVA) is a statistical technique used to test for differences or correlations in the effects of independent variables on a dependent variable.
Below-ground biomass	The BGB carbon pool consists of the biomass contained within live roots.
Biomass	Biomass is the organic material that comes from plant or animal and can be used as renewable bioenergy sources.
Canopy Density	Percent area of land covered by canopy of trees. It is expressed as a decimal coefficient, taking closed canopy as unity.
Carbon Pool	Carbon pools are major components of an ecosystem that can either accumulate or release carbon.
Carbon Sink	A carbon sink is a carbon pool from which more carbon flows in than out: forests can act as sink through the process of tree growth and resultant biological carbon sequestration.
Climate change	Refers to any significant change in the measures of climate lasting for an extended period of time.
Geographic Information System	A computer based system for capturing, storing, manipulating, analysing and displaying data, which are spatially referenced to the earth.
IceSAT-2	ICESat-2, part of NASA's Earth Observing System, is a satellite mission for measuring ice sheet elevation and sea ice thickness, as well as land topography, vegetation characteristics, and clouds.
Land Use, Land-Use Change and Forestry	It is a category within UNFCCC accounting framework for greenhouse gas (GHG) emissions. It includes carbon pools of living biomass (above and below ground), dead organic matter (dead wood and litter) and organic soil carbon.
LiDAR	Lidar, which stands for Light Detection and Ranging, is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth.
Litter	All non-living biomass with a diameter less than 5cm, lying in various states of decomposition above the organic soil.
Mangroves	Salt tolerant evergreen forest ecosystem found mainly in tropical and subtropical coastal and/or inter-tidal regions.
Moderately Dense Forest	All lands with forest cover having a canopy density of 40 percent and more but less than 70 percent.
Open Forest	Lands with forest cover having a canopy density of 10 percent and more but less than 40 percent.
REDD+	REDD+ is a United Nations-backed framework that aims to curb climate change by stopping the destruction of forests. REDD stands for "Reducing Emissions from Deforestation and forest Degradation"; the "+" signifies the role of conservation, sustainable management of forests and enhancement of forest carbon stocks.

Remote sensing	Remote sensing is the acquisition of data, such as total forest area, forest type, canopy cover and height, from sensors on board aircraft or space-based platforms.
Soil Organic Carbon (SOC)	The carbon pool that includes all organic material in soil, but excluding the coarse roots of the belowground biomass pool.
Source (of carbon)	A carbon source is a carbon pool from which more carbon flows out than flows in: forests can often represent a net source of carbon due to the processes of decay, combustion and respiration.
Student's t-test	Student's t-test is a type of statistical analysis used to compare the average of two groups and determine whether the difference between them are more likely because of chance/error or it's a real (significant) difference.
Synthetic Aperture Radar	Synthetic Aperture Radar (SAR) is a type of active data collection where a sensor produces its own energy and then records the amount of that energy reflected back after interacting with the Earth. This technique is used for producing fine-resolution images from a resolution-limited radar sensor mounted either on an airplane or on a satellite platform in space.
Very Dense Forest	Lands with forest cover having a canopy density of 70 per cent and above.

UNITS USED

SI. No	Name of Unit	Symbol	Value
1.	Meter	m	1 m = 100 cm
2.	Square Kilometer	km^2	1 km^2= 1,000,000 m^2
4.	Tonnes	t	1 t = 1,000 kg
5.	Kilogram	kg	1kg = 1,000 gm
5.	Hectare	ha	1 ha = 0.01 km^2 100 ha = 1 km^2
6.	Million hectare	Mha	1 m ha = 1,000,000 ha = 10^6 ha = 10,000 km^2
7.	Kilo hertz	kHz	1 kHz = 1,000 Hz
8.	Nanometer	nm	1 nm = 1 x 10^{-9} m

CHAPTER 1
INTRODUCTION

1.0 Introduction

Mangroves are one of the specialized ecological aggregation of halophytic plants acting as a transient zone between land and ocean. Mangroves consist of diverse species of shrubs and trees, distributed along tropical and sub-tropical environments having specific habitats such as shores, estuaries, tidal creeks, backwaters, lagoons, marshes, mudflats and even at upstream points where water remains saline **(Qasim, l998)**. Mangrove forests are distinctive functional ecosystems having social, biological and economic importance. They are among one of the most productive ecosystems of the world as they provide important ecosystem services to human society as well as coastal and marine systems **(Bouillon 2003; FAO, 2007).**

Mangroves are having unique adaptations in terms of adapting to regular fluctuations in tides, higher saline conditions and nil/near nil oxygenic conditions. Evolving stilt roots enables mangroves to cope-up with tidal fluctuations. Xeromorphic and halophytic conditions enables mangroves to adapt to higher saline conditions and evolving pneumatophores are to deal with nil /near nil oxygenic conditions. Mangroves accompanies spectrum of services viz; Protection of coast, Carbon sequestration, Land accretion, Water quality and Pollution control, Food, Timber, Dyes and others. Out of these mangroves coastal protection role is incredible in which mangroves protect the coasts from tsunamis, cyclones, floods and sea inundations **(Miththapala S., 2008).**

Mangrove ecosystems are under constant pressure due to anthropogenic interventions in coastal areas due to increasing human population in coasts and rising demand for land, timber, fodder, fuel-wood and other non-wood forest products (NWFPs). Adequate management activities are required for efficient conservation of Mangrove forest. The Government of India has taken steps to protect sustain, conserve and augment forests in the country through promotional as well as regulatory measures. The promotional measures are being implemented through a Central Sector Scheme under National Coastal Mission Programme on 'Conservation and Management of Mangroves and Coral Reefs'. Under this programme, annual Management Action Plan (MAP) for conservation and management of mangroves are formulated and implemented in all the coastal States and Union Territories.

Regulatory measures are implemented through Coastal Regulation Zone (CRZ) Notification (2019) under the Environment (Protection) Act, 1986; the Wild Life (Protection) Act, 1972; the Indian Forest Act, 1927; the Biological Diversity Act, 2002; and rules under these acts as amended from time to time.

As per information provided by the World Wide Fund for Nature, (WWF), India, the WWF India has enjoined citizens in nine states, which include Maharashtra, Goa, Gujarat, Andhra Pradesh, Tamil Nadu, Kerala, Odisha, West Bengal and Karnataka on mangrove conservation through the Magical Mangroves campaign. About 180 volunteers have committed their time towards being educated on mangrove conservation and to inspire more community members to do the same. Volunteers are equipped with a curated toolkit of presentations, videos, story books, and a mangroves app. in addition, the Magical Mangroves campaign has sensitized close to 15,600 citizens in India's coastal states through 220 webinars.

The Government under Centrally sponsored scheme for conservation & Management of Mangroves, extend assistance to Coastal State/UTs for implementation of action plans including survey and demarcation, alternation and supplementary livelihood, protection measures and education and awareness activities.

The Ministry piloted an Integrated Coastal Zone management Project in Coastal stretches of 3 states namely Gujarat, Odisha and West Bengal, with objective of Conservation and Protection of Coastal resources which included plantation of mangroves as one of the major activities.

In addition, State Government of Maharashtra has taken several proactive steps for conservation of Mangroves and a Mangrove Cell, dedicated for Mangrove conservation, has been established by the State Government. Further, Mangrove and Marine Biodiversity Conservation Foundation is also created for enhancing Mangrove cover and to promote research and livelihood activities under the Forest Department by the State Government.

1.1 Status of Mangrove Cover Worldwide

Three fourths of the tropical and sub-tropical nations coasts have been sprawled by mangroves, but currently less than half of them remains and out of it more than half are in degraded conditions. Globally mangroves are distributed mainly in two zones i.e. West zone and East zone. West zone comprises African coast of Atlantic, North and South American portions, which also incorporates Galapagos Islands and the East zone embodies eastern part of African coast, South Asian countries viz., India and Pakistan, South East Asian countries like Indonesian archipelago and Australia and New Zealand **(Basha, S.K., 2018)**. As per Global Forest Resource Assessment, 2020 **(FRA 2020)**, world over, 113 countries have Mangrove forests covering an estimated 14.79 Mha. The greatest extent of mangrove species is found in the Indo-Malaysian region (**Chapman, 1975**) and thus, it can be considered as the cradle of

evolution of mangrove vegetation. There are about 60-100 species of mangroves totally present in the world coming under 30 genera and more than 20 different families (**Singh et al., 1987**). The largest Mangrove area is reported in Asia (5.55 Mha), followed by Africa (3.24 Mha), North and Central America (2.57 Mha) and South America (2.13 Mha). The Sundarbans National Park in India and the Sundarbans Mangrove Forests in Bangladesh have been known to possess the world's largest continuous stretch of mangrove forest (**UNESCO**). Oceania has reported the smallest area of Mangroves (1.30 Mha). More than 40 % of the total area of Mangroves was reported to be in the four countries: Indonesia (19% of the total), Brazil (9%), Nigeria (7%) and Mexico (6%) (**FAO, 2020**). Over the last two decades of the 20th century, nearly 35% of the world's mangrove forests has disappeared, causing mangroves in distress **(Bosire et al., 2008; Valiela et al., 2001)**.

1.2 Status of Mangrove cover in India

Mangroves are classified in Type Group-4 Littoral & Swamp Forests and are covered under 4A/L1 Littoral forest, 4B/TS1 Mangrove scrub, 4B/TS2 Mangrove forest, 4B/TS3 Saltwater mixed forest, and 4B/TS4 Brackish water mixed forest types according to **Champion and Seth Classification (1968)**. Mangroves are keystone coastal ecosystems providing various environmental services and ecological functions affecting both upland and oceanic resources. Mangrove ecosystem values include protection from storms and tsunamis **(Giesen et al., 2007; Mitsch and Gosselink 2007; Alongi 2009)**. Regulation of water quality, breeding habitats for fish and shellfish, source of wood and other forest products for local people, biodiversity and habitats for many rare and endangered species **(Duke at al., 2007; FAO 2007)**. Mangrove ecosystems are under pressure due to increasing human interference in coastal areas and growing demand for non-wood forest products, fuelwood, fodder and small timber. In India, mangroves are present along the East Coast, West Coast and Andaman & Nicobar Islands, which are classified as Deltaic, Estuarine, Backwater and Insular according to Thom's classification of estuary habitats.

In India, mangroves spread over an area of 4,992 km^2 (**ISFR 2021**) which is nearly 3.37% of world's mangrove vegetation. 60 species of mangroves belonging to 41 genera and 29 families have been reported (**Blasco, 1975**). **Blasco (1977)** reported 58 mangrove species in the Indian territories, while **Rao (1986)** listed 60 species from 41 genera and 29 families. Studies have reported that the country occupies an area of about 7% of the world mangroves **(Krishnamurthy, 1987)** and 8% of the Indian coastline (**Umali et al., 1987**). **Naskar (2004)**

has reported 85 species of mangroves / mangrove associates that were common to the Indian coasts. Studies have also reported that, there are 55 species of true mangroves in India and majority are coming under the families Acanthaceae, Avicenniaceae, Meliaceae and Rhizophoraceae (**Vidyasagaran and Gopikumar, 2006**). Detailed account on the diversity of Indian mangroves has been given by **Mandal and Naskar (2008).**

The total extent of mangroves has been classified into 3 groups as 'Major mangroves,' 'Mangrove associates,' and 'Back mangal'. From a total of 12 habitats, 82 species of mangroves belonging to 52 genera and 36 families have been reported. Calculation has been done using the total number of families, genera and species and relative mangrove diversity. In a study done by **(Mandal and Naskar, 2008)** on mangrove diversity, it has been found that among different habitats studied, maximum value for relative mangrove diversity has been reported from Sundarbans and minimum from Lakshadweep. An overview on the status of biodiversity and distribution of Indian mangroves stated that there are 59 species in 41 genera and 29 families. 34 species belonging to 21 families have been noticed as unique species along the west coast and the east coast comprised of 25 species **(Pillai, N.G, 2018)**. The most important species distributed along west coast were Sonneratia caseolaris, Suaeda fruticosa, Urochondra setulose etc. Distribution status with respect to different states revealed 16 species from Gujarat, 20 species from Maharashtra, 14 species from Goa and 10 species from Karnataka **(Singh et al., 2012)**.

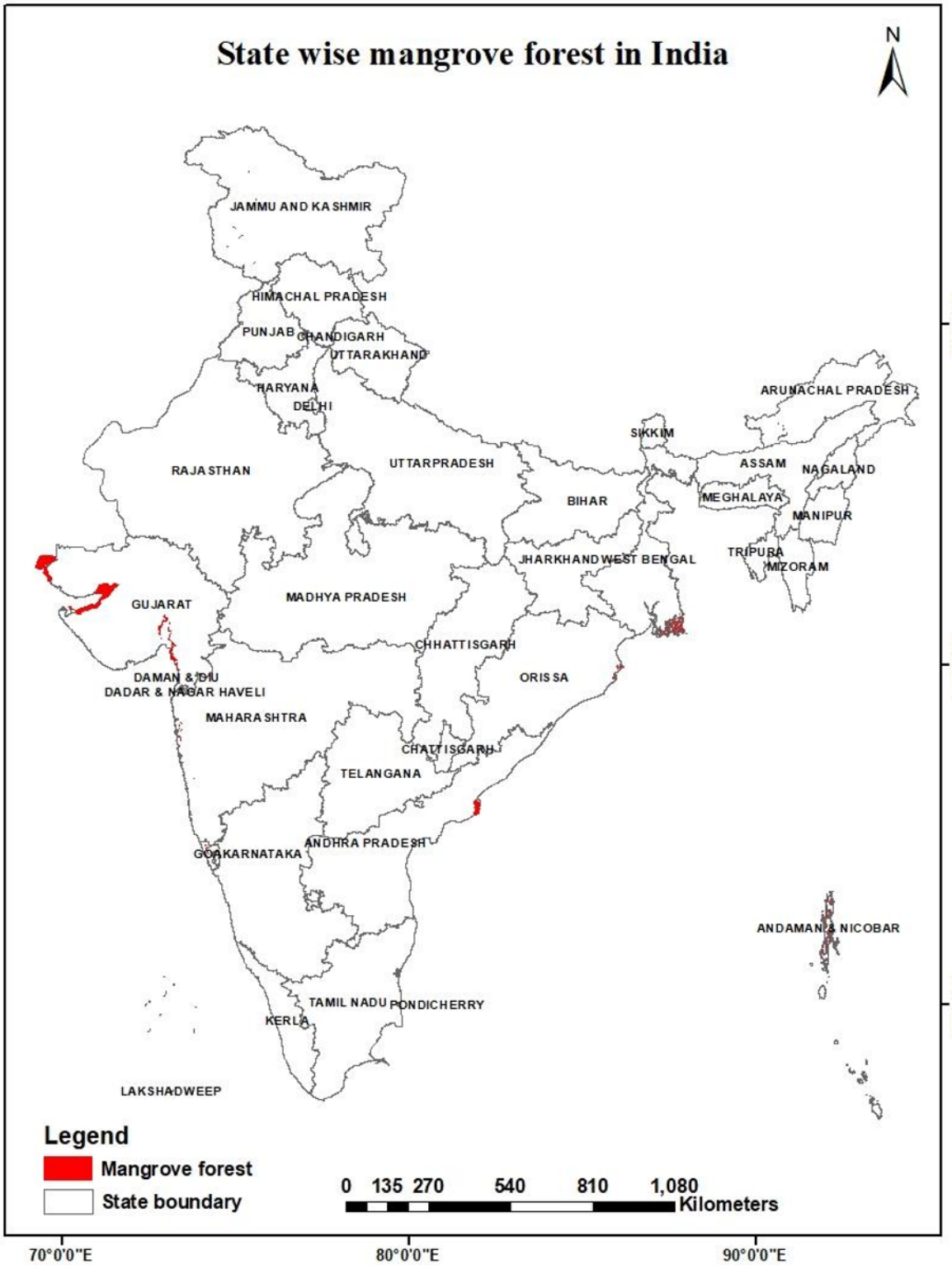


Figure 1.1 Distributional details of Mangroves in India

Figure 1.1 is showing States having Mangrove forest, namely; Andhra Pradesh, Andaman & Nicobar Islands, Dadra & Nagar Haveli & Daman & Diu, Goa, Gujarat, Kerala, Karnataka, Maharashtra, Odisha, Puducherry, Tamil Nadu and West Bengal in India. Mangrove

dominating States in the Country are implementing various measures for mangroves conservation and management. Gujarat State adopted direct seed sowing, bed plantation raising and fishbone channel plantation techniques to restore the degraded mangrove habitats. In Andhra Pradesh, Forest Department has formed 'Eco-Development Committees and Van Samrakshan Samithis' for joint implementation of projects in mangrove forest. Maharashtra State conserve ecology and biodiversity of mangroves by protection, restoration, regeneration and maintenance. Avicennia officinalis, Morinda citrifolia, Rhizophora mucronata, Sonneratia alba, Avicennia alba, Bruguiera cylindrica, Heritiera littoralis, Phoenix paludosa and Ceriops tagal are important species of mangroves in India.

1.3 Mangrove cover assessment in India

Mangroves show conspicuous tone and texture on the satellite images. The Forest Survey of India (FSI) has been assessing Mangrove Cover of the country in three density classes i.e. Very dense (canopy density of 70% and above), Moderately dense (canopy density of 40% and more but less than 70%) and Open Mangrove Cover (canopy density of 10% and more but less than 40%) on biennial basis and publishes the findings in the India State of Forest Report (ISFR). First assessment of Mangroves in year 1987 was based on interpretation of 1:1 million scale satellite data, whereas subsequent interpretations was based on 1:2,50,000 scale satellite data from year 1989 to year 1999 and 2001 onwards scale of interpretation is 1:50,000 . As per the ISFR 2021, the mangrove cover in the country has increased by 17 km^2 in year 2021 as compared to the mangrove cover assessed in year 2019.

Table 1.1: Mangrove Cover Assessment 2021

(Area in km^2)

Sl. No.	State/UT	Very Dense Mangrove	Moderately Dense Mangrove	Open Mangrove	Total	Change with respect to ISFR 2019
1	Andhra Pradesh	0.00	213.00	192.00	405.00	1.00
2	Goa	0.00	21.00	6.00	27.00	1.00
3	Gujarat	0.00	169.00	1006.00	1175.00	-2.00
4	Karnataka	0.00	2.00	11.00	13.00	3.00
5	Kerala	0.00	5.00	4.00	9.00	0.00
6	Maharashtra	0.00	90.00	234.00	324.00	4.00
7	Odisha	81.00	94.00	84.00	259.00	8.00
8	Tamil Nadu	1.00	27.00	17.00	45.00	0.00
9	West Bengal	994.00	692.00	428.00	2114.00	2.00
10	A&N Islands	399.00	168.00	49.00	616.00	0.00
11	D&NH and Daman & Diu	0.00	0.00	3.00	3.00	0.00
12	Puducherry	0.00	0.06	2.00	2.00	0.00
Total		**1,475.00**	**1,481.00**	**2,036.00**	**4,992.00**	**17.00**

Table 1.1 is showing State/UT wise extent of mangrove cover of Year 2021 in three canopy density classes (Very Dense, Moderately Dense and Open) along with the change in comparison to 2019 assessment done by Forest Survey of India (ISFR 2021). The Mangrove cover in the country is 4,992 km^2 which is 0.15% of the country's total geographical area. Very Dense mangrove covers 1,475 km^2, which is 29.55% of the mangrove cover, moderately dense mangrove is 1,481 km^2which is 29.67 % and open mangroves constitute an area of 2,036 km^2 (40.78 %). Net increase of 17 km^2 has been observed in mangrove cover of the country as compared to 2019 assessment. Odisha and Maharashtra States shows increase of 8 km^2 and km^2 respectively in mangrove cover. Reason for increased mangrove cover in Odisha is natural regeneration, plantation activities on the river banks and on intertidal mud-flats mainly in Kendrapara, Jagatsinghpur and Balasore districts. The increase has also been observed in the South 24 Parganas district of West Bengal. Natural regeneration is the main reason for increased mangrove cover in Maharashtra State.

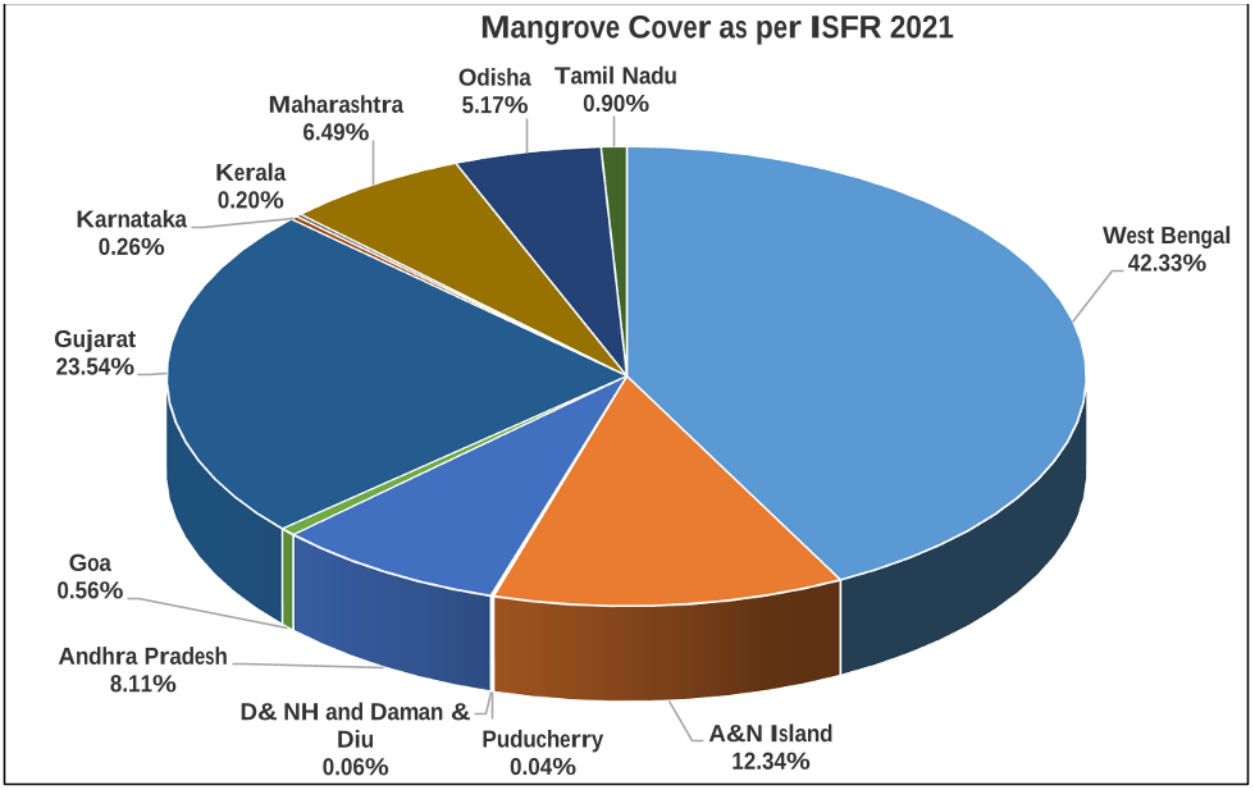


Figure 1.2 Percentage distribution of Mangroves in India (ISFR 2021)

Figure 1.2 is showing that West Bengal has 42.33% of India's mangrove cover, followed by Gujarat 23.54% and A&N Islands 12.34%.

1.4 Mangrove Forest of Andhra Pradesh State

The State of Andhra Pradesh has a geographical area of 1,62,968 km^2, out of which an area of 37,258 km^2 is under forests (RFA), which accounts to 23% of the geographical area. The forest cover in the State is 29,784 km^2, of which only 405 km^2 is mangrove (ISFR 2021). The mangrove forest is distributed in two major density classes of which 213 km^2 is in Moderately Dense Forest (MDF) and 192 km^2 is in Open Forest (OF). Andhra Pradesh has the geographical advantage of having most of the east flowing rivers in the heart of the state bringing in copious supplies of sediments from the Western and Eastern Ghats and Deccan Plateau up to the coast. Out of these, the most important rivers are Godavari, Krishna, Pennar, and Vamsadhara. The majority of the mangrove areas are present in the estuaries of these rivers. The Godavari mangroves are located in the Godavari estuary in the East Godavari district. Krishna mangroves are located in the Krishna estuary of Krishna and Guntur districts.

Major Vegetation types

Dense Mangroves: Areas close to the sea especially the areas found near Corangi and Gaderu river mouths are characteristic of dense vegetation because of daily inundation. Avicennia marina and Excoecaria agallocha are the dominant species. Avicennia alba, Sonneratia apetala. Rhizophora apiculata, Ceriops decandra, Bruguiera gymnorrhiza, Excoecaria agallocha and Xylocarpus moluccensis are present in the middle zone. Towards the landward area mostly Excoecaria agallocha, Avicennia marina and A. officinalis occur. Mean height of the trees in this area is 4-5 m **(Ramasubramanian et al., 2003).**

Sparse Mangroves: Occasionally inundating areas support species like Excoecaria agallocha and Lumnitzera racemosa and generally they are of short stature. Suaeda maritima, S. nudiflora and Aeluropus lagopoides are common in this area.

Casuarina Plantations: The Casuarina plantations raised by the Forest Department along the coast are seen in the Hope Island, along the shore near Masanitippa and in Kandikuppa R.F. near Sacramento lighthouse.

1.5 Mangrove Forest of Goa State

Goa is the smallest State of the country having a geographic area of 3,702 km^2, out of which an area of 1,271 km^2 is under forests (RFA), which accounts to 34% of the geographical area. The forest cover in the State is 2,244 km^2, of which only 27 km^2 is mangrove (ISFR 2021). The mangrove forest is distributed in two major density classes of which 21 km^2 is in Moderately Dense Forest (MDF) and 6 km^2 is in Open Forest (OF). It lies between latitude 14°53' and 15°40' N and longitude 73°40' and 74°21' E. Mandovi and Zuari are two major rivers which are lifeline of Goa. These two rivers originate from the Western Ghats and flow towards the southern boundary to join the Arabian Sea. The Goa territory has seven estuaries and on the intertidal zones of all these estuaries are flat lands formed with silty sand and silty clay along with abundant organic matter. Mangroves along the coastal zones of Goa and the estuarine mouths are relatively poor in number and are subjected to severe biotic pressure.

Mangrove distribution and species in Goa

The dominant mangrove flora of Goa comprises of Avicennia officinalis, Avicennia alba, Rhizophora mucronata, Excoecaria agallocha, Sonneratia alba, Sonneratia caseolaris, Kandelia candel, Bruguiera gymnorrhiza and Bruguiera cylindrica. Less dominant mangroves include Rhizophora apiculata, Aegiceras corniculatum, Avicennia marina, Ceriops tagal etc.

Mangrove associates like Acanthus ilicifolius and Acrostichum aureum are dominant throughout the estuaries. Mainly twelve species of mangroves find their home in the saline waters of Goa. The estuaries of rivers housing mangroves in Goa are Terekhol, Chapora, Mapusa, Mandvi, Zuari (North bank) in North Goa District and Sal, Talpona, Galgibag and Zuari (South bank) in South Goa District. Besides these, good mangrove cover is also present in Kumbharjua canal, which joins Mandovi and Zuari rivers.

In Goa, mangroves have also come up very well in many privately owned areas, which are inundated by backwaters of sea and these areas are termed as "Khazan Lands" in Goa. Almost all the species are found in all the river estuaries. Kandelia candel, a rare species on west coast, is found in plenty in Mandovi, Mapusa and Zuari rivers. However, Avicennia sp. are dominant in most of the places having high salinity and Sonneratia sp. is dominant in low salinity areas.

1.6 Mangrove Forest of Gujarat State

The State of Gujarat has a geographical area of 1,96,244 km^2, out of which an area of 21,870 km^2 is under forests (RFA), which accounts to 11% of the geographical area. The forest cover in the State is 14,926 km^2, of which only 1,175 km^2 is mangrove (ISFR 2021). The mangrove forest is distributed in two major density classes of which 169 km^2 is in Moderately Dense Forest (MDF) and 1,006 km^2 is in Open Forest (OF). The Gujarat coast lies between 20° 00'- 24°'N latitudes and 68° 00'- 73° 30'E longitudes. Gujarat is having longest shoreline of 1,600 km among all the maritime states of India. The Gujarat coast is having two gulfs, namely, Gulf of Kachchh and Gulf of Khambhat. Total seven estuaries exist in Gulf of Khambhat and delivering large amount of water and sediments, whereas in Gulf of Kachchh riverine inputs are very little. Gujarat coast provides a wide variety of coastal features due to its varied physiography, geomorphology and coastal processes. Western most part of Gujarat coast, known as Kori Creek, is a part of lower Indus deltaic plain and is characterized by network of tidal creeks and small overbank splays that houses large block of mangrove on a sand/silt substrate. Coastal wetlands of the Rann of Kachchh broadly comprise high tide mudflats with or without salt encrustation, salt marsh vegetation and mangrove around the Kori creek area (**Coastal zones of India, 2012**).

Mangrove distribution and species in Gujarat

The mangrove forests are predominantly distributed over three mangrove areas, viz. Gulf of Khambhat, Gulf of Kachchh and Kori creek. The three major mangrove areas of the State collectively account for 99.4% (10.1% in Gulf of Kahmbhat, 15.2 % in Gulf of Kachchh and

74.1% in Kachchh district including Kori creek) of the total Mangrove cover of the State. The remaining 0.6% mangroves are distributed in South Gujarat (Valsad and Navsari districts). Gujarat has 22% of the country's mangrove cover but only 15% of the total mangrove species of the country.

Fifteen species of mangroves are found in Gujarat. Among that Avicennia marina covers over 90% of total mangroves. Rhizophora mucronata and Ceriops tagal occur in small patches in the Gulf of Kachchh. Other species are Avicennia officinalis, Sonneratia apetala, Acanthus illicifolius, Avicennia alba, Rhizophora apiculata, Aegiceras corniculatum, Excoecaria agallocha, Bruguiera gymnorrhiza, Bruguiera cylindric, and Lumnitzera racemose. Kandelia candel and Ceriops decandra are rare with restricted distribution and are found in south Gujarat.

1.7 Mangrove Forest of Karnataka State

The State of Karnataka has a geographical area of 1,91,791 km^2, out of which an area of 38,284 km^2 is under forests (RFA), which accounts to 20% of the geographical area. The forest cover in the State is 38,730 km^2, of which only 13 km^2 is mangrove (ISFR 2021). The mangrove forest is distributed in two major density classes of which 2 km^2 is in Moderately Dense Forest (MDF) and 11 km^2 is in Open Forest (OF). Karnataka's coast stretches across approximately 320 kilometers in the districts of Dakshin Kannada (62 km of coastline), Udupi (98 km) and Uttar Kannada (160 km). The coastline is flanked by the moderately unpolluted Arabian Sea in the west and vast beautiful Western Ghats in the east. The northern coast of Karnataka is rocky while the southern coast has long linear beaches. The coastal zone is narrow except around the estuaries. It has long, narrow and straight beaches at Surathkal, Panamburu Manura and near Coondapur as well as small crescent shaped pocket beaches can be observed at Ullal, Suratkal, Malpe and Udipi. Also, spectacular spits are observed near Bengare, north of Chitrapa near Coondapur and near Kolluru. Double spits are observed near Honavar, shallow lagoons near Coondapur and the Kalinadi are observed. Mudflats and small patches of mangroves also exist.

Karnataka coast mangrove vegetation is found in three districts viz., Dakshin Kannada, Udupi and Uttar Kannada in the estuarine regions of the principal rivers. The species Avicennia officinalis, Rhizophora mucronata are the dominant mangroves in all coastal sites in Karnataka. The next dominating species are Kandelia candel, Bruguiera gymnorrhiza,

Sonneratia alba, Aegiceras corniculatum. The other dominant species are Excoecaria agallocha and Acanthus ilicifolius. The Mangrove associated species such as Derris trifoliata, Acrostichum aureum, Clerodendron inerme, Ipomoea pes-caprae, Sesuvium portulacastrum, Aeluropus lagopoides and Fimbristylis ferruginea were found distributed at all coastal sites in Karnataka (**Kumar, K.M.V. and Vijaya, K., 2012**).

1.8 Mangrove Forest of Kerala State

The State of Kerala has a geographical area of 38,852 km^2, out of which an area of 11,522 km^2 is under forests (RFA), which accounts to 30% of the geographical area. The forest cover in the State is 21,253 km^2, of which only 9 km^2 is mangrove (ISFR 2021). The mangrove forest is distributed in two major density classes of which 5 km^2 is in Moderately Dense Forest (MDF) and 4 km^2 is in Open Forest (OF). Kerala state is situated between 8°18′ - 12°48′ N latitude and 74°52′- 77°22′E longitude. Kerala has a narrow coastline of about 550 km. The Kerala coast is famous for its beautiful beaches, estuaries and lagoons. The coastline is more or less linear, at places it is offset by the presence of promontories. Another characteristic feature of Kerala coastal zone is high population density, 2362 persons / km^2 resulting in a more or less urbanized coastal zone. The Kerala coast extends from Manjeswaram in north to Pozhiyur in the south. Well-developed sandy beaches are in Chittari, Kappad, Ponnani, Calicut, Cochin, Alleppey and Kovalam. Cliff and rocky coasts are observed at many places on the Kerala coast. The rocky shores are made up of laterites or Precambrian crystalline such as Khondalites or Charnockites. Some of the prominent rocky coasts are near Bekal, Ezhimala, Azhikode and Kadalur point in the north and Vizhinjam, Varkala and Tangasseri in the south.

Kerala coast has fascinating distribution pattern of mangrove species. Acanthus ilicifolis, Excoecaria agallocha, Avicennia officinalis and Rhizophora apiculata are commonly found throughout Kerala coast. Aegiceras corniculatum, Avicennia marina, Bruguiera cylindrica, Kandelia candel and Rhizophora mucronata are more or less common along Malabar as well as Travancore coast. Sonneratia caseolaris is occasionally found along Malabar as well as Travancore coast, whereas Bruguiera gymnorrhiza, Bruguiera sexangula, Excoecaria indica, Lumnitzera racemosa and Sonneratia alba are found rarely along Kerala coast.

Avicennia officinalis is found abundantly along the Kallai and Chaliyar river banks near Beypore and at Thalassery. Avicennia marina dominates in Kunhimangalam. Rhizophora apiculata grows profusely in chittari and Kumarakam while Rhizophora mucronata grows in kannamali and Edappally near Cochin and in Pazhayangadi in Kannur district. Kumarakam is populated by Bruguiera gymnorrhiza and Kunhimangalam and Pazhayangadi by Bruguiera cylindrica. Luxuriant growth of Kandelia candel can be seen at Pappinisseri Chirakkal and Valapattanam estuary.

1.9 Mangrove Forest of Maharashtra State

The State of Maharashtra has a geographical area of 3,07,713 km^2, out of which an area of 61,952 km^2 is under forests (RFA), which accounts to 20% of the geographical area. The forest cover in the State is 50,798 km^2, of which only 324 km^2 is mangrove (ISFR 2021). The mangrove forest is distributed in two major density classes of which 90 km^2 is in Moderately Dense Forest (MDF) and 234 km^2 is in Open Forest (OF). The Maharashtra coast lies between 15° 45'- 20° 00'N latitudes and 68° 00'- 73° 30'E longitudes. The Maharashtra coast is characterized by pocket beaches surrounded by rocky cliffs of Deccan basalt from North to south, estuaries and the patches of the mangroves along it. Beaches of the Maharashtra coast are small, crescent shaped and flanked by promontories. They are termed as pocket beaches as they are pocketed between headlands. They are delineated southwest of Dahnu, Andheri, north of Alibag, Vadamirya and Rajapur creek. Long and linear beaches are observed near Guhaghar and Malvan. Mudflats are found mainly along the estuaries and bay. They are broad at the mouth and gradually tapered down. They are observed near Thane creek, Panvel creek, and Vasai creek, along the bank of Kundalika river and along the Rajapur creek. Mumbai coast has 66 km^2 of mangroves.

Mangroves are mainly observed along the intertidal region of estuaries and creeks. Large patches of mangroves are observed along the Panvel creek, Vasai creek, Thane creek and Dharamtar creek, along the estuaries of Vasisth, Savitri and Kundlika. Coastal dunes are found with Casurina plantation near Malvan and Devgarh. Mangrove dominated area in Thane district is along Vasai, Vaitarna River, Dandi and Dahanu creek. In Mumbai district Thane creek, Mahim, Malad creek and Manori creek are mangrove dominated areas. Raigad district has mangroves in Hareshwar, Shrivardhan, Murud, Kirlai and Uran areas.

Avicennia marina is commonly found mangrove species in whole Maharashtra along with Avicennia officinalis but is not as common as Avicennia marina. Aegiceras corniculatum, Acanthus ilicifolius, Sonneratia apetala and Sonneratia alba are other common species but rarely found in districts of Ratnagiri and Sindhudurg (south of Alibag). Other important mangrove species which are relatively rare such as Bruguiera cylindrica, Bruguiera gymnorrhiza, Sonneratia caseolaris, Rhizophora apiculata, Kandelia candel and Xylocarpus granatum.

1.10 Mangrove Forest of Odisha State

The State of Odisha has a geographical area of 1,55,707 km^2, out of which an area of 61,204 km^2 is under forests (RFA), which accounts to 39% of the geographical area. The forest cover in the State is 52,156 km^2, of which only 259 km^2 is mangrove (ISFR 2021). The mangrove forest is distributed in all the three density classes of which 81 km^2 is in Very Dense Forest (VDF), 94 km^2 is in Moderately Dense Forest (MDF) and 84 km^2 is in Open Forest (OF). It lies between latitude 17°47' and 22°34' N and longitude 81°22' and 87°29' E. Physiographically, the state can be divided into four regions, viz., Northern Plateau, Eastern Ghats, Central Tableland, and Coastal Plains. The three major rivers of the state are Mahanadi, Brahmani, and Baitarni. The total length of the coast line in Orissa is about 430 km and this coastline is mainly in the depositional stages, with the sediments carried down by the rivers, Mahanadi and other two minor rivers, i.e., the Brahmani and the Baitarani. Bhitarkanika Forest Reserve is home to diverse flora and fauna including some endangered species and is the second largest mangrove forest in India.

Bhitarkanika is the third important mangrove habitat among the Indian mangals with respect to mangrove species diversity. Important mangrove and mangrove associate species of the Mahanadi-Brahmani-Baitarani deltas are Avicennia alba, Avicennia officinalis, Aegiceras corniculatum, Aegialitis rotundifolia, Acrostichum aureum, Bruguiera parviflora, Bruguiera gymnorrhiza, Bruguiera cylindrica, Ceriops decandra, Excoecaria agallocha, Heritiera kanikensis (rare & endemic), Heritiera fomes, Kandelia candel, Phoenix paludosa, Porteresia coarctata, Sonneratia apetala, Rhizophora mucronata, Rhizophora apiculata, and Salvadora persica. Bhitarkanika is the important natural breeding place of estuarine crocodiles (Crocodilus porosus) and several species of threatened sea turtles, Lepidochelys olivacea, Batagur baska and the king crab, Carcinoscopius rotundicauda and Tachypleus gigas.

1.11 Mangrove Forest of Tamil Nadu State

The State of Tamil Nadu has a geographical area of 1,30,060 km^2, out of which an area of 23,188 km^2 is under forests (RFA), which accounts to 18% of the geographical area. The forest cover in the State is 26,419 km^2, of which only 45 km^2 is mangrove (ISFR 2021). The mangrove forest is distributed in all the three density classes of which 1 km^2 is in Very Dense Forest (VDF), 27 km^2 is in Moderately Dense Forest (MDF) and 17 km^2 is in Open Forest (OF). The State is situated at the south eastern extremity of the Indian peninsula bounded on the north by Karnataka and Andhra Pradesh, on the east by Bay of Bengal, on the South by the Indian Ocean and on the West by Kerala. It has one of the longest coastlines in India with 13 coastal districts.

Tamil Nadu has major mangrove wetlands in two areas: Pichavaram in Cuddalore District and the other in Muthupet region in Thiruvarur, Thanjavur Districts. The Pichavaram mangrove covers an area of 1,100 ha and the Muthupet mangrove forest spreads over an area of approximately 6,800 ha on the southeast coast of the peninsular India. Small patches of mangroves are also present along the Palk Bay, particularly in the Devipattinam region and also in some of the islands of the Gulf of Mannar in Ramanathapuram District.

Pichavaram has a well-developed mangrove forest dominant with Rhizophora spp., Avicennia marina, Excoecaria agallocha, Bruguiera cylindrica, Lumnitzera racemosa, Ceriops decandra and Aegiceras corniculatum . Mangroves also occur near places like Vedaranyam, Kodiakarai (Point Calimere), Muthupet, Chatram and Tuticorin **(Basha, 2018).**

1.12 Mangrove Forest of West Bengal State

The State of West Bengal has a geographical area of 88,752 km^2, out of which an area of 11,879 km^2 is under forests (RFA), which accounts to 13% of the geographical area. The forest cover in the State is 16,832 km^2, of which only 2,114 km^2 is mangrove (ISFR 2021). The mangrove forest is distributed in all the three density classes of which 994 km^2 is in Very Dense Forest (VDF), 692 km^2 is in Moderately Dense Forest (MDF) and 428 km^2 is in Open Forest (OF). The State occupies a latitudinal range of 21°31′ N to 22°30′ N and the longitudinal range of 88°10′ E to 89°51′ E. In the State, the mangroves mainly exist in the Sunderbans area which is largest single block of halophytic mangroves of the world. These are in the form of dense forest along the east and the south east part of the coast. Sundarbans lies in the delta of two rivers, the Ganges and the Brahmaputra of the Indian subcontinent (FAO, 2007). It spreads over the

southern part of South 24 Parganas and North 24 parganas districts in India. The rivers Raimangal and Hoogly on the east and west, respectively, demarcate the boundary of the Sundarbans within India. The term 'Sundarbans' came into existence either from the vernacular name 'Sundri' of the once prevalent mangrove species Heritiera fomes or from the words 'Sundar' (meaning beautiful) and 'ban' (meaning forest) i.e. beautiful forest (**Naskar and Guha Bakshi, 1987**).

The major species of the dense mangrove forest include Heritiera fomes, Rhizophora apiculata, Rhizophora mucronata, Bruguiera gymnorrhiza, Bruguiera parviflora, Ceriops decandra, Sonneratia apetala, Sonneratia caseolaris and Avicennia spp. Nypa fruticans is the major species found on the creek side and in sparse categories. Phoenix paludosa almost cover all the tidal zones of the Sunderbans. Avicennia marina, Avicennia alba and Bruguiera cylindrica grow in the lower coastal sections while Bruguiera gymnorrhiza, Ceriops decandra and Rhizophora mucronata are more common upstream. The least salt-tolerant taxa, found in riverine environments and more common to the east, are the eponymous Sundari-tree Heritiera fomes, Excoecaria agallocha and Sonneratia caseolaris (**Ghosh, A., 2015**).

1.13 Mangrove Forest of Andaman & Nicobar Islands

The UT of Andaman & Nicobar Islands has a geographical area of 8,249 km^2, out of which an area of 7,171 km^2 is under forests (RFA), which accounts to 87% of the geographical area. The forest cover in the State is 6,744 km^2, of which only 616 km^2 is mangrove (ISFR 2021). The mangrove forest is distributed in all the three density classes of which 399 is in Very Dense Forest (VDF), 168 km^2 is in Moderately Dense Forest (MDF) and 49 km^2 is in Open Forest (OF). Andaman and Nicobar Islands are the largest archipelago which comprises of more than 572 scattered islands, islets and rocky outcrops. The Andaman groups of islands are the emerged part of a mountain chain and lie on a ridge which extends south-ward from the Irrawaddy delta areas of Burma. They have been divided into north, middle, south and little Andaman. The Nicobar groups of islands are high islands forming part of an emerged mountain chain, continuing that of the Andamans. On the Andaman & Nicobar Islands, there are many small tidal estuaries, long inlets and the lagoons which support a dense and diverse mangrove flora. The tidal creeks of Andaman and Nicobar Islands often form the outlets to the rain-fed stream that flow from the interior and carry silt to the shore to form muddy plains facilitating the spread and regeneration of mangroves.

The A&N Islands are endowed with diverse mangroves, next only to Sundarbans and Gujarat in the floristic diversity. In Andaman and Nicobar Islands, 34 true mangrove species belonging to 15 genera, 10 orders and 12 families have been documented (Roy et al., 2009). The major mangrove species known in Andaman are Scyphiphora hydrophyllacea, Cynometra iripa, Avicennia marina, Avicennia officinalis, Excoecaria agallocha, Bruguiera cylindrica, Bruguiera gymnorrhiza, Bruguiera parviflora, Bruguiera sexangula, Ceriops tagal, Rhizophora apiculata, Rhizophora mucronata, Rhizophora stylosa, Heritiera littoralis, Lumnitzera littorea, Lumnitzera racemosa, Sonneratia alba, Sonneratia caseolaris, Sonneratia ovata, Aegiceras corniculatum, Xylocarpus granatum, Nypa fruticans and Phoenix paludosa. This community of transition mangroves comprises of Cerbera odalum, Scyphiphora, Cynometra, Intsia bijuga, Flageleria indica, Fimbxylistis, Excoecaria ebractata, etc.

Mangroves of the Nicobar group of islands have been destructed by the tsunami waves and in almost all the islands, degraded mangroves dominate in the area contribution, followed by dense Rhizophora-Bruguiera, Avicennia- Excoecaria, mixed dense, Nypa (dense) and fringe mangroves.

1.14 Mangrove Forest of Dadra & Nagar Haveli and Daman & Diu

The UT of Dadra & & Nagar Haveli and Daman & Diu has a geographical area of 602 km^2, out of which an area of 214 km^2 is under forests (RFA), which accounts to 36% of the geographical area. The forest cover in the State is 228 km^2, of which only 3 km^2 is mangrove (ISFR 2021). The mangrove forest is in only Open Forest (OF) density class which is 3 km^2. With an area of 602 km^2, it was the smallest administrative subdivision of India on the mainland. The territory comprised three districts, Dadra & Nagar Haveli, Daman and Diu, geographically separated by the Gulf of Khambat. The state of Gujarat and the Arabian Sea bordered the territory. Four mangrove species viz., Avicennia marina, Acanthus ilicifolius, Aegiceras corniculatum and Sonneratia apetala have been recorded from the UT **(Sharma and Sikarvar, 2014)**.

1.15 Mangrove Forest of Puducherry

The UT of Puducherry has a geographical area of 490 km^2, out of which an area of 13 km^2 is under forests (RFA), which accounts to 3% of the geographical area. The forest cover in the State is 53 km^2, of which only 2 km^2 is mangrove (ISFR 2021). The mangrove forest is

distributed in only one density class i.e. Open Forest (OF) having an area of 2 km^2. The UT is scattered over four locations, each having the status of a district: Puducherry (Tamil Nadu), Karaikal (Tamil Nadu), Yanam (Andhra Pradesh) and Mahe (Kerala). Puducherry lies on the Coromandal coast between 11° 46' and 12° 30' N latitude and between 79° 36' and 79° 52' E longitude. Karaikal lies on the east coast about 150 km south of Puducherry and 300 km south of Chennai located on the Coromandel Coast of the Bay of Bengal. Mahe is situated on the west coast in Kerala, on the Malabar coast of the Arabian Sea. Yanam is situated on the east coast and falls in the state of Andhra Pradesh (Coastal zones of India, 2012).

The mangrove forest of Puducherry is classified into eight communities. Avicennia marina and Avicennia officinalis species are the prominent constituents of the different communities in majority of mangrove forests in Puducherry. **Avicennia marina - Moderately Dense** This community is found in some areas in Yanam but dominates the mangrove forests in Puducherry and Karaikal. A small pure patch of moderately dense Avicennia marina is present at the extreme northern part of Yanam district in the west of Gaderu channel. On the other hand, a very big patch of the same community is present in the backwater area at Thengaithettu-Puducherry. **Avicennia marina – Sparse** Small patches of sparsely dense pure Avicennia marina are present only in the Puducherry and Karaikal districts at the places namely, Huppalam (old port area) in Puducherry district and near Arsalar river at Vikram Sarabhai Road in Karaikal district. **Avicennia officinalis - Moderately Dense** Small patches of pure Avicennia officinalis in moderately dense condition are present mainly in Yanam district near to Gaderu channel area. These patches are facing threats of degradation because of the construction of a refinery in the nearby area. **Excoecaria agallocha - Moderately Dense** Pure patch of moderately dense Excoecaria agallocha is present only in Karaikal district at a place commonly known as Pilaithirunasal. This patch is a three kilometre long stretch along the Nula river. **Avicennia marina – Excoecaria agallocha -Moderately Dense** This community is present only at the eastern most part of Yanam district near to the Gaderu river. **(Coastal zones of India, SAC, 2012).**

1.16 Five Carbon pools

The carbon stock refers to the amount of carbon stored in forests in the form of above ground biomass (AGB), below ground biomass (BGB), soil organic carbon (SOC), deadwood and litter. Together these five are called 5 carbon pools. In forest ecosystems, extensive amount of

carbon gets stored in these 5 carbon pools **(GPG, 2003)**. Diagrammatic representation of carbon pools is shown in figure 1.3.

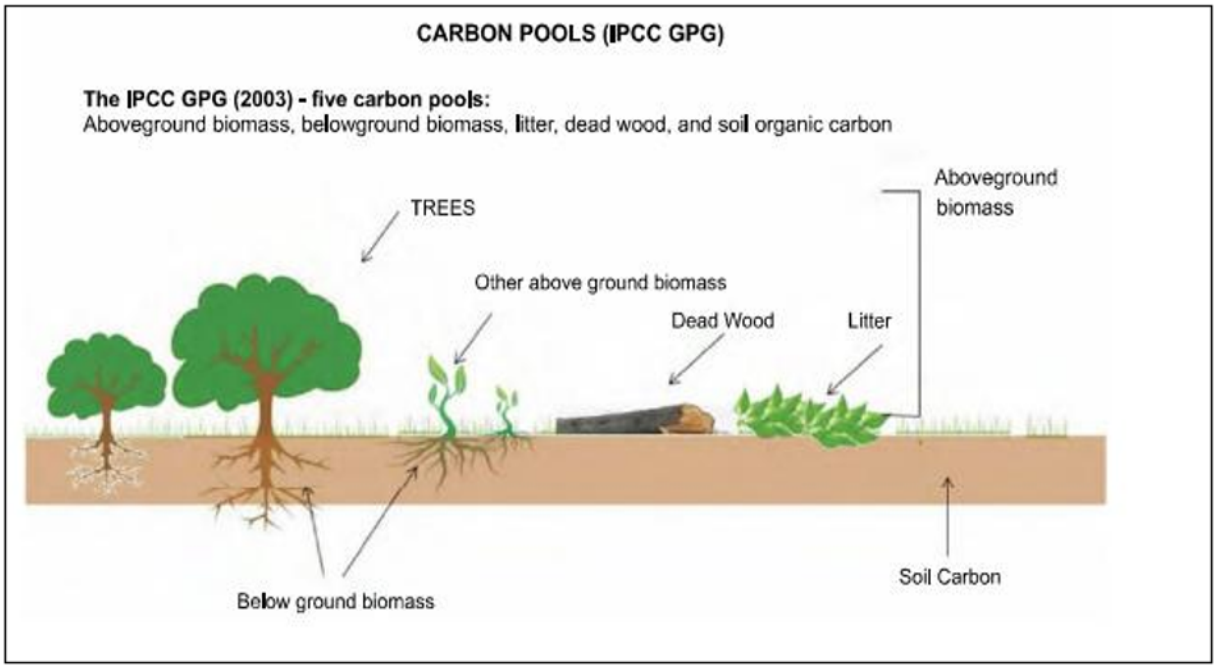


Figure 1.3. Pictorial representation of five Forest Carbon Pools

Table 1.2: Description of five forest carbon pools

Pools		Description
Living Biomass	**Above ground biomass (AGB)**	All living biomass above the soil including stems, stumps, branches, bark, seeds and foliage.
	Below ground biomass (BGB)	All living biomass of live roots. Fine roots of less than 2mm diameter are excluded because these cannot be distinguished from soil organic matter or litter.
Dead organic carbon	**Dead wood**	All non-living woody biomass standing or lying on the ground. Dead wood also includes dead roots and stumps larger than or equal to 5 cm in diameter.
	Litter	All non-living biomass with a diameter less than 5cm (FSI), lying dead in various states of decomposition above the organic soil.
Soil	**Soil organic carbon**	Organic carbon in mineral and organic soils to a depth of 30 cm (FSI).

Table 1.3: Table showing forest canopy density classes with respect to crown density range

Forest Cover	Canopy density range
Very Dense Forest (VDF)	**≥ 70 %**
Moderately Dense Forest (MDF)	**≥ 40 % but < 70 %**
Open Forest (OF)	**≥ 10 % but < 40 %**

CHAPTER 2
MATERIALS, METHODS & FIELD STUDY

2.1 Objective of the study

India is having vast mangrove cover spread across 12 States & UTs, namely; West Bengal, Gujarat, A&N Islands, Andhra Pradesh, Maharashtra, Odisha, Goa, Karnataka, Kerala, Tamil Nadu, Dadra & Nagar Haveli & Daman & Diu and Puducherry. Mangrove forest store more carbon than other type of forest and are considered as a sink and source of carbon. Quantification of carbon stored in mangrove forest is fetching a significant role in carbon accounting. Carbon stock estimation of mangrove forest in India is the major objective of this study.

Broadly, forest cover has been classified in very dense, moderately dense and open canopy density classes and accordingly carbon stored in different density classes varies. Carbon stored in the forest broadly depends upon canopy density. So, very dense, moderately dense and open canopy density classes have been used for stratification for assessment of carbon in mangrove forests over all the mangroves States/UTs in this study.

Carbon pools are reservoirs of carbon that have the capacity to take in and release carbon. Broadly, carbon pools are divided in five pools namely above ground biomass, below ground biomass, soil organic carbon, deadwood and litter. The objective of the study is to estimate the carbon stock in all the 5 carbon pools in mangrove forest.

As mangrove are complex ecosystem so traditional method of surveying and data collection is quite difficult process. Remote sensing technology is proving to be boon for monitoring inaccessible complex eco-systems on earth. Accurate and precise estimation of carbon stock is required for further Climate Change studies. Tree height is important parameter for carbon estimation and LiDAR technology is proved to be recent advanced technique and used in many published studies for precise tree height retrieval.

For the carbon estimation of the mangrove in the present study, NASA's Ice, Cloud and land Elevation Satellite-2 (IceSat-2) LiDAR data, launched in year 2018 has been used. Mean canopy height and canopy openness retrieved from LiDAR data for all mangrove forest in different density classes have been used for model development with the help of field data collected from the ground for the three states.

2.2 Materials, Methods and Field study

Mangroves are efficient at sequestering carbon and may contribute to climate change mitigation efforts **(Bouillon et al., 2008; Kristensen et al., 2008)**. Measuring biophysical and

structural parameters within mangrove forests to estimate biomass and quantify mangrove blue carbon storage is difficult and labor intensive **(Wannasiri et al., 2013)**. Direct measurements of above ground biomass (AGB) require extraction, drying and weighing of stems, roots, trunks, leaves from forests. These measurements can be used to develop allometric equations and these equations can then be applied elsewhere **(Owers et al., 2018).** Allometric assessments still require the measurement of mangrove structural parameters like tree height (H) and DBH (diameter at breast height), which can be difficult to obtain due to inaccessibility to field plots because of unstable substrates and complex root system. Both direct measurements and allometric approaches require extensive field work; due to which, blue carbon inventories of large mangrove forest areas are rarely undertaken **(Salum et al., 2020).**

Remote sensing is a powerful technique of mapping and monitoring mangroves because of their distinct structural characteristics and signatures which are easily detectable on the satellite images. Mangrove phenology and NDVI relationship enabled the application of NDVI for studying the effect of periodic and episodic events on mangrove AGB, including seasonal wet and dry periods **(Brooke et al., 2017).** Traditional remote sensing approaches enable mapping of mangrove extent such as NDVI (Normalized Difference Vegetation Index) technique **(Kovacs et al., 2010; Kuenzer et al., 2011; Zhang et al., 2013).** Study of mangrove phenology in relation with NDVI depicts the effect on mangrove AGB in dry and wet seasons **(Brooke et al., 2017).**

In Indian context, study done by **Suresh et al (2017) and Chave et al (2005)**, developed allometric equation for AGB estimation of Rhizophora mucronata mangrove species using equation AGB = ρ*exp (–1.349+1.980*ln D) + 0.207*(ln)) ^2–0.0281(ln (D))^3), Where ρ = wood specific gravity (g cm–3), D = DBH. **Bhavsar et al (2020) and Pandey et al (2013)** studied mangrove forest of Gujarat in Saurashtra, Gulf of Cambay and Gulf of Kachchh on species Avicennia marina (Bain Tree) using equations for Above Ground Biomass A (kg) = 0.0509*ρ*(sqr D)*H, Below ground biomass B (kg) =0.199*ρ*0.899* (D) ^ 2.22; where ρ is the wood density of the species, D = Diameter at breast height , H = Height.

Advanced remote sensing techniques such as SAR (Synthetic Aperture Radar) and LiDAR (Light Detection and Ranging) provides scope for structural information extraction over mangrove forests **(Heumann, 2011; Lagomasino et al., 2016).** PolSAR (Polarimetric Synthetic Aperture Radar), InSAR (Interferometric Synthetic Aperture Radar) and LiDAR (Light Detection and Ranging) provide an opportunity to extract mangrove structural information. Many studies concluded that SAR (Synthetic Aperture Radar) images have ~~been~~ provided significant information about AGB **(Cougo et al., 2015; Lucas et al., 2015; Proisy**

et al., 2000). Airborne LiDAR has been widely utilized in forestry to map forest structure **(Popescu, 2007; Zhao et al., 2009). Fatoyinbo et al (2018)** correlated field based heights of the tallest trees in plots with estimates of tallest trees in a LiDAR point cloud to determine AGB; **Rocha de Souza, Pereira et al (2018)** correlated point cloud distribution metrics with field based AGB measurements to estimate total mangrove AGB for a region; and **Hickey et al (2018)** averaged LiDAR derived height measurements for a mangrove stand to generate a mean stand height that could be applied to global stand height-biomass allometric equation developed by **Saenger and Snedaker (1993).**

LiDAR is a laser scanner that uses a pulsed laser to measure distances to the Earth's surface. The sensor measures the return time of laser pulses that is calibrated using a GPS (global positioning system) to provide absolute x, y and z values for each returned pulse. With the increasing need to quantify carbon stored within forests for national carbon accounts, as required under the United Nations Framework Convention on Climate Change **(UNFCCC, 2014),** other carbon related payment for ecosystem services schemes e.g. REDD+ (Reducing Emissions from Deforestation and Degradation) and voluntary carbon markets the application of LiDAR data may offer enhanced accuracy when estimating mangrove AGB and will be powerful tool for quantifying the carbon sequestered by mangrove forests **(Salum et al., 2020).**

Information about three-dimensional structure of forests related to ecosystem health and functioning is necessary to promote sustainable management of forests **(Narine et al., 2020)**. At global scale robust information about the three-dimensional structure of forests helps in to improve the uncertainties in the carbon budget and to aid better understanding of climate change. For this study, National Aeronautics and Space Administration's (NASA's) Ice, Cloud and land Elevation Satellite-2 (IceSat-2) (launched in Year 2018) ALT08 (Land Water Vegetation Elevation) products have been used.

2.3 Overview of ICESat-2 satellite

ICESat-2 (Ice, Cloud and land Elevation Satellite-2) is the Advanced Topographic Laser Altimeter System (ATLAS) that uses 532 nm wavelength laser beam and creates 3 pairs of beams on the Earth's surface which are approx. 3.3 km apart, at a repetition rate of 10kHz **(Markus et al., 2017)**. ICESat-2 began its 3-year mission in September 2018 and carries a photon – counting light detection and ranging (PCL) instrument, which records elevation measurements through transects along the Earth's surface **(Narine et al., 2020)**. Within pairs,

there is 90 meter spacing and instrument generates 17-meter diameter footprints every 0.7 meter in along – track direction **(Narine et al., 2020)**. ATLAS instrument work on the photon-counting detection technology that improve the along track resolution due to high repetition rate of laser beam **(Neuenschwander and Margruder 2019)**.

Figure 2.1 is showing diagrammatic representation of IceSAT-2 LiDAR laser scanning over earth surface. Each ground track beam pair consist of GT3R and GT3L; strong and weak energy beam respectively. Strong beams acts for lower reflectance objects e.g. vegetation and weak beams provides data in night acquisitions when the background noise rate is small **(Neuenschwander and Margruder, 2019)**. So both the beams are extracted for canopy matrices calculation. The IceSat-2 mission provide data of different surface types that include land ice (ALT06), sea ice (ALT07), land/vegetation (ALT08) **(Neumann et al, 2019)**, atmosphere (ALT09), oceans (ALT12) and inland water (ALT13). ALT08 algorithm has been mainly developed for the extraction of terrain and canopy height at a 100-meter step size in along track direction.

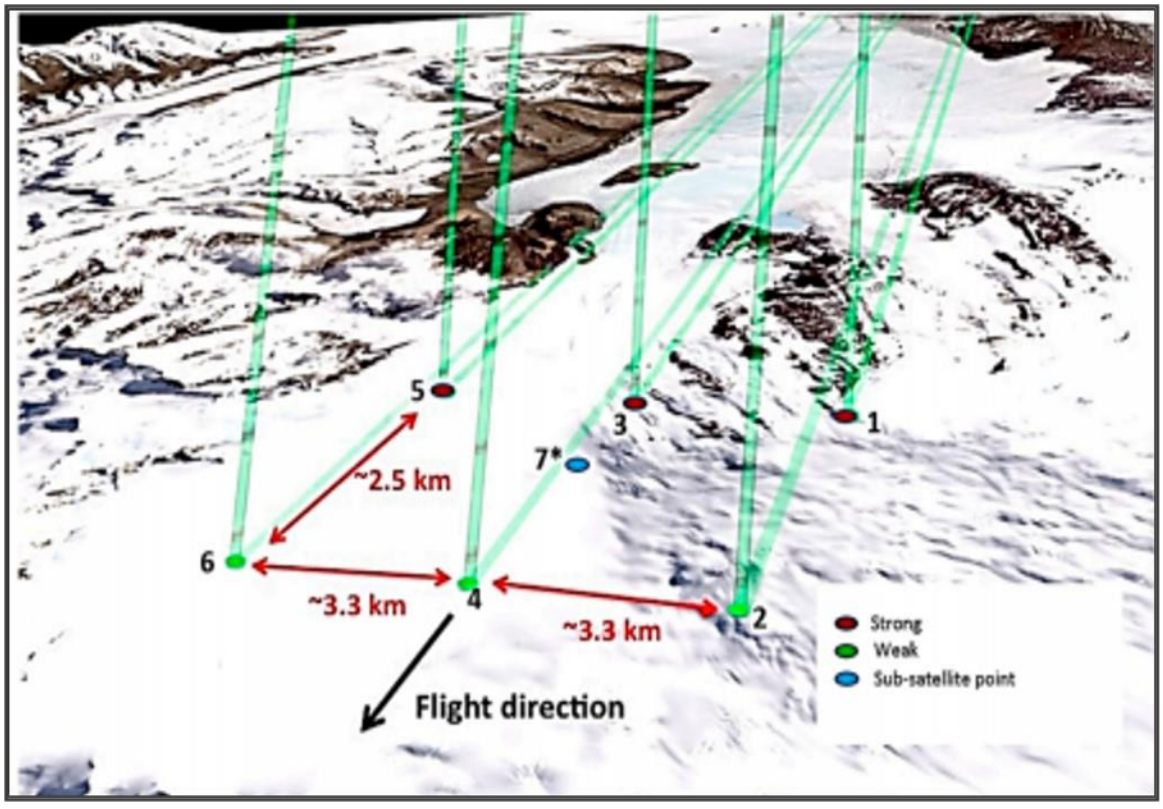


Figure 2.1 Ice, Cloud and land Elevation Satellite-2 (ICESat-2) beam configuration on the Earth's surface

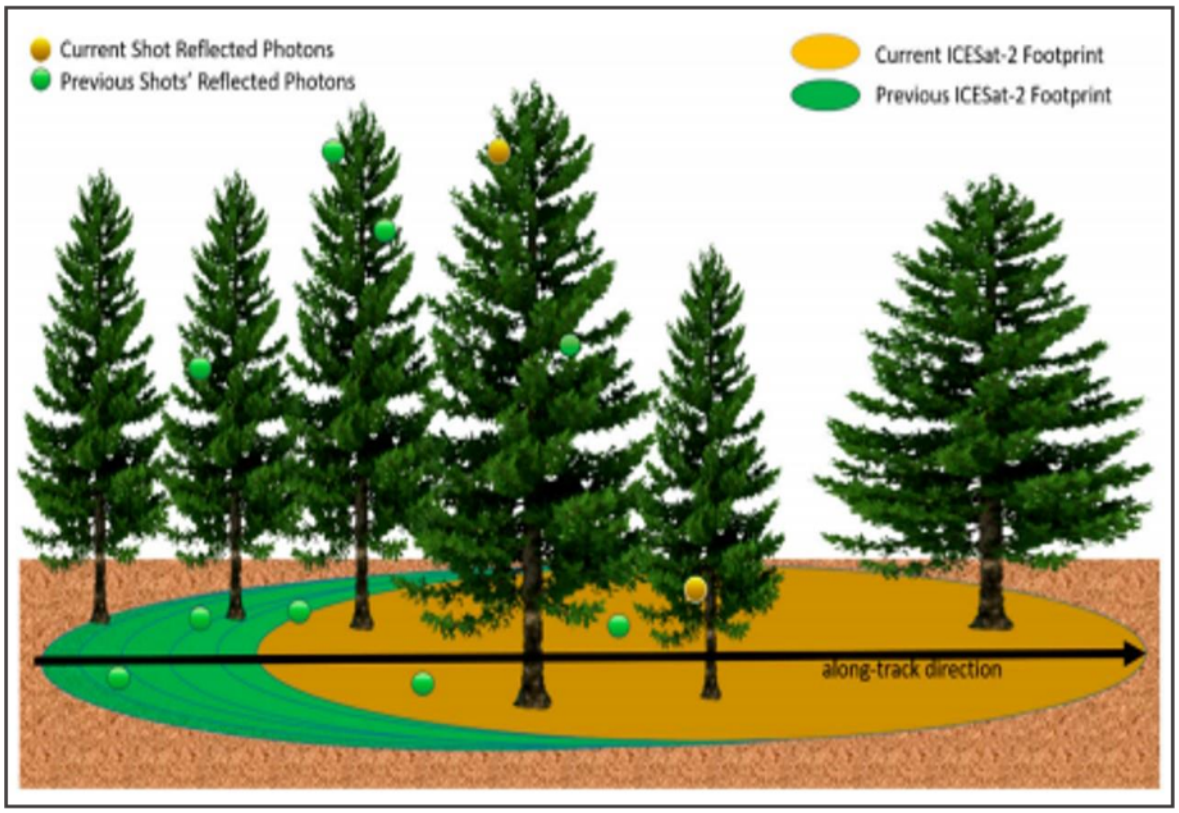


Figure 2.2 ICESat-2 photon sampling over vegetation

Figure 2.2 is showing the laser scanning over forest. The first recorded signals are reflected by the highest surface, in case of mangrove forest, this is upper canopy foliage and the last return signal have been reflected from the bare earth. Point cloud data processed and developed in 3D model of forest stand has been shown in figure 2.3.



Figure 2.3 3D tree height model developed after processing LiDAR point cloud data

2.4 Method

ALT08 data product are extracted over Mangrove forests between Years 2018 to 2020. ALT08 product consist of many granules having detected photons. An overview of methodology depicting in flow chart for estimating AGB with ICESat-2 data is provided in figure 2.4.

2.4.1 ICESat-2 ALT08 product data download

Classified raster data of Mangrove forest for all the 12 States/UTs has been acquired from Forest Geo-Informatics Division (FGD) of Forest Survey of India (ISFR 2019). Classified mangrove forest Raster layer has been converted to vector layer to get the polygon of mangrove forest of all the corresponding states using "Raster to Polygon" conversion tool on ARC GIS ver. 10.8.1. Figure 2.5 is showing raster to polygon conversion. Polygon of mangrove forests are extracted and overlaid on Earth data website's search map for locating the ICESat-2 ALT08 data product granules within the polygon. ICESat-2's ALT08 product for all the 12 States/UTs over mangrove forest's area are downloaded except for Dadra & Nagar Haveli & Daman & Diu Union territory (LiDAR tracks not available on Mangrove cover of Dadra & Nagar Haveli & Daman & Diu) from NASA's Earth data website (https://nsidc.org/data/ATL08/versions/3) in Hierarchical Data Format –version 5 (HDF-5). Mean canopy height, canopy openness latitude and longitude data has been extracted from 100-meter Point Cloud Library (PCL) segments of ALT08 data product.

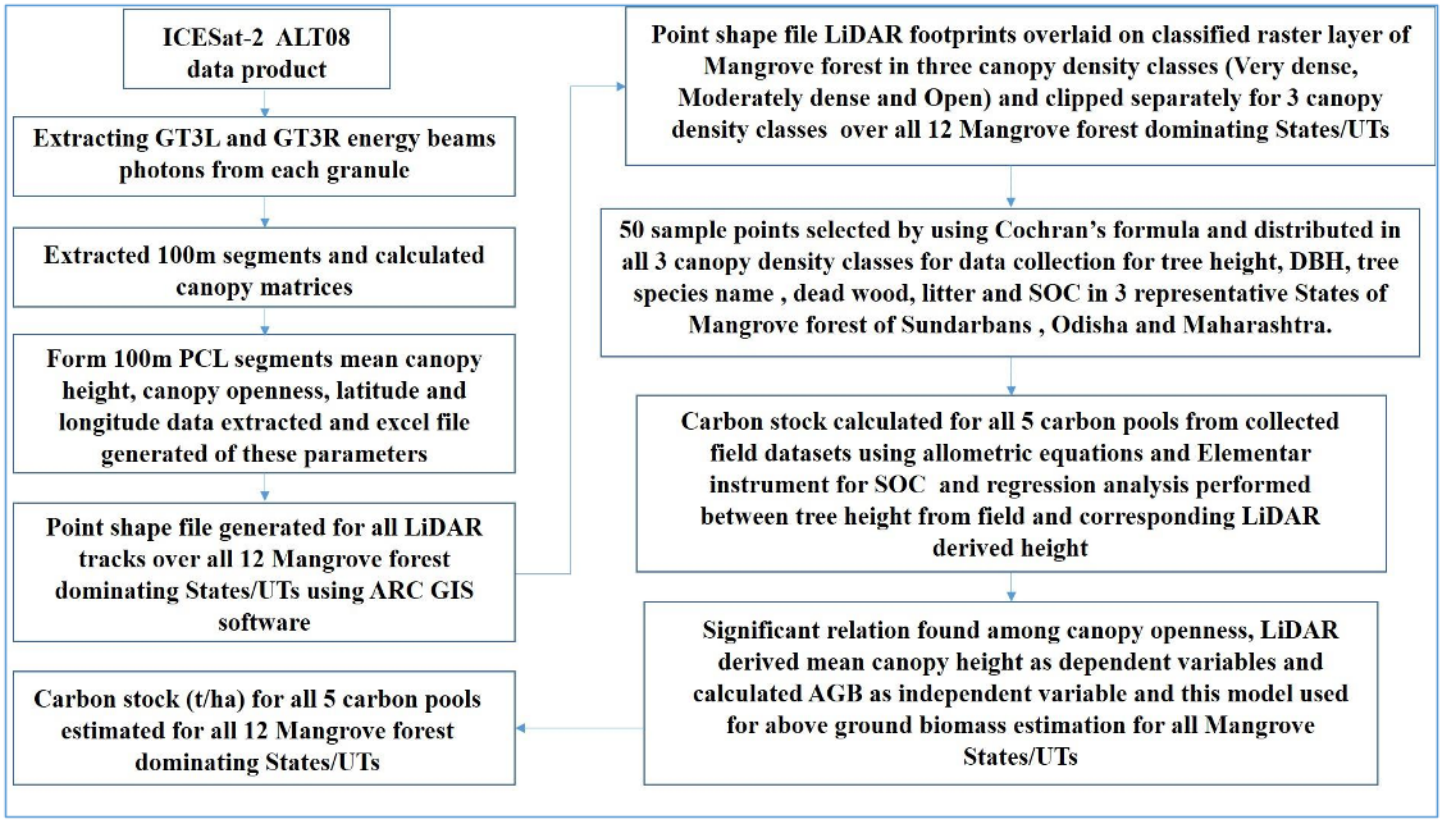


Figure 2.4 An overview of methodology

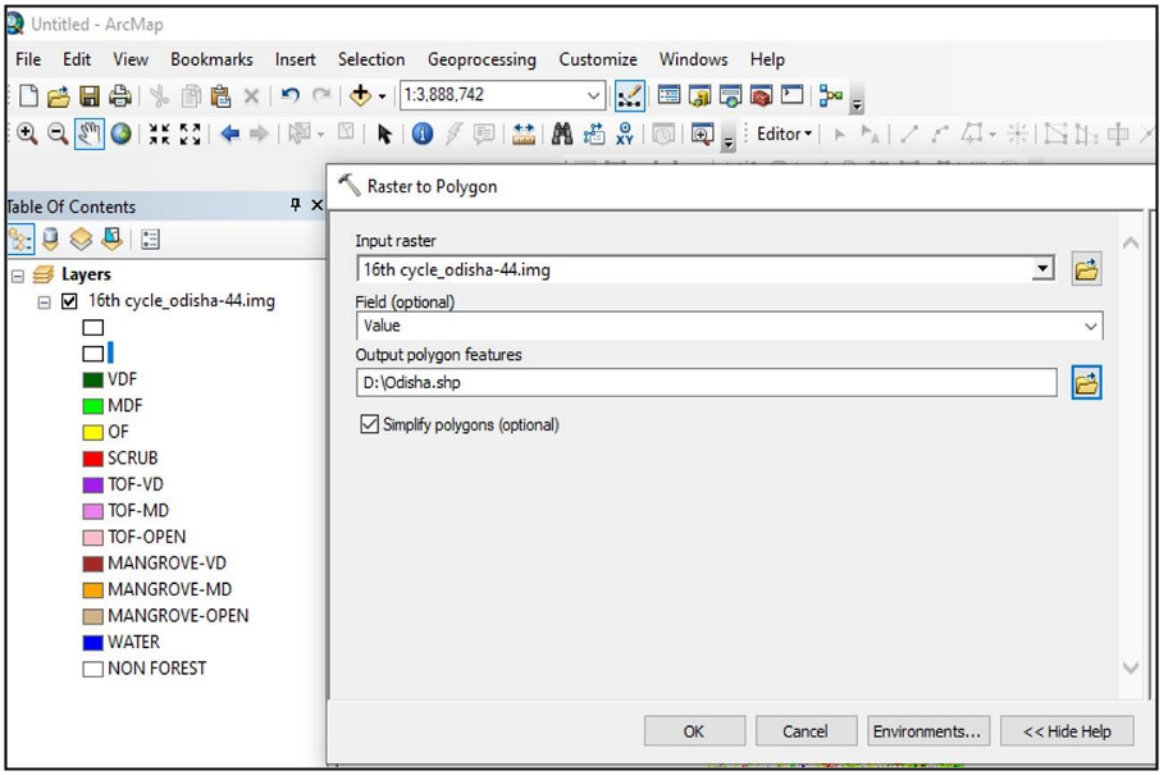


Figure 2.5 Raster to polygon conversion in ARC GIS software

ICESat-2 ALT08 data product has 6 ground track (GT) beams namely GT1L, GT1R, GT2L, GT2R, GT3L, GT3R respectively and each beam broadly contains 2 segments of data i.e. land segments and signal segments. Inside land segment latitude, longitude parameters are available and this land segment contains Canopy sub-segment where canopy height and canopy openness parameters are available. Latitude, longitude, canopy height and canopy openness parameters for all the 3 pairs of beams read for all the LiDAR tracks over all 12 States/UTs mangrove forest and downloaded. Figure 2.6 is showing the ICESat-2 tracks over Andhra Pradesh State.

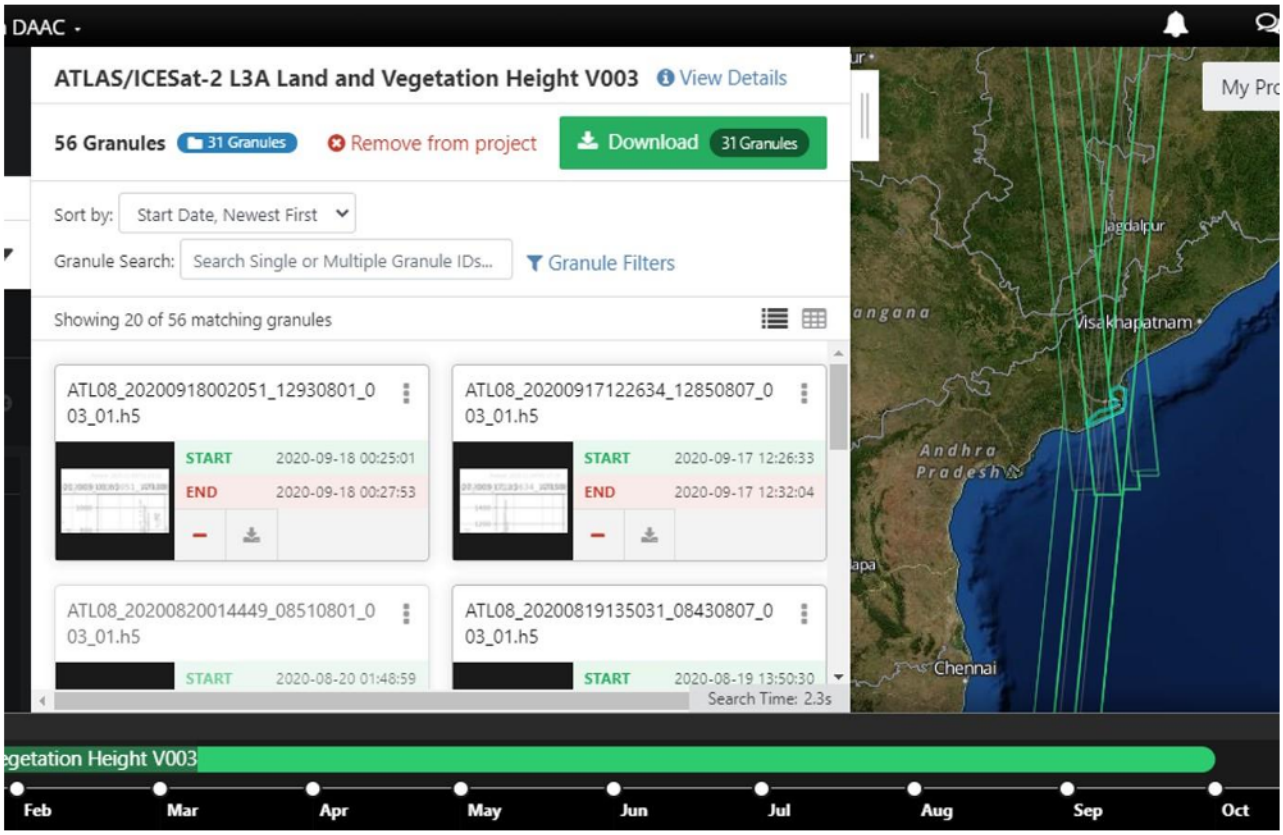


Figure 2.6 IceSat2 ALT08 Data Product Footprints over Mangrove of Andhra Pradesh

These data are in *.H5 format. Data extraction has been done in HDFView ver. 3.1.1 software. HDFView software consists of the HDFView utility and the Java HDF Object Package. HDFView is a visual tool written in Java for browsing and editing HDF (HDF5 and HDF4) files. Data granules are imported and read in HDFView software and latitude, longitude, canopy height and canopy openness parameters within canopy section of data from each pair of beams are exported in Microsoft excel.



Figure 2.7 Extraction of ALT08 data product in HDF View software

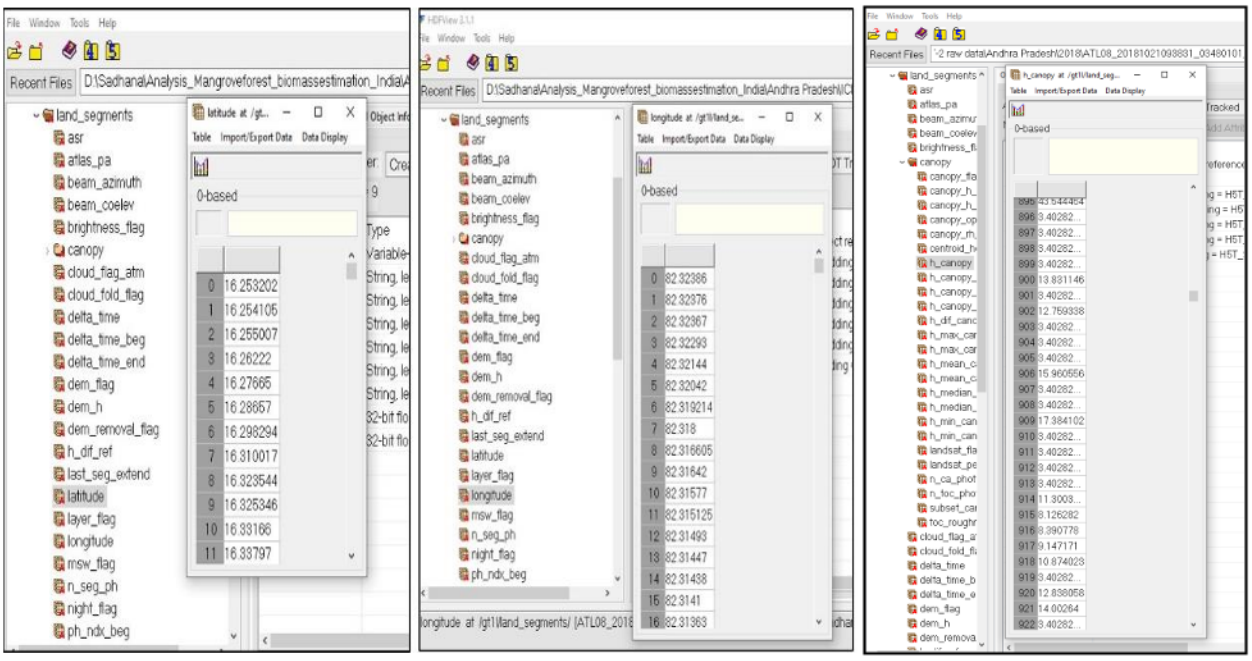
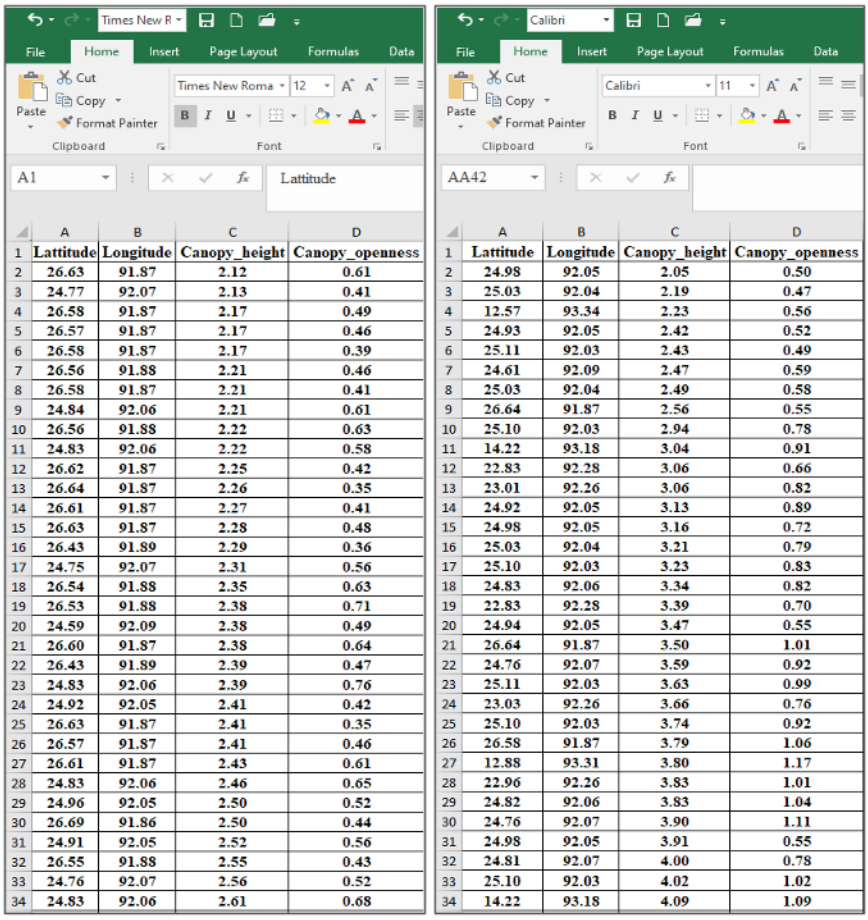


Figure 2.8 Export of latitude, longitude, mean canopy height and canopy openness parameters from beams



	A	B	C	D
1	Lattitude	Longitude	Canopy_height	Canopy_openness
2	26.63	91.87	2.12	0.61
3	24.77	92.07	2.13	0.41
4	26.58	91.87	2.17	0.49
5	26.57	91.87	2.17	0.46
6	26.58	91.87	2.17	0.39
7	26.56	91.88	2.21	0.46
8	26.58	91.87	2.21	0.41
9	24.84	92.06	2.21	0.61
10	26.56	91.88	2.22	0.63
11	24.83	92.06	2.22	0.58
12	26.62	91.87	2.25	0.42
13	26.64	91.87	2.26	0.35
14	26.61	91.87	2.27	0.41
15	26.63	91.87	2.28	0.48
16	26.43	91.89	2.29	0.36
17	24.75	92.07	2.31	0.56
18	26.54	91.88	2.35	0.63
19	26.53	91.88	2.38	0.71
20	24.59	92.09	2.38	0.49
21	26.60	91.87	2.38	0.64
22	26.43	91.89	2.39	0.47
23	24.83	92.06	2.39	0.76
24	24.92	92.05	2.41	0.42
25	26.63	91.87	2.41	0.35
26	26.57	91.87	2.41	0.46
27	26.61	91.87	2.43	0.61
28	24.83	92.06	2.46	0.65
29	24.96	92.05	2.50	0.52
30	26.69	91.86	2.50	0.44
31	24.91	92.05	2.52	0.56
32	26.55	91.88	2.55	0.43
33	24.76	92.07	2.56	0.52
34	24.83	92.06	2.61	0.68

	A	B	C	D
1	Lattitude	Longitude	Canopy_height	Canopy_openness
2	24.98	92.05	2.05	0.50
3	25.03	92.04	2.19	0.47
4	12.57	93.34	2.23	0.56
5	24.93	92.05	2.42	0.52
6	25.11	92.03	2.43	0.49
7	24.61	92.09	2.47	0.59
8	25.03	92.04	2.49	0.58
9	26.64	91.87	2.56	0.55
10	25.10	92.03	2.94	0.78
11	14.22	93.18	3.04	0.91
12	22.83	92.28	3.06	0.66
13	23.01	92.26	3.06	0.82
14	24.92	92.05	3.13	0.89
15	24.98	92.05	3.16	0.72
16	25.03	92.04	3.21	0.79
17	25.10	92.03	3.23	0.83
18	24.83	92.06	3.34	0.82
19	22.83	92.28	3.39	0.70
20	24.94	92.05	3.47	0.55
21	26.64	91.87	3.50	1.01
22	24.76	92.07	3.59	0.92
23	25.11	92.03	3.63	0.99
24	23.03	92.26	3.66	0.76
25	25.10	92.03	3.74	0.92
26	26.58	91.87	3.79	1.06
27	12.88	93.31	3.80	1.17
28	22.96	92.26	3.83	1.01
29	24.82	92.06	3.83	1.04
30	24.76	92.07	3.90	1.11
31	24.98	92.05	3.91	0.55
32	24.81	92.07	4.00	0.78
33	25.10	92.03	4.02	1.02
34	14.22	93.18	4.09	1.09

Figure 2.9 Excel sheet showing Latitude, Longitude, canopy height and canopy openness values from gt1l and gt1r beam

Figure 2.9 is showing Processed excel sheet having latitude, longitude, canopy height and canopy openness parameters from GT1L and GT1R beam. All the beams downloaded from LiDAR footprint over mangrove forest of all the 12 States/UTs has been processed and excel file created for all with latitude, longitude, canopy height and canopy openness parameters. LiDAR footprints over all 12 States/UTs Mangrove forests except Dadra & Nagar Haveli & Daman & Diu union territory Point shape file has been generated for all LiDAR tracks using ARC GIS software. Figure 2.10 is showing LiDAR footprint over moderately dense and open forest in mangrove forest layer of Andhra Pradesh State. LiDAR tracts have been overlaid on classified mangrove raster layer of Andhra Pradesh State and the LiDAR footprints have been clipped within the forest boundary. 60 and 58 LiDAR footprints are extracted from moderately dense and open forest respectively having total 1403 photons. Figure 2.11 is showing ICESat-2 ALT08 product footprint over moderately dense and open forest in Coringa Mangroves of Andhra Pradesh State.

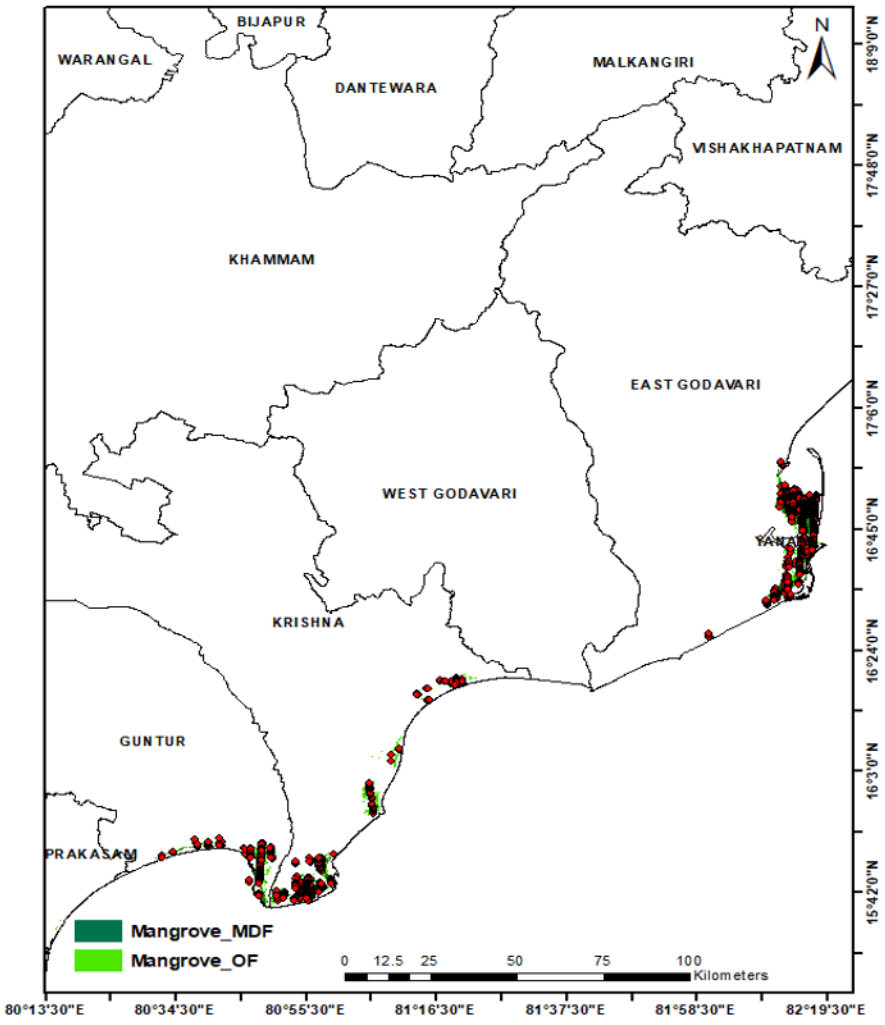


Figure 2.10 ICESat-2 ALT08 product footprint over moderately dense and open Mangrove forest of Andhra Pradesh State

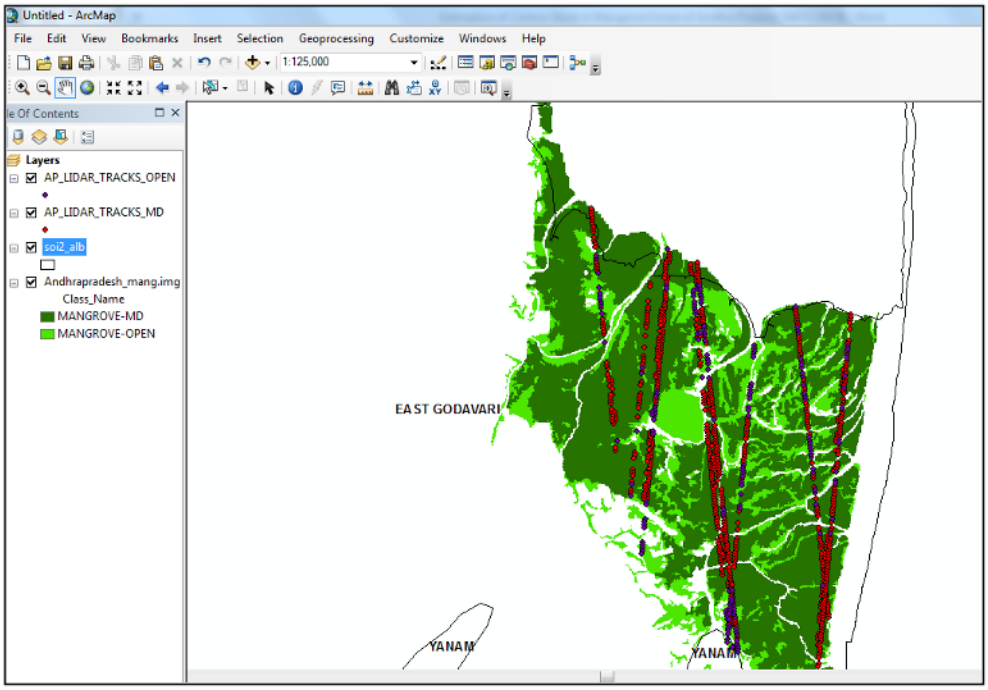


Figure 2.11 ICESat-2 ALT08 product footprint over Moderately dense and open forest in Coringa Mangroves of Andhra Pradesh State

2.5 Field data collection

Strategy for field data collection has been decided by considering the area under mangrove forest in States/UTs, tree species diversity and canopy density classes (Among all 12 states / UTs i.e., Andhra Pradesh, Andaman & Nicobar Islands, Dadra & Nagar Haveli & Daman & Diu, Goa, Gujarat, Kerala, Karnataka, Maharashtra, Odisha, Puducherry, Tamil Nadu and West Bengal). With the advice of the internal review committee at FSI, mangrove dominated States West Bengal, Odisha and Maharashtra with high species diversity in different canopy density classes have been chosen for field data collection for all carbon pools (except below ground biomass) viz., above ground biomass, dead wood, litter and SOC and for validation of LiDAR derived AGB.

2.5.1 Sample size

Cochran formula has been used for sample size calculation for the study, with a permissible error of 15% at 95% confidence level, which came out as 42.68. It was divided to collect data from 50 sample plots. These sample points were distributed in mangrove forest of 3 representative States i.e., Maharashtra, West Bengal and Odisha proportionately in the very dense, moderately dense and open forest areas.

Cochran (1977) developed a formula to calculate a representative sample for proportions as

$$n_0 = \frac{z^2 pq}{e^2} \quad \text{——————} \quad (1)$$

Where, n_0 is the sample size, z is the selected critical value of desired confidence level (C) as shown in table 2.1, p is the estimated proportion of an attribute that is present in the population, $q = 1 - p$ and e is the desired level of precision. In this study, assuming the maximum variability in a large population i.e., 50% (p =0.5) and taking 95% confidence level with ≈15% permissible error, the calculation for required sample size will be as follows-

p = 0.5 and hence q =1-0.5 = 0.5; e ≅ 0.15; z =1.96

$$n_0 = \frac{(1.96)^2\,(0.5)(0.5)}{(0.0225)^2} = 42.68 \quad \text{——————} \quad (2)$$

Table 2.1: Normal Critical Values for Confidence Levels

Confidence Level, C	Critical value, z
99%	2.58
98%	2.33
95%	1.96
90%	1.65
80%	1.28

Table 2.2: State-wise sample points for field study **(Area in km²)**

States/UTs	Very Dense Forest	Moderately Dense Forest	Open Forest	Total	sample plots	Very Dense Forest	Moderately Dense Forest	Open Forest	Total
Maharashtra	0.00	89.98	234.31	**324.29**	15.00	0	4	11	15
Odisha	80.43	94.31	84.24	**258.98**	12.00	4	4	4	12
West Bengal	994.31	692.02	427.44	**2113.77**	23.00	11	8	4	23
Total	**1074.74**	**876.31**	**745.99**	**2697.04**	50				**50**

Table 2.2 is showing State wise distribution of sample plots with respect to area of mangrove forest in each canopy density classes. Out of 50 sample points, a total of 15 points have been laid out in Maharashtra, 12 in Odisha and 23 in West Bengal. The sample points were further segregated proportionately to the area under each density class in the mangrove forest. On the basis of area proportion, it was decided to lay 4 points in moderate dense and

11 points in open forest of Maharashtra mangrove forest; 4 points in very dense, 4 points in moderately dense and 4 points in open forest of Odisha mangrove forest; 11 points in very dense, 8 points in moderately dense and 4 points in open forest of West Bengal State.

2.5.2 Sampling design

Stratified random sampling technique has been used and three canopy density classes' i.e. very dense, moderately dense and open forest formed the three different strata. All the laser beams falling in mangrove forest cover were identified and stratified as per the canopy density in three states (Maharashtra, Odisha and West Bengal). The circular plot design similar to National Forest Inventory (NFI) of FSI (with radius 8.5 meter) has been adopted for the sample plot design for the study. A circular plot of 17-meter diameter has been laid out at each sample plot location. The reason for taking 17-meter diameter circular plot is due to the fact that the resolution of LiDAR footprint is 17 meter. Desired number of sample points were randomly selected from each of strata. The latitude and longitude of the sample point form the plot centre around which a plot of radius 8.5 m is laid out. Other three sub-plots are laid out at a distance of 4.25 meter from plot centre at a specified angle. Further micro-plots within each sub-plot are laid out for collection of data on dead wood, litter and soil. The size of the sub-plot for dead wood is a circular plot of radius 2.8 meter and 1.7 m for litter and 1m x 1m at midpoint between subplots for soil sample collection. The plot design adopted for field data collection is given in figure 2.12.

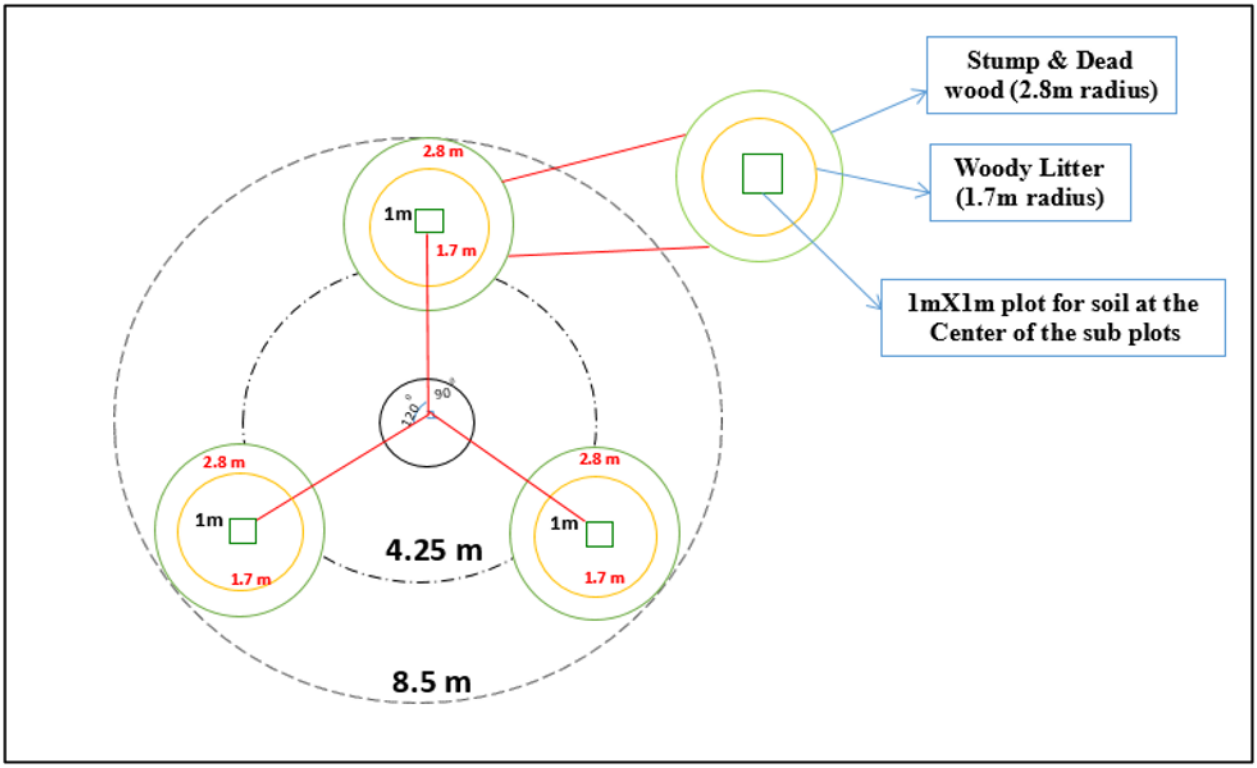


Figure 2.12 Plot design adopted for field data collection

2.5.3 Field equipment's and materials

Following equipment and materials have been used in field for data collection.

1. Plastic bags (150)
2. Soil tags
3. GPS, Camera
4. Rubber bands
5. Range finder
6. Inch tape
7. Marker, pen
8. Field form
9. Khurpi
10. Scale, paper cutter
11. Hard board
12. Punching machine
13. Stapler, File folder, flags
14. One big bag to keep collected samples
15. News papers
16. Rope
17. Cello tape wide

The formats of field data collection have been given in Annexure of the report. In plot enumeration form, the name of tree species with their diameter (cm) at breast height i.e., 1.37 meter from base of the tree and their height in meter has been recorded. In soil and forest floor carbon form, soil colour, gravel % is recorded from each sample plot. In stump, dead wood and woody litter form dead wood, stump height and diameter data are recorded along with litter weight data present in each sample plot.

2.5.4 AGB and BGB estimation of field collected data

Inside each plot, the diameter at breast height (DBH) of all mangrove trees, having diameters of 10 cm and more at breast height (dbh) and their height (m) and name of tree species have been recorded. Using the allometric equations, of each tree has been calculated. Here, allometric equations adapted from **Komiyama et al. 2005** were used to estimate AGB and BGB as shown in Equations (3) and (4) as these equations were developed from the mangroves of the Southeast Asia (**Aye, W.N., 2022**).

$$AGB = 0.251\ \rho\ D^{2.46} \quad \text{(3)}$$

$$BGB = 0.199\ \rho^{0.899}\ D^{2.22} \quad \text{(4)}$$

Where:

AGB (kg) = aboveground biomass estimates in kg per tree

BGB (kg) = belowground biomass estimate in kg per tree

D = diameter at breast height (dbh) in cm

ρ= wood density in gm cm^3

The AGB and BGB were converted to above and below-ground carbon stock by multiplying by 0.47 and 0.39 respectively as a conversion factor (**FAO, 2011; IPCC, 2006**) using the equations given below:

Aboveground carbon stock = AGB * 0.47 ——— (5)

Belowground carbon stock = BGB * 0.39 ——— (6)

2.5.5 Dead wood /stump, litter biomass estimation

Inside each plot of dead wood/stump, the length and diameter and name of the species have been recorded. From the field data, volume of dead wood/stump was calculated and then volume was multiplied by wood density of respective tree species to get their biomass. Dead wood/stump carbon (t/ha) is calculated by multiplying dead wood/stump biomass to carbon conversion factor i.e. 0.47 that has been used for above ground carbon estimation. Litter weight in grams has been collected from each sample plot and it's further converted into tons/ ha. The collected litter samples are air dried and then oven-dried at controlled temperature. The dried litter samples are there after crushed in mortar-pestle and passed through sieve. The prepared sieved litter samples are then weighed in weighing machine and analysed for litter Carbon in all litter samples by 'Elementar' Instrument to get litter carbon percentage for all collected litter samples. Litter carbon (t/ha) is calculated by multiplying litter carbon percentage to litter biomass (t/ha).

2.5.6 Soil organic carbon (SOC) estimation

The collected soil samples are air dried and then oven-dried at controlled temperature. The dried soil samples are thereafter crushed in mortar-pestle and passed through sieve to remove gravels. The prepared soil samples are then weighed in weighing machine and analysed for

Organic Carbon by 'Elementar' Instrument to get Total Soil Organic Carbon (SOC). In this method the Carbon is estimated by the IR detector instrument.

2.6 Field data collection in Mangrove forest of Maharashtra State

Field works for data collection of Mangrove forest of Maharashtra State was carried out during 19th April 2022 to 5th May 2022.

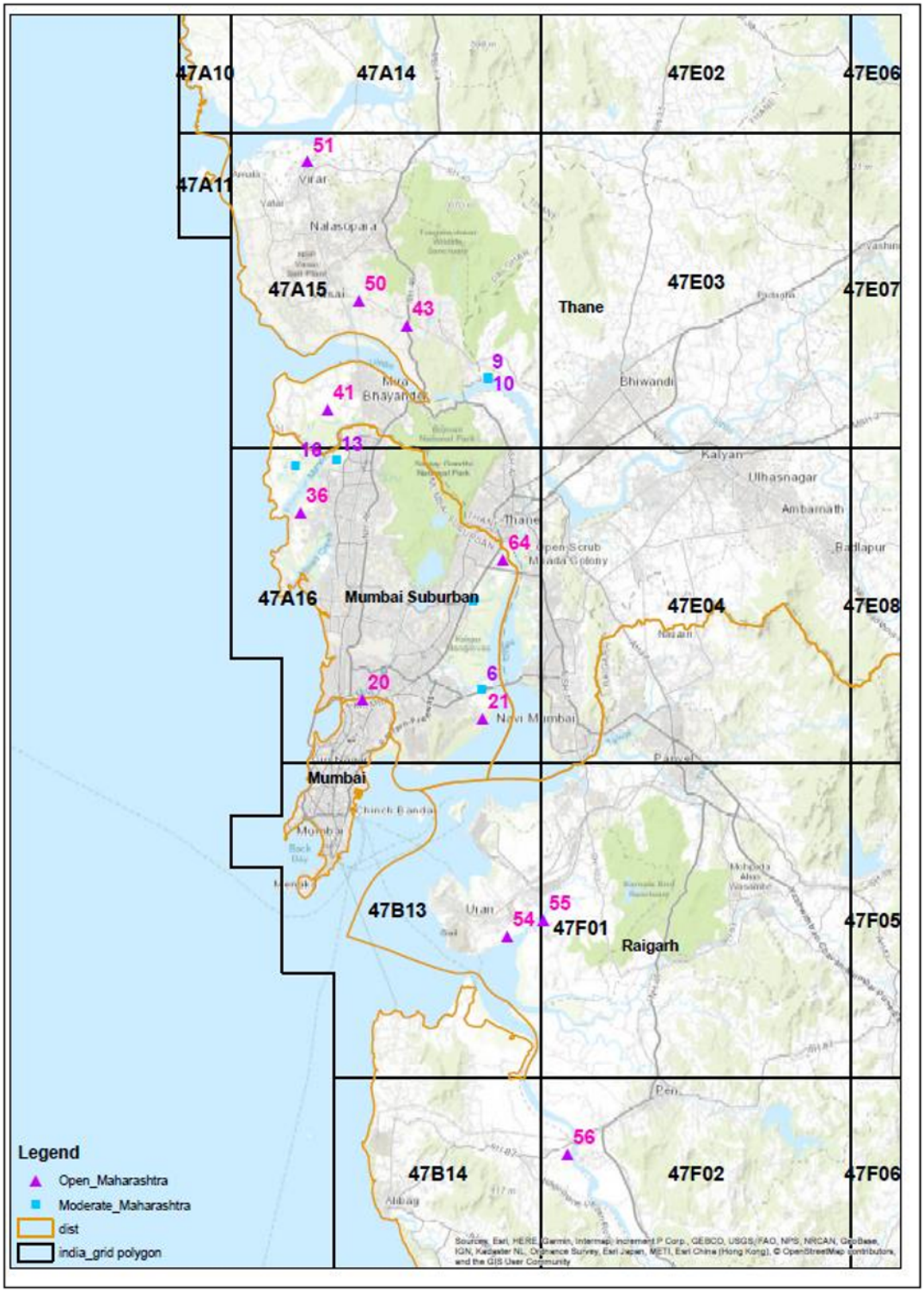


Figure 2.13 Base map showing sample points in mangrove forest in Maharashtra State

Table 2.3: Point location of sample points in open mangrove forest of Maharashtra

Sl.No.	State	ID	Latitude	Longitude	Tree height (LiDAR) (m)	Forest Density Class	District
1	Maharashtra	20	19.0500	72.8558	7.31	Open Forest	Mumbai
2	Maharashtra	21	19.0344	72.9527	4.58	Open Forest	Mumbai sub.
3	Maharashtra	36	19.1983	72.8060	5.29	Open Forest	Mumbai sub.
4	Maharashtra	41	19.2803	72.8279	3.82	Open Forest	Thane
5	Maharashtra	43	19.3466	72.8916	10.30	Open Forest	Thane
6	Maharashtra	50	19.3666	72.8532	9.12	Open Forest	Thane
7	Maharashtra	51	19.4765	72.8113	6.25	Open Forest	Thane
8	Maharashtra	54	18.8624	72.9726	6.01	Open Forest	Raigarh
9	Maharashtra	55	18.8750	73.0018	5.84	Open Forest	Raigarh
10	Maharashtra	56	18.6892	73.0211	8.45	Open Forest	Raigarh
11	Maharashtra	64	19.1607	72.9691	4.44	Open Forest	Mumbai sub.

Table 2.4: Point location of sample points in moderately dense mangrove forest of Maharashtra

Sl.No.	State	ID	Latitude	Longitude	Tree height (LiDAR) (m)	Forest Density Class	District
1	Maharashtra	6	19.0580	72.9522	4.07	Mod. Dense Forest	Mumbai Sub.
2	Maharashtra	8	19.1283	72.9449	12.79	Mod. Dense Forest	Mumbai Sub.
3	Maharashtra	9	19.3059	72.9569	6.14	Mod. Dense Forest	Thane
4	Maharashtra	10	19.3050	72.9570	7.77	Mod. Dense Forest	Thane

Table 2.3 and 2.4 are showing point location with latitude, longitude, forest density and LiDAR derived height with district in which point falls. Out of 11 points of open forest, 1 point lies in Mumbai district, 3 points in Mumbai suburban district, 4 points in Thane district and 3 points lie in Raigarh district. 2 points of moderately dense forest lie in Mumbai suburban district and 2 points lie in Thane district.

The Regional Director, Forest Survey of India (Central Zone), Nagpur was requested for deputing one NFI crew to accompany with FSI (HQ) team in data collection. The local staff of the Maharashtra Forest Department had helped the FSI team in data collection in different sample points located in mangrove forest in Maharashtra (Figure 2.15 & 2.16).

Avicennia marina is dominating mangrove species found in Maharashtra State along the creeks in Thane, Mumbai, Mumbai suburban, and Raigadh districts. Besides Avicennia marina

Rhizophora mucronata, Sonneratia apetala and Sonneratia alba mangrove tree species is also found in few plots along Mumbai and Mumbai suburban creeks.

Table 2.5: Mangrove species found in mangrove forest of Maharashtra

Wood density data taken from International Centre for Research in Agroforestry (ICRAF) website (http://db.worldagroforestry.org/).

Sl.No.	Mangrove species	Wood density (gm/cm^3)
1	Rhizophora mucronata	0.85
2	Avicennia marina	0.73
3	Sonneratia apetala	0.53
4	Sonneratia alba	0.64





Figure 2.14 Team members approaching in Mumbai suburban creeks for data collection



Figure 2.15 Plot lay out and data collection at a plot location in Mumbai creeks

2.7 Field data collection in Mangrove forest of West Bengal State

Field work for data collection for Mangrove forest in West Bengal was carried out during 23rd June 2022 to 16th July 2022.

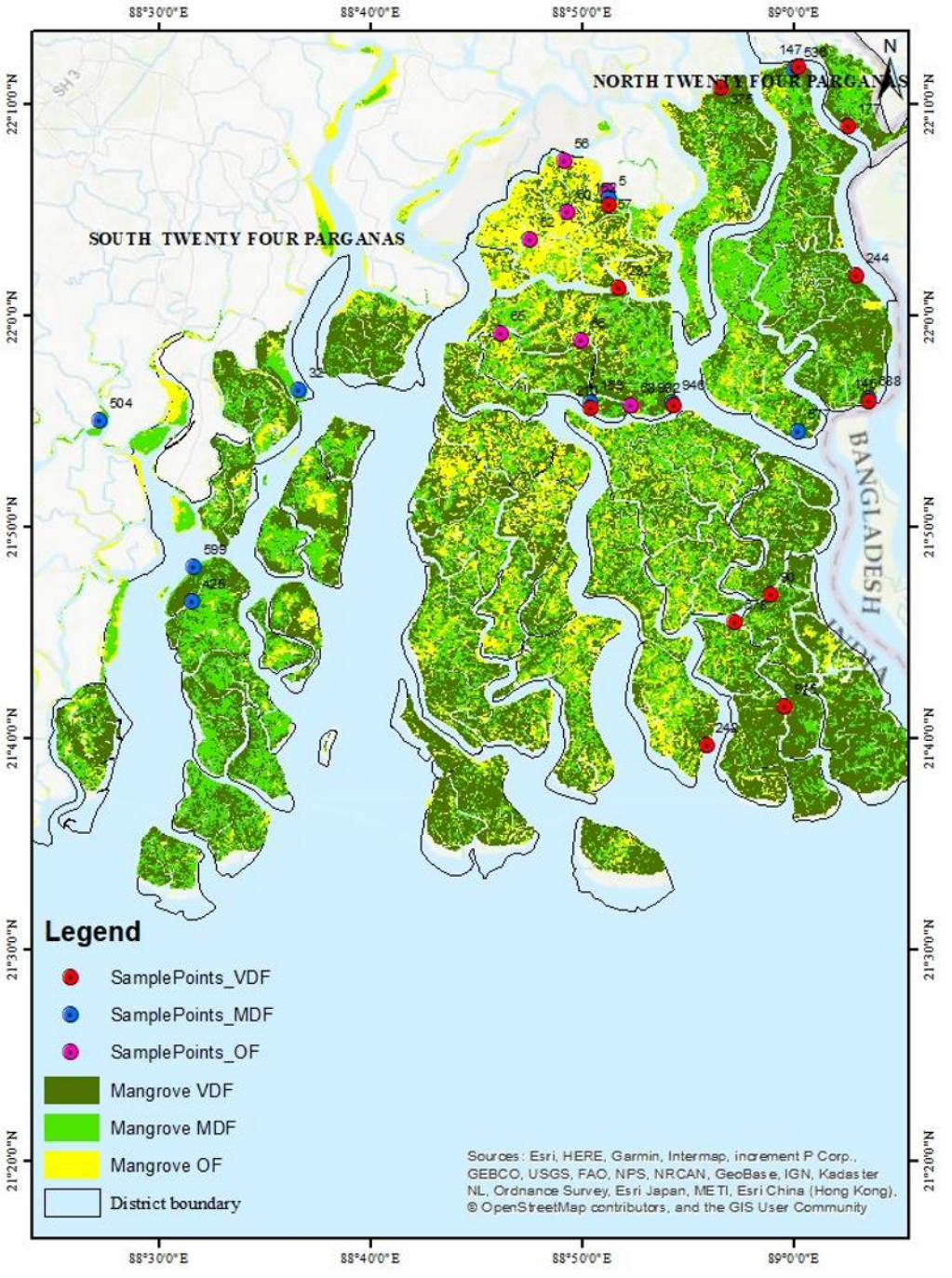


Figure 2.16 Base map showing sample points in mangrove forest in Sundarbans, West Bengal State

The Sundarbans Mangrove eco region lies in a vast delta, formed by the confluence of South Asia's largest rivers, the Ganges, Hooghly, Padma, Brahmaputra and Meghna. This tidal dominated deltaic complex is the largest of its kind and covers an area of 1,000,000 ha of land and water, the major part (60%) of which is situated in Bangladesh while the remaining western portion (40%) lies within India. The mighty Indian river, the Ganges and its associated estuaries like Muriganga, Saptamukhi, Bidyadhari, Haribhanga, Matla, and Thakuran etc. open into the Bay of Bengal having a north – south direction of water flow. This largest tidal wetland and only mangrove tiger land on the earth, declared by IUCN, 1997 as 'World's Heritage Site', represents a highly valued ecosystem in terms of economy, ecology and environment. It includes a Tiger Reserve (2585 km^2, 1970), 3 wild life sanctuaries (Lothian, 3,800 ha; 1948; Sojnekhali, 35,240 ha; 1960 and Holiday Island, 595 ha; 1976) and one National Park (1330 km^2; 1972) (**Chakraborty, S.K., 2011**).

Table 2.6: Point location of sample points in very dense mangrove forest in West Bengal

Sl. No	ID	Latitude	Longitude	Tree height (LiDAR) (m)	Forest Density
1	915	21.692286	88.993120	5.31	Very Dense
2	90	21.780674	88.982480	2.92	Very Dense
3	678	21.758629	88.954666	4.73	Very Dense
4	992	21.929764	88.905780	5.30	Very Dense
5	177	22.149763	89.043816	12.07	Very Dense
6	242	21.661322	88.931960	5.78	Very Dense
7	152	22.087479	88.855460	4.83	Very Dense
8	292	22.021690	88.862526	5.86	Very Dense
9	210	21.926706	88.841400	5.62	Very Dense
10	147	22.196154	89.003845	5.00	Very Dense
11	375	22.180042	88.943306	7.59	Very Dense

Table 2.7: Point location of sample points in moderately dense mangrove forest in Sundarbans, West Bengal

Sl. No	ID	Latitude	Longitude	Tree height (LiDAR) (m)	Forest Density
1	946	21.931564	88.905580	5.06	Mod dense
2	5	22.092888	88.854910	2.43	Mod dense
3	153	21.931211	88.840904	5.07	Mod dense
4	32	21.941900	88.611275	4.51	Mod dense
5	577	21.908247	89.004010	5.49	Mod dense
6	599	21.801617	88.529106	6.22	Mod dense
7	504	21.916914	88.454865	7.57	Mod dense
8	425	21.774542	88.527580	5.58	Mod dense

Table 2.8: Point location of sample points in open mangrove forest in West Bengal

Sl.No.	ID	Longitude	Latitude	Tree height (LiDAR) (m)	Forest Density
1	56	88.820700	22.122300	9.86	Open Forest
2	60	88.822100	22.082200	5.77	Open Forest
3	66	88.832900	21.980300	5.50	Open Forest
4	68	88.872200	21.929700	6.35	Open Forest

Table 2.9: Extra sample points laid out in moderately dense forest in West Bengal

Sl. No	ID	Latitude	Longitude	Tree height (LiDAR) (m)	Forest Density
1	A_1	22.134694	89.060722	9.84	Mod dense
2	A_2	22.190778	89.052250	11.00	Mod dense
3	A_3	21.880417	88.608028	8.09	Mod dense
4	A_4	21.880944	88.611167	8.68	Mod dense
5	A_5	21.843917	88.515944	8.53	Mod dense

Table 2.6, 2.7 and 2.8 are showing point location in very dense, moderately dense and open forest with latitude, longitude, forest density and LiDAR derived height. In total 23 sample points have been laid out in mangrove forest in West Bengal. Out of this, 11 sample points to lay out in very dense forest, 8 sample points in moderately dense forest and 4 points in open forest. Due to bad weather conditions 2 sample points in moderately dense forest could not be laid out and therefore 5 extra sample points have been laid out in moderately dense forest as a compensation of those points, as shown in Table 2.9.

The Regional Director, Forest Survey of India (Eastern Zone), Kolkata was requested for deputing one NFI crew to accompany with FSI (HQ) team in data collection. The data collection was carried out by FSI team of headquarters and Eastern zone. The local forest officials have extended necessary field assistance in the data collection. The field work was conducted near Sajnekhali wildlife sanctuary and Sudhanyakhali camp. In second section rest of the sample plots were laidout. Different mangrove species were found in Sundarbans, 13 Mangrove species have been reported in the study. In table 2.10 Mangrove species found in Sundarbans along with their wood density is listed.

Table 2.10: Mangrove species found in mangrove forest of Sundarbans, West Bengal

Wood density data taken from International Centre for Research in Agroforestry (ICRAF) website (http://db.worldagroforestry.org/).

Sl.No.	Mangrove Species	Wood density (gm/cm^3)
1	Avicennia alba	0.70
2	Avicennia marina	0.73
3	Avicennia officinalis	0.74
4	Aegiceras corniculatum	0.60
5	Bruguiera gymnorrhiza	0.87
6	Ceriops decandra	0.97
7	Excoecaria agallocha	0.43
8	Heritiera fomes	0.88
9	Rhizophora apiculata	0.88
10	Sonneratia apetala	0.53
11	Sonneratia caseolaris	0.86
12	Xylocarpus mekongenesis	0.73
13	Xylocarpus granatum	0.67



Figure 2.17 Sundarbans mangrove forest



Figure 2.18 Few sample plot locations showing mixed mangrove species of Avicennia marina and Excoecaria agallocha and pneumatophores





Rhizophora apiculata



Phoenix paludosa



Aegialitis rotundifolia



Ceriops tagal

Figure 2.19 Few dominating mangrove species in Sundarbans mangrove forest

2.8 Field data collection in Mangrove forest of Odisha State

Field work for data collection for Mangrove forest in Odisha was carried out during16th August 2022 to 6th September 2022.

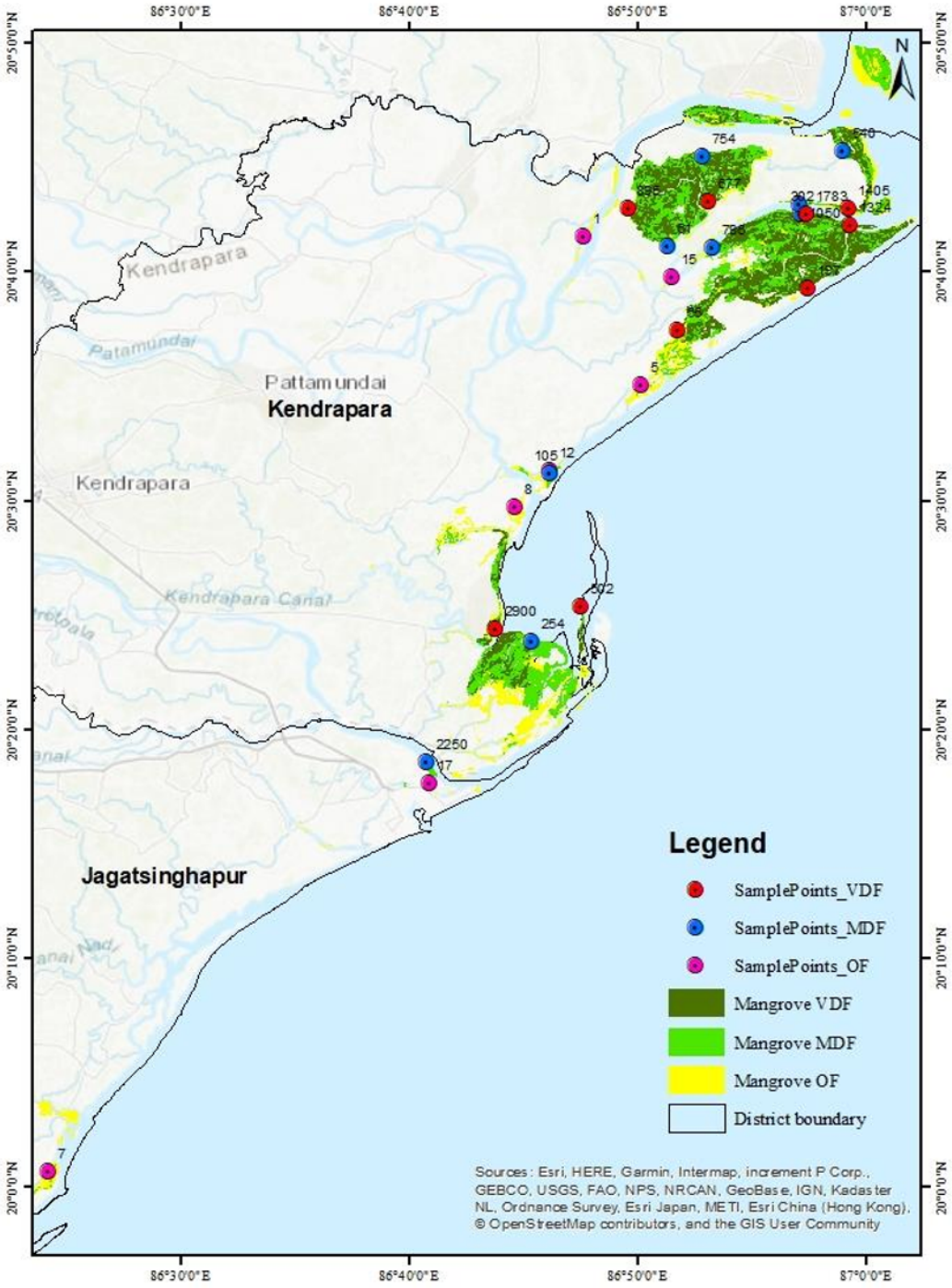


Figure 2.20 Base map showing sample points in mangrove forest in Odisha State

Table 2.11: Point location of sample points in very dense mangrove forest in Odisha

Sl.No.	ID	Latitude	Longitude	Tree height (LiDAR) (m)	Canopy Density
1	1783	20.7086	86.9571	7.87	Very Dense
2	1324	20.7008	86.9889	6.73	Very Dense
3	1405	20.7080	86.9880	7.06	Very Dense
4	1135	**23.7762**	86.5352	14.33	Very Dense

Table 2.12: Point location of sample points in moderately dense mangrove forest in Odisha

Sl.No.	ID	Latitude	Longitude	Tree height (LiDAR) (m)	Canopy Density
1	1621	20.1104	86.7613	8.56	Mod Dense
2	302	20.7054	86.9581	9.97	Mod Dense
3	796	23.7988	86.5328	10.44	Mod Dense
4	540	20.7544	86.9838	12.63	Mod Dense

Table 2.13: Point location of sample points in open mangrove forest in Odisha

Sl.No.	ID	Latitude	Longitude	Tree height (LiDAR) (m)	Canopy Density
1	5	20.584256	86.836136	4.85	Open forest
2	8	20.495525	86.744844	6.67	Open forest
3	12	20.521981	86.770200	5.62	Open forest
4	15	20.662367	86.858728	8.17	Open forest

Table 2.11, 2.12 and 2.13 are showing point location with latitude, longitude, forest density and LiDAR derived height. In total 12 sample points laid out in mangrove forest in Odisha State. 4 sample points to lay out in very dense forest, 4 sample points in moderately dense forest and 4 points in open forest.

Table 2.14: Mangrove species found in mangrove forest of Odisha State

Wood density data taken from International Centre for Research in Agroforestry (ICRAF) website (http://db.worldagroforestry.org/).

Sl.No.	Tree Species	Wood density (gm/cm^3)
1	Avicennia alba	0.70
2	Avicennia marina	0.73
3	Avicennia officinalis	0.74
4	Aegiceras corniculatum	0.60
5	Aglaia cucullata	0.62
6	Ceriops decandra	0.97
7	Excoecaria agallocha	0.43
8	Heritiera fomes	0.88
9	Kandelia candel	0.53
10	Rhizophora apiculata	0.88
11	Rhizophora mucronata	0.88
12	Sonneratia apetala	0.53
13	Sonneratia alba	0.64
14	Xylocarpus granatum	0.67

Field photographs – Odisha Mangroves







Figure 2.21 Data collection and recording at sample plot with old Avecennia marina species near to Jamboo dweep area of Odisha mangroves



Figure 2.22 Mixed mangrove species Avecennia marina, Avecennia officinalis and Excoecaria agallocha



Figure 2.23 Sample plot with mixed mangrove species Avecennia marina and Xylocarpus granatum in high tide condition



Figure 2.24 Few sample plots inundated in flood water, bottom two pictures are showing plantations of Phoenix paludosa and Rhizophora mucronata mangrove species

2.9 Modelling for above ground biomass estimation for all the mangrove States/UTs in India

Under the study, an attempt has been made to develop a model for estimation of above ground biomass using LiDAR derived parameters i.e. mean canopy height (m) and canopy openness (m) as dependent variables on AGB. **Canopy openness** is the standard deviation of relative heights for all photons classified as canopy photons within the segments. This parameter will potentially provide an indicator of canopy openness as a greater standard deviation of heights indicates greater penetration of the laser energy into the canopy. **Mean canopy height** is the relative canopy heights, computed by differencing the canopy photon height from the estimated terrain surface in the ATL08 processing. These heights are averaged.

The first step in the model development was to test whether there is any significance difference between collected ground tree height and their respective LiDAR derived mean canopy height. T-test has been performed between tree height collected from 50 samples from the ground and their respective LiDAR derived mean canopy height.

2.9.1 Student's T-test

A t-test is a statistical test that is used to compare the means of two groups. It is often used in hypothesis testing to determine whether a process or treatment actually has an effect on the population of interest, or whether two groups are different from one another. The t test estimates the true difference between two group means using the ratio of the difference in group means over the pooled standard error of both groups. Table 2.7 is showing the results obtained after performing 'T-Test: Paired Two Sample for Means' between LiDAR derived mean canopy height and field data collected tree heights for 50 sample plots. The results revealed that there is no statistical significant difference between these two variables so LiDAR derived mean canopy height can be used as an independent variable instead of ground based canopy height.

Table 2.15: T-test output between ground tree height and their respective LiDAR derived mean canopy height

t-Test: Paired Two Sample for Means		
	Height field data (m)	Lidar height (m)
Mean	7.02	6.95
Variance	4.05	4.55
Observations	50	50
Pearson Correlation	0.85	
Hypothesized Mean Difference	0	
df	49	
t Stat	0.46	
P(T<=t) one-tail	0.33	
t Critical one-tail	1.68	
P(T<=t) two-tail	0.65	
t Critical two-tail	2.01	

2.9.2 Modelling for AGB

In the next step, development of regression analysis model was performed among LiDAR derived mean canopy height, canopy openness and calculated AGB for all 50 sample points. A significant relationship was found between ground heights data of all 50 samples and their respective LiDAR derived canopy height for AGB estimation. Multiple linear Regression Analysis (MLRA) was performed taking LiDAR derived canopy height and canopy openness as independent variables and AGB as dependent variable. When the results were analysed, it was found that t-statistics for intercept was less than the critical value implying that the intercept is not significantly different from zero. Therefor the model was fitted again keeping the intercept as zero. Figure 2.25 is showing regression statistics for LiDAR derived mean canopy height and canopy openness as independent variable and field calculated AGB as dependent variable with multiple R value of 0.95, R square = 0.91 with SE = 19.78 t/ha and residual graph.

Regression Statistics	
Multiple R	0.954577551
R Square	0.911218301
Adjusted R Square	0.888535349
Standard Error	19.7821109
Observations	50

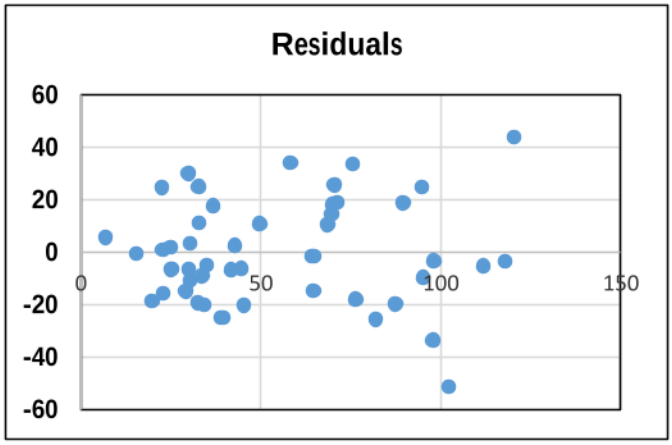


Figure 2.25 Regression statistics and residual graph for regression analysis between canopy height and canopy openness variables for AGB estimation

Table 2.16: Table showing coefficients and standard error of LiDAR height and Canopy openness after regression analysis

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
Lidar height	-4.02	1.33	-3.03	0.004	-6.69	-1.35	-6.69	-1.35
Canopy openness	46.26	4.98	9.28	2.72E-12	36.24	56.28	36.24	56.28

Using coefficients of LiDAR height (-4.02) and canopy openness (46.26) an equation has been formed for AGB estimation. Mean canopy height and canopy openness LiDAR parameters for all the Mangrove States/UTs has been extracted and tabulated for all the beams in excel sheets separately for different canopy density classes State/UTs wise. This equation has been developed through the above analysis for AGB estimation of all the 12 Mangrove dominated States/UTs.

AGB = -4.0218* Mean canopy LiDAR height + 46.2604* Canopy Openness

It has been decided to use model for all canopy density classes in Mangroves States/UTs for AGB estimation. Developed equation has been used separately in different canopy density classes for all the LiDAR points in each mangrove State/UTs. one way ANOVA test has been performed for all States/UTs to test whether the average AGB of VDF, MDF and Open Forest

are same or not. If the analysis come out that the average AGB of three classes are different then, it is line with common perception and gives strength to the developed model.

2.9.3 One-way ANOVA results interpretation for West Bengal Mangroves above ground biomass estimation

Null hypothesis (H_O): There is no difference in average above ground biomass of VDF, MDF and OF i.e. H_O: AGB(VDF) = AGB(MDF)= AGB(OF).

Alternate hypothesis (H_A): There is difference in average above ground biomass of VDF, MDF and OF i.e., H_O is not true.

A one-way ANOVA revealed that there was a statistically significant difference in estimating the above ground biomass using three canopy density classes between at least two groups F (2, 2831) = (688.06), p = (2.9552E-244). Since the p-value is less than $\alpha = 0.05$ and F value (688.06) is greater than the F critical value (3.00), we would reject the null hypothesis.

Table 2.17: Table showing single ANOVA output for different canopy density classes in Sundarbans, West Bengal State

Anova: Single Factor

SUMMARY

Groups	Count	Sum		Average	Variance	
VDF_AGB(t/ha)	523	42131.42		80.56	269.68	
MDF_AGB(t/ha)	1512	79732.88		52.73	287.39	
OF_AGB(t/ha)	799	34049.29		42.61	496.07	
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F critical**
Between Groups	471935.18	2	235967.59	688.06	2.9552E-244	3.00
Within Groups	970882.36	2831	342.95			
Total	1442817.54	2833				

The results of ANOVA in table 2.17 is showing that there is statistical difference in average AGB of three canopy density classes and F value is greater than F critical value. It may be informed that the developed AGB model is predicting the AGB of mangrove areas, in addition the other statistical validations of Regression Analysis.

2.9.4 Below ground biomass estimation

Below ground biomass has been estimated using root-to-shoot ratio which gives a relationship between above ground biomass (AGB) to the below ground biomass (BGB). GPG, 2003 also provides default values of root-to-shoot ratios for six major global forest types. IPCC GPG

LULUCF document listed the root-to-shoot ratio = 0.42 for Tropical/sub-tropical forest for above ground biomass less than 125 t/ha. In this study 0.37 root-to-shoot ratio has been used for below ground biomass (BGB) estimation for littoral and swamp forests (ISFR, 2021; IPCC GPG LULUCF, 2003).

2.9.5 Dead wood / Litter carbon and Soil organic carbon (SOC) estimation

Dead wood /litter and SOC carbon has been calculated in t/ha from all 50 samples listed separately in three canopy density classes i.e., very dense, moderately dense and open forest. Average carbon (t/ha) has been calculated for dead wood carbon, litter carbon and soil organic carbon in all the three canopy density classes from 50 collected samples. Average carbon value (t/ha) of dead wood, litter and SOC has been multiplied by area in hectare to all rest of the mangrove States/UTs where field data was not available i.e., Andhra Pradesh, Goa, Gujarat, Karnataka, Kerala, Tamil Nadu, A & N Islands and Puducherry to estimate the Dead wood, litter and SOC carbon.

CHAPTER 3
RESULTS AND DISCUSSION

3. Results and discussions

3.1 Estimation of Carbon Stock in Mangrove Forest of Andhra Pradesh State

Above ground carbon stocks of moderately dense and open forest have been estimated as **633.68 thousand tonnes (29.75 t/ha)** and 380.54 **thousand tonnes (19.82 t/ha)** respectively.

Below ground carbon stocks of moderately dense and open forest have been estimated as 194.47 **thousand tonnes (9.13 t/ha)** and 116.74 **thousand tonnes (6.08 t/ha)** respectively.

Dead wood carbon stocks of moderately dense and open forest have been estimated as 35.44 **thousand tonnes (1.66 t/ha)** and 11.63 **thousand tonnes (0.61 t/ha)** respectively.

Litter carbon stocks of moderately dense and open forest have been estimated as **3 thousand tonnes (0.14 t/ha)** and 1.33 **thousand tonnes (0.07 t/ha)** respectively.

Soil organic carbon (SOC) carbon stocks of moderately dense and open forest have been estimated as **491.77 thousand tonnes (23.09 t/ha)** and 351.47 **thousand tonnes (18.31 t/ha)** respectively.

Table 3. 1 Canopy Density wise per hectare Carbon Stock in Mangrove Forest in Andhra Pradesh in different carbon pools.

(in t/ha)

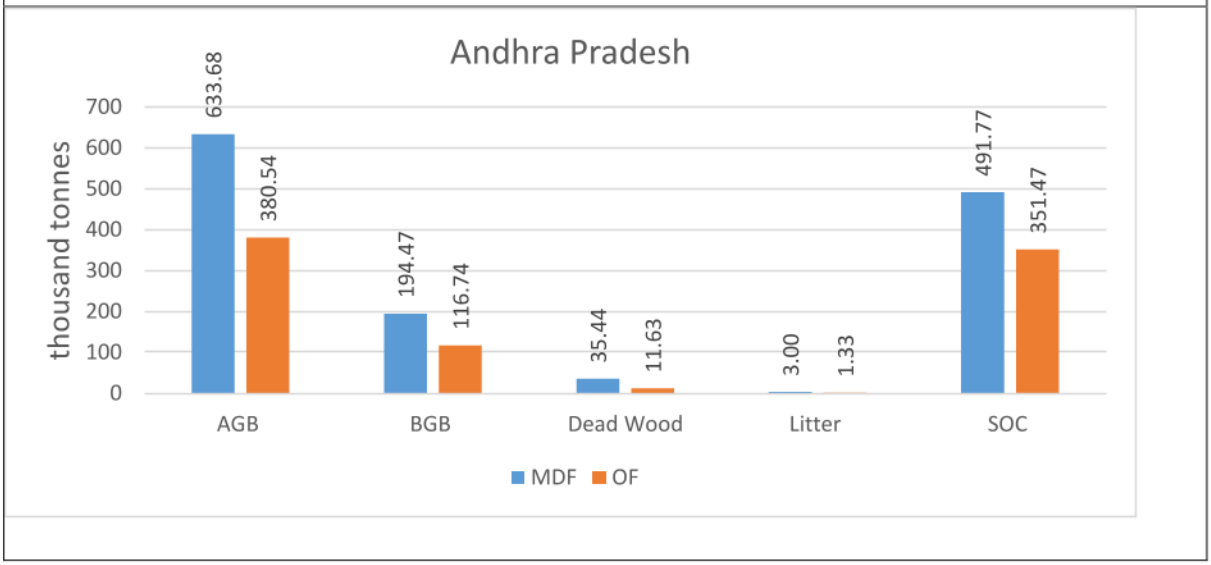
Canopy density	Area (km^2)	AGB	BGB	Dead wood	Litter	SOC	Total Carbon
MDF	213	29.75	9.13	1.66	0.14	23.09	63.77
OF	192	19.82	6.08	0.61	0.07	18.31	44.88

Table 3. 2 Canopy Density wise Carbon Stock in Mangrove Forest in Andhra Pradesh under different carbon pools.

(in '000 tonnes)

Canopy density	Area (km^2)	AGB	BGB	Dead wood	Litter	SOC	Total Carbon
MDF	213	633.68	194.47	35.44	3.00	491.77	1,358.35
OF	192	380.54	116.74	11.63	1.33	351.47	861.71

Figure 3. 1 Bar diagram of Canopy Density wise Carbon Stock in Mangrove Forest in Andhra Pradesh under different carbon pools.



3.2 Estimation of Carbon Stock in Mangrove Forest of Goa

Above ground carbon stocks of moderately dense and open forest have been estimated as **71.51 thousand tonnes (34.05 t/ha)** and **8.41 thousand tonnes (14.01 t/ha)** respectively.

Below ground carbon stocks of moderately dense and open forest have been estimated as **23.16 thousand tonnes (11.03 t/ha)** and **2.58 thousand tonnes (4.30 t/ha)** respectively.

Dead wood carbon stocks of moderately dense and open forest have been estimated as **2.57 thousand tonnes (1.23 t/ha)** and **0.30 thousand tonnes (0.51 t/ha)** respectively.

Litter carbon stocks of moderately dense and open forest have been estimated as **0.58 thousand tonnes (0.27 t/ha)** and **0.07 thousand tonnes (0.11 t/ha)** respectively.

Soil organic carbon (SOC) carbon stocks of moderately dense and open forest have been estimated as **148.98 thousand tonnes (70.95 t/ha)** and **16.35 thousand tonnes (27.25 t/ha)** respectively.

Table 3. 3 Canopy Density wise per hectare Carbon Stock in Mangrove Forest in Goa in different carbon pools.

(in t/ha)

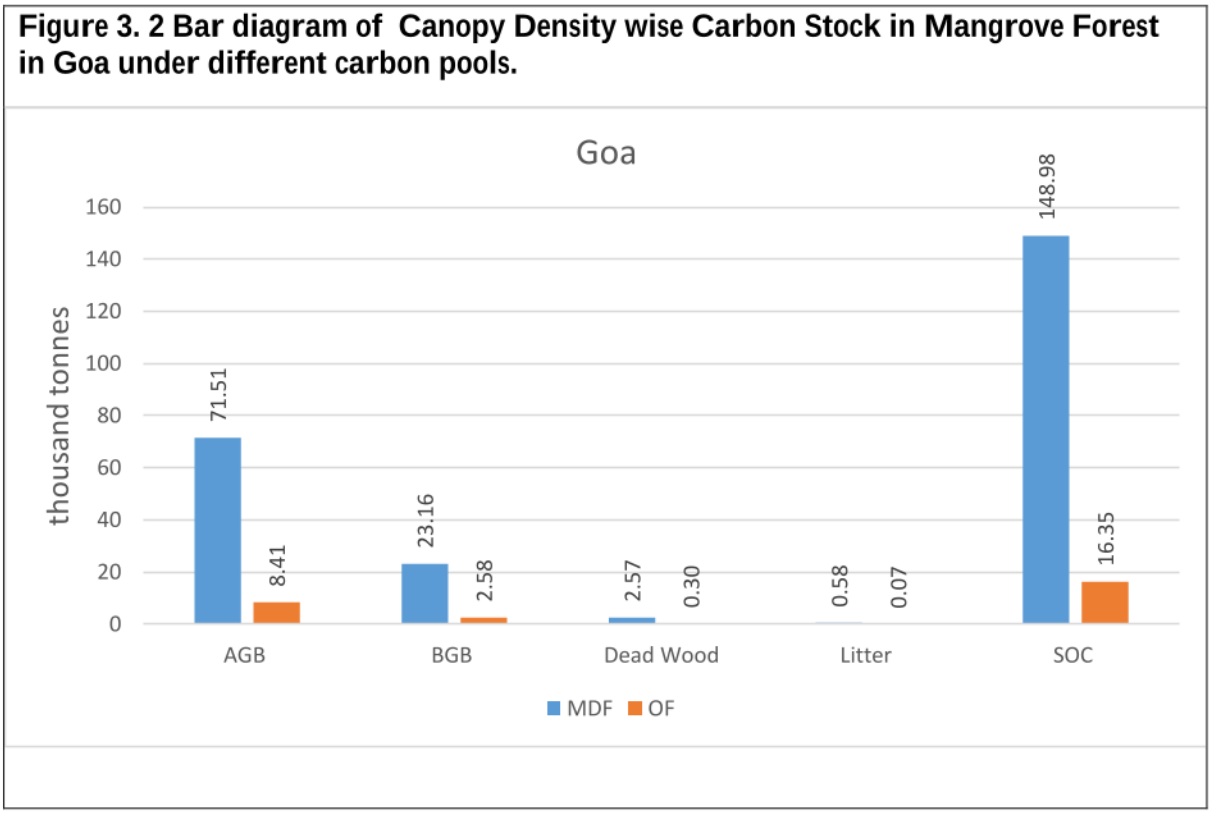
Canopy density	Area (km^2)	AGB	BGB	Dead wood	Litter	SOC	Total Carbon
MDF	21	34.05	11.03	1.23	0.27	70.95	117.53
OF	6	14.01	4.30	0.51	0.11	27.25	46.18

Table 3. 4 Canopy Density wise Carbon Stock in Mangrove Forest in Goa under different carbon pools.

(in '000 tonnes)

Canopy density	Area (km^2)	AGB	BGB	Dead wood	Litter	SOC	Total Carbon
MDF	21	71.51	23.16	2.57	0.58	148.98	246.80
OF	6	8.41	2.58	0.30	0.07	16.35	27.71

Figure 3. 2 Bar diagram of Canopy Density wise Carbon Stock in Mangrove Forest in Goa under different carbon pools.



3.3 Estimation of carbon stock in Mangrove forest in Gujarat

Above ground carbon stocks of moderately dense and open forest have been estimated as **544.86 thousand tonnes (32.24 t/ha)** and **1384.26 thousand tonnes (13.76 t/ha)** respectively.

Below ground carbon stocks of moderately dense and open forest have been estimated as **167.31 thousand tonnes (9.90 t/ha)** and **424.53 thousand tonnes (4.22 t/ha)** respectively.

Dead wood carbon stocks of moderately dense and open forest have been estimated as **19.61 thousand tonnes (1.16 t/ha)** and **50.03 thousand tonnes (0.50 t/ha)** respectively.

Litter carbon stocks of moderately dense and open forest have been estimated as e **4.40 thousand tonnes (0.26 t/ha)** and **10.07 thousand tonnes (0.11 t/ha)** respectively.

Soil organic carbon (SOC) carbon stocks of moderately dense and open forest have been estimated as **1135.24 thousand tonnes (67.17 t/ha)** and **2692.50 thousand tonnes (26.76 t/ha)** respectively.

Table 3. 5 Canopy Density wise per hectare Carbon Stock in Mangrove Forest in Gujarat in different carbon pools.

(in t/ha)

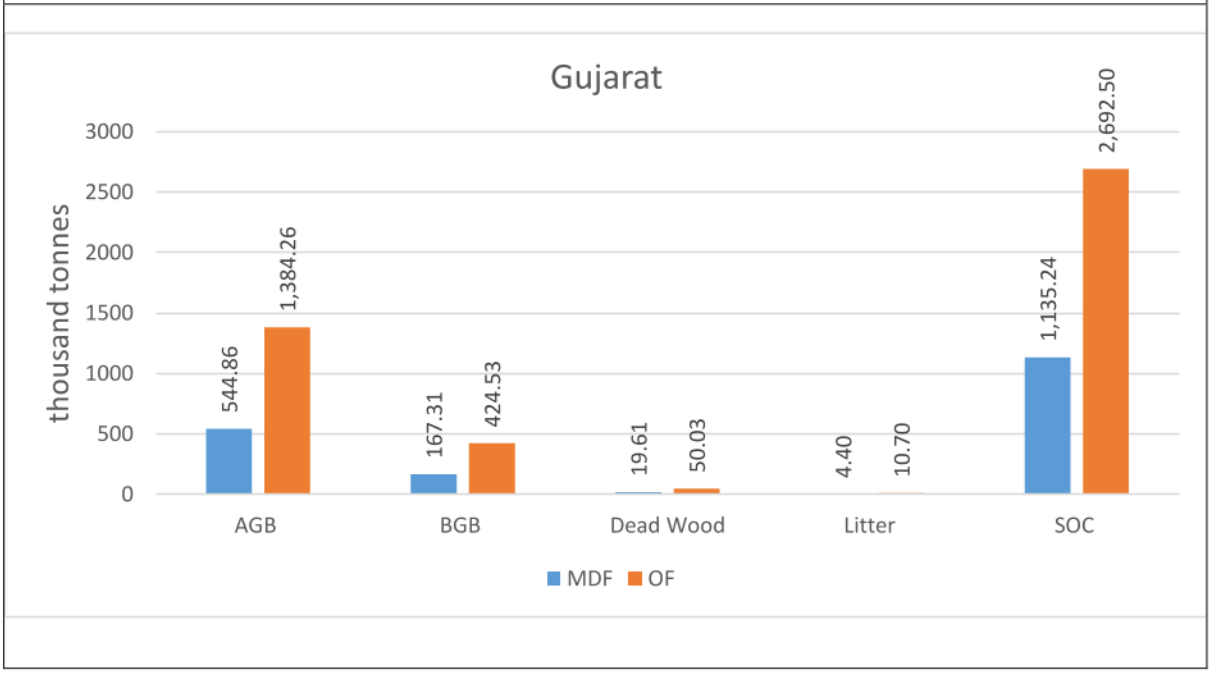
Canopy Density	Area (km^2)	AGB	BGB	Dead wood	Litter	SOC	Total Carbon
MDF	169	32.24	9.90	1.16	0.26	67.17	110.73
OF	1,006	13.76	4.22	0.50	0.11	26.76	45.35

Table 3. 6 Canopy Density wise Carbon Stock in Mangrove Forest in Gujarat under different carbon pools.

(in '000 tonnes)

Canopy Density	Area (km^2)	AGB	BGB	Dead wood	Litter	SOC	Total Carbon
MDF	169	544.86	167.31	19.61	4.40	1,135.24	1,871.41
OF	1,006	1,384.26	424.53	50.03	10.70	2,692.50	4,562.02

Figure 3. 3 Bar diagram of Canopy Density wise Carbon Stock in Mangrove Forest in Gujarat under different carbon pools.



3.4 Estimation of carbon stock in Mangrove forest in Karnataka

Above ground carbon stocks of moderately dense and open forest have been estimated as **6.48 thousand tonnes (32.42 t/ha) and 19.56 thousand tonnes (17.79 t/ha)** respectively.

Below ground carbon stocks of moderately dense and open forest have been estimated as **1.99 thousand tonnes (9.95 t/ha)** and **3.94 thousand tonnes (3.58 t/ha)** respectively.

Dead wood carbon stocks of moderately dense and open forest have been estimated as **0.23 thousand tonnes (1.17 t/ha)** and **0.71 thousand tonnes (0.64 t/ha)** respectively.

Litter carbon stocks of moderately dense and open forest have been estimated as **0.05 thousand tonnes (0.26 t/ha)** and **0.15 thousand tonnes (0.14 t/ha)** respectively.

Soil organic carbon (SOC) carbon stocks of moderately dense and open forest have been estimated as **13.51 thousand tonnes (67.55 t/ha)** and **38.05 thousand tonnes (34.59 t/ha)** respectively.

Table 3. 7 Canopy Density wise per hectare Carbon Stock in Mangrove Forest in Karnataka in different carbon pools.

(in t/ha)

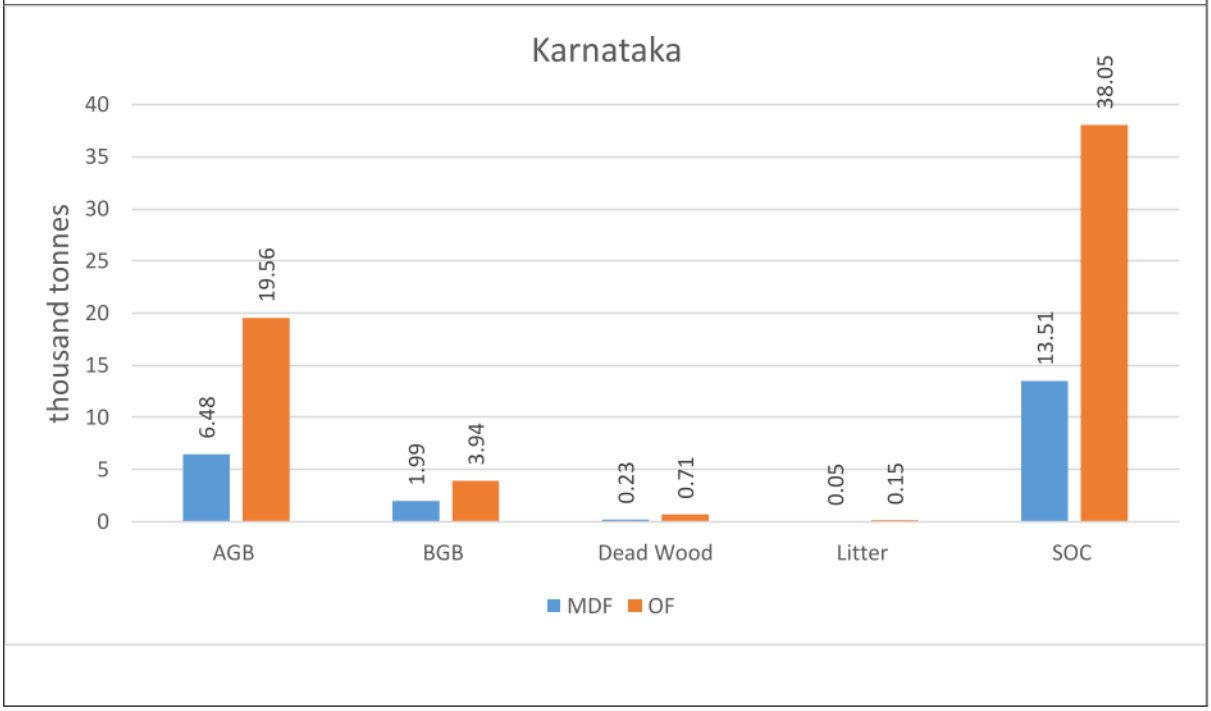
Canopy Density	Area (km^2)	AGB	BGB	Dead wood	Litter	SOC	Total Carbon
MDF	2	32.42	9.95	1.17	0.26	67.55	111.35
OF	11	17.79	3.58	0.64	0.14	34.59	56.74

Table 3. 8 Canopy Density wise Carbon Stock in Mangrove Forest in Karnataka under different carbon pools.

(in '000 tonnes)

Canopy density	Area (km^2)	AGB	BGB	Dead wood	Litter	SOC	Total Carbon
MDF	2	6.48	1.99	0.23	0.05	13.51	22.27
OF	11	19.56	3.94	0.71	0.15	38.05	62.41

Figure 3. 4 Bar diagram of Canopy Density wise Carbon Stock in Mangrove Forest in Karnataka under different carbon pools.



3.5 Estimation of Carbon Stock in Mangrove Forest of Kerala

Above ground carbon stocks of moderately dense and open forest have been estimated as **15.01 thousand tonnes (30.02 t/ha) and 7.82 thousand tonnes (19.54 t/ha)** respectively.

Below ground carbon stocks of moderately dense and open forest have been estimated as **4.61 thousand tonnes (9.22 t/ha)** and **2.40 thousand tonnes (6.00 t/ha)** respectively.

Dead wood carbon stocks of moderately dense and open forest have been estimated as **0.54 thousand tonnes (1.08 t/ha)** and **0.28 thousand tonnes (0.71 t/ha)** respectively.

Litter carbon stocks of moderately dense and open forest have been estimated as **0.12 thousand tonnes (0.24 t/ha)** and **0.06 thousand tonnes (0.15 t/ha)** respectively.

Soil organic carbon (SOC) carbon stocks of moderately dense and open forest have been estimated as **31.27 thousand tonnes (62.55 t/ha)** and **15.20 thousand tonnes (38.01 t/ha)** respectively.

Table 3. 9 Canopy Density wise per hectare Carbon Stock in Mangrove Forest in Kerala in different carbon pools.

(in t/ha)

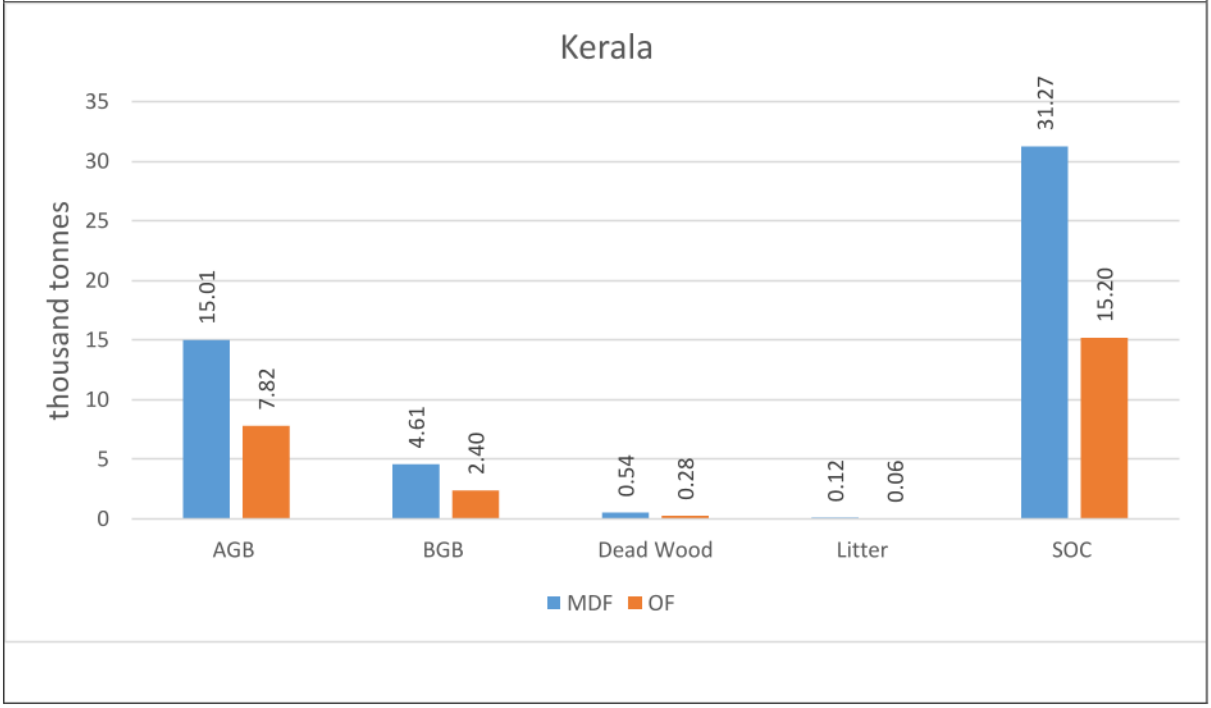
Canopy Density	Area (km^2)	AGB	BGB	Dead wood	Litter	SOC	Total Carbon
MDF	5	30.02	9.22	1.08	0.24	62.55	103.11
OF	4	19.54	6.00	0.71	0.15	38.01	64.40

Table 3. 10 Canopy Density wise Carbon Stock in Mangrove Forest in Kerala under different carbon pools.

(in '000 tonnes)

Canopy density	Area (km^2)	AGB	BGB	Dead wood	Litter	SOC	Total Carbon
MDF	5	15.01	4.61	0.54	0.12	31.27	51.56
OF	4	7.82	2.40	0.28	0.06	15.20	25.76

Figure 3. 5 Bar diagram of Canopy Density wise Carbon Stock in Mangrove Forest in Kerala under different carbon pools.



3.6 Estimation of carbon stock in Mangrove forest in Maharashtra

Above ground carbon stocks of moderately dense and open forest have been estimated as **265.05 thousand tonnes (29.45 t/ha) and 504.50 thousand tonnes (21.56 t/ha)** respectively.

Below ground carbon stocks of moderately dense and open forest have been estimated as **82.89 thousand tonnes (9.21 t/ha)** and **66.92 thousand tonnes (2.86 t/ha)** respectively.

Dead wood carbon stocks of moderately dense and open forest have been estimated as **9.54 thousand tonnes (1.06 t/ha)** and **18.23 thousand tonnes (0.78 t/ha)** respectively.

Litter carbon stocks of moderately dense and open forest have been estimated as **2.14 thousand tonnes (0.24 t/ha)** and **3.90 thousand tonnes (0.17 t/ha)** respectively.

Soil organic carbon (SOC) carbon stocks of moderately dense and open forest have been estimated as **552.25 thousand tonnes (61.36 t/ha)** and **981.31 thousand tonnes (41.94 t/ha)** respectively.

Table 3. 11 Canopy Density wise per hectare Carbon Stock in Mangrove Forest in Maharashtra in different carbon pools.

(in t/ha)

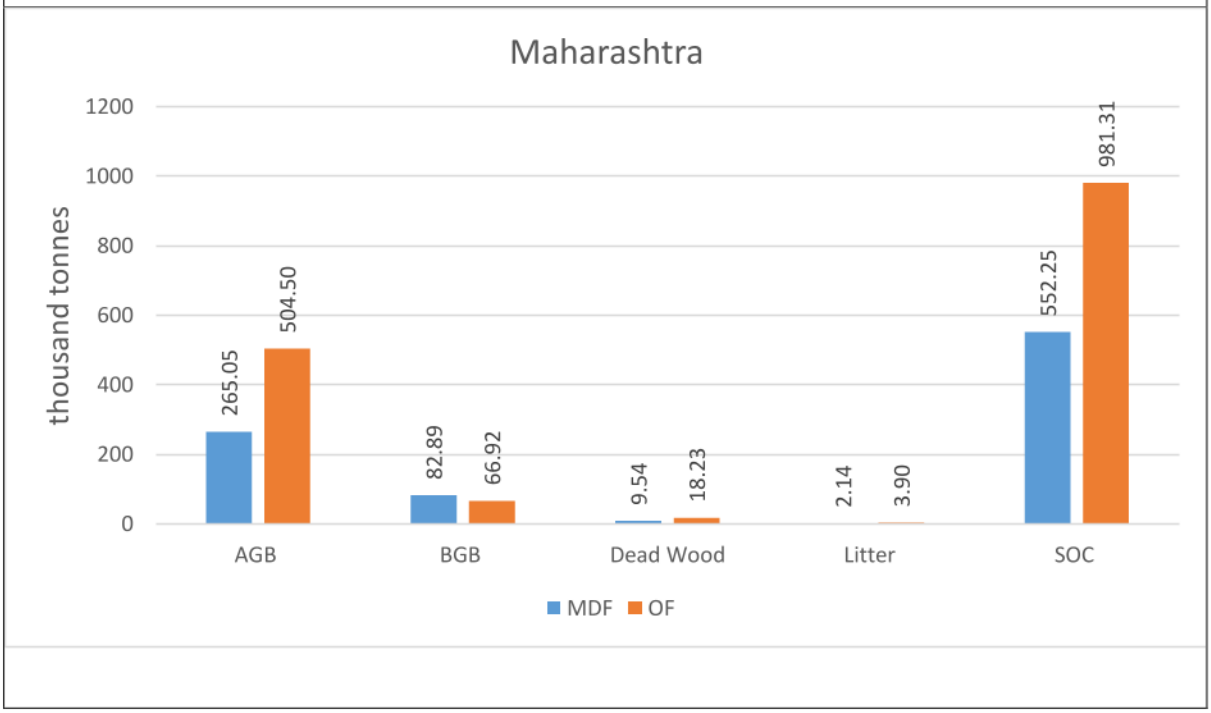
Canopy Density	Area (km^2)	AGB	BGB	Dead wood	Litter	SOC	Total Carbon
MDF	90	29.45	9.21	1.06	0.24	61.36	101.32
OF	234	21.56	2.86	0.78	0.17	41.94	67.30

Table 3. 12 Canopy Density wise Carbon Stock in Mangrove Forest in Maharashtra under different carbon pools.

(in '000 tonnes)

Canopy density	Area (km^2)	AGB	BGB	Dead wood	Litter	SOC	Total Carbon
MDF	90	265.05	82.89	9.54	2.14	552.25	911.86
OF	234	504.50	66.92	18.23	3.90	981.31	1,574.87

Figure 3. 6 Bar diagram of Canopy Density wise Carbon Stock in Mangrove Forest in Maharashtra under different carbon pools.



3.7 Estimation of carbon stock in Mangrove forest in Odisha

Above ground carbon stocks of very dense, moderately dense and open forest have been estimated as **275.81 thousand tonnes (34.05 t/ha), 275.89 thousand tonnes (29.35 t/ha)** and **174.64 thousand tonnes (20.79 t/ha)** respectively.

Below ground carbon stocks of very dense, moderately dense and open forest have been estimated as **107.08 thousand tonnes (13.22 t/ha), 78.40 thousand tonnes (8.34 t/ha)** and **32 thousand tonnes (3.81 t/ha)** respectively.

Dead wood carbon stocks of very dense, moderately dense and open forest have been estimated as **13.74 thousand tonnes (1.70 t/ha), 15.43 thousand tonnes (1.64 t/ha)** and **5.34 thousand tonnes (0.64 t/ha)** respectively.

Litter carbon stocks of very dense, moderately dense and open forest have been estimated as **1.20 thousand tonnes (0.15 t/ha), 1.31 thousand tonnes (0.14 t/ha)** and **0.61 thousand tonnes (0.07 t/ha)** respectively.

Soil organic carbon (SOC) carbon stocks of very dense, moderately dense and open forest have been estimated as **229.42 thousand tonnes (28.32 t/ha), 214.11 thousand tonnes (22.78 t/ha)** and **161.29 thousand tonnes (19.20 t/ha)** respectively.

Table 3. 13 Canopy Density wise per hectare Carbon Stock in Mangrove Forest in Odisha in different carbon pools.

(in t/ha)

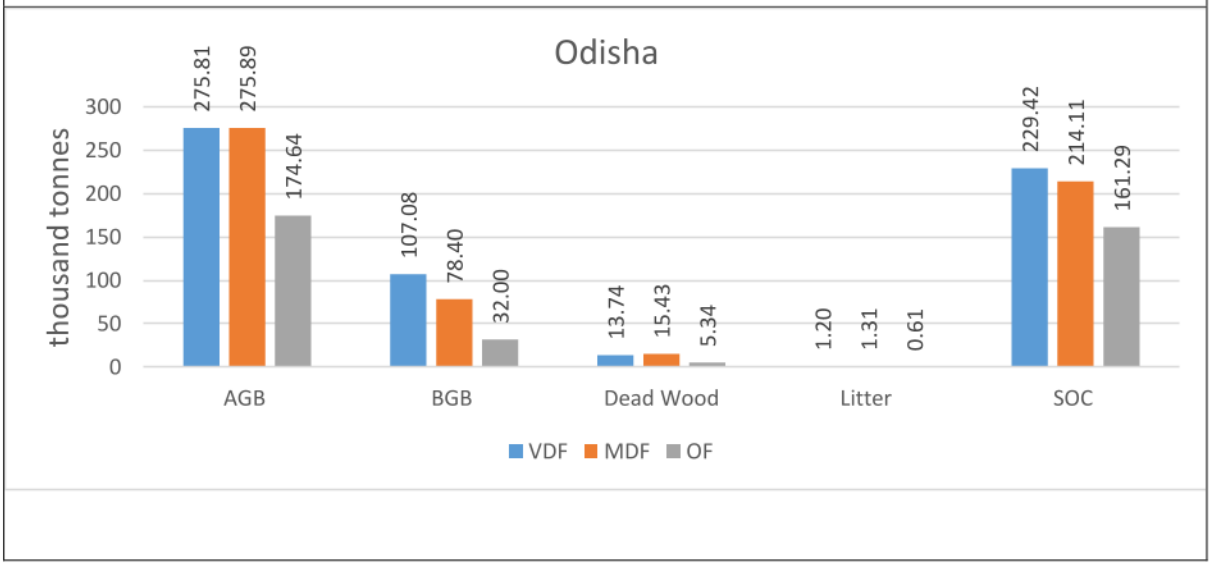
Canopy Density	Area (km^2)	AGB	BGB	Dead wood	Litter	SOC	Total Carbon
VDF	81	34.05	13.22	1.70	0.15	28.32	77.44
MDF	94	29.35	8.34	1.64	0.14	22.78	62.25
OF	84	20.79	3.81	0.64	0.07	19.20	44.51

Table 3. 14 Canopy Density wise Carbon Stock in Mangrove Forest in Odisha under different carbon pools.

(in '000 tonnes)

Canopy Density	Area (km^2)	AGB	BGB	Dead wood	Litter	SOC	Total Carbon
VDF	81	275.81	107.08	13.74	1.20	229.42	627.25
MDF	94	275.89	78.40	15.43	1.31	214.11	585.13
OF	84	174.64	32.00	5.34	0.61	161.29	373.88

Figure 3. 7 Bar diagram of Canopy Density wise Carbon Stock in Mangrove Forest in Odisha under different carbon pools.



3.8 Estimation of Carbon Stock in Mangrove Forest of Tamil Nadu

Above ground carbon stocks of very dense, moderately dense and open forest have been estimated as **3.90 thousand tonnes (38.98 t/ha), 77.38 thousand tonnes (28.66 t/ha)** and **20.79 thousand tonnes (12.23 t/ha)** respectively.

Below ground carbon stocks of very dense, moderately dense and open forest have been estimated as **1.20 thousand tonnes (11.97 t/ha), 23.76 thousand tonnes (8.80 t/ha)** and **6.38 thousand tonnes (3.75 t/ha)** respectively.

Dead wood carbon stocks of very dense, moderately dense and open forest have been estimated as **0.19 thousand tonnes (1.94 t/ha), 4.33 thousand tonnes (1.60 t/ha)** and **0.64 thousand tonnes (0.37 t/ha)** respectively.

Litter carbon stocks of very dense, moderately dense and open forest have been estimated as **0.02 thousand tonnes (0.17 t/ha), 0.37 thousand tonnes (0.14 t/ha)** and **0.07 thousand tonnes (0.04 t/ha)** respectively.

Soil organic carbon (SOC) carbon stocks of very dense, moderately dense and open forest have been estimated as **3.24 thousand tonnes (32.42 t/ha), 60.05 thousand tonnes (22.24 t/ha)** and **19.20 thousand tonnes (11.30 t/ha)** respectively.

Table 3. 15 Canopy Density wise per hectare Carbon Stock in Mangrove Forest in Tamil Nadu in different carbon pools.

(in t/ha)

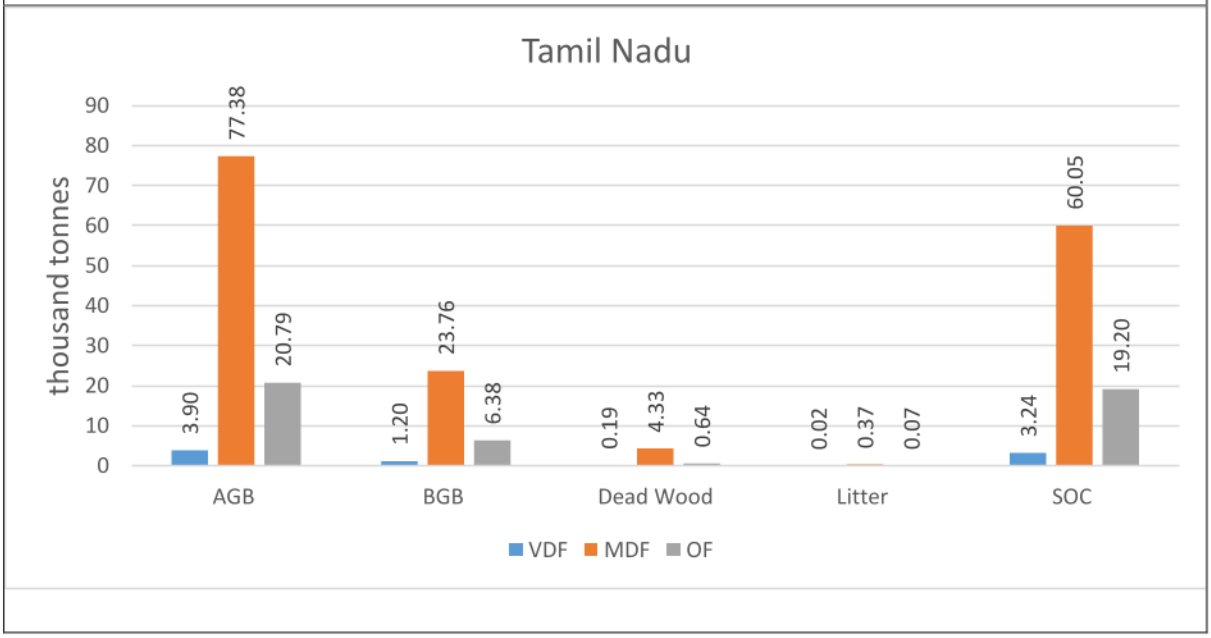
Canopy Density	Area (km^2)	AGB	BGB	Dead wood	Litter	SOC	Total Carbon
VDF	1	38.98	11.97	1.94	0.17	32.42	85.48
MDF	27	28.66	8.80	1.60	0.14	22.24	61.44
OF	17	12.23	3.75	0.37	0.04	11.30	27.69

Table 3. 16 Canopy Density wise Carbon Stock in Mangrove Forest in Tamil Nadu under different carbon pools.

(in '000 tonnes)

Canopy density	Area (km^2)	AGB	BGB	Dead wood	Litter	SOC	Total Carbon
VDF	1	3.90	1.20	0.19	0.02	3.24	8.55
MDF	27	77.38	23.76	4.33	0.37	60.05	165.89
OF	17	20.79	6.38	0.64	0.07	19.20	47.08

Figure 3. 8 Bar diagram of Canopy Density wise Carbon Stock in Mangrove Forest in Tamil Nadu under different carbon pools.



3.9 Estimation of Carbon Stock in Mangrove Forest of West Bengal

Above ground carbon stocks of very dense, moderately dense and open forest have been estimated as **3,763.28 thousand tonnes (37.86 t/ha), 1,711.32 thousand tonnes (24.73 t/ha)** and **857.28 thousand tonnes (20.03 t/ha)** respectively**.**

Below ground carbon stocks of very dense, moderately dense and open forest have been estimated as **1,189.62 thousand tonnes (11.97 t/ha), 608.96 thousand tonnes (8.80 t/ha)** and 1**60.50 thousand tonnes (3.75 t/ha)** respectively**.**

Dead wood carbon stocks of very dense, moderately dense and open forest have been estimated as **555.54 thousand tonnes (5.59 t/ha), 373.39 thousand tonnes (5.40 t/ha)** and **61.46 thousand tonnes (1.44 t/ha)** respectively**.**

Litter carbon stocks of very dense, moderately dense and open forest have been estimated as **29.31 thousand tonnes (0.29 t/ha), 12.82 thousand tonnes (0.19 t/ha)** and **5.88 thousand tonnes (0.14 t/ha)** respectively**.**

Soil organic carbon (SOC) carbon stocks of very dense, moderately dense and open forest have been estimated as **2,229.98 thousand tonnes (22.43 t/ha), 1,470.08 thousand tonnes (21.24 t/ha)** and **720.09 thousand tonnes (16.82 t/ha)** respectively**.**

Table 3. 17 Canopy Density wise per hectare Carbon Stock in Mangrove Forest in West Bengal in different carbon pools.

(in t/ha)

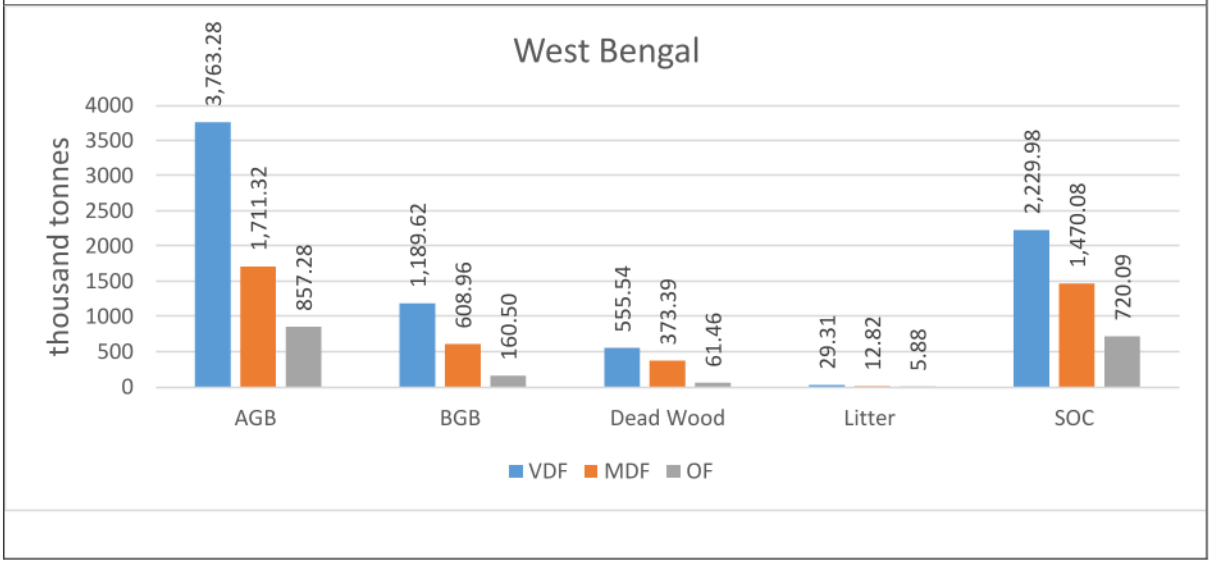
Canopy Density	Area (km^2)	AGB	BGB	Dead wood	Litter	SOC	Total Carbon
VDF	994	37.86	11.97	5.59	0.29	22.43	78.15
MDF	692	24.73	8.80	5.40	0.19	21.24	60.35
OF	428	20.03	3.75	1.44	0.14	16.82	42.18

Table 3. 18 Canopy Density wise Carbon Stock in Mangrove Forest in West Bengal under different carbon pools.

(in '000 tonnes)

Canopy density	Area (km^2)	AGB	BGB	Dead wood	Litter	SOC	Total Carbon
VDF	994	3,763.28	1,189.62	555.54	29.31	2,229.98	7,767.73
MDF	692	1,711.32	608.96	373.39	12.82	1,470.08	4,176.56
OF	428	857.28	160.50	61.46	5.88	720.09	1,805.21

Figure 3. 9 Bar diagram of Canopy Density wise Carbon Stock in Mangrove Forest in West Bengal under different carbon pools.



3.10 Estimation of Carbon Stock in Mangrove Forest of Andaman & Nicobar

Above ground carbon stocks of very dense, moderately dense and open forest have been estimated as **2,366.47 thousand tonnes (59.31 t/ha), 731.64 thousand tonnes (43.55 t/ha)** and **80.46 thousand tonnes (16.42 t/ha)** respectively.

Below ground carbon stocks of very dense, moderately dense and open forest have been estimated as **726.58 thousand tonnes (18.21 t/ha), 224.62 thousand tonnes (13.37 t/ha)** and **24.70 thousand tonnes (5.04 t/ha)** respectively.

Dead wood carbon stocks of very dense, moderately dense and open forest have been estimated as **349.34 thousand tonnes (8.76 t/ha), 159.63 thousand tonnes (9.50 t/ha)** and **5.77 thousand tonnes (1.18 t/ha)** respectively.

Litter carbon stocks of very dense, moderately dense and open forest have been estimated as **18.43 thousand tonnes (0.46 t/ha), 5.48 thousand tonnes (0.33 t/ha)** and **0.55 thousand tonnes (0.11 t/ha)** respectively.

Soil organic carbon (SOC) carbon stocks of very dense, moderately dense and open forest have been estimated as **1,402.28 thousand tonnes (35.14 t/ha), 628.50 thousand tonnes (37.41 t/ha)** and **67.58 thousand tonnes (13.79 t/ha)** respectively.

Table 3. 19 Canopy Density wise per hectare Carbon Stock in Mangrove Forest in Andaman & Nicobar in different carbon pools.

(in t/ha)

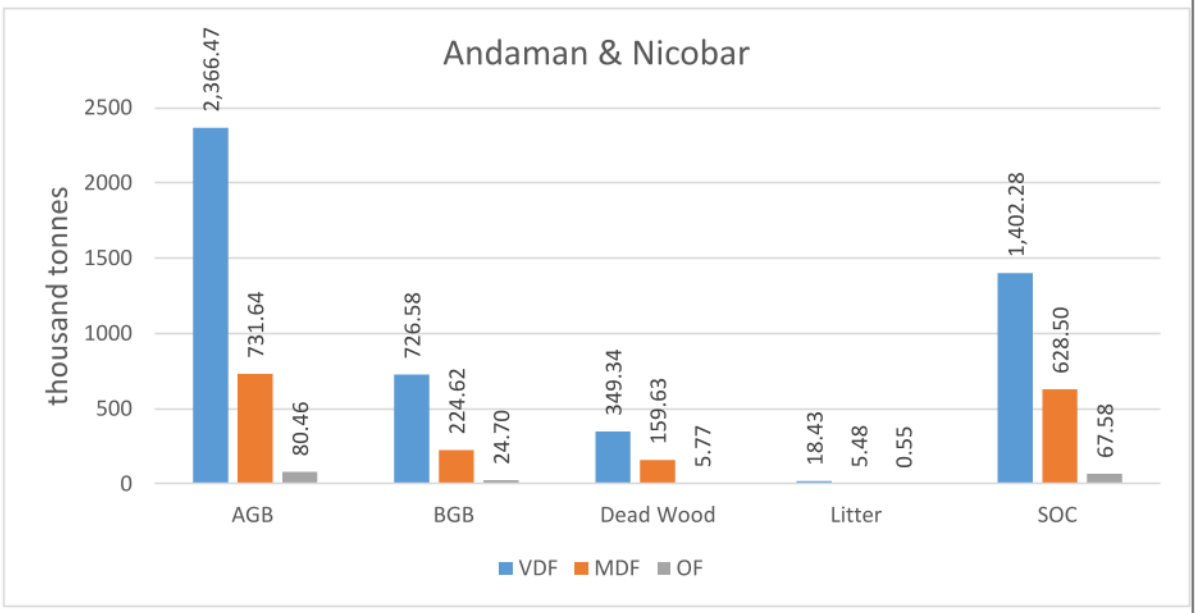
Canopy Density	Area (km^2)	AGB	BGB	Dead wood	Litter	SOC	Total Carbon
VDF	399	59.31	18.21	8.76	0.46	35.14	121.88
MDF	168	43.55	13.37	9.50	0.33	37.41	104.16
OF	49	16.42	5.04	1.18	0.11	13.79	36.54

Table 3. 20 Canopy Density wise Carbon Stock in Mangrove Forest in Andaman & Nicobar under different carbon pools.

(in '000 tonnes)

Canopy density	Area (km^2)	AGB	BGB	Dead wood	Litter	SOC	Total Carbon
VDF	399	2,366.47	726.58	349.34	18.43	1,402.28	4,863.10
MDF	168	731.64	224.62	159.63	5.48	628.50	1,749.88
OF	49	80.46	24.70	5.77	0.55	67.58	179.06

Figure 3. 10 Bar diagram of Canopy Density wise Carbon Stock in Mangrove Forest in Andaman & Nicobar under different carbon pools.



3.11 Estimation of Carbon Stock in Mangrove Forest of Dadra & Nagar Haveli & Daman & Diu

Above ground carbon stocks of open forest has been estimated as **10.46 thousand tonnes (34.88 t/ha).**

Below ground carbon stocks of open forest has been estimated as **2.42 thousand tonnes (8.06 t/ha)** and **0.38 thousand tonnes (1.26 t/ha)** respectively**.**

Dead wood carbon stocks of open forest has been estimated as **0.38 thousand tonnes (1.26 t/ha).**

Litter carbon stocks of open forest has been estimated as **0.08 thousand tonnes (0.27 t/ha).**

Soil organic carbon (SOC) carbon stocks of open forest has been estimated as **4.70 thousand tonnes (15.68 t/ha).**

Table 3. 21 Canopy Density wise per hectare Carbon Stock in Mangrove Forest in Daman & Diu in different carbon pools.

(in t/ha)

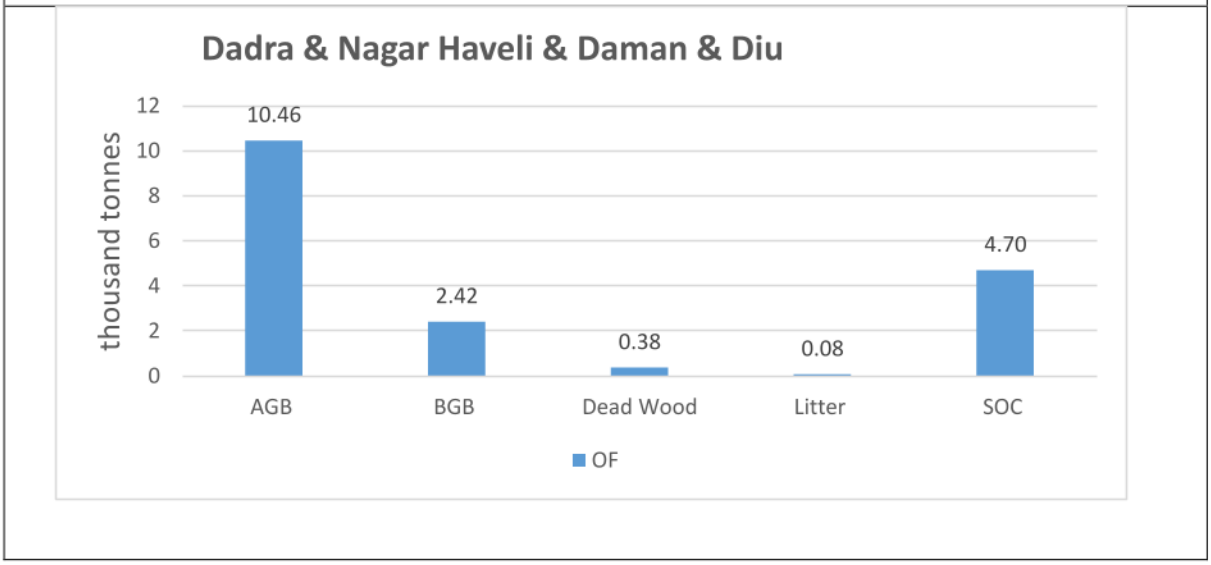
Canopy Density	Area (km^2)	AGB	BGB	Dead wood	Litter	SOC	Total Carbon
OF	3	34.88	8.06	1.26	0.27	15.68	60.15

Table 3. 22 Canopy Density wise Carbon Stock in Mangrove Forest in Daman & Diu under different carbon pools.

(in '000 tonnes)

Canopy density	Area (km^2)	AGB	BGB	Dead wood	Litter	SOC	Total Carbon
OF	3	10.46	2.42	0.38	0.08	4.70	18.04

Figure 3. 11 Bar diagram of Canopy Density wise Carbon Stock in Mangrove Forest in Dadra & Nagar Haveli & Daman & Diu under different carbon pools.



3.12 Estimation of Carbon Stock in Mangrove Forest of Puducherry

Above ground carbon stocks of open forest has been estimated as **3.10 thousand tonnes (15.50 t/ha).**

Below ground carbon stocks of open forest has been estimated as **0.95 thousand tonnes (4.76 t/ha).**

Dead wood carbon stocks of open forest has been estimated as **0.22 thousand tonnes (1.11 t/ha).**

Litter carbon stocks of open forest has been estimated as **0.02 thousand tonnes (0.11 t/ha).**

Soil organic carbon (SOC) carbon stocks of open forest has been estimated as **2.60 thousand tonnes (13.02 t/ha).**

Table 3. 23 Canopy Density wise per hectare Carbon Stock in Mangrove Forest in Puducherry in different carbon pools.

(in t/ha)

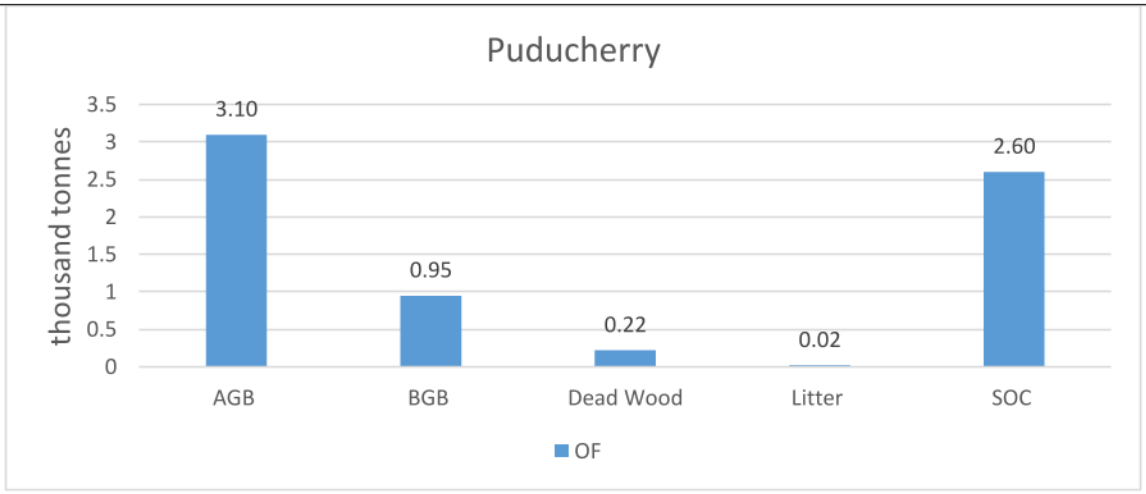
Canopy Density	Area (km^2)	AGB	BGB	Dead wood	Litter	SOC	Total Carbon
OF	2	15.50	4.76	1.11	0.11	13.02	34.50

Table 3. 24 Canopy Density wise Carbon Stock in Mangrove Forest in Puducherry under different carbon pools.

(in '000 tonnes)

Canopy density	Area (km^2)	AGB	BGB	Dead wood	Litter	SOC	Total Carbon
OF	2	3.10	0.95	0.22	0.02	2.60	6.90

Figure 3. 12 Bar diagram of Canopy Density wise Carbon Stock in Mangrove Forest in Puducherry under different carbon pools



CHAPTER 4

CONCLUSION AND FUTURE VISION

CONCLUSION & WAY FORWARD

Optical remote sensing provides two dimensional representation of land-surface vegetation and its reflectance properties which can be indirectly related to biophysical parameters like NDVI, LAI and forest cover. Vertical dimension as third dimension in interpretation adds the information to help and understand the features in the context of their height, volume and spatial relation to each other. In contrast to estimates of forest parameters obtained from passive optical data, active LiDAR remote sensing provides a unique means of directly estimating biophysical parameters using physical interaction of the laser pulse with the vegetation structure. That enables vertical profile of forest canopy represented and canopy heights, metrics and cover to be calculated and these structural parameters further used for biomass estimation. Laser technology is capable of measuring tree heights in closed canopies and therefore offer a non-destructive means of estimating vegetation volume, biomass or carbon content. Hence, time consuming field work can be avoided and inaccessible regions become accessible using a relatively low cost and automated LiDAR system.

Under the project work, field data were collected in different canopy density stratum i.e. very dense, moderately dense and open forest in Maharashtra, Odisha and West Bengal mangroves following standard field forms which is then used to derive estimation of AGB, BGB, Dead wood, Litter and SOC. The study revealed that ICESat-2 LiDAR derived mean canopy height has statistically significant correlation with actual heights observed during the field work. Accordingly, a model was developed for AGB estimation using regression analysis (dependent variable = Calculated AGB; independent variable = LiDAR mean canopy height and canopy openness). Findings of this study revealed that LiDAR based model can be efficiently used for AGB estimation of mangrove forest in different canopy density stratum. Canopy openness is prominent LiDAR parameter that prove to be best indicator for AGB differences in all density classes VDF, MDF and OF which in general is not found in passive remote sensing data. The BGB was calculated for all the beams used for AGB following IPCC default values on predicted AGB. The estimation was done following weighted average formula for each state. The Dead wood, Litter and SOC which are minor pools of carbon estimation are based on actual field data collected from Maharashtra, Odisha and West Bengal. For rest of the States/UTs, the per hectare carbon for Dead wood, litter and SOC is calculated using average per hectare estimate of the State in the respective pool (Deadwood, Litter & SOC), multiplied with area of mangroves in the States/ UTs in different canopy density classes. The use of

LiDAR derived canopy height information for AGB estimation has been demonstrated in the report. Canopy height is found as the most important variable explaining variability in AGB of the forest. Traditionally, researchers have used parametric methods (simple linear or multiple linear regression) for relating remote sensing derived proxy variables to field measured AGB values, the same technique is applied this study as well. The model developed in this study can be adopted in other study area and help in fulfilling the mandate of AGB monitoring of tropical forests required in various climate change mitigation programme (e.g. REDD+). In future studies along with LiDAR derived canopy height, a range of other variables derived from SAR and optical data can be used for AGB estimation with more accuracy.

Estimation of Carbon Stock of Mangrove Forest in India under different carbon pools

('000 tonnes)

Density	Mangrove Area (km^2)	AGB	BGB	Dead Wood	Litter	SOC	Total
VDF	1,475	6,409.46	2,024.48	918.81	48.97	3,864.92	13,266.63
MDF	1,481	4,332.81	1,410.16	620.70	30.26	4,745.77	11,139.71
OF	2,036	3,451.82	844.06	154.98	23.42	5,070.36	9,544.64
Total	**4,992**	**14,194.08**	**4,278.70**	**1,694.49**	**102.65**	**13,681.05**	**33,950.98**

Estimation of Carbon Stock of Mangrove Forest in India under different carbon pools

(t/ha)

Density	Mangrove Area (km^2)	AGB	BGB	Dead Wood	Litter	SOC	Total
VDF	1,475	43.454	13.725	6.229	0.332	26.203	**89.943**
MDF	1,481	29.256	9.522	4.191	0.204	32.044	**75.217**
OF	2,036	16.954	4.146	0.761	0.115	24.904	**46.879**
Total	**4,992**	**28.434**	**8.571**	**3.394**	**0.206**	**27.406**	**68.011**

Annexure: Field formats used for data collection

Forest Survey of India

PLOT ENUMERATION FORM

Plot id	Location Name	Latitude	Longitude	Sub-plot	Sub-plot status	Total No. of trees

S.No.	Species Name	Dia (cm)	Height (in meter)

Date.....

Signature of the Crew Leader.....

Forest Survey of India

STUMP, DEAD WOOD AND WOODY LITTER FORM

Plot id	Latitude	Longitude	Presence of Dead Wood information

Stump and Dead wood: circular plot of size 2.8 m radius

Woody litter: circular plot of size 1.7 m radius

Sub-plot number	Stump Information				Dead wood information			Woody litter (branch less than 5 cm)	
	Species code	Status of stump (alive/ dead)	Dia in cm.	Height in cm.	Species code	Dbh/Dia (cm)	Length of the Log (cm)	Sub-plot number	Weight (in kg upto two decimal places)
								1	
								2	
								3	
								4	

Date.....

Signature of Crew Leader.....

Forest Survey of India

SOIL AND FOREST FLOOR CARBON FORM

Plot id	State	District	Location Name

Latitude	Longitude	Soil Colour	Photographs id

Date.....

Signature of Crew Leader.....

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About FSI

Forest Survey of India (FSI) is a premier national organization under the Ministry of Environment, Forest and Climate Change, Government of India. It is responsible for assessment and monitoring of the forest resources of the country on regular basis. Established on 1st June 1981, Forest Survey of India succeeded the "Pre-investment Survey of Forest Resources" (PISFR), a project initiated in 1965 by Government of India with the sponsorship of FAO and UNDP. The main objective of PISFR was to ascertain the availability of raw material for establishment of wood based industries in selected areas of the country. In its report in 1976, the National Commission on Agriculture (NCA) recommended for the creation of a National Forest Survey Organization for a regular, periodic and comprehensive forest resources survey of the country leading to creation of FSI.

The major activities of FSI include remote sensing based nation-wide forest cover mapping in biennial cycle, National Forest Inventory based on large number of sample plots laid across the country, forest fire monitoring, forest carbon assessment, forest type mapping and several projects on emerging issues and State specific requirements. Since 1987, FSI is publishing biennial 'State of Forest Reports' on the status of the forest resources of the country. These reports are widely acclaimed nationally and as well as internationally and are treasure trove of primary information on Indian Forests.

FSI has headquarters at Dehradun and has pan India presence with four regional offices at Shimla, Kolkata, Nagpur and Bangalore. The Eastern zone has a sub center at Burnihat.

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