ASSESSMENT OF CARBON STOCK AND CARBON SEQUESTRATION SCENARIO THROUGH LAND USE CHANGE IN THE STATE OF GOA

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ABBREVIATIONS

AGB: Above Ground Biomass

BGB: Below-Ground Biomass

BHWS: Bhagwan Mahaveer Wildlife Sanctuary

CCS: Carbon Capture and Storage

COP: Conference of Parties

CWS: Cotigao Wildlife Sanctuary

DBH: Diameter at Breast Height

ETM+: Enhanced Thematic Mapper Plus

FAO: Food and Agriculture Organization

FCC: False Color Composite

FSI: Forest Survey of India

GHG's: Green House Gases

GIS: Geographic Information System

GPS: Global Positioning System

GVI: Green Vegetation Index

IDW: Inverse Distance Weighted

IEA: International Energy Agency

IPCC: Inter-governmental Panel on Climate Change

IUCN: International Union for Conservation of Nature

LULC: Land Use and Land Cover

MWS: Mhadei Wildlife Sanctuary

MEA: Millennium Ecosystem Assessment

MLC: Maximum Likelihood Classification

MoEF: Ministry of Environment and Forests

NDVI: Normalized Differential Vegetation Index

NEP: Net Ecosystem Production

NPP: Net Primary Production

NWS: Netravali Wildlife Sanctuary

OECD: Organization for Economic Cooperation and Development

OLI: Operational Land Imager

REDD: Reductions in Emissions from Deforestation in Developing countries

RS: Remote Sensing

SOC: Soil Organic Carbon

SOCS: Soil Organic Carbon Stock

SOM: Soil Organic Matter

TIRS: Thermal Infrared Sensor

TOC: Total Organic Carbon

TOF: Tree Outside Forests

UNFCCC: United Nations Framework Convention on Climate Change

USGS: United States Geological Survey

UTM: Universal Transverse Mercator

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INTRODUCTION

1. Introduction:

During the last century, the carbon dioxide (CO_2) concentration in the atmosphere has increased from 280 to 367 parts per million (ppm) (IPCC, 2001). The industrial revolution and increasing urbanization in the modern world are leading to an increase in the concentration of greenhouse gases (GHGs). CO_2 is a major contributor to global warming (Hangarge L M *et al.* 2012). The enhancement of atmospheric CO_2 coupled with the temperature rise is the main reason behind the global climate change which has raised the global mean temperature by 0.5°C during the last hundred years and 0.4°C in the last 70 years for the Indian sub-continent (Negi J D S *et al.* 2003). The Land Use and Land Cover (LULC) change sector is the second most important source of CO_2 emissions (IPCC, 2001) as forest areas are rapidly changing into agriculture, livestock, and other man-made vegetation and degraded areas (Lambin, 1994). Acknowledging that it is the entire forest carbon balance that is crucially linked to the atmosphere, not only the balance of some parts of it (Jari Liski *et al.* 2006). Additionally, studies at the regional level are needed to improve national greenhouse gas inventories and could be developed as a basis for regional baselines of carbon sequestration projects in the forestry sector (Pearson T R *et al.* 2007). Thus increasing CO_2 emission is one of the major environmental concerns and it has been well addressed in the Kyoto protocol (Hangarge L M *et al.* 2012). Under the Protocol, 37 industrialized countries and the European Community have committed to reducing their emissions by an average of 5 percent against 1990 levels over the five years 2008-2012. The Conference of Parties (COP) named these pools as above and below-ground biomass, deadwood, litter, and soil organic carbon (Rokhmatuloh, 2009). According to the National Oceanic and Atmospheric Administration of the USA, the concentration of CO_2 in the atmosphere has steadily increased from 280 ppm in 1800 to 385 ppm in 2008. The CO_2 source and sink dynamics as trees grow, die, and decay is subjected to disturbance and forest management. Evidence of climate change linked to the human-induced increase in greenhouse gas (GHG) concentrations is well-documented in international studies (IPCC 2001, 2007). The recognized importance of forests in mitigating climate change has led countries to study their forest carbon budgets and initiate the assessment of enhancing and maintaining carbon sequestration of their forests resource. The total global potential for afforestation and reforestation activities for the period 1995–2050 is estimated to be between 1.1 and 1.6 Pg C (1 Pg = Peta gram, 1015g) per year, of which 70% could occur in the tropics (IPCC, 2000). Afforestation and reforestation are seen as potentially attractive mitigation strategies, as wood production and carbon (C) storage can be combined (Meenakshi Kaul *et al.* 2010). To contribute to the reduction of GHG emissions, and to partly offset deforestation, the Kyoto protocol explicitly considered reforestation and afforestation activities for carbon sequestration accounting (IPCC, 2007). The total global potential for afforestation and reforestation activities for the period 1995–2050 is estimated to be between 1.1 and 1.6 Pg C (1 Pg = Petagram, 1015 g) per year, of which seventy percent could occur in the tropics (IPCC, 2001_a). United Nations Framework Convention on Climate Change (UNFCCC) has recognized the importance of plantation forestry as a GHG mitigation option, as well as the need to monitor, preserve and enhance terrestrial carbon stocks (Updegraff *et al.* 2004). Biomass production is an indication of the productivity of any plants and carbon capture is an indication of the reduction of atmospheric carbon dioxide which can mitigate global warming. Forests have an important role in the global C cycle and are valued globally for the services provided to society. International negotiations to limit greenhouse gases require an understanding of the current and potential future role of forest C emissions and sequestration in both managed and unmanaged forests. Estimates by the Intergovernmental Panel on Climate Change show that the net uptake by terrestrial ecosystems ranges from less than 1.0 to as much as 2.6 Pg C per year for the 1990s. More recent global carbon analyses have estimated a terrestrial carbon sink in the range of 2.0 to 3.4 Pg C per year based on atmospheric CO_2 observations and inverse modeling, and land observations. Because of this uncertainty and the possible change in magnitude over time, constraining these estimates is critically important to support future climate mitigation actions (Yude Pan *et al.* 2011). It is estimated that about 86% of the terrestrial above-ground carbon and 73% of the earth's soil carbon are stored in the forests. The tropical forests are said to play a major role in the global carbon cycle, storing up to about 46% of the world's terrestrial carbon pool and about 11.55% of the world's soil carbon pool, acting as a carbon reservoir and functioning as a constant sink of atmospheric carbon (Kuimi T Vashum *et al.* 2012). The fact that carbon is stored for long periods in living biomass and soil is well documented extensively since 1992, although studies were carried out in this field since 1980. Several studies have established the fact that carbon sequestration by trees could provide relatively low-cost net emission reductions. Houghton predicted that carbon dioxide emission to the atmosphere would increase from 7.4 Gt C per year in 1997 to approximately 26 Gt C per year by 2100. Many scientists agree that a doubling of atmospheric CO_2 could have a variety of serious environmental consequences (A. Ramachandran *et al.* 2007).

1.1 Origin of the Research Problem:

India has rich biodiversity due to different climatic conditions from the north to south and east to waste. It covers 1, 26,188 species of plants and animals. India with a total area of about 3,029 million ha is considered to be one of the 12 mega biodiversity hotspots of the origins and diversity of several plant species (Ishan Pandya *et al.* 2012). It has a direct effect on carbon sequestration, more than 116 million tons of CO_2 per year is sequestered contributing to reducing atmospheric carbon. The living vegetation, sea-water, and soils play a key role in absorbing atmospheric CO_2 (Hangarge L M *et al.* 2012).

The state of Goa encompasses the rich biological diversity of the Western Ghats on the Eastern part and the coastal Ecosystem all along the western side with humid and pre-humid climates. The State's total Government forest is spread over 1224 sq. km. which constitutes 33.06% of the total geographical area.

There are forest areas and also other tree vegetation including horticulture crops/ plantations on private land holding in the state. Thus the total cover based on the satellite data of December 2004 is 2431 sq. km which is 65.69% of the geographic area of the state (Sawant Committee Report and Karapurkar Committee Report). Two territorial and a wildlife division administer the forest area and all cashew and rubber plantations raised by the department are being managed by the Goa Forest Development Corporation Ltd. Out of the total Government forest area (1,224 sq. km) about 755 sq. km areas constitute protected area network covering about 62% of the total forest area. A total of four types of vegetation regimes are found in Goa that are estuarine vegetation of mangroves along swampy river banks, Strand and creek vegetation along the coastal belt, and plateau vegetation along undulating terrain and hills. A major portion of the vegetation in Goa belongs to this category, which is further divided into the open scrub jungle and moist deciduous forests. Moist deciduous further classified as Secondary moist mixed deciduous forests, Sub-tropical Hill forests, and Semi-evergreen and Evergreen vegetation along the upper Ghats mostly above 500 MSL. It consists of lateritic semi-evergreen forests and evergreen forests (Forest Goa. Gov.). All along the river banks due to tides, the soil remains inundated. These inundated patches are vital for inland fisheries and agriculture locally known as Khazan land. The lateritic surfaces of plateaus are covered by very thin veneer detritus. A scattered patch of Cree and talus supports the thick vegetation on the slope and foothill zones. Substantial agriculture is sustained on the alluvial soil at the low-lying plains. Estuaries are well marked by marshy soil with lush green mangroves. Scenic sandy beaches along the coastline boost the tourism industry. Due to rapid urbanization and industrialization forest cover is tangible. Rapid socioeconomic transformation is the legacy of outmigration. Tourism, industrialization, high standards of living, and levels of urbanization have brought a change in the State economy, but there have been growing concerns related to the land and people. Increasing density with a large voluminous floating population has put pressure on land, water, vegetation, and other natural resources. It resulted in a decrease in the forest cover, degradation of land quality, and contamination of water. It has created threats to mangroves and Khazan land. The river Zuari acts as the waterway for the transportation of inland minerals to the port. Lately, there has been an issue of siltation and water pollution, and encroachment. Rapid urbanization has led to the emergence of slum (unseen before 1971) garbage and sewerage management. The rapid development of industries, tourism, urbanization, mining, and deforestation contributes to the emission of CO_2. It may lead the local environment to microclimate change. As stated in Kyoto Protocol and IPCC guidelines there is an urgent need to take action to minimize the concentration of CO_2 by developing more effective and efficient carbon sinks in prevailing terrestrial ecosystems availing the diversified geo-environmental setup.

1.2 Objectives:

The present research topic entitled “Assessment of Carbon Stock and Carbon Sequestration Scenario Through Land Use Change in the State of Goa” aims to

- To analyze the dynamics of land use and land cover to assess carbon sequestration potentialities in the study region.
- To analyze Spatio-temporal variations in above and below-ground biomass in the study region.
- To monitor the spatial and temporal distribution of carbon stock and carbon sequestration in the study region.
- To suggest a suitable alteration in the potential sites for reforestation, afforestation, and agro-forestry in the study region.

1.3 Research design and Methodology:

The project boundary was defined as the geographically marked area dedicated to the project activities. The present study area is the state of Goa and the LULC categories such as Agricultural land, Wetlands, Mangroves, and Forest areas were mapped with GIS for precise and accurate plotting.

1.3.1 Project scaling

The size of the project determines the methods to be used for carbon inventory. Carbon stock changes in small-scale projects could be monitored using field measurements whereas large-scale projects require the adoption of remote sensing and modeling techniques. Small-scale projects are likely to be more homogenous concerning soil, topography, and species dominance (Sanz *et al.* 2005). Since the present study site is a large-scale project, remote sensing, GIS and modeling techniques have been implemented. Field collection of soil sample and biometric measurements of tree species at selected sites in the study area.

1.3.2 Sampling

There are four options for sampling design; complete enumeration, simple random sampling, systematic sampling, and stratified random sampling. For the present study, a stratified random sampling design has been applied. Stratified random sampling generally yields more precise estimates than the other options (McDicken, 1997b). Stratified random sampling requires stratification to divide the populations into non-overlapping sub-populations. Each stratum (or sub-population) can be defined by vegetation type, soil type, or topography. For carbon inventory, strata may be most logically defined by estimated total carbon pool weight. Since that largely depends on above-ground biomass, stratification criteria that reflect biomass are generally the most appropriate. Useful tools for defining strata include satellite images, aerial photographs, and maps of vegetation, soils, or topography which may be preferred as per availability (MacDicken, 1997a; Brown, 1997; Ravindranath and Ostwald, 2008).

1.3.3 Filed work:

Researchers have also collected 280 soil samples belonging to agriculture (160), forest (50), wetlands (45), and mangroves (25) areas of the state of Goa. Samples were collected using stratified random sampling techniques. The soil samples were obtained from 0-10cm depth. Collected samples were dried at room temperature for 8-10 days.

1.3.4 Secondary data of Soil OC

Total of 7834 soil sample data is obtained for cycles from 2015 to 2021. The major amount of information belongs to cycles 2017-18 (2047), 2018-19 (2074), and 2019-20 (3474) soil testing cycles. The data was obtained from *https://soilhealth.dac.gov.in/PublicReports/GridFormNSVW* Web site (figure 4.1 page 112).

1.3.5 Use of GPS

The GPS location was recorded for each sampling site using Garmin Etrex-vista at ±10 ft (3m) accuracy. This accuracy is adequate for most land area estimations (Greenhouse, 2002).

1.3.6 Analytical methods

The plant biomass Above Ground Biomass (AGB) and Below Ground Biomass (BGB) estimated using Allometric equations developed for the Western Ghats (Murali *et al.* 2005), were used for this purpose. Carbon conversion coefficients are different, considering species, age, formation, and community structure of vegetation types, from 0.45 to 0.55 (Kauppi *et al.* 1992; Goodale *et al.* 2002; Xia *et al.* 2005, and Ramachandran *et al.* 2007). Since such coefficients are not available for the study area, a carbon conversion coefficient of 0.5 is used in the present study (please refer to Chapter 3 for details).

1.3.7 Lab testing:

Dried samples were crushed into fine pieces using mortar and pestle. The fine pieces were passed through 0.40mm sieves using an electrical sieve shaker. The bulk density of each soil sample was estimated using standard procedure. The sieved samples were analyzed in the soil laboratory for the estimation of Soil Organic Carbon (SOC) and Soil Organic Matter (SOM) through two different methods i.e. (a) Loss on Ignition (LOI) (Storer *1984*) and (b) Revised Walkley-Black rapid titration (W-B) method (Trivedi and Goel, 1986) (please refer chanter three for details).

For comparative purposes, both methods were used for the estimation of SOC and SOM. Out of this, the W-B method proved to be efficient for its accurate reading and consumes less time when compared to the LOI method (Ismael *et al.* 2017).

The % of SOC value obtained from the W-B method was multiplied by a standard correction factor of 1.32 (De Vos *et al.* 2007) to obtain the corrected SOC. The SOC stock was computed by multiplying the SOC values (g/kg) with bulk density (g/cm^3) and depth (cm) and was expressed in ton/ha (Joao Carlos *et al.* 2001).

The Biomass of tree species was estimated from four different forest sites such as Cotigao Wildlife Sanctuary (CWS), Netravali Wildlife Sanctuary (NWS), Bhagwan Mahaveer Wildlife Sanctuary (BMWS), and Mhadei Wildlife Sanctuary (MWS). The present forest sites were further classified into three forest covers i.e. Semi-Evergreen (SE), Moist Deciduous (MF), and Open Forest (in some cases Plantations) (OF/PT). A total of 35 dominant tree species were recorded from four forest sites in Goa (Table 3.1 Page 174).

1.3.8 Use of Remote sensing and GIS

Remote sensing and GIS are widely used to estimate the regional distribution of SOCs at the micro level. Cellular Automat (CA) and Marco Chain Model (MCM) are used for the 3 map change model.

Multispectral satellite imageries used for this research consisted of cloud-free Landsat-5, Landsat-7, and Landsat-8 imagery obtained on 17th July for the years 1990, 2000,2010, and 2020. The images have been classified using the Maximum Likelihood Classification Algorithm (MLC) which is a robust supervised classification method. The error of commission and omission can be expressed in terms of the user's accuracy and the producer's accuracy (PA). User's accuracy (UA) represents the probability that a given

Study Region

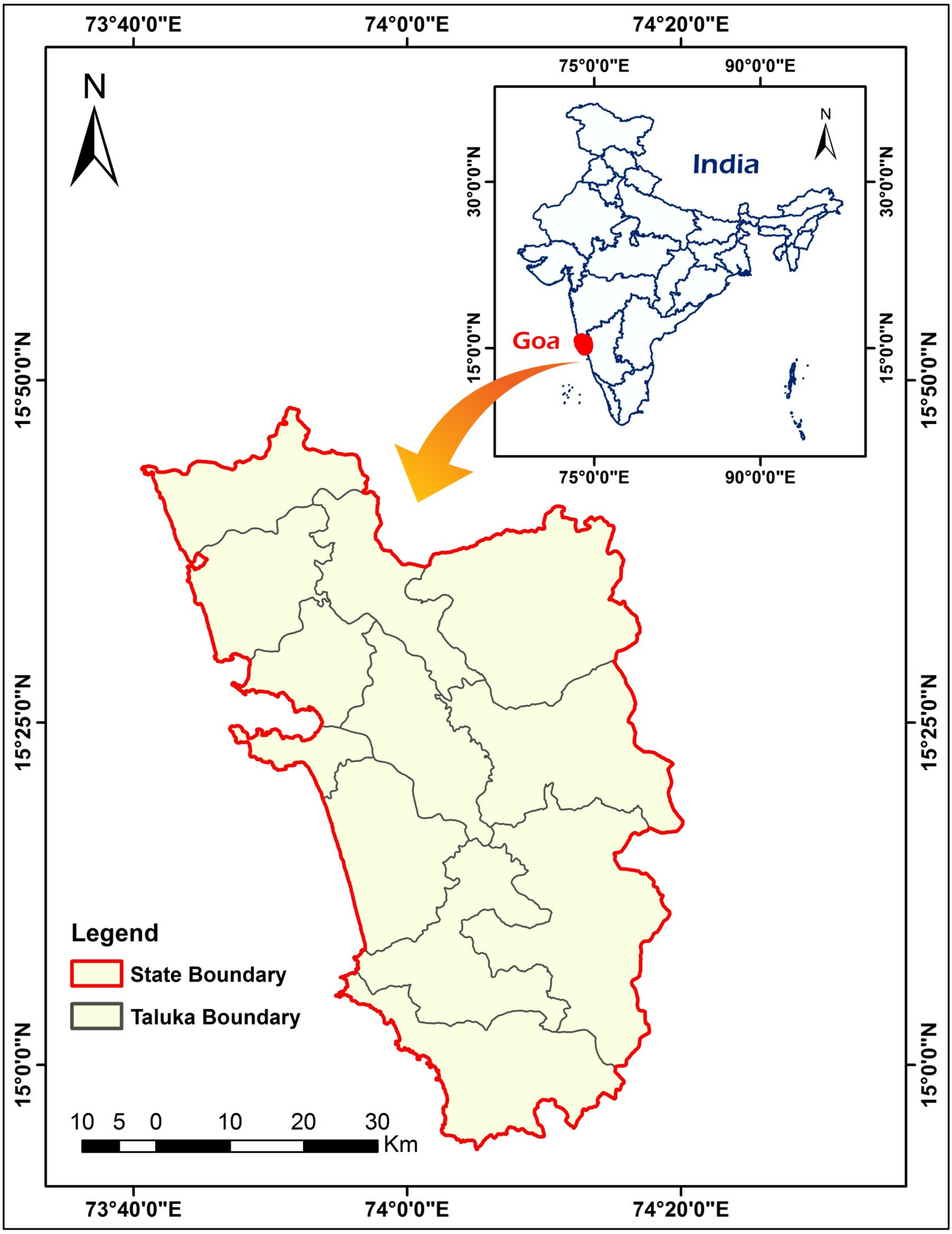


Figure 1.1 Goa Location and Extension

pixel will appear on the ground as has been classified, while producer's accuracy represents the percentage of a given class that is correctly identified on the map.). Kappa Coefficient was also used as a measure of classification accuracy, subtracting the effect of random accuracy. The probability to change is projected for the year 2030 based on the CA-MCM model.

1.4 Study area

Goa is India's smallest state by area and the fourth smallest by population. It is located in West India in the region known as the Konkan (figure1.2). It is bounded by Ratnagiri and Sawantwadi districts of Maharashtra on the north, Belgaum and Dharwar districts of Karnataka on the east, and Uttara Kannada district on the south. On the west Arabian sea forms the boundary. The State is bestowed by nature with lovely coastal tracks along the Arabian sea and beautiful hill ranges of the Western Ghats. It has a partly hilly terrain with the Western Ghats rising to nearly 1200 meters in some parts of the state. The state measures about 60 km east-west and 105 km north-south (Walvekar G S 2007).

1.4.1 Location and extension

It encompasses an area of 3,702 km² (1,430 sq. mile). It lies between the latitudes 14°53′ 54″ N and 15°40′00″ N and longitudes 73°40′33″ E and 74°20′13″ E. Most of Goa is a part of the coastal country known as the Konkan, which is an escarpment rising to the Western Ghats range of mountains, which separate it from the Deccan Plateau. The highest point is the Sonsogor, with an altitude of 1,167 meters (3,827 feet). It has a coastline of 101 km. The main rivers are the Mandovi, the Zuari, the Terekhol, the Chapora River, and the Sal. The Mormugao harbor on the mouth of the river Zuari is one of the best natural harbors in South Asia. The Zuari and the Mandovi are the lifelines of Goa, with their tributaries draining 69% of its geographic area (figure2.3). These rivers are one of the busiest rivers in India. Goa has more than forty estuarine, eight marine, and about ninety riverine islands. The total navigable length of Goa's rivers is 253 km (157 miles) (Walvekar G S, 2007). The state is divided into two districts: North Goa and

Goa Physiography

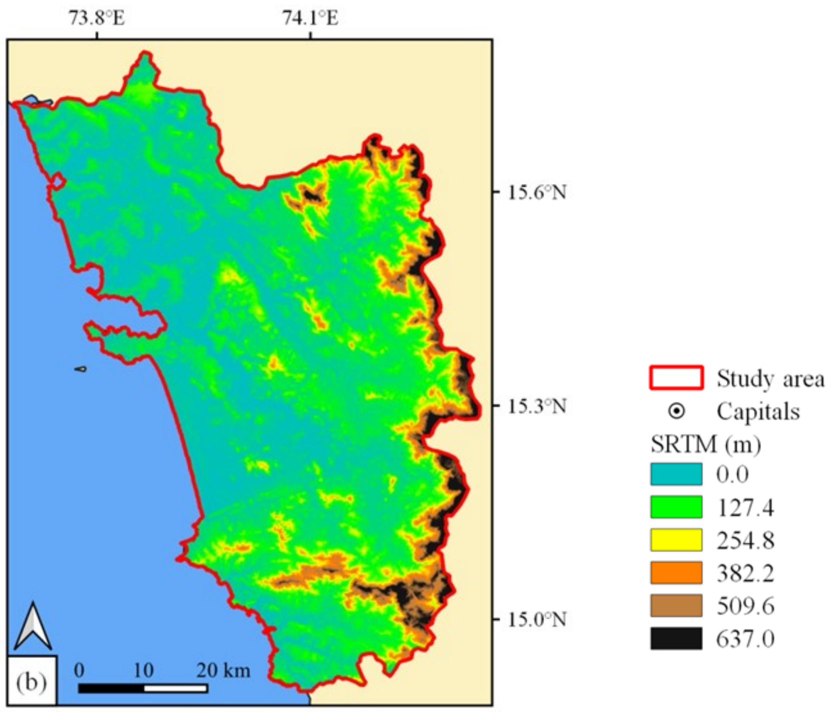


Figure 1.2 Goa Physical setup

Elevation derived from SRTM data

Figure 1.3 Goa Rivers

https://indiariversblog.wordpress.com/2017/05/17/the-rivers-of-goa/

South Goa. Panaji is the headquarters of the north Goa district and Margao of the south district. Each district is governed by a district collector, and an administrator appointed by the Indian government. The districts are further divided into twelve talukas-Talukas of North Goa are Bardez, Bicholim, Pernem, Ponda, Sattari, and Tiswadi, the talukas of South Goa are Canacona, Mormugao, Quepem, Salcete, and Sanguem. The headquarters of the respective talukas are Mapusa, Bicholim, Pernem, Ponda, Valpoy, Panjim, Chaudi, Vasco, Quepem, Margao, and Sanguem. Goa's major cities include Vasco, Margao, Mormugao, Panaji, and Mapusa. The region connecting the first four cities is considered a de facto conurbation, or a more or less continuous urban area (Walvekar G S, 2007).

1.4.2 Geographical Setup of Study region

1.4.2.1 Physiography of Goa:

Goa is a part of the Konkan area. Goa has hills and low and highland areas. Geographically Goa has mainly three natural divisions namely the Lowlands, the Plateaus, and the Mountain region. Low Lands: Low land area is mainly coastal lines. It is about 110 km long. Many beaches are along the coast in this area. Many rivers flow east to the east in this area therefore this area's land is fertile. This area is thickly populated. 6 Plateau Lands: The plateau region is found between the mountain region in the east and the lowlands in the west. Plateau land height ranges from 30 meters to 100 meters (Fig. 1.1 &1.2). In this region mainly plenty of laterite stone is found. It is used for building houses. Some of the parts of plateau land is called the headland of Goa. Lighthouses are built on these headlands.

Land in the plateau region is not fertile; few crops are taken in this region. Mountain region: Sahyadri Mountains are to the east of South Goa. This part is covered with dense forest. In this area, some of the mountains are very steep. In the South Goa peaks are Chandranath at Paroda, Dudhsagar in Sanguem taluka and Cormolghant in Canacona taluka. Many streams and rivers flow from this region to low lands. In South Goa, rivers are Zuari, Talpona, Sal and Galgibag (figure 1.2). Rivers are used for transportation. Inland waterways play an important role in the transport of mineral ores from the mining sites in Sanguem taluka such as Costi, Kirlapal, Netravalim, Rivona, Ducorcond, and Kuddegal to the Mormugao harbor for export South (Walvekar G S, 2007).

1.4.2.2 Climate of Goa:

The state has a warm and humid climate for most of the year as the state is in the tropical zone and near the Arabian Sea. The climatic conditions are pleasant and normal throughout the year. The temperature generally ranges from a mean minimum of 20^0C to a mean maximum of 35^0C. Monsoon enters normally in the first week of June. The State receives good rainfall on an average of 2500 mm annually, mostly during June to September period, which is drained by an extensive network of waterways. May is the hottest month. During this month the day temperature is over 35°C (95°F) coupled with high humidity. It has a short cool season between mid-December and February. These months are marked by cool nights of around 20°C (68°F) and warm days of around 29°C (84°F) with moderate amounts of humidity. Further inland, due to altitudinal gradation, the nights are a few degrees cooler (Walvekar G S, 2007).

1.4.2.3 Soils of Goa:

Geographically, Goa is a part of the Konkan coastline. The climate, topography, geology, and vegetation have played a prominent role in the development of the soils of Goa. Topography influences drainage and in turn affects soil formation. The soils in the state of Goa have been predominantly categorized into lateritic, alluvial, sandy coastal, saline, and marshy soils (Report Resources Survey of Goa Forests, 1985).

Lateritic Soils

These soils are formed due to heavy rainfall and high temperature typical of a tropical region. The lateritic soils are highly acidic and are rich in organic matter. They are sandy loam to silt loam in texture and well drained and are generally brownish black to reddish brown. The high intensity of precipitation and temperature during wet and dry periods has resulted in the formation of laterites and lateritic soils which occur on an extensive scale.

Alluvial Soils

These soils are fertile, acidic, rich in humus, silt, and clayey loams, and occur in reddish brown to yellowish red.

Sandy Coastal Soils

Mostly occur along the coastal belt. They are sandy to sandy loams, well-drained, acidic, and fairly rich in organic matter.

Saline Soils

They are poorly drained, silt-clay loam mostly occurring in Khazan land along the flood plains of both the Zuari and Mandovi rivers.

Marshy Soils

The low-lying areas along the river banks subjected to frequent tidal waters and marshy soils are found supporting mangrove vegetation (Report Resources Survey of Goa Forests, 1985).

1.5 Review of Literature:

Organizations such as the International Energy Agency (IEA), an autonomous agency linked with the Organization for Economic Cooperation and Development (OECD), the Intergovernmental Panel on Climate Change (IPCC), a joint program of the World Meteorological Organization and the United Nations Environment Programme, and the U.S. Department of Energy (US DOE) have developed global scenarios of future energy use and greenhouse gas emissions (Mike Fowler, 2008). Several studies over the last two decades have analyzed the potential impact of forest carbon sink programs by estimating their cost effectiveness and carbon sequestration capacity in a variety of settings. The studies vary according to geographic scope (Kenneth R. Richards and Carrie Stokes, 2004).

a) International Status:

Forestry had been the first focus of the interest of the scientist as it is the chief source of carbon sequestration. Samson R (1999) suggested the implications of growing short-rotation tree species for carbon sequestration in Canada through forestry culture. The trend of application of remote sensing is confirmed by the work of Namayanga L N (2002). The type's terrestrial carbon sink remained the center of the work of Houghton R A (2002). The application of Remote sensing and GIS in the assessment of carbon stocks and modeling win-win scenarios of carbon sequestration through land use changes is introduced by Ponce-Hernandez R (2004). Spadavecchia L (2004) used Remote Sensing within a GIS database to Estimate the Land use Change of the Nhambita Community Forest, in Mozambique. National level survey of carbon stock using remote sensing has been undertaken by Powell DC *et al* (2005). It was supported by the detailed methodology of field investigation for measuring the dimensions and biomass of trees. Other than the forest the significance of the grassland has been emphasized by Rumore D *et al.* (2006). He reported the potential of a grass seed cropping system for carbon sequestration in western Oregon. Bremer D (2007) analyzed the eco-friendly benefits of carbon sequestration in turf grass. A technical report on grassland management and climate change mitigation explains the Challenges and opportunities for carbon sequestration in grassland systems (Cotant R T *et al.* 2010). Silveira P (2012) worked on pasture management for the sequestration of carbon. Zirkle G *et al.* (2011) modeled carbon sequestration in a home lawn. Like natural grassland mangroves and marshland is recognized as a significant terrestrial carbon sink (Khairunnisa R *et al.* 2012). Estimation of biomass for calculating carbon storage and CO_2 sequestration using remote sensing technology in Yok Don National Park, Central Highlands of Vietnam (Nguyen V L *et al.* 2012) Research, development, and demonstration at the U.S. Department of Energy (Folger P *et al.* 2013), carbon sequestration in types of forests in the U.S.A. (Gorte R W *et al.* 2009; Johnson I *et al.* 2010) stock measurement in Thailand (Laosuwan T *et al.*

World's forests (Pan Y *et al.* 2011), and amount of carbon sink in forests throughout the planet is monitored, modeled and managed by (Jeyanny V *et al.* 2011) using Geo-spatial technologies. The use of quantitative methods is observed in the work of (Dreyfus M *et al.* 2012). He introduced the Carbon Farming approach (CFI Reforestation Modelling Tool) and explains different methods of carbon sequestration calculation. Research shreds of evidence from fast-developing countries, like China, reported the integration of scientific and socio-economic perspectives of forest carbon sequestration (Chen J M *et al.* 2007). The potential of native tree species is assessed by (Thomas S C *et al.* 2007) in Northern China region. Local to the regional approach of monitoring carbon stock in the tropics and the management of natural coastal carbon sinks was conducted by (Sanchez-Azofeifa G A *et al.* 2009; Laffoley D *et al.* 2009).

b) National Status:

The development in the field of carbon sequestration is evident in the current decade only. The species-level analysis is carried out by Negi J D (2003), and Kaul M et al. (2010) carbon. Storage and sequestration potential and carbon allocation in different components of selected tree species of India. That is considered a new approach to carbon estimation. Recently the application of remote sensing and GIS at the micro-scale has been adopted for studies at the University campus, Aurangabad-Maharashtra, (Chavan B L *et al.* 2010), Pune University campus (Haghparast H *et al.* 2013), Somjaichi Rai (Sacred grove) at Nandghur village, in Bhor region of Pune District, Maharashtra State (Hangarge L M *et al.* 2012). Warren, A. *et al.* 2008 also analyzed the carbon sequestration potential of trees in and around Pune. The current trend is determined by the application of remote sensing and GIS in non-destructive methods of estimation of carbon sequestration (Tripathi S *et al.* 2010). Various methods to estimate above-ground biomass and carbon stock in natural forests. Vashum K T (2012) has reviewed the work of Kumar P (2010) and Sinha R K (2011), in the deforested region of Ranchi in Jharkhand. Forest carbon management in Sagar District (M.P) Pereta K *et al.* (2011), subtropical pine forest in North-Western Himalayas (Sharma D P *et al.* 2010). Moreover, the application of RS & GIS is reflected in the study undertaken by Pandey C N *et al.* (2013) to assess carbon sequestration by mangroves and quantitative analysis on carbon storage of selected species of the Gujarat region (Pandya I Y *et al.* 2013).

1.6 Layout of project

The project is organized into five chapters. Chapter one deals with the statement of the problem, objectives of research, a short review of data and methodology, study region, and review of the literature. Chapter second deals with the land use and land cover and carbon stock under major land use and land cover categories and changes therein. Chapter third focuses on forest inventory and estimation of above-ground and below-ground biomass using the allometric equation, Loss on Ignition (LOI) (Storer *1984*), and Revised Walkley-Black rapid titration (W-B) method (Trivedi and Goel, 1986).

Chapter four deals with the carbon stock scenario and regional sequestration potential through land use land cover change model using Cellular Automata (CA) and three maps Marco Chain Model (MCM). Last chapter five concludes the work with major findings and recommendations.

1.7 Significance of the Study:

In recent years, carbon sequestration in the form of forestry projects has evolved into a viable alternative to tackle global warming and climate change. As per the 3rd assessment report of the IPCC - forests, agricultural lands, and other terrestrial ecosystems offer significant carbon mitigation potential (IPCC, 2001). The report states that in addition to the reduction in atmospheric CO_2, such projects may also provide other social, economic, and environmental benefits such as sustainable land management and rural employment. Moreover, policy initiatives such as the Kyoto Protocol have introduced flexible mechanisms that encourage carbon trading and promote forestry activities. Carbon sequestration also constitutes valuable environmental services provided by forests, other important services being watershed protection, biodiversity conservation, eco-tourism, etc. Recent efforts to put a monetary value on such services have also led to an increase in awareness of the need to protect forest resources, particularly as they can be traded in emerging markets. Several existing challenges ultimately must be resolved before Carbon Capture and Storage (CCS) can be demonstrated and widely deployed as a CO_2 emissions control option. As important as timely technology development is to establishing CCS, having definitive standards, practices, and procedures; encouraging private-sector investment; and addressing liability and regulatory issues are also essential (Carbon Sequestration Leadership Forum, 2011) As the above discussion brings out, there is an urgent need to look at the emerging markets for environmental services such as carbon sequestration. The lessons from such a study would constitute important research outcomes, which could be used to inform the ongoing policy debates on the subject as well as to improve the effectiveness of various projects being implemented in different parts of the world. The study would provide valuable feedback to all those who are involved in creating and regulating markets for environmental services, viz. governments, NGOs, corporate organizations, research institutions, and common citizens. As markets for environmental services such as carbon sequestration continue to expand, Such a study will not only bridge the present gap that exists on the subject but will also aid in regulating the evolving markets for environmental services by making specific recommendations on how they could be made pro-poor (Rohit Jindal, 2004; Kenneth R Richards and Carrie Stokes, 2004) to meet the scale requirements of Clean Development Mechanism (Aukland L *et al.* 2002).

The model of carbon stock and sequestration through land use changes holds significance to various stakeholders of the state. Namely, the Department of Planning and Urban Development, Department of Agriculture, Department of Forestry, Water Resource Department, Goa State Pollution Control Board, and NGOs. The proposed research work is based on empirical analysis using remote sensing, GIS, and GPS technology. This study would be of importance in Spatio-temporal perspectives for researchers and scientists for academic degrees in geography and environmental science. The generated database could be applied in disseminating knowledge to related individuals or groups of the society for governance, management, and conservation for sustainable development. The results and model can be utilized for other States of India to assess the carbon stock and carbon sequestration potentials of their terrestrial forest, grassland, and mangrove forests to mitigate the rising CO_2 concentration in the atmosphere as well as it will be an opportunity to capture world carbon market.

CHAPTER 2

LAND USE- LANDCOVER (LULC) AND CARBON STOCK

1. Introduction:

The Land Use and Land Cover (LULC) pattern of a region is an outcome of natural and socio-economic factors and their utilization by man in time and space. The land is becoming a scarce resource due to immense agricultural and demographic pressure. Hence, information on LULC and possibilities for their optimal use is essential for the selection, planning, and implementation of land use schemes to meet the increasing demands for basic human needs and welfare. This information also assists in monitoring the dynamics of land use resulting from changing demands of the increasing population. LULC change has become a central component in current strategies for managing natural resources and monitoring environmental changes. The advancement in the concept of vegetation mapping has greatly increased research on LULC change thus providing an accurate evaluation of the spread and health of the world's forest, grassland, and agricultural resources have become an important priority. Viewing the earth from space is now crucial to understanding the influence of man's activities on his natural resource base over time. In situations of rapid and often unrecorded land use change, observations of the earth from space provide objective information on human utilization of the landscape. Over the past years, data from earth-sensing satellites has become vital in mapping the earth's features and infrastructures, managing natural resources, and studying environmental change where urbanization and agriculture are the primary drivers for LULC change.

LULC change due to human activities is currently proceeding more quickly in developing countries than in the developed world, and it has been projected that by the year 2020, most of the world's megacities will be in developing countries (World Bank, 2007). The increasing population in developing cities has caused rapid changes in land use land cover and increased environmental degradation (Holdgate, 1993). The effect on the population is particularly relevant given that the global urban population is projected to almost double by 2050 (UN, 2008). To mitigate the detrimental effects associated with urban growth on the environment and to maintain optimal ecosystem functioning (Fang *et al.* 2005), spatial and temporal land use land cover patterns, and the factors affecting these changes (Serra *et al.* 2008), are considered important in developing rational economic, social and environmental policies (Long *et al.* 2007). Land use data are needed in the analysis of environmental processes and problems, which must be understood if living conditions and standards are to be improved or maintained at the current level (Anderson *et al.* 1976*,* Kacchwaha, 1985; Khorram and John, 1991). Information on the rate and kind of change in the use of land resources is essential for proper planning, management, and regularizing the use of such resources (Narayan and Sen, 1997). Traditionally, the methods of monitoring changes in land use were field methods and large-scale aerial photography, which is time-consuming and expensive. Satellite remote sensing technology has emerged as an efficient and powerful tool in providing reliable information on various natural resources of a region where the changes in LULC can be linked to human and natural activities (Jaiswal *et al.* 1999).

Mapping the present LULC helps to identify the resources and to utilize the resource properly. To compare the present and the past LULC, GIS and remote sensing techniques are very important (Wilkie and Finn, 1996). These tools help to quantify the change in different land use and land cover of the area. Land cover refers to the vegetation (natural and planted), water, bare rock, sand, and similar surface, and also man-made construction that occurs on the earth’s surface. While Land use refers to a series of operations on land, carried out by humans, intending to obtain products and/or benefits through using land resources including soil resources and vegetation resources which are part of land cover (FAO, 1995). Thus, land use often influences land cover. Milne, (1993) defined change as an alteration in the surface component of the landscape and is only considered to occur if the surface has a different appearance when viewed on at least two successive occasions. Changes like the clearing of forests or plantation areas for urban expansion can be detected using remotely sensed data. Remote sensing is very effective in illustrating the interactions between people and the urban environments in which they live (Cantrell and Jensen, 2008). Space-borne satellite data are particularly useful for developing countries due to the cost and time associated with traditional survey methods (Dong, Forster, and Ticehurst, 1997), and these techniques have become viable alternatives to conventional survey and ground-based urban mapping methods (Jensen *et al.* 2005). Several studies have demonstrated the applicability of remote sensing to developing sourcing information and supporting decision-making activities in a wide range of urban applications (Gatrell and Jensen, 2008; Jensen and Cowen, 1999). In particular, RS-based multi-temporal land use change data provide information that can be used for assessing the structural variation of LULC patterns (Liu, Gao, and Yang, 2003), which can be applied to avoiding irreversible and cumulative effects of urban growth (Yuan, 2008) and are important to optimize the allocation of urban services (Barnsley and Barr, 1996). In addition, accurate and comprehensive land use change statistics are useful for devising sustainable urban and environmental planning strategies (Alphan, 2005; Hardin *et al.* 2007). Remote sensing data provide valuable multi -temporal data on the processes and patterns of LULC change, and GIS is useful for mapping and analyzing these patterns (Zhang *et al.* 2002). In addition, retrospective and consistent synoptic coverage from satellites are particularly useful in areas where changes have been rapid (Blodget *et al.* 1991). Furthermore, since digital archives of remotely sensed data provide the opportunity to study historical LULC changes, the geographic pattern of such changes concerning other environmental and human factors can be evaluated. It is therefore very important to estimate the rate, pattern, and type of LULC changes to predict future changes.

2.2. Forest:

Forest resources are the best asset a Nation could ever retain. A country's health is determined by the natural wealth it possesses (Khoshoo, 1996). Forests are the home of the Plant kingdom which works as a storehouse to supply all the Basic Life Supporting

Systems (Bliss) to mankind and other organisms**.** Besides the tangible and intangible benefits flow, the Plant kingdom also extends subtle blessings and wisdom to the aspirants through their spirit of unending services in silence as monks. Thus forests as a composition of enumerable plants operate as the Sea of monks being the panacea to human beings and other organisms (Sarkar, 2010). Forests are amongst the most biologically-rich terrestrial systems. Tropical, temperate, and boreal forests together offer diverse sets of habitats for plants, animals, and micro-organisms, and harbor the vast majority of the world's terrestrial species. Ecologically intact forests store and purify drinking water, mitigate natural disasters such as droughts and floods, help store carbon and regulate the climate, provide food and produce rainfall and provide a vast array of goods and services for medicinal, cultural, and spiritual purposes. The health of forests and the provision of forest ecosystem services depend on the diversity between species, the genetic diversity within species, and the diversity of forest types (Khandekar and Srivastava, 2014).

2.2.1. Global Distribution of Forests

Forest ecosystems play multiple roles at global as well as local levels and provide a range of important economic, social and environmental goods and services that impact the well-being of poor rural communities, local and national economies, and global environmental health. It is estimated that at the global level, forestry formally contributes some 2 percent to the world GDP or more than US$ 600 billion per annum (FAO, 1997, Lomborg, 2001). However, the actual contribution of forests to the world economy is considered to be much higher, though extremely difficult to quantify (Constanza *et al.* 1997, World Bank, 2000).

The total area covered by forests worldwide is approximately 3869 million ha, almost one-third of the world's land area, of which 95 percent is natural forest and 5 percent is planted forest; 17 percent is in Africa, 14 percent in Asia, 27 percent in Europe, 14 percent in North and Central America and 23 percent in South America and 5 percent in Oceania (FAO, 2000).

FRA, 2000 also estimated the distribution of forest area by ecological zones: 47 per cent is in the tropics, 33 percent in the boreal zone, 11 percent in temperate areas, and 9 percent in the subtropics. Tropical and subtropical dry forests are concentrated in Africa (containing 36 per cent of the world's total), South America (30 per cent), and Asia (21 per cent). The majority of tropical rainforests are located in South America (58 per cent), but a large proportion (24 per cent) is also found in Africa; most of the rest is in Asia (17 per cent). Nearly all temperate and boreal forests are located in Europe and North and Central America. Mountain forests are found mainly in Europe (40 per cent) and North and Central America (34 percent). Two-thirds of the world's forests are located in ten countries alone: the Russian Federation, Brazil, Canada, the United States, China, Australia, the Democratic Republic of the Congo, Indonesia, Angola, and Peru. Only 22 countries have more than 3 ha of forest per capita, and only about 5 per cent of the world's population lives in these countries - mostly in Brazil and the Russian Federation. Three-quarters of the world's population, on the other hand, live in countries with less than 0.5 ha per capita, including most of the densely populated countries in Asia and Europe. The proportion of total land area under forest varies significantly by region and country. About half the land area of South America and Europe is covered by forest, but only one-sixth of Asia's land is forested. Africa, North and Central America, and Oceania fall in between, each with about one-fourth of its land covered by forest. Fifty countries and two "areas" (e.g. territories, protectorates) are reported to have less than 10 percent of their land covered by forest. Twenty countries and two areas have more than 60 percent of their land under forest (FAO, 2001a).

2.2.2 Forest resources of India :

India is a large developing country known for its diverse forest ecosystems and mega-biodiversity. It ranks 10th amongst the most forested nations of the world (FAO, 2006) with 76.87 million ha (23.4 percent of its geographical area under forest and tree cover), comprising 42.33 million ha of Reserved Forest (12.88 % of the country's geographic area), 217,245 km^2 of Protected Forest (6.61 %) and 127,881 km^2 of un-classified Forest (3.89 percent) (*FSI, 2008*). India is endowed with diverse forest types ranging from tropical wet evergreen forests in the northeast and the southwest to tropical dry thorn forests in central and western India. The forests of India can be divided into 16 major types comprising 221 sub-types. Most of these forests are located in the Western Himalayas, East Deccan, and North Eastern regions including the Himalayas and the Western Ghats (MoEF, 2012). India's per capita forest cover is 0.064 ha against the world average of 0.64 ha (MoEF, 2006a). The productivity of India's forests is also low (1.34 m / ha/year) when compared to the world average (2.1 ur'/ha/year) (The Eleventh Five Year Plan, 2007-12).

2.2.3 Forest of Goa:

The recorded forest cover in the state is 2,219 km^2, which is 59.94% of the state's geographical area. The estimated tree cover in the state is 286 km^2 which is 7.73% of the geographical area of the state. Of which, North Goa and South Goa comprise forest cover of 923 km^2 (53.17%) and 1,296 km^2 (65.92%) respectively. In terms of forest canopy density classes, the state has 543 km^2 of very dense forest, 585 km^2 of moderately dense forest, and 1,091 km^2 of open forest. The state has five types of forest cover i.e. Very Dense Forest (13.80%), Moderately Dense Forest (16.86%), Open Forest (27.44%), Scrub (0.03%), and Non-Forest (41.87%). The total forest area of Goa is 1424.46 km^2, of which ~200 km^2 is privately owned. This amounts to 33.08% of the geographical area of Goa being government forest and 5.40% being private forest and 61.52% being non-forest land. The state has one National Park (Mollem) and six Wildlife Sanctuaries covering an area of 107 km^2 and 648 km^2 respectively. As per *Champion & Seth* classification, the state has five forest types i.e. Tropical Wet Evergreen (24.97%), Tropical Semi-Evergreen (19.33%), Tropical Moist Deciduous (25.39%), Tropical Dry Deciduous (0.01%) and Littoral & Swamp forests (0.45%). The state has Plantations/Tree Outside Forests (TOF) which covers 29.85% (Goa Forest Department-at a glance).

2.2.4. Carbon Stock in Forests:

Forests play a significant role in capturing carbon dioxide from the atmosphere through photosynthesis, converting it to forest biomass, and releasing it into the atmosphere through plant respiration and decomposition. Therefore forests contribute positively to the global carbon balance. Carbon sequestration in forest soil and vegetation has been used to achieve the greenhouse gas reduction target. Thus forests play an important role in climate mitigation and adaptation as well as the need for forest-dependent people and forest ecosystems to adapt to this challenge. Forests maintain high carbon stock by reducing deforestation and promoting the sustainable management of all types of forests. Sustainable forest management provides an effective framework for forest-based climate mitigation and adaptation (Stern, 2006). The aboveground biomass constitutes the major portion of the carbon pool (Ravindranath, 2008). Estimating the amount of forest biomass is required for estimating the forest's potential to sequester and store carbon in the forest ecosystem (Wang *et al.* 2004). Managing forests through forestry, agro-forestry, and plantation forests are seen as an important opportunity for climate change mitigation and adaptation (Canadell and Raupach, 2008; IPCC, 2007). The carbon stocks in different types of forests ecosystems have been estimated based on forest inventories and using appropriate conversion factors to both biomass and carbon (Chhabra *et al.* 2002; Dadhwal *et al.* 2009; Lal and Singh, 2000; Ravindranath *et al.* 1997). Litterfall constitutes an important component of organic matter dynamics in a forest and its input depends upon vegetation composition, age of trees, canopy cover, weather conditions, and biotic factors (Bargali, 1995; Lodhiyal, 1997; Rawat and Singh, 1988). Soil carbon sequestration is also important in maintaining a balance in greenhouse gas emissions and is strongly related to site conditions, i.e., soil structure, initial soil carbon content, and climate (Montagnini and Nair, 2004; Nair *et al.* 2009). Soil carbon in its various pools within the soil provides structure and stability to soil (Palm *et al.* 2007). Soil organic carbon is controlled by the balance of carbon inputs from plant production and outputs through decomposition (Schlesinger, 1977) and its storage is the most accepted method for long-term carbon sequestration in terrestrial ecosystems. Soil carbon pool enhancement and optimization are essential for social, ecological, and economic sustainability. FAO's most recent global estimations of carbon emissions from deforestation and forest degradation for the period 2011–2015 point to a reduction of over 25 percent in emissions from deforestation over this period, i.e. from an average of 3.9 to an average of 2.9 Gt (or billion tonnes) of CO_2 per year. Globally, each cubic meter of growing stock equals, on average, 1 tonne of above-ground biomass, 1.3 tonnes of total biomass, and 0.7 tonnes of carbon in biomass (*FAO, 2006*). The country reports of FAO indicate that global forest vegetation stores 283 Gt of carbon in its biomass, and an additional 38 GT in dead wood, for a total of 321 GT, and IPCC (2000) assumed 359 Gt of carbon in these pools. Over the past 25 years, global carbon stocks in forest biomass have decreased by almost 11 gigatonnes (GT). This reduction has been mainly driven by conversion to other land uses and a lesser extent by forest degradation. The forest growing stock was estimated to be 531 billion m^3. The carbon in above and below-ground biomass was 296 Gt (FAO, 2015). IPCC (2000) estimated an average carbon stock of 86 tonnes per hectare in the vegetation of the world's forests for the mid-1990. The corresponding carbon in biomass and dead wood in forests reported in FRA, 2005 amounts to 82 tonnes per hectare for the year 1990 and 81 tonnes per hectare for the year 2005. Each cubic meter of growing stock equals different amounts of biomass and carbon (in biomass) in different regions. Earlier attempts for estimating forest carbon did not take into consideration soil carbon. The biomass carbon stock in India's forests was estimated at 7.94 Mt C in 1880 and nearly half of that after 100 years (Richards and Flint, 1994). The first available estimates for forest carbon stocks (biomass and soil) for the year 1986, are in the range of 8.58 to 9.57 Gt C (Ravindranath *et al.* 1997; Haripriya, 2003; Chhabra and Dadhwal, 2004). As per FAO estimates (FAO, 2005), the total forest carbon stocks in India have increased over 20 years (1986–2005) and amount to 10.01 Gt C.

The carbon stock projections for the period 2006–30 are projected to be increasing from 8.79 to 9.75 Gt C (IISc, 2006) with forest cover becoming more or less stable, and new forest carbon accretions coming from the current initiatives of afforestation and reforestation program (Ravindranath *et al.* 2008). Needless to say that the present state of forest carbon stocks owes its origin to the drive of plantation forestry in India started in the late 1950s and was supplemented later by the social and farm forestry initiatives of the 1980s and early 1990s.

All the same, the National Communication (NATCOM) of the Government of India to the UNFCCC for 1994 has reported that the LULUCF sector is a marginal source of emissions with a figure of 14.29 mt (million tonnes) of CO_2. However, in the LULUCF sector 'changes in forest and other woody biomass stock' account for a net removal of 14.25 mt of CO_2 (NATCOM, 2004). Thus, for forests alone, the NATCOM presents a net sink of 14.25 mt CO_2eq. With the knowledge and information that is now emerging, the role of forests and plantations in mitigation is becoming more and more important. The compounded annual growth rate of CO_2eq emissions in India is 4.2 percent. Some may consider this to be higher than the desired, but the absolute value of these emissions is still one-sixth that of the United States and the lowest for the per capita GHG emissions (Rawat and Kishwan, 2008). In India, CO_2 emissions from forest diversion or loss are largely offset by carbon uptake due to forest increment and afforestation. Many authors concluded that for the recent period, the Indian forests are nationally a small source with some regions acting as small sinks of carbon as well (Ravindranath *et al.*1997; Haripriya, 2003; Chhabra and Dadhwal, 2004; Ravindranath *et al.* 2008). The improved quantification of pools and fluxes related to the forest carbon cycle is important for understanding the contribution of India's forests to net carbon emissions as well as their potential for carbon sequestration in the context of the Kyoto Protocol (Chhabra and Dadhwal, 2004).

2.3. Mangroves:

Mangrove forests occur worldwide on tropical sheltered shores and are a rich source of biodiversity. This forest consists of a group of taxonomically diverse flora ranging from ferns to flowering plants that share a suite of convergent adaptations toward saline and anoxic habitat (Tomlinson, 1986; Stewart and Popp, 1987; Ball, 1988b; Duke *et al.* 1998; Hogarth, 1999; Vannucci, 2001; Upadhyay, 2002; Selvam, 2003). The adaptations induce several complex anatomical and physiological features such as aerial root system, succulent and sclerophyllous leaves, viviparous seedlings, osmolyte accumulation, and high levels of scavenging enzymes which together constitute diverse taxa in response to environmental constraints (Farnsworth and Farrant, 1998).

The word 'Mangrove' is used for salt-tolerant plants. Mac Nae, (1968) proposed the term 'Mangal' to denote the mangrove ecosystem. In the ecological distribution of mangroves, Tomlinson (1986) has used the word 'mangrove' either to the constituent plants of tropical intertidal forest communities or the ecosystem itself. Mangroves are woody communities that are periodically submerged in saline waters of the inter-tidal zone of tropical and subtropical regions, covering nearly 75% of coastlines (Lu and Lin, 1990; Pernetta, 1993). These plants are specialized to tolerate high salinity, tidal extremes, high fluctuations in wind, temperature, and muddy anaerobic soil with the development of some adaptive morphological characteristics. No other groups of terrestrial plants survive well under such conditions. A muddy substratum of varying depth and consistency is the necessary phytogeographical condition for their growth. The plants have special adaptations such as stilt roots, viviparous germination, salt-excreting leaves, breathing roots, and knee roots by which these plants survive in water-logged, anaerobic saline soils of coastal environments. Mangrove plants have a great potential to adapt to the changes in climate, rise in sea levels, and solar ultraviolet–B radiation (Rahaman, 1990; Swaminathan, 1991; Moorthy, 1995; Kathiresan, 1996). With an average productivity of 2500 mg C/d, mangroves are amongst the most productive ecosystems with an immense potential to influence the global carbon budget (Dittmar *et al.* 2006; Kristensen *et al.* 2008). Mangrove-derived detritus is an important food source for decomposer food webs including many macroinvertebrates, such as sesarmid crabs (*Grapsidae*), which consume mangrove litter (Kristensen *et al.* 2008). The important biogeochemical services of mangroves include entrapment of sediments and pollutants, filtering of nutrients, re-mineralization of organic and inorganic matter, and export of organic matter (Alongi *et al.* 1992; Singh *et al.* 2005). They also function as carbon sinks by removing and storing carbon dioxide from the atmosphere, which is a major contributor to global warming (Ramesh, 2003; Purvaja *et al.* 2004; Chauhan *et al.* 2008). They play a valuable role in various regional and site-specific ecosystem functions (Ewel *et al.* 1998; Gilman *et al.* 2008). Reduced mangrove areas and health will increase the threat to human safety and shoreline from coastal hazards such as erosion, flooding, storm waves and surges, and tsunami. Mangrove loss will affect coastal water quality, reduce biodiversity and crustacean nursery habitat and eliminate fish, thus adversely affecting adjacent coastal habitats, and eliminating a major resource for human communities that rely on mangroves for numerous products and services (Ewel *et al.* 1998; Mumby *et al.* 2004; Nagelkerken *et al.* 2008; Walters *et al.* 2008). Mangrove destruction can also release large quantities of stored carbon and exacerbate global warming and other climate-related changes in coastal areas (Ramsar Secretariat, 2001; Kristensen *et al.* 2008).

2.3.1. Global distribution of mangroves:

Mangroves are generally found along the coastal lines of tropical and subtropical regions, distributed globally in 112 countries and territories restricted to latitudes between 30°N and 30°S. The total coverage of mangroves is 18 x 10^4 km^2, which is about 0.45% of world forests and woodland (Spalding *et al.* 1997). Five countries i.e. Indonesia, Australia, Brazil, Nigeria, and Mexico together account for 48% of the total global area and 65% of the total mangrove area. Asia has the largest extent of mangroves (~6 million hectares), and five of the ten countries with the largest extent of mangroves worldwide are found in this region. According to Scott (1971), globally an area of 14 million ha was covered by mangrove forests, which spread along the coasts consisting of third-world nations. The Indian Ocean and the west pacific region together account for 20% of the world's total area of mangroves. Later, global coverage has been variously estimated by different authors - 10 million hectares (Bunt, 1992), 14-15 million hectares (Schwamborn and Saint-Paul, 1996), and 24 million hectares (Twilley *et al.* 1992). Spalding, (1997) had given an estimation of coverage of world mangroves of over 18 million hectares, with 41.4% of it in the south and southeast Asia and 23.5% of it in Indonesia.

2.3.2. Mangroves in India:

Krishnamurthy *et al.* (1987) observed that the Indian coastline mangroves are about 7% of the world's mangroves while Untawale, (1987) estimated it as 8%. The extent of mangrove forest cover in India is probably the third largest formation in the world after Indonesia and Australia (Banerjee, 1998). The mangroves of the west coast constitute 12% of Indian coastal mangroves and the east coast (including Andaman and Nicobar islands) mangroves form 88% of it. Blasco, (1977) analyzed the distribution pattern of mangrove vegetation of the Indian subcontinent, extending over an area of 356,500 ha, revealed that more than 80% of Indian Mangals were confined to West Bengal and the islands of the Bay of Bengal, whereas the remaining 20% had a sporadic appearance on either side of the Indian coasts. Ganapathy, (2002) opined that Indian mangroves are bestowed with a coastline of 8,000 km, including certain stretches along which mangroves are distributed intermittently. The latest assessment of the Forest Survey of India (FSI) 2009 shows that mangrove cover in the country is 4639 Sq.km, which is 0.14% of the country's total geographic area. The very dense mangrove comprises 1405 sq. km (30.29% of mangrove cover); a moderately dense mangrove is 1659 Sq.km (35.76%), while open mangrove covers an area of 1575 Sq.km (33.95%). In recent years, the country has recorded an increase in mangrove cover by 58 Sq.km. According to Thom (1982), Indian mangrove habitats are classified into three categories i.e., deltaic mangroves, coastal mangroves, and island mangrove habitats. Distribution and the status of 12 mangrove habitats in India were estimated by the Government of India (1987) (Blasco, 1977; Untavale and Jagtap, 1992; Mandal, 1996; Sandhya *et al.* 1998). Banerjee, (2002) reported that the Krishna-Godavari delta of Andhra Pradesh is spread over an area of 585 Sq.km with a mangrove cover of 251 sq. km. Later, in 2009 (FSI report), it is reported that Andhra Pradesh has a mangrove cover of 354 sq. km, out of which the Krishna- Godavari delta has 347 sq. km.

Worldwide mangroves comprise approximately 59 species of 41 genera, of which 34 species and 29 genera are present in India. This includes 25 species along the east coast and 25 species on the west coast (Banerjee *et al.* 1989; Singh 1990; Deshmukh, 1994). Species-wise distribution and composition for the Indian sub-continent have been enumerated by several authors but a detailed account and authentic estimation showed that the Indian mangroves represent approximately 59 species, 41 genera, and 29 families of which 25 genera and 21 families of 34 species present along the west coast and remarkably, the east coast represents 51 species, 41 genera belonging to 29 families (Venkateswarlu, 1944; Mathauda, 1957; Rao, 1959; Sidhu, 1963)**.** A recent estimate reveals that 82 species of mangroves are distributed in 52 genera and 36 families in all 12 habitats in India (Mandal and Naskar, 2008).

2.3.4. Mangroves of Goa:

Goa has seven major micro-tidal estuaries with swamps composed of laterite, loamy and alluvial soils. Out of 130 km^2 of coastal wetlands in the state 67.30 km^2 is contributed by mudflats and mangroves. These mangroves are present in the narrow intertidal mudflats along the estuary banks and are of fringing nature which is said to be due to the rising topography of the coast. These habitats are been reclaimed for urbanization and agricultural purposes (Jagtap and Singh, 2004). The state of Goa covers 26 sq. km of mangrove forest of which North Goa comprises 20 sq. km and South Goa 6 sq. km which accounts for 0.47% of the total mangrove cover in India. Mangrove forests are classified into

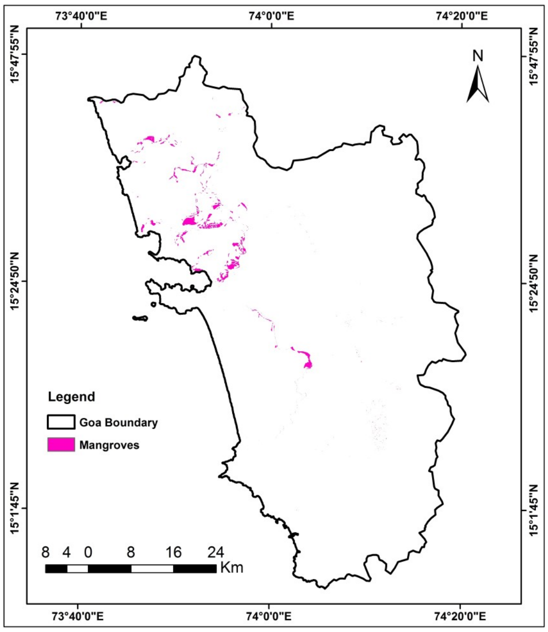


Figure 2.1 Goa Distribution of Mangroves 2017

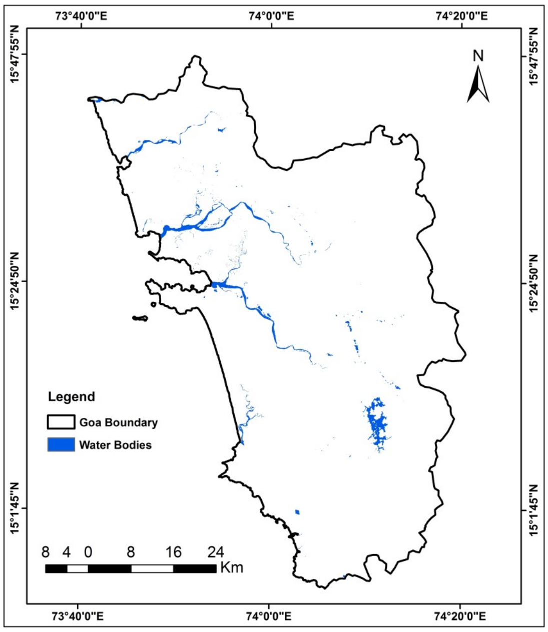


Figure 2.2 Goa Distribution of Water Bodies 2017

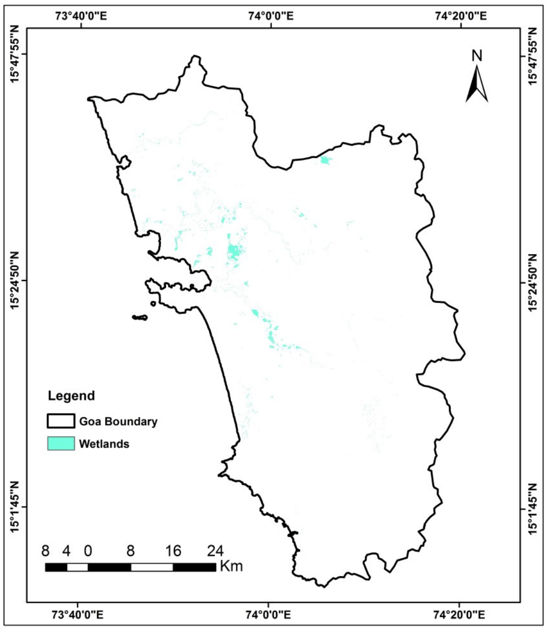


Figure 2.3 Goa Distribution of Wetlands 2017

three types i.e. Type I: Very Dense Mangrove (VDM); Type II: Moderately Dense Mangrove (MDM) and Type III: Open Mangroves but in Goa only Type II and Type III mangrove forests are present which accounts for 20 sq. km and 6 sq. km respectively (FSI, 2017). In Goa, mangroves are present in the Mandovi estuary, Zuari estuary, and Cumbarjua Canal. In addition, other parts of Galgibag, Talpona, Sal, Chapora, and Terekhol river mouths also are endowed with mangrove vegetation. Goa has 16 true mangrove species belonging to 11 genera and 7 families. Mandovi River is one of the best-developed mangrove forests and houses most of the species found in Goa (Sanjappa *et al.* 2011). Mangroves flora in Goa comprises 16 species generally dominated by *Rhizophora mucronate, Avicennia alba, Sonneratia alba, S. caseolaris, Exoecaria agallocha,* and *Acanthus ilicifolius* (Jagtap and Singh, 2004) (figure 2.1).

2.3.3. Carbon Stock in Mangroves:

Mangroves are usually highly productive forests and, as a significant fraction of their soil carbon is plant-derived (Kristensen *et al.* 2008), it is crucial to assess rates of net primary productivity of mangroves and associated plants, especially benthic microalgae. Measurement of primary production in mangrove forests is limited by methodological shortcomings, but the best estimates suggest that mangrove carbon production is more rapid than other estuarine and marine primary producers (Duarte *et al.* 2005). Rates of mangrove net primary production (NPP) based on different methods range from 0.5 to 112.1t dry weight (DW) ha^{-1} $year^{-1}$ but most methods either significantly overestimate (the light attenuation method) or underestimate (litterfall) the true rates of production. Mangroves are among the most carbon-rich ecosystems in the tropics but at a global level, mangroves occupy only approximately 137,760 km^2, and a simple scaling up of the mean carbon burial rate equates to a global carbon sequestration rate of 13.53 Gt/year. The same exercise for boreal, temperate, and tropical terrestrial forests extrapolates to global sequestration rates of 451.1, 327.6, and 422.4 GT/year, respectively (IPCC, 2003). Mangroves account for approximately 3% of carbon sequestered by the world’s

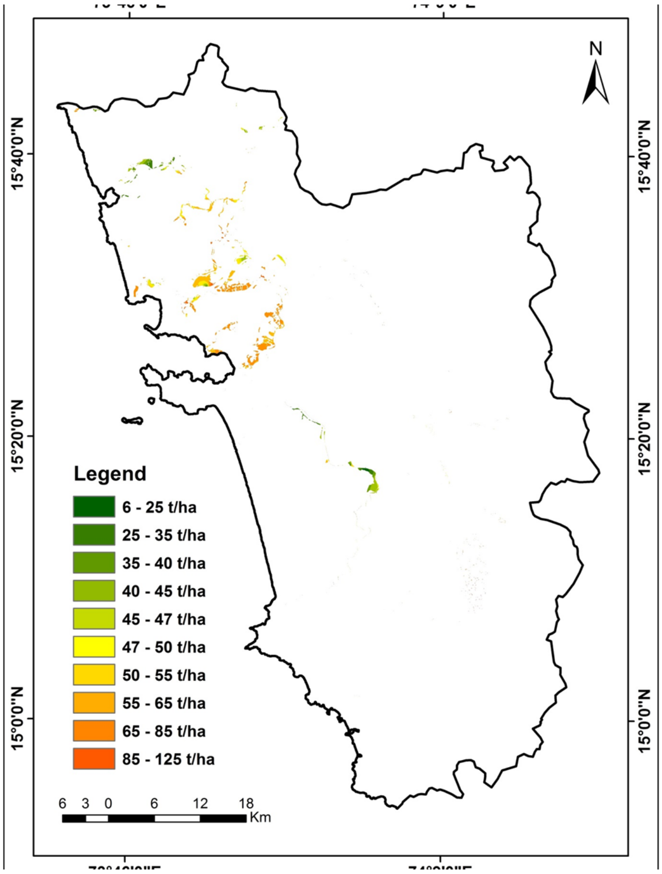


Figure 2.4 SOC stock from Mangrove of Goa

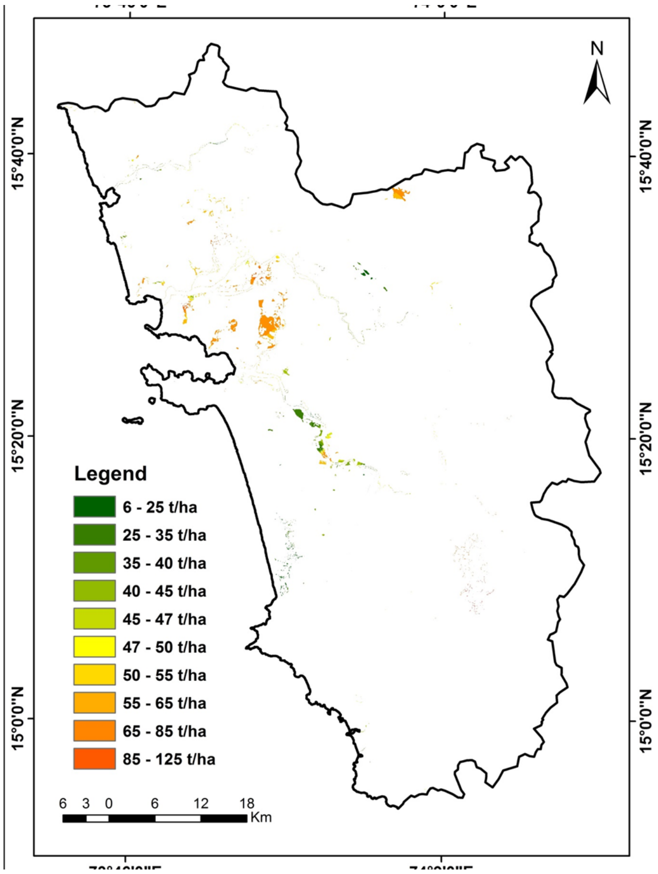


Figure 2.5 SOC stock from wetlands of Goa

tropical forests, although they account for <1% of the total area of tropical forests. The most reasonable means at present to assess the NPP of forests is to measure aboveground biomass accumulation plus litter fall, and there are quite a several such measurements for both mangroves and tropical terrestrial forests. For mangroves, the mean rate of aboveground NPP is 11.1 t DW ha^{-1} $year^{-1}$ with a median value of 8.1 t DW ha^{-1} $year^{-1}$; for tropical terrestrial forests, the mean rate of aboveground NPP is 11.9 t DW ha^{-1} $year^{-1}$ with a median value of 11.4 t DW ha^{-1} $year^{-1}$; for both mangroves and terrestrial forests, NPP declines with increasing latitude (Alongi, 2009). Considering the differences within and between both forest groups in biomass, height, age, and species, the rates are very close and imply that rates of NPP are equivalent between mangroves and other forests.

Compilation of studies in India revealed that Andaman Island possessed the highest carbon stocks in biomass (118.3 t/ha) followed by Tamil Nadu (62.81 t/ha), Karnataka (50.40 t/ha) and Gujarat (24.57 t/ha). Covering 2,118 km², the mangroves of the Indian Sundarbans are thought to absorb over 41.5 million tonnes of carbon dioxide daily, valued at around US$79 billion in the international market. Therefore, mangrove restoration could be a novel mitigation option against climate change (Sahu *et al.* 2015). (figure

2.4. Wetlands:

Wetlands are important natural resources, utilized by the human population inhabited around them, serve as a source of natural beauty, provide a serene environment and in turn fetch economic return (in terms of eco-tourism interface). From an economic point of view, wetlands serve as drinking water resources, irrigation, fisheries, tourism, the abode of migratory waterfowl, and associated aquatic biodiversity, etc. (Gibbs, 1993; Das, 2000). They have been described as the *kidneys* of the landscape as they filter the sediments and nutrients from the surface water. Wetlands soil is generally very rich in micro and macro-nutrients, which are accountable for the survival of their rich and diverse floral, faunal and microbial inhabitants. According to Tiner (1999), it is a generic term used to define the universe of wet habitats including marshes, swamps, bogs, fens, and similar areas. Wetlands are also considered ecotonal habitat as it lies in the transition zone of tension between two or more communities with rich biota (Mitsch and Gosselink, 1993; Clark, 1954; Odum, 1959). But, traditionally wetlands have been contemplated as useless wastelands and used mainly for muck-filled urban sewage, dumping grounds for household garbage, and extending concrete structures after an artificial increase of elevation. In folktales, the swamps are expressed as dirty, murky places full of hidden dangers. Wetlands are the most beautiful water bodies and are full of unique biodiversity including plants, animals, and microbes (Chowdhury, 2009). The 'Wetland' has been defined differently by various authors and agencies for different purposes depending on the specific objective and needs.

A. One of the early definitions of wetland but still habitually used by Ecologist, and Researcher was given by S.P. Shaw & C.G. Fredine (1956) who suggested:

"The term Wetlands refer to lowlands covered with shallow and sometimes temporary or intermittent waters. They are referred to by such names as marshes, swamps, bogs, wet meadows, potholes, sloughs, and river-overflow lands. Shallow lakes and ponds, usually with emergent vegetation as a conspicuous feature, are included in the definition, but the permanent waters of the streams, reservoirs, and deep lakes are not included. Neither are water areas that are so temporary as to have little or no effect on the development of moist soil vegetation''.

B. Ramsar definition

The Ramsar Convention takes a broad approach to determine the wetlands which come under its regulations. Under the text of the Convention (Article 1.1), wetlands are defined as:

"areas of marsh, fen, peatland, or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish, or salt, including areas of marine water the depth of which at low tide does not exceed 6 meters".

Considering the biodiversity point, wetlands are the 2nd richest ecosystem after the tropical rainforests of the world. Thus, wetlands exhibit enormous diversity according to their genesis, geographical location, water regime and chemistry, dominant plants, and soil or sediment characteristics. Because of their intermediary nature, the boundaries of wetlands are often difficult to delineate (Cowardin *et al*. 1979). One of the first widely used classification systems was devised by Cowardin *et al.* (1979). By Ramsar Convention (1971), wetlands are associated with hydrological, ecological, and geological aspects, such as Marine (coastal wetlands including rock shores and coral reefs, Estuarine (including deltas, tidal marshes, and mangrove swamps), lacustrine (lakes), Riverine (along rivers and streams), palustrine ('marshy'- marshes, swamps, and bogs).

2.4.1. Distribution of Wetlands:

Wetlands occur expansively all over the world in all the climatic zones and are appraised to harbor nearly 6.4% of the Earth's surface, of which India domiciles about 18.4% of global wetlands. Wetlands occur in every country, from the tropics to the tundra. The World Conservation Monitoring Centre has suggested an estimated of about 5.7 million square kilometers i.e., roughly 6% of the Earth's land surface (WCMC, Global Biodiversity, 1992) is a wetland. Out of this 6 % of total wetlands, only 2.53 % area is covered with freshwater wetlands and the rest vast areas are seawater. Of the global freshwater 69.6% is locked away in the continental ice, 30.1 % is in underground aquifers and 0.26% is composed of rivers and lakes. However, 0.0075 % of freshwater areas are covered by particular lakes (UNEP, 1994). Out of total global wetlands, 30 % are bogs, 26 % are fens, 20 % are swamping, about 15 % are flood plains, etc. (IUCN, 1999). As per Millennium Ecosystem Assessment (MEA), wetlands deliver 45% of the world's natural productivity and ecosystem services of which the benefits are estimated at $20 trillion a year.

2.4.2. Global Scenario of Wetlands:

Wetlands are among the most productive ecosystems on the Earth and aid in many beneficial outcomes to human society (Russi *et al.* 2013). However, they are also ecologically sensitive and adaptive systems (Turner *et al.* 2000).

Wetlands exhibit enormous diversity according to their genesis, geographical location, Hydrogeological regime and chemistry, dominant species, and soil and sediment characteristics (Space Applications Centre (SAC), 2011). Globally, the areal extent of wetland ecosystems ranges from 917 million hectares (mha) (Lehner and Doll, 2004) to more than 1275 mha (Finlayson and Spiers, 1999) with an estimated economic value of about US$15 trillion a year (MEA, 2005). Overall, 1052 Sites in Europe; 289 Sites in Asia; 359 Sites in Africa; 175 Sites in South America; 211 Sites in North America; and 79 Sites in the Oceania region have been recognized as per international recognition for designation to be handled under protected areas (Ramsar Secretariat, 2013).

2.4.4. Wetland Inventory of India:

India with its large geographical spread supports diverse wetland classes, some of which are unique. Wetlands are estimated to be occupying 1-5 percent of the geographical area of the country, and support about a fifth of the known biodiversity. In India, a variety of wetlands covering inland and coastal areas even small ponds and ephemeral water bodies are located in different altitudinal ranges. It is recorded that around 18.4% of the total geographical area of the country is occupied by wetland areas except for rivers and 70 % of these wetlands are paddy fields (Deepa *et al.* 1999). In India, assessing their wetland wealth in different times, primary inventory by the Dept. of Science and Technology, Govt. of India recorded a total of 1,193 wetlands, covering an area of about 3,904,543 ha, of which 572 were natural (Scott and Poole, 1989; Anonymous, 1993a and 1993b). The latest inventory records a total 67,429 number of wetlands in the Indian territory, which covers about 4.1 million hectares of total land, out of which 2,175 wetlands are natural and 65,254 are manmade i.e. artificial and are occupying 1.5 and 2.6 million hectares of area, respectively (MoEF, 1990). The highest percentage of declared Ramsar Sites are established in the state of Kerala (31 %) followed by Orissa (27%) and in West Bengal (2%) only one Ramsar site is present covering 12,500 ha and the lowest in Tripura covering only 240 ha. (Anonymous, 1993c).

2.4.5. Wetlands in Goa:

In the state of Goa 383 wetlands have been delineated (figure 2.1). In addition, 167 wetlands smaller than 2.25 ha have also been discerned. The total wetland area estimated is 21337 ha. The major wetland types are River/Stream (9362 ha), Intertidal mud flats (3286 ha), Salt pans (2929 ha), Reservoirs (2363 ha), and Mangroves (1752 ha) (figure 2.2 &3). The important wetlands of Goa are Carambolim Lake, Chorao Island, Salauli Reservoir, Anjuna Reservoir, and Mayem lake. Goa is known for its numerous beaches such as Bogmalo, Calangute, Colva, Mandrem, Morjim, Anjuna, Baga, Condolim, Sinquerim, Majorda, Benaulim, Varca, Agonda, and Vagator. The Aravelam waterfalls adjacent to it are Rudreshwara temple and interesting rock-cut caves, the Mayem lake, and the Dudsagar waterfalls- a little downward is the Devil’s Canyon suitable for trekkers and hikers. The major west-flowing rivers that crease the territory are Mandovi, Zuari, Terekhol, Chapora, and Betul. The total navigable length of these rivers, which form the waterways by which Goa’s main export commodity iron and manganese ore is transported to the Margao harbor is virtually the confluence of the Mandovi and Zurai rivers.

2.4.6 Carbon Stock in Wetlands:

The total extent of wetlands has been estimated to be $7x10^6$ - $9x10^6$ km^2 globally (Mitsch, 1994). Moreover, the net primary productivity (NPP) of freshwater wetlands is very high (1180 g C m^{-2} yr^{-1}) compared to various ecosystems including tropical forests (Amthor *et al.* 1998). Wetlands produce about 40% of the global CH_4 emissions, they have the highest C density among terrestrial ecosystems and relatively greater capacities to sequester additional CO_2. They sequester C through high rates of organic matter inputs and reduced rates of decomposition. The organic matter accretion rates are in the order of millimeters to 1 cm yr^{-1} for both constructed and natural wetlands. Soil C in wetlands is recognized as an important component of global C budgets, hence has received significant research interest in understanding and enhancing the mechanisms of sequestration (Rapalee *et al.* 2001; McCarty *et al.* 2002; Richey *et al.* 2002; Thom *et al.*

2002). Of the past anthropogenic CO_2 addition to the atmosphere, about 50 Pg C is estimated from the loss of soil organic matter in cultivated soils (Paustian, 2000). It is estimated that terrestrial ecosystems, including wetlands, can potentially sequester 5-10Gt C/yr, which is currently at 2Gt C/yr approximately. Wetlands sequester C through high rates of organic matter inputs and reduced rates of decompositions (Pant *et al.* 2003). Wetland soils may contain as much as 200 times more C than their vegetation. However, the drainage of large areas of wetlands and their subsequent cultivation at many places had made them a net source of CO_2. Restoration of wetlands can reverse them to a sink of atmospheric CO_2 (Lal, 2008). As per the estimations, the carbon sequestration potential of restored wetlands (over 50 year period) comes out to be about 0.4 tonnes C/ha/year (IPCC, 2000). Wetlands have the greatest carbon density of any ecosystem type at 860 Mg ha^{-1}. Forests and grass/shrublands contain the most soil carbon on a global basis, but the carbon density in wetlands is ~three times greater than that in forests (265 Mg ha^{-1}) and ~six times greater than that in grasslands/shrublands (141 Mg ha^{-1}).

In India, coastal wetlands are playing a major role in carbon sequestration. The total extent of coastal ecosystems (including mangroves) in India is around 43,000 km^2 (Kathiresan and Thakur, 2008). As carbon sinks, wetlands in eastern India are more important than those on the west coast, as they are larger in size, higher in diversity, and more complicated due to tidal creeks and canal networks. Similarly, tropical coastal wetlands such as the Vembanad Lake, a lagoon along the West Coast of India, were found to be releasing up to 193.2 $mg/m^2/h$ of CH_4 (Verma *et al.* 2002). Wetlands function as net sequesters or producers of greenhouse gases depending on their bio-geo-chemical processes and hydrology. Thus more research is required to ascertain whether wetlands can be managed as net carbon sinks over time and their potential role in climate change mitigation and the international carbon trading system.

2.5. Mapping of LULC using Remote Sensing (RS) and Geographic Information System (GIS):

Modern technologies like Remote Sensing (RS) and Geographic Information Systems (GIS) can quantify the spatial pattern of a landscape and its change over a certain period in a cost-effective manner. Satellite remote sensing has long been used as a means of detecting and labeling changes in the condition of the land surface over time (Coppin and Bauer, 1996). Satellite sensors are well-suited to this task because they provide consistent and repeatable measurements at a spatial scale appropriate for capturing the effects of many processes that cause change, including natural and anthropogenic disturbance (Jin and Sader, 2006; Muchoney and Haack, 1994; Royle and Lathrop, 2002), climate change (Silapaswan *et al.* 2001) and urbanization (Kwarteng and Chavez, 1998). Accordingly, the field of change detection in remote sensing is rich with case studies, methods, and applications in a wide range of practical situations.

2.5.1. Forest Cover Mapping:

Characterizing change in forested areas is of particular interest. With large stores of carbon in live vegetation and soil, forests play an important role in the global carbon cycle (Houghton *et al.* 2001a). Because the magnitude of carbon loss during and after disturbance is large relative to the yearly carbon flux in undisturbed forest stands, spatially integrated net carbon flux in forests at any given time is largely determined by the spatial extent of disturbance and by the rate of re-growth of forested vegetation (Harmon, 2001; Körner, 2003; Law *et al.* 2004; Kennedy *et al.* 2007). Remote sensing and Geographical Information System techniques are becoming increasingly important to assess the change in forest ecosystems to prioritize the efforts of conservation (Salem, 2003; Ambastha and Jha, 2010; Pattanaik *et al.* 2010; Roy *et al.* 2013; Krishna *et al.* 2014). Studying changes in land-use patterns using remotely sensed data is based on the comparison of time-sequential data. Change detection using satellite data can allow for timely and consistent estimates of changes in land-use trends over large areas and has the additional advantage of the ease of data capture into a GIS.

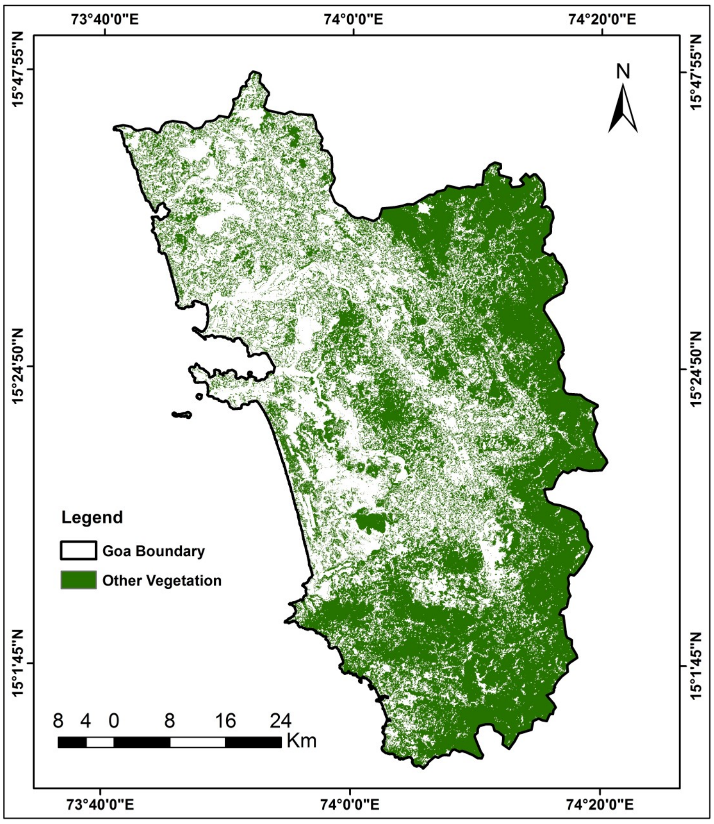


Fig 2.6 Goa Forest Resources 2017

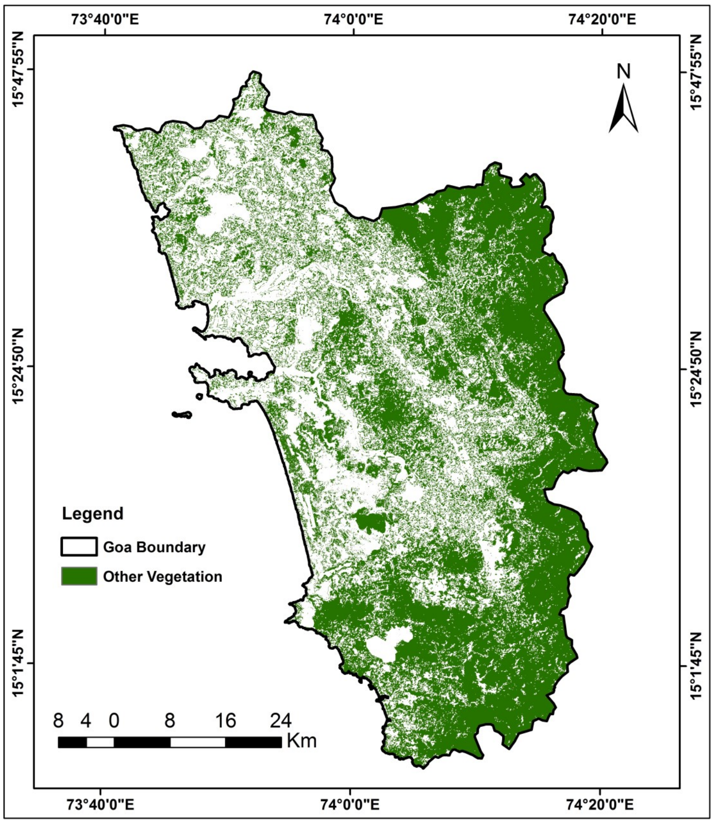


Fig 2.7 Goa Forest Resources 2007

Change detection methods are fundamental to most monitoring programs.

2.5.2. Mapping of Mangrove cover:

Remotely sensed data have been popularly used with GIS in mangrove forest mapping for inventory and monitoring purposes in many parts of the world (Mausel *et al.* 1993; Green *et al.* 1998; Trisurat *et al.* 2000; Hossain *et al*. 2003; Kovacs *et al.* 2005; Hossain *et al.* 2007a; Kovacs *et al.* 2008). The increasing use of remote sensing techniques in mangrove forest mapping is possible because of the high reflectance values from forested areas in the near-infrared, moderate reflectance in the middle-infrared, and low reflectance in the red spectral regions (Trisurat *et al.* 2000). Landsat TM data could be used to identify the primary mangrove forest (Sader *et al.* 1990), and different succession stages conveniently (Mausel *et al.* 1993). Mangroves grow at the land-sea interface. Therefore, the three major features contributing to the pixel composition in remotely sensed imagery are vegetation, soil, and water. Any mixture of the individual surface appearance is also influenced by seasonal and diurnal intertidal interactions. These circumstances greatly affect the spectral characterization of the image components and described them as the major obstacles to a rigorous radiometric characterization (Blasco *et al.* 1998). Additionally, the diversity of mangrove species in Asia is much higher than in the tropical or subtropical regions of the New World (Ramsey *et al.* 1996). This is very important for remote-sensing applications because such circumstances aggravate discrimination difficulties as the result of a higher amount of spectrally unique species.

Textural and spectral characteristics of the canopy and leaves are the main features used to distinguish mangrove communities (Ramsey *et al.* 1996). Their structural appearance, partially more homogeneous or heterogeneous, depends on several factors, such as species composition, distribution pattern, growth form, density growth, and stand height. Meza Diaz and Blackburn (2003), described the spectral variations of the canopy reflectance as a function of several optical properties, such as leaf area index (LAI), background reflectance, and leaf inclination.

The spectral signature of a single species is defined by age, vitality, and phenological and physiological characteristics (Blasco *et al.* 1998). Periodic climatic changes that influence the leaf dynamics of foliation and leaf senescence may also have an impact on the spectral response. It was observed that a flush of fresh red mangrove leaves after seasonal rainfalls during the early wet season in Panama. This led to the inference that imagery of the early wet season is very helpful because of the greater spectral distinction among species (Wang *et al.* 2008). Remote-sensing techniques have demonstrated a high potential to detect, identify, map, and monitor mangrove conditions and changes during the last two decades, which is reflected by the large number of scientific papers published globally.

2.5.3. Mapping of Wetlands:

Organic matter accumulations in wetlands are generally positively correlated with net primary production (NPP). Net primary production in a wetland is closely tied to hydrology as modified by water flow, hydro-period, and landscape (Brinson, 1993), which in turn, controls organic matter decomposition and nutrient cycling (Brinson, 1981). Apart from detritus and water samples, soil samples should be obtained from different depths to examine the vertical distributions of C in wetlands qualitatively and quantitatively. The intrinsic hypothesis of geo-statistics states that geophysical phenomena vary in a continuum and predictable pattern at some spatial scale (Burrough, 1993). Thus, geo-statistical techniques can be used to obtain information on the pattern of spatial variation. The pattern is often determined with semi-videography, a graphical approach used to show the range of spatial dependence. However, samples drawn outside of the range behave as independent random variables, consequently no reliable interpolation between sampling locations is possible. Thus, nested sampling can be used so that it can provide information for the most efficient sample spacing (Burrough, 1993). Such a pattern can be repeated in the minimum number of locations, which would provide sufficient information for the construction of semi-variograms, ultimately efficient sample spacing for a larger grid.

In case of high spatial variability, a flexible approach to spatial characterization of C could be adapted to a restricted extent so that C could be adequately mapped.

Application of Multispectral data

The spatial data used for the present analysis includes Landsat Satellite imageries, Google Earth data for LULC classification, and also for spatial distribution patterns of Soil Organic Carbon Stock (SOCS). The non-spatial data includes Tree Inventory data, GPS coordinates, and SOCS values obtained from the soil analysis. Landsat 7 (Enhanced Thematic Mapper Plus) ETM+ satellite image of the year 2007 and Landsat 8 (Operational Land Imager) OLI satellite image of the year 2017 with a spatial resolution of 30m (***Source: USGS***) were used for the Land Use and Land Cover (LULC) Classification. Two satellite imageries with different periods were used to study the spatio-temporal changes in the state of Goa.

Image Pre-Processing:

Data pre-processing forms an integral and vital component of the data processing workflow for image classification. Broadly, image pre-processing comprises two processes:

1. Radiometric correction

2. Geometric correction

All the datasets have been rectified to a common UTM (Universal Transverse Mercator) WGS84 projection and datum based on the topographical base map and resampled using the nearest neighbour algorithm. Removing the effects of the atmosphere in the thermal region is the essential step necessary to use the thermal band imagery for absolute temperature studies. The procedure based on the online radiative transfer equation by standard atmosphere parameters along with geometric parameters has been estimated and applied to each of the satellite images for atmospheric corrections. After applying radiometric and geometric corrections the DN number of the Landsat 7 ETM+ satellite image of the year 2007 and Landsat 8 OLI satellite image of the year 2017 datasets were converted into spectral radiance.

Satellite and Google Earth imageries were analyzed using Arc GIS and ERDAS IMAGINE software with the help of ground truth data collected from GPS and land use and land cover classes viz., Agriculture, Settlements, Mangroves, Wetlands, and Forests were identified. By using ERDAS IMAGINE, the LULC thematic map and their area estimation were done by supervised classification. LULC categories such as Agriculture, Wetlands, Mangroves, and Forests areas were extracted from the LULC thematic map.

Classification Scheme:

It has been often realized that no single classification scheme can be applied to all kinds of images and scales. There are many Land Use/Land Cover Classification Systems (LULCCS). Anderson *et al.* (1976) developed a hierarchical LULC classification system for use with remote sensor data. It has been implemented by the USGS for 1:250,000 and 1:100,000 scales LULC mapping. Other classification schemes existing for use with remotely sensed data are mostly modifications of the Anderson scheme.

Keeping in view the research objectives and satellite data being used for the preparation of the LULC map of Goa, seven major classes have been identified as per Anderson's classification scheme. Interpretation keys - colour, shape, size, tone, pattern, and texture – have been used for the identification of samples for the supervised classification of various images. The colour and tones of different classes as visible in FCC images are as under:

(i) Agriculture or Agro-ecosystems (Figure 2.12 &2.13)

(ii) Mangroves (Figure 2.1)

(iii) Other Vegetation or Forests (Figure 2.6 & 2.7)

(iv) Water Bodies (Figure 2.2)

(iv) Wetlands (Figures 2.3)

2.6 Analysis:

The general understanding of LULC information has been derived from thematic maps generated by classifying the images, Google Earth, and a pre and post-ground survey

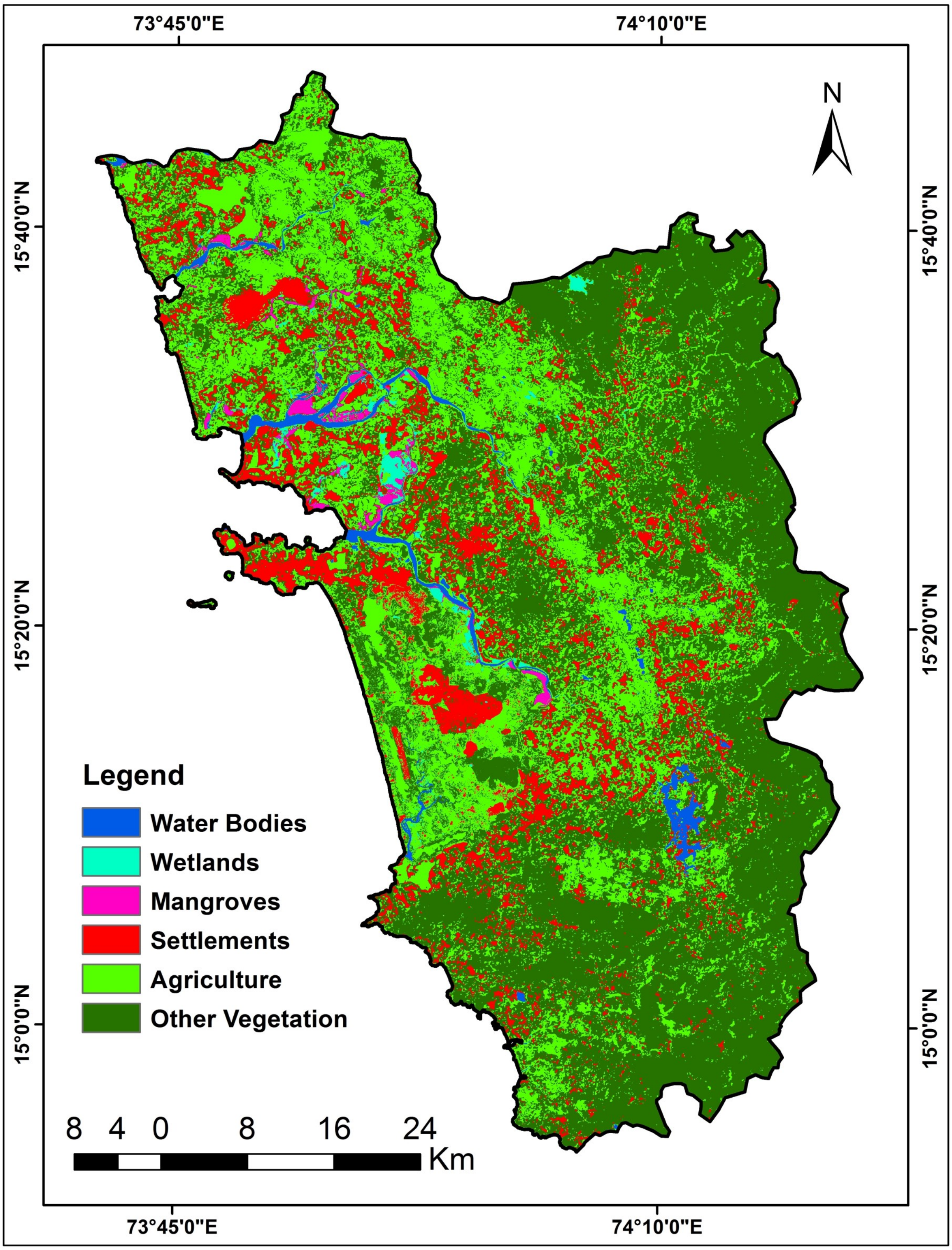


Figure 2.8 : Goa Land Use Land Cover 2017

Table 2.1 Land use/land cover statistics

GOA LULC 2017				
Sr. No.	LULC Classes	Area (sq. km)	Area (ha)	Area %
1	Water Bodies	60.13	6013	1.624
2	Wetlands	27.19	2719	0.734
3	Mangroves	26.8	2680	0.724
4	Settlements	481.1	48110	12.996
5	Agriculture	1094.17	109417	29.556
6	Other Vegetation	2012.61	201261	54.365
	Total	*3702*	*370200*	*100*

Source : Compiled by researcher based on hybrid LULC classification 2017

Table 2.2: Land Use and Land Cover (LULC) of Goa (2007)

GOA LULC 2007				
Sr. No.	**LULC Classes**	**Area (sq.km)**	**Area (ha)**	**Area %**
1	Water Bodies	63.89	6389	1.73
2	Wetlands	30.43	3043	0.82
3	Mangroves	22.6	2260	0.61
4	Settlements	462.56	46256	12.49
5	Agriculture	1126.3	112630	30.42
6	Other Vegetation	1996.22	199622	53.92
	Total	***3702***	***370200***	***100***

Source : Compiled by researcher based on hybrid LULC classification 2007

Table 2.3: LULC Change from 2007 to 2017

GOA LULC CHANGE from 2007 to 2017				
Sr. No.	**LULC Classes**	**Area (Gain/Loss)**	**Net Change (sq.km)**	**Net Change (ha)**
1.	Water Bodies	Loss	3.76	376
2.	Wetlands	Loss	3.24	324
3.	Mangroves	Gain	4.2	42
4.	Settlements	Gain	18.54	1854
5.	Agriculture	Loss	32.13	3213
6.	Other Vegetation	Gain	16.39	1639

Source : Compiled by researcher based on hybrid LULC classification 2007 & 2017 from the field. In the present study, LULC analysis is made for the state of Goa at two different times. LULC maps for the years 2007 and 2017 have been generated using LANDSAT 7 ETM+ (2007) and LANDSAT 8 OLI (2017) datasets respectively. Supervised classification has been applied to selected bands (FCC). The digitized Google Earth images of the respective years were superimposed on the classified data. The first level classification has been used for LULC analysis. The present LULC classification has six major classes and they are as follows:

- Agriculture or Agro-ecosystems (figure 2.12 & 2.13)
- Water Bodies
- Wetlands
- Mangroves
- Other Vegetation and Forest area (Figure 2.6 & 2.7)
- Settlements or Urban areas (Figure 2.10 & 2.11)

2.6.1 Land use and land cover of 2017

The LULC map for the state of Goa in the year 2017 have been shown in (Fig.2.8 and 2.9) and the extracted maps of the individual class have been represented in Figure 2.1. to Figure 2.12 respectively. The spatial extent of the state of Goa in the year 2017 has been shown in Table 1. In the LULC classification of the year 2017, the lush green represents the area of agriculture or agro-ecosystems which includes paddy fields, current fallow land, fallow land, barren land, grazing land, and grassland. The examples of such lands are given in Figures The electric blue colour signifies the areas of wetlands which include marshes, swamps, bogs, and fens which are shown in Photo Plate 2. and Fig. 2.3. The other vegetation or forest areas are represented in forest green colour which includes semi-evergreen forest, moist-deciduous forest, open forest, plantations and hilly regions shown in Fig.8. and the water bodies are denoted through azure blue colour. The state of Goa encompasses a total area of 3,702 sq. km. The spatial extent of the state in the year 2017 is shown in Table 1. In

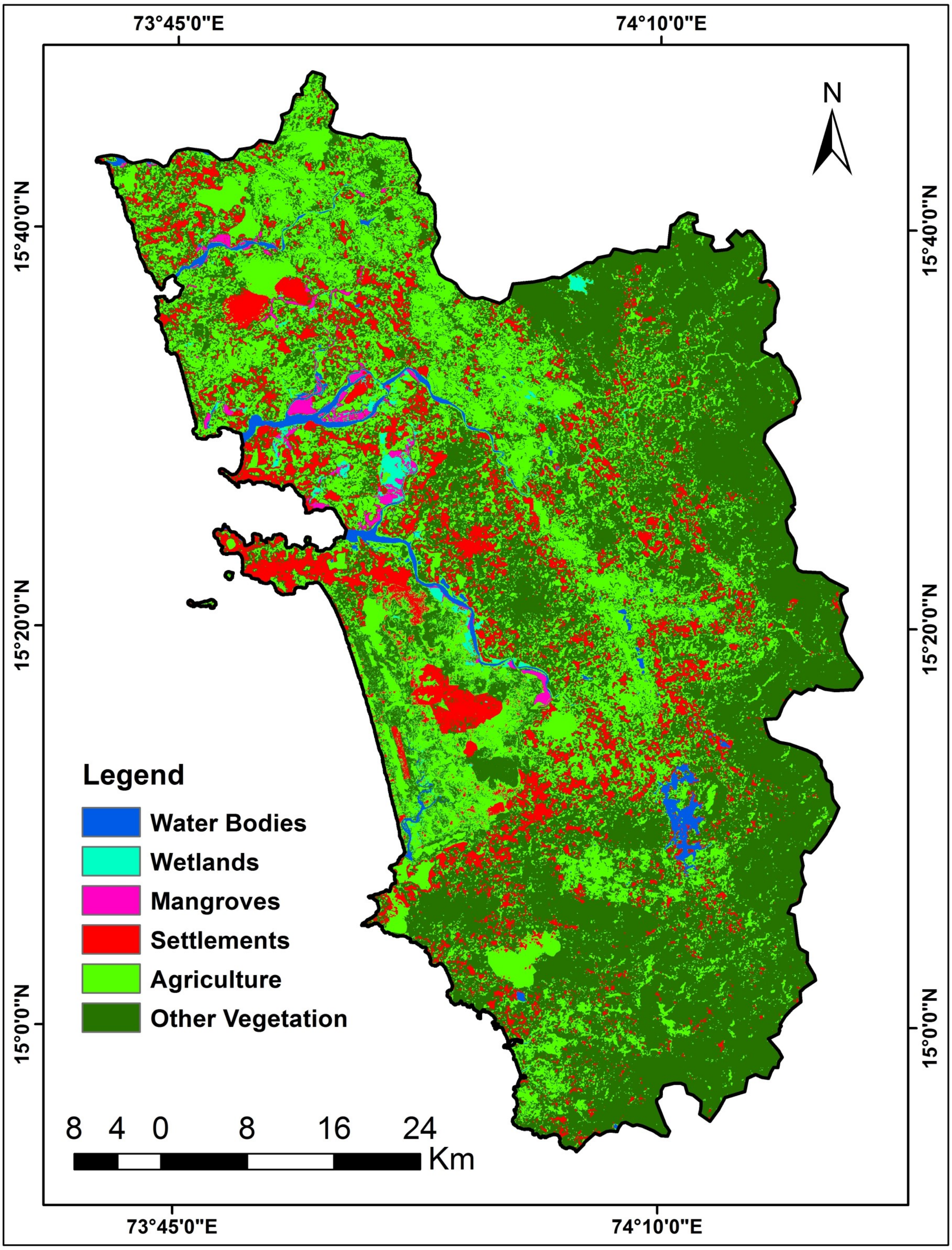


Figure 2.9 : Goa Land Use Land Cover 2007

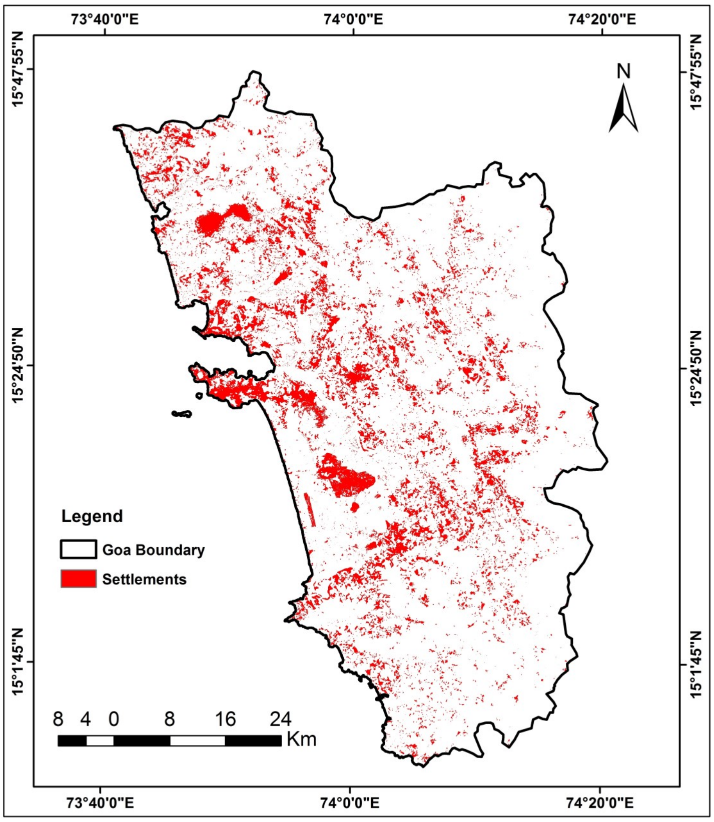


Figure 2.10 Goa Distribution of Settlements & Built-up area 2017

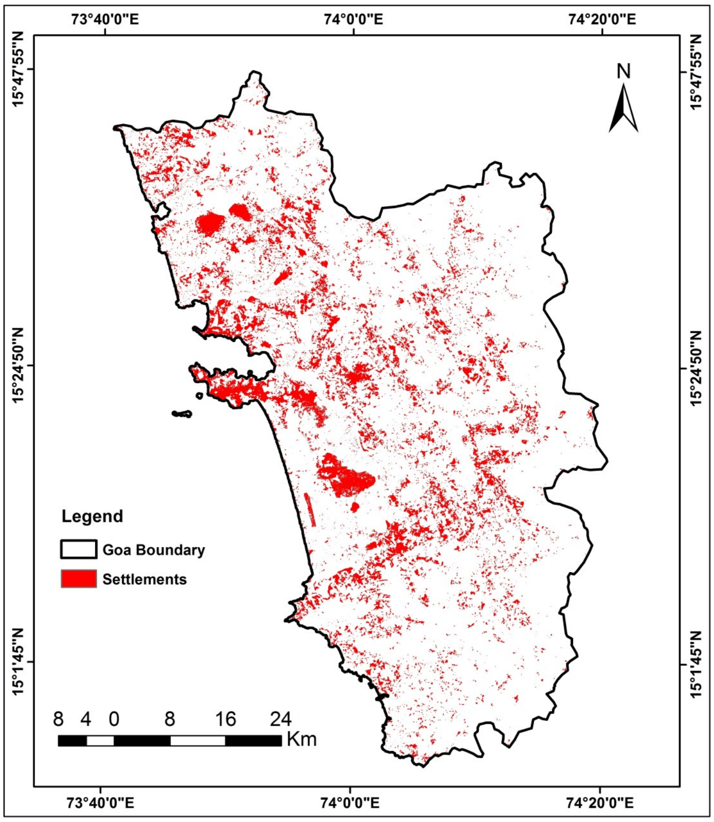


Figure 2.11Goa Distribution of Settlements & Built-up area 2007

the case of distribution of the area, other vegetation or the forest areas covers 2012.61 sq. km (54.37%), agriculture or agro-ecosystems cover 1094.17 (29.57%), settlements 481.1 (~13%), water bodies 60.13 (1.62%), wetlands 27.19 (0.73%) and mangrove cover 26.8 (0.72%).

2.6.2 Land Use and Land Cover of 2007

The LULC map for the state of Goa of the year 2007 have been shown in Fig. 42.9 and the extracted maps of the individual class have been represented in Figure 4. a, 4. b, 4. c, 4.d, 4. e and 4. f respectively. In the LULC classification of the year 2007, a similar colour scheme was used to depict the classes the same as that of the year 2017. The spatial extent of the state of Goa in the year 2007 has been shown in Table 2. In the case of distribution of the area, other vegetation or the forest areas covers 1996.22 (53.92%), agriculture or agro-ecosystems cover 1126.3 (30.42%), settlements 462.56 (12.5%), water bodies 63.89 (1.73%), wetlands 30.43 (0.82%) and mangrove covers 22.6 (0.61%).

In general, the LULC classification maps for the state of Goa for the year 2017 and 2007 reveals that the majority portion of the state is covered by other vegetation or forest areas followed by agriculture or agro-ecosystems, settlements or urban areas, water bodies, wetlands, and mangrove areas respectively.

2.6.3 Land Use and Land Cover Changes 2007-2017

From the LULC maps of Goa for the years 2017 and 2007, the net change in the spatial extent of LULC classes over the study area was observed which were represented as either gain or loss in the area (sq. km) (Table 2.3). Gains indicate the addition of new areas to the corresponding LULC category while losses indicate a change in landscape characteristics to some other class. Any increase in the area of a particular class from other classes has been termed as the gain, whereas the decrease in the area of a particular class to another class has been termed as the loss. Net change (loss) has been recorded in the categories of agriculture, wetlands, and water bodies with a decrease in an area (sq. km) of 32.13, 3.24, and 3.76 respectively whereas in the case of net change (gain) has been

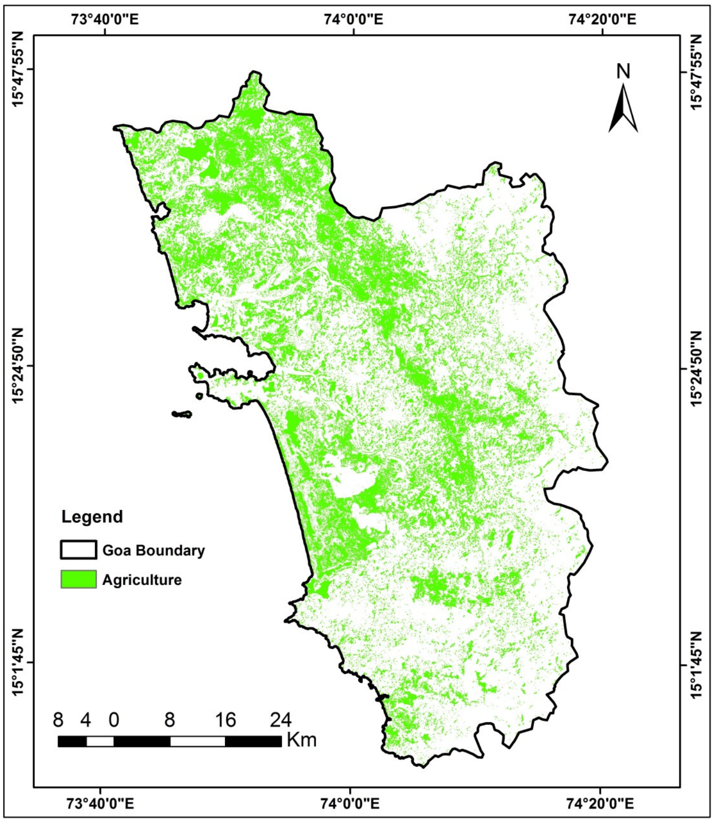


Figure 2. 12 Goa Agricultural regions 2017

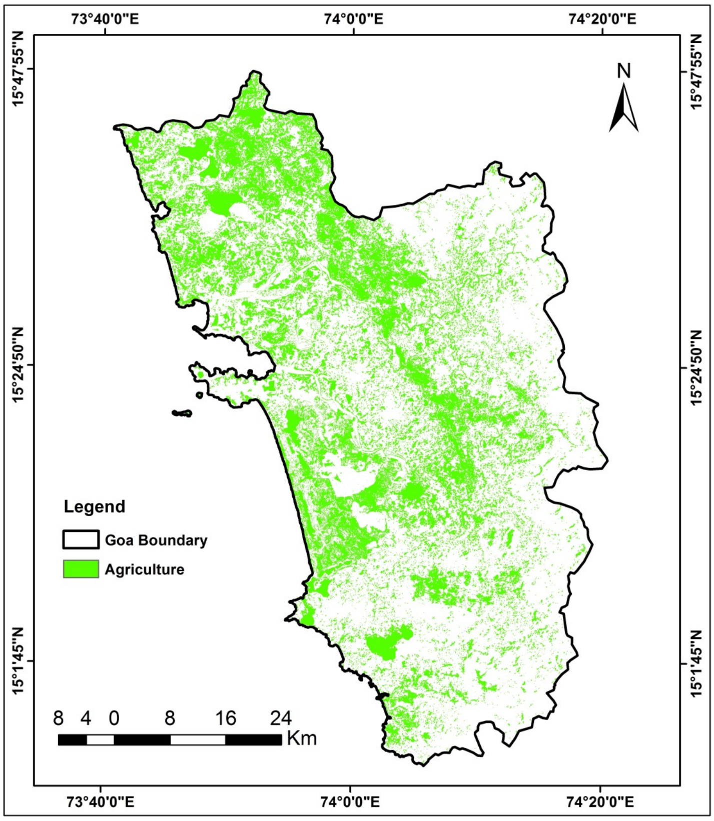


Figure 2. 13 Goa Agricultural regions 2007

noted in the classes of forests, settlements, and mangroves with an increase in an area (sq. km) of 16.39, 18.54 and 4.2 correspondingly. Maximum gain in the area was observed in settlements however there was an extreme loss in agricultural areas. The total forest cover of Goa (figure has been increased by 20.59 sq. km which includes wildlife sanctuaries, a national park, a bird sanctuary, a mangrove forest, and the hilly regions which is a good addition to the contribution of Western Ghats. From 2007-2017 (figure3.7 &3.8) , there has been an increase in forest area by ~16.4 sq. km. Taking into consideration the plantations, particularly cashew plantations, the total tree cover accounted for nearly 60 percent of the geographical area of the State. According to the FSI's, 'state of forest' report, 2015 states that the reason for the increase in forest cover in Goa is mainly due to the increase in mangrove area. Mangroves have contributed to almost 20.4 percent of the increase in the total forest cover of Goa. Non-cultivation of paddy fields over a couple of decades has led to an increase in mangrove forest areas and a decrease in agricultural land. Pollution and fallow conditions of paddy fields cause their eutrophication, which helps in the growth of mangroves. It has been noticed that there has been a severe loss in the agroecosystems of Goa where the areas covering it have decreased by 32.13 sq. km. The rapid growth of population, unplanned urbanization, industrialization, and agricultural modernization in the area has created a loss in agricultural land. This loss in agricultural land led to an increase in the mangrove area which ultimate result in an increase in the forest area. The ban on mining activities since 2012 may have prevented further increase in the forest cover. According to the 2017 report, completely denuded lands were converted into dense forests between 2015 and 2017. The positive change in the mangrove forest is mainly due to the plantation and regeneration of mangroves. Apart from the agro-ecosystem, it is noticed that there has been a decrease in the river basins and the wetlands of Goa by 7 sq. km. Road construction projects have harmed the khazan lands and water bodies of Goa. Previous mining projects had caused a tremendous loss in such areas. Wetlands near urban centers are under increasing developmental pressure for residential, industrial, and commercial facilities. Vast stretches of wetlands have been converted to paddy fields. Construction of a large number of reservoirs, canals, and dams to provide for irrigation significantly altered the hydrology of the associated wetlands. Demand for shrimps and fish has provided economic incentives to convert wetlands to develop pisciculture and aquaculture ponds. The construction of canals and diversion of streams and rivers to transport water to lower arid regions for irrigation has altered the drainage pattern and significantly degraded the wetlands of the region. Due to unplanned urban and agricultural development, industries, road construction, impoundment, resource extraction, and dredge disposal, wetlands have been drained and transformed, causing substantial economic and ecological losses in the long term. Insignificantly the settlements or urban areas have increased by 18.54 sq. km. Many plateaus and barren lands are being targeted for new industries, educational institutes, and housing. Loss of agricultural land, wetlands, water bodies, and few forest areas results in the increase in industrialization and the urban sector.

CHAPTER 3: BIOMASS AND CARBON STOCK ESTIMATION

1. Introduction

Carbon dioxide (CO_2) in the atmosphere has been increasing steadily since pre-industrial times from 280 ppm to the latest record of 396.80 ppm in February 2013 (NOAA, 2013). CO_2 is one of the most important greenhouse gases which is responsible for absorbing energy from the sun, leading to the warming of the Earth's atmosphere through the phenomenon of the greenhouse effect and likely to affect climate change (Zhou *et al.* 2011). There is unequivocal evidence that tire Earth's climate is warming at an unprecedented rate. The majority of informed scientists agree that this is the result of the increase of greenhouse gases in our atmosphere, directly caused by human activities. The effects of climate change are geographically inequitable, varied, and unpredictable with potentially devastating and unplanned-for consequences, both for global plant diversity and ultimately for human survival (Hawkins 2008). Plants are of particular importance as they are the major regulators of global climate and are the keystone of the carbon cycle. The uptake of CO_2, one of the principal greenhouse gases, during photosynthesis is the major pathway by which carbon is removed from the atmosphere and made available to animals and humans for growth and development. Forests are especially important in this regard, acting as major carbon sinks by soaking up CO_2 and storing it as biomass and in soils. Rapid industrialization, urbanization, agricultural expansion, forest exploitation, and conversion in the past few decades along with fossil fuel burning have all led to the release of high levels of greenhouse gases, particularly CO_2, into the atmosphere. High concentration of these GHGs has resulted in a significant warming of the earth's surface and rising average temperatures and consequently leading to the alarming loss of biodiversity. All plant material contains carbon (normally around 50% of dry weight), and burning or decomposition of cleared vegetation releases it into the atmosphere, mainly in the form of CO_2.

The United Nations Framework Convention on Climate Change (UNFCCC) recently agreed to study and consider a new initiative, led by forest-rich developing countries, that calls for economic incentives to help facilitate reductions in emissions from deforestation in developing countries (REDD) (UNFCCC 2011). The REDD concept is at its core a proposal to provide financial incentives to help developing countries voluntarily reduce national deforestation rates and associated carbon emissions below the baseline. Countries that demonstrate emissions reductions may be able to sell those carbon credits on the international carbon market or elsewhere. These emissions reductions could simultaneously combat climate change, conserve biodiversity and protect other ecosystem goods and services. Implementation of climate policies aimed at reducing carbon emissions from deforestation will require the resolution of scientific challenges. Foremost among these challenges is quantifying the nation's carbon emissions from deforestation and forest degradation (Gibbs *et al.* 2007), which requires information on forest clearing and carbon storage. Plants and particularly trees, because of their large biomass per unit area of land, continue to make an important contribution to the global carbon cycle. Forest vegetation contains over 350,000 Tg of carbon and plays a major role in the global carbon cycle (Dixon *et al.* 1994). Forests sequester and store more carbon than any other terrestrial ecosystem and are an important natural 'brake' on climate change. When forests are cleared or degraded, their stored carbon is released into the atmosphere as CO_2. Tropical deforestation is estimated to have released the order of 1-2 billion tonnes of carbon per year during the 1990s, roughly 15-25% of annual global greenhouse gas emissions (Malhi and Grace 2000; Fearnside and Laurance 2003, 2004; Houghton 2005a). While deforestation is estimated to have released an additional 1.6 Gt C per year into the atmosphere during the 1990s, terrestrial vegetation is believed to have absorbed between 2-3 Gt C per year at the same time (Broadmeadow and Matthews 2003). When considering the contribution made by forests to the carbon balance at any scale, the rate at which CO_2 is removed from the atmosphere and/or the quantity of carbon retained in the forest as a reservoir (also known as a carbon pool) should be assessed. Tropical forests harboring rich biodiversity are responding in several ways to global climate change leading to shifts in species composition and the overall increase in turnover (Phillips and Gentry 1994). However, species play a potentially important role in enhancing the ecosystem's capacity to recover and adapt to the impacts of climate change. Substantial amounts of carbon can be sequestered through forestry, compared to the net volume of carbon released into the atmosphere. The main carbon pools in tropical forest ecosystems are the living biomass of trees and understory vegetation and the dead mass of litter, woody debris, and soil organic matter the carbon stored in the aboveground living biomass of trees is typically the largest pool and the most directly impacted by deforestation and degradation (Gibbs *et al.* 2007). Thus, estimating aboveground forest biomass is the most critical step in quantifying carbon stocks and fluxes from tropical forests. Tree inventories are an efficient way of assessing forest carbon stocks and emissions to the atmosphere during deforestation (Chave *et al.* 2004). Biomass is closely related to and often estimated directly from the growing stock (Volume). Estimation of above-ground biomass (AGB) is an essential aspect of studies of carbon sequestration, carbon stocks, and to study the effect of deforestation on the global carbon balance. Above-ground biomass estimates are still an important source because of the scarcity of reliable estimates of biomass and its variation across landscapes and forest types (Houghton *et al.* 2009). The major carbon pools in India are estimated based on very coarse resolution data and extrapolation because the primary data for the many regions of the country are non-existed or over-estimated (Dadhwal and Nayak 1993). Due to the lack of reliable data on standing biomass and rates of forest degradation, the net carbon emission estimates for India are highly variable (Ravindranath *et al.* 1997). Thus, the improved quantification of carbon pools and fluxes in forest ecosystems is important for understanding the contribution of forests to net carbon emissions and their potential for carbon sequestration.

3.2. Biomass estimation:

The quantity of living plant material in a forest is called biomass. Photosynthesis is the unique biochemical process by which carbohydrate from carbon dioxide is synthesized in green parts of the plant and stored in the form of organic matter which is termed live plant biomass. Biomass is an important parameter to assess the assimilation of carbon by plants. Biomass and carbon storage in forest ecosystems play an important role in the global carbon cycle (Goodale *et al.* 2002; Li *et al.* 2011) because forest ecosystems act as a major carbon sink and store more carbon per unit area than any other terrestrial ecosystem (Houghton *et al.* 2007). Tree biomass plays a key role in sustainable forest management by regulating different aspects of ecosystem structure and function. The plant biomass is mainly compartmentalized in AGB (AGB) and BGB (BGB) in different types of forest ecosystems. Above-ground biomass consists of all living biomass above the soil including stems, stumps, branches, bark, seeds, and foliage. AGB is a useful measure for assessing changes in forest structure and an essential aspect of studies of the carbon cycle (Cairns *et al.* 1997). BGB consists of all living roots excluding fine roots (<2mm in diameter). AGB is a key variable in the annual and long-term changes in the global terrestrial carbon cycle and other earth system interactions. The quantification of forest biomass has a long history because of its importance for timber and fuel to many societies around the world. In the past decades, forest biomass quantification has attracted renewed interest because forest standing biomass represents about 44 % of the world's forest carbon pool (Pan *et al.,* 2011), thereby having a key role in climate change mitigation.

The forests accumulate the greatest plant biomass which has been reported to increase generally from temperate to tropical forest ecosystems. The perennial aerial structures in the forests account for nearly three-fourths of the total biomass, while the roots account for only about one-fourth. AGB estimates provide information on the location of sources and sinks of carbon and allow the quantification of the amount of carbon lost from sinks through deforestation and degradation (Ketterings *et al.* 2001; Houghton 2005). Estimates of AGB are critical for analyzing the carbon stocks and fluxes of forest communities (*Brown 1997*); the amount of primary energy that can be obtained from forests as an alternative to fossil fuels (Richardson *et al.* 2002) as well as estimating the stocks and fluxes of other biogeochemical elements, such as nitrogen (Hughes *et al.* 1999). Studies have indicated that biomass in mature tropical forests generally increases along precipitation gradients. Recently, a review of 229 estimates of AGB from 44 studies in seasonally dry tropical forests confirmed the paramount importance of precipitation (Becknell *et al.* 2012). In this analysis, the AGB of mature forests ranged from 39 to 334 Mg/ha and showed a positive relationship with mean annual precipitation which explained >50% of the variation in AGB. The biomass in dry tropical forests is not uniformly distributed across the forest but exhibits patchy distribution (Chaturvedi *et al.* 2011). Tree diameter and height data from forest plots have been used to estimate carbon stocks through the calculation of AGB (Chave *et al.* 2005). Estimating the amount of forest biomass gives an idea of carbon sequestration potential in forest ecosystems (Gupta and Kumar 2014).

Primary production of a community or any part thereof is defined as the total radiant energy or CO_2-C fixed by the photosynthetic activity of producer organisms, chiefly the green plants; (Chapin III *et al.* 2006) per unit area in a given period. The term net ecosystem production (NEP) was first introduced by Woodwell and Whittaker, (1968) to represent the difference between the ecosystem-level photosynthetic gain of CO_2-C (i.e. GPP) and ecosystem-level (plant, animal, and microbial) respiratory loss of CO_2-C (i.e. ecosystem respiration, ER). The tropical forest biome is characterized by high productivity and tropical forests contribute approximately one-third of the global terrestrial productivity (Beer *et al.* 2010). Improved measurements of NPP have included annual litter fall, thereby resulting in high values of forest biomass (Martínez-Yrízar *et al.* 1996; Bullock *et al.* 1995). Biomass distribution in a forest ecosystem is a function of vegetation type, structure, and site condition. Dimension analysis involving measurement of the easily measurable parameters of tree growth and weight of trees and tree components is the commonly used method for estimating productivity in tree plantations and forest ecosystems (Kira *et al.* 1967; Whittaker and Woodwell 1971).

Litter-fall is a major pathway for the return of organic matter and nutrients from aerial parts of the plant to the soil surface. It is another important component of organic matter dynamics and nutrient cycling in a forest and its input depends upon a variety of factors such as species, age groups, canopy cover, weather conditions, and biotic factors (Lodhiyal *et al.* 2002). A substantial amount of nutrients taken up by plants is returned to the soil as litter fall followed by its decomposition in the soil. Standing crop of litter accumulated on the ground floor acts as an input-output system of nutrients, and litter decomposition; regulate energy flow, primary productivity, and nutrient cycling in forest ecosystems, however, due to variations in canopy architecture and tree species, amounts and rates of litter-fall and decomposition show considerable spatial variation (Sundarpandian and Swamy 1999*)*. Tropical forest canopy productivity consists of the formation and growth of leaves, twigs, flowers, and fruits, and is typically estimated to be equal to the rate of litterfall. Indeed, litter fall is one of the most frequently measured components for estimating net primary productivity in forest ecosystems. Leaf litterfall is typically the largest fraction of total litterfall (*Malhi 2012*).

3.2.1 Estimation methods:

Detailed estimation of biomass of all land cover types is necessary for carbon accounting. There are several methods for estimating forest biomass. These can be grouped into destructive (conventional method) and non-destructive methods. Destructive methods are categorized into (i) by harvesting all materials in a unit area, (ii) by harvesting average tree size (girth or height) classes, or (iii) by harvesting individuals over a wide range in size and establishing the relationship between biomass and easily measurable plant parameters such as diameter/girth and/or height (Tiwari 1994; Roy and Ravan 1996; Parresol 1999; Kale *et al.* 2005).

Non-destructive methods involve the application of component-wise equations for different species, through the sampling of tree components like bole, branch, twig, and leaves (Loetsch *et al.* 1973; Tiwari 1994). According to FAO (2004), AGB can be estimated in mainly three different ways and they are as follows:

Classification of vegetation cover and generation of a vegetation-type map. This partitions the spatial variability of vegetation into relatively uniform zones or vegetation classes. These can be useful in the identification of groups of species and the spatial interpolation and extrapolation of biomass estimates.

Indirect estimation of biomass by using some form of the quantitative relationship between band ratio indices. Examples of this standard procedure are the Normalized Differential Vegetation Index (NDVI) and Green Vegetation Index (GVI).

An application of ground observations together with diameter and height calculations of trees.

Sampling methods are also crucial in biomass estimation stratified sampling is recommended for an ecological zone (one forest type) than a single-hectare plot which is considered to be insufficient (GOFC-GOLD 2008). To reduce variability in the sample population, it is divided into homogenous groups in which the population is divided are called strata and the procedure of sample selection is called stratified random sampling (Husch *et al.* 1972). Chave *et al.* (2004) quantify four types of uncertainties that could lead to statistical error in AGB estimates i.e. error due to tree measurement; error due to the choice of an allometric model relating AGB to other three dimensions; sampling uncertainty, related to the size of the study plot; representativeness of a network of small plots across a vast forest landscape. Overestimation of forest phytomass by an area-based approach compared to the more accurate volume-based inventory has also been noted by Brown and Lugo (1984). Chave *et al*. (2005) have tried to model the tropical forest area at a global scale through different allometric equations for different regions, sites, and tropical forest types to estimate the plot-wise AGB and changes from available datasets. The prime focus of their work was to provide allometric equations for the tropical forests of different environmental conditions to estimate carbon stocks. Nabuurs *et al.* (2008) compare uncertainties of carbon sequestration estimates in tropical and temperate forests and concluded that stem parameters are largely determining output. The selection of the appropriate allometric model is a key element in the accurate estimation of volume and biomass (Navar, 2009). Navar, (2010) reviewed the Measurement and Assessment Methods of Forest AGB and the Challenges Ahead. Forest biomass equations are usually derived from allometric relationships based on measurements of the dimensions and mass of destructively sampled trees (Martinez-Yrizar *et al.* 1992; Baker *et al.* 2004). Practically, most allometry employs diameter at breast height (DBH) as the only independent variable and develops an allometric relationship between DBH and component biomass (Gower *et al.* 1999). Some studies proposed to include tree height as the second predictor and develop DBH-H combined equation to improve the precision of biomass estimates (Ketterings *et al.* 2001). There are several sources of uncertainty in determining the biomass of a given area of the forest; first, many areas are composed of structurally and floristically differing forests which each needs to be sampled; secondly, there are difficulties in utilizing models to convert tree diameter measurements to AGB estimates (Chave *et al.* 2005) especially in case of tropical forests as they often comprised of hundreds of different tree species; therefore it is not practically possible to use species-specific regression models, as in the temperate zone (Brown *et al.* 1999; Fays, 2008); thirdly, different species have different densities of wood, which also needs to be taken into account when assessing biomass (Chave *et al.* 2009). Published regression models are based on a relatively small number of directly harvested trees and include very few large-diameter trees, thus do not necessarily well represent these larger trees that contain much of the forest biomass. Hence, different models applied to the same forest may yield different AGB estimates, often driven by the number of large trees, which imposes large uncertainty on stand-level biomass estimates (*Brown 1997).*

Estimations of AGB mostly used diameter, height, and wood-specific gravity (Baker *et al.* 2004; Brown 1984; Chave *et al.* 2001; Clark *et al.* 2001). Saldarriaga *et al.* (1986); Uhl and Kauffman, (1990); Uhl *et al.* (1988) considered 10-40% of AGB to quantify coarse woody debris. Saatehi *et al.* (2007) used an average of 9% (range: 2-17%) of above-ground live biomass to estimate above-ground dead biomass. Whole tree biomass including roots can be assessed from above-ground biomass with the help of the root-shoot ratio (IPCC, 2003). Root Biomass is often estimated from root: shoot ratios (R/S). An average of 21% (range: 13-26%) of above-ground live biomass was used as BGB by Saatehi *et al.* (2007). A mean R/S ratio of 0.26 with a range of 0.18 to 0.30 was reported by Cairns *et al.* (1997) and included a literature review of more than 160 studies covering tropical, temperate, and boreal forests. The R/S did not vary significantly with latitudinal zone, soil texture, or tree type. According to Brown and Lugo (1982), root biomass can vary from 10 to 50% (with an average value of 17%) of AGB for many tropical moist forests. In Indian forests, a below-ground biomass ratio of 0.266 was used by Kishwan *et al.,* (2009). In the last couple of decades satellite, remote sensing has been successfully used for biomass and productivity estimation in India at local and national levels (Chhabra *et al.* 2002b). In India; biomass, carbon stock, and carbon budget estimation is done by various workers (Lal and Singh 2000; Chhabra *et al.* 2002) based on growing stock (GS) volume data of forest inventories and appropriate conversion factors related to both biomass and carbon. The growing stock-based approach for AGB estimation has been used widely and is considered superior to the remote sensing-based method (Chhabra *et al.* 2002a). Kale *et al.* (2004) developed a biomass equation for dominant species of dry deciduous forest in Madhya Pradesh and found a good correlation between cbh^2 and height. Manhas *et al.* (2006) estimated the biomass and carbon stock of Indian forests for 1984 and 1994 by taking growing stock and specific gravity (SG) of die-dominant tree species of various strata. Mani and Parthasarathy (2007) estimated the above-ground biomass (AGB) distribution in ten 1-ha permanent plots, established in five sites each in Inland and coastal tropical dry evergreen forests of peninsular India by using two linear regression equations, one using basal area (BA, Method 1) and the other using BA and height (Method 2) were followed. The basic wood-specific gravity of 41 tree species determined by oven-dry weight by volume ranged from 0.46 to 0.92 g/cm for inland sites and 0.47 to 0.89 g/cm for coastal sites.

3.2.2 Global level estimation:

Brown *et al.* (1989) estimated the total biomass in tropical forests of Asia and reported 20.86 Mt in undisturbed forests and 10.47 Mt in logged forests. The total forest biomass of china was estimated as 9103 Tg (Fang *et al.* 1998). Henrique *et al.* (2001) quantified total aboveground dry biomass (TAGB) in undisturbed central Amazonian rainforests, averaging 397.7±30.0 Mg/ha. Cairns *et al.* (2003) assessed the species composition and biomass density in an intact Mexican forest representative of the tropical dry forest biome. Their results show total aboveground tree biomass was estimated to be 225 Mg/ha. Guillermo *et al.* (2005) estimated the tree AGB (LTAB) and total AGB (TAGB), in old-growth stands in different regions of the most widespread type of tropical American lowland rainforest (*terra firms* forest). TAGB estimates ranged throughout the region from 160 to 435 Mg/ha, while estimates of LTAB range from 167 to 419 Mg ha4. Rachel (2006), determined the coarse woody debris (CWD) biomass and tree species diversity between forest variables within the Coniferous Forests of Western Washington. They concluded that biomass quantities varied depending on the stand type, with the lowest biomass value (5.83 Mg/ha) in the old growth stand, and the highest falling into the mature stand (209.6 Mg/ha). Mutanga and Rugege (2006), estimated herbaceous biomass in Kruger National Park, part of the tropical savannah. The biomass varied between 42 Kg/ha and 9655 kg/ha, with an average of 3796 Kg/ha and a standard deviation of 1628 Kg/ha. Creighton *et al.* (2006) studied the effects of non-native grass invasion on aboveground carbon pools in a tropical dry forest of Hawaii. The results showed that total aboveground live biomass (tree + understorey) ranged from 7.8 Mg/ha in the converted site, and to >108.9 Mg/ha in the native and grass-invaded forests. Kasawani *et al.* (2007) attempted to give information about the biomass of 8 mangrove species at Tok Bali and estimated the total above-ground biomass for Mixed Mangrove Forest was 2,664.57 kg/ha. Among eight species, *Sonneratia alba* recorded the highest AGB with 665.73 kg/ha. Xiao-Tao Lu *et al.* (2009) estimated the AGB of lianas in the tropical seasonal rain forests of Xishuangbanna, SW China. They recorded that the mean AGB of lianas was 3,396 kg/ha. Mean deadwood biomass in New Zealand was 54 Mg/ha but ranged across plots from 0 to 550 Mg/ha estimated by Richardson *et al.,* (2009). Mazzei *et al.* (2010) estimated a 23% (average 94.5 Mg/ha) reduction in biomass as a result of logging in Eastern Amazon trees. Marie *et al.,* (2010) estimated the AGB of three forest types heterogeneous terra feme forests (TFF), Gilbertiodendron Dewevrei Forests (GDF), and Periodically Flooded Forests (PFF) in the Dja Biosphere Reserve, in South-East Cameroon, part of the contiguous tropical forest of the Congo Basin. Mean AGB values were respectively, 596.1 ± 62.24, 401.67 ± 58.06, and 383.14 ± 61.91 Mg/ha) in GDF, TFF, and PFF. Abbas *et al.* (2011) determined the biomass of *Olea Gerruginea,* the study showed that the average contribution of a stem portion of the tree was 49.01% of the total tree biomass, and branches showed 31.17%, leaves 1.98%, twigs 1.05% and roots 16.65% of the total tree biomass. Johan Cohn (2011), evaluated carbon storage in the Nyungwe tropical mountain forest in Rwanda estimated the AGB as 427.7 t C/ha, and found that old trees with large DBH were of crucial importance for the AGB storage. Cleber *et al.* (2011) estimated state-wide biomass carbon stocks in Acre, Brazil, and calculated the total above-ground biomass of the 163,000 km^2 State of an acre to be 3.6±0.8 Pg including non-forest biomass; state-wide, estimated average above-ground biomass in forested areas was 246±90 Mg/ha and dense forest shown the highest biomass (322±20 Mg/ha) and oligotrophic dwarf forest shown the lowest biomass (20±30 Mg/ha).

3.2.3 National level estimation:

Roy and Ravan (1996), estimated biomass in the range of 0.29 (scrub) to 130.99 (riparian) Mg/ha in Madhav national park, Madhya Pradesh. Haripriya (2003), estimated the total biomass in Indian forests ranged from 24.5 to 218 Mg/ha with an average biomass of 92 Mg/ha, and observed feat fee amount of biomass in trees <10 cm diameter class accounts for 29.7% of fee total stand biomass in Indian forests. A study conducted by Lodhiyal *et al.* (2002) in Central Himalaya for estimating biomass and productivity of 5 to 15-year-old *Dalbergia sissoo* forests revealed the biomass and productivity at 58.7-136.1 Mg/ha and 12.6-20.3 Mg/ha respectively. Biomass and productivity in some tropical dry deciduous disturbed teak (*Tectona grandis)* forests of the Satpura plateau was estimated by Pande (2005) in three communities and the allocation of biomass in different sites ranged from 47.13 to 100.88 t/ha. Manhas *et al.* (2006) estimated the biomass stock of Indian forests for 1984 and 1994. In the forest area, wood biomass was 63.86 M/ha, 2398.19 Mt in 1984 and with the reduction in forest area, 63.34 M/ha, in 1994, wood biomass (2395.12 Mt) also reduced subsequently. Mani and Parthasarathy (2007), estimated the AGB distribution and established five sites each in Inland and coastal tropical dry evergreen forests of peninsular India by using two methods. On using method 1, the AGB varied from 39.69 to 170.02 Mg/ha and by method 2, it varied from 73.06 to 173.10 Mg/ha. Mani and Parthasarathy (2009), investigated changes in AGB in two tropical dry evergreen forests (Kuzhanthaikuppam and Thirumanikkuzhi) of peninsular India by censusing all trees after the 10-year interval (1995-2005). During this census interval, the total AGB increased by 2% in KK and 11.52% in TM. Madugundu *et al.* (2008) estimated the biomass in the deciduous forests in the Western Ghats of Karnataka, India based on IRS P6 LISS-IV high-resolution multispectral sensor data. They found that the mean value of estimated above-ground biomass and RS-based above -ground biomass in the study area is 280 (±72.5) and 297.6 (+55.2) Mg/ha, respectively. Singh *et al.* (2009b), recorded the total biomass as 192.933 Mg/ha in the natural forest followed by 95.64 Mg/ha in 32 years old converted to forest, 85.78 Mg/ha in 23 years old converted to a forest, and 92.05 Mg/ha in the 15-year-old converted forest of Bamawapara Wildlife Sanctuary. Vishal *et al.* (2009), estimated aspect-related changes in biomass stocks and carbon sequestration rates of the *Shorea Robusta* (Sal) forest of Central Himalaya. The total biomass of the tree layer in the North Eastern aspect was 411.28 t/ha and 415.76 t/ha in the South eastern aspect. Baishya *et al.* (2009), compared tree AGB distribution and carbon storage in different DBH classes between natural semi-evergreen forests and Sal plantation forests in the humid tropical region of northeast India. The natural forest had a lower AGB (323.9 Mg/ha) than the plantation forest (406.4 Mg/ha). About 49% of the AGB was present in > 60 cm dbh trees in the natural forest against 24% in the plantation forest.

Sharma *et al.* (2010), estimated total biomass ranged from 129 to 533Mg/ha from four forests standing each of twenty major forest types in sub-tropical to temperate zones of Garhwal Himalaya. Sumeet *et al.* (2011) studied the tree biomass and carbon variation along an altitudinal gradient in moist temperate valley slopes of the Garhwal Himalaya (India). The total live tree biomass density (Total biomass density) varied from 215.5 to 468.2 Mg/ha.

3.3 Methodology:

Biomass was calculated using allometric equations developed for the Western Ghats (Murali *et al.* 2005). Allometric equations were used for this purpose. Carbon conversion coefficients are different, considering species, age, formation, and community structure of vegetation types, from 0.45 to 0.55 (Kauppi *et al.* 1992; Goodale *et al.* 2002; Xia *et al.* 2005 and Ramachandran *et al.* 2007). Since such coefficients are not available for the study area, a carbon conversion coefficient of 0.5 is used in the present study. Carbon storage of each forest type was estimated by multiplying forest carbon density per hectare by forest area.

a. Trees sample inventory

Based on the principle of stratified random sampling, outline a sample tree inventory method, requiring no level of pre-existing information, by knowing the total number of existing trees (Jaenson *et al.* 1992). The data sets consist of individual tree measurements such as Diameter at Breast Height (DBH), height, and total aboveground biomass of tree species used (Banaticla 2009; Maco and McPherson 2003).

b. Method for estimating Above-ground Biomass

Carbon stock was estimated in terms of biomass of above-ground biomass forest types using field methods such as plot and plotless methods after conducting the field survey. The carbon stocks are measured and estimated using literature methods (Banaticla 2009; Paustian *et al.* 2000; Chave *et al.* 2005; Jana*, et al.* 2009). For the present study, the plotless method is being applied to carbon inventory.

c. Estimation of the Aboveground Biomass pool

The goal of measurement and monitoring was to estimate the stocks of above-ground biomass or its rate of growth on a per hectare basis as well as for the total area based on identification and selection of a key set of indicators parameters such as tree species, DBH, height, Volume, Wood density (Green *et al.* 2007; Chave *et al.* 2005)

d. Method for estimating belowground biomass

Below-ground or root biomass is necessary for natural forests, areas under natural regeneration, protected areas, and agroforestry systems. The Below Ground Biomass (BGB) includes all biomass of live roots excluding fine roots having <2mm diameter (Chavan and Rasal 2011). Biomass estimation equations for tree roots are relatively uncommon in the literature. The belowground biomass (BGB) has been calculated by multiplying above-ground biomass taking 0.26 as the root-to-shoot ratio (Cairns *et al.* 1997; Ravindranath and Ostwald 2008).

3.3.1 Allometric Equation

The allometric equations are being used for estimating the above-ground and below-ground biomass in the present study region.

$AGB = 0.0396 \times D^2 \times H\ 0.932$,

$BGB = 20\% \times AGB$,

$TAB = AGB + BGB$

Where:

AGB - above-ground tree biomass (kg);

BG - below-ground tree biomass (kg);

TAB - the amount of biomass (tons);

D - Diameter at breast height (cm);

H - Height of tree stand (m).

The amount of carbon storage of vegetation will be calculated with the equations based on guidelines in the IPCC report (2006) and with the equations by S.V. Belop (1976, 1980) i.e.

$CBS = 0.5 \times TAB$

Where: CBS - the amount of carbon (tons/ha);

TAB – the amount of biomass (tons/ha);

Total carbon in present land use will be estimated using a generic coefficient to transform SOM to SOC: SOC = 0.57 SOM. Adding these SOC values to the C present as biomass will yield the total carbon stock for the present land use.

With the allometric method, consideration will be first given to the basal area (Ab) of the trunk. **$Ab = \pi \times r^2$**

where: $\pi = 3.1415927$;

and r is the radius of the tree at breast height (0.5 DBH).

With Ab, the volume (V) in cubic meters can be calculated from

$V = Ab \times H \times Kc$

where Ab is the basal area;

H is the height;

and Kc is a site-dependent constant (0.5 - default conversion factor) in standard cubing practice used in forest inventory. Using the calculated volume of the trunk, total trunk biomass in kilograms may be calculated by multiplying by the wood density (WD) corresponding to each tree species measured as

Biomass = V x WD x 1000.

3.4 Carbon stock:

Forests fix, store and emit carbon dioxide through the processes of photosynthesis, respiration, and decomposition. Forests represent a major pool in the global C cycle and contain over 350,000 Tg C (Dixon *et al.* 1994). The carbon fixed by the plants is the primary source of organic matter inputs into the soil both from the aboveground and belowground parts of the plants. The organic matter inputs into the soil provide substrate for microbial processes and accumulation of soil organic matter. The mechanism for the removal of carbon from the atmosphere by storing it in the biosphere is known as Carbon sequestration. Carbon sequestration can occur in plant biomass and carbon storage in soil profiles. In global vegetation carbon pools, forest vegetation carbon constitutes nearly three-fourths, therefore is important to understand the vegetation carbon cycle. Globally, forests represent an important carbon stock, estimated to contain 638 Gt of carbon, of which 28 Gt C is present in biomass alone (FAO 2005). The organic matter in soils is 1500–2000 Pg C in the top meter and as much as 2300 Pg in the top 3m (Jobbagy and Jackson 2000). The potential of tropical forests for increased carbon sequestration can be assessed either through the amount of carbon stored or by estimating the annual carbon sequestration rate (Brown *et al.* 1993). The studies on carbon sequestration have been focused on and expressing carbon sequestration in terms of biomass carbon accumulation over some time and the total carbon stock of the system (Lewis *et al.* 2009b, Pan *et al.* 2011).

The rainforests of West and Central Africa are the second largest block of rainforest in the world (Baccini *et al.* 2008) and contain the highest levels of biomass per hectare (*c.* 250 t/ha) worldwide (FAO 2010). Tree diameter and height data from forest plots have been used to estimate carbon stocks through the calculation of AGB (Chave *et al.,* 2005). The forest ecosystems could be important for carbon storage in the soil-plant system which is an indicator of regulatory ecosystem services. Soil carbon plays a vital role in regulating climate, water supplies, and biodiversity, and therefore in providing the ecosystem services that are essential to human well-being. Soil delivers provisioning, regulating, cultural, and supporting ecosystem services and is regulated by the physical, chemical, and biological properties of the soil. The ability of soils to deliver ecosystem services directly depends on soil regulatory services of filtering and detoxifying water, soil biodiversity, decomposition of organic materials, regulation of fluxes of greenhouse gases to and from the atmosphere, and plant-soil nutrient cycles (*Palm et al., 2007*). Soil carbon exists in both organic and inorganic forms. SOC is the main constituent of SOM. The SIC pool can be classified as lithogenic inorganic C (LIC) and pedogenic inorganic C (PIC). The role of soil organic C in the greenhouse effect has received *considerable attention* (Bouwman 1990). Since the C sequestration potential of soils depends partly on the C stock under present-day conditions, an accurate quantitative assessment of soil C storage is needed as a baseline to estimate the overall C budget and to assess the impact of land use change on the inventory to identify regions where C sequestration effort should be concentrated (Sleutel *et al.* 2003).

Díaz (2003), examined the role of functional biodiversity in facilitating carbon sequestration in semi-arid forests by analyzing three major measures of functional biodiversity i.e., the most abundant functional trait values, the variety of functional trait values; and the abundance of particular species. They found that all three major components of plant functional diversity contributed to explaining the observed distribution of carbon stocks. They concluded that the relative abundance of species with tall and to a lesser extent dense stems with a narrow range of variation around these values were the most important factors for predicting carbon sequestration. Kirby and Potvin (2007), examined the evidence for a functional relationship between species diversity and carbon storage in managed tropical moist forests, agro-forests, and pastures in Panama.

3.4.1 Estimation methods:

Vegetation carbon components are usually calculated as dry biomass multiplied by a conversion factor that represents the average carbon content or carbon concentration of biomass (Gower *et al.* 1999). Recent studies have shown that the carbon varies from 44.4% to 55.7% depending upon tree species and biomass tissues, and using a generic conversion factor of 50% will be introduced in as much as 10% carbon stock estimation studies (Laiho and Laine 1997; Elias and Potvin 2003; Lamlom and Savidge 2003; Bert and Danjon 2006). Currently, a mass-based of 50% for woody tissues and 45% for foliage and fine root is widely accepted as a constant factor for the conversion of biomass to carbon stock (Houghton 1996; Gower *et al.* 2001). Several authors have used different conversion factors to calculate carbon from total biomass. A carbon fraction of 0.45% was used to convert litter fall into carbon flux (Ajtay *et al.* 1979). Chaturvedi (1994), used 0.48% to convert biomass into carbon. A conversion factor of 0.50% was widely used by Brown and Lugo (1982); Dixon *et al.* (1994); Ravindranath *et al.* (1997); Winjum (1992); Haripriya (2000); Haripriya (2002); Kaul *et al.* (2009). Pilot studies have been done in India to estimate forest/vegetation carbon and these estimates are spread over a decade and are based on different approaches, scales, and classification schemes and objectives. Richards and Flint (1994), estimated the carbon pool and density in phytomass of Indian forests for the year 1880 based on historical records, ecological data, and population-based forest biomass.

3.4.1.1 Global level estimation:

Brown (1993), using GIS estimated that in 1980 the average C density of tropical forests in Asia was 144 Mg C/ha in biomass and 148 Mg C/ha in soils (up to 100 cm), which corresponds to total estimates of 42 and 43 Pg C for the whole continent, respectively. He reported an average maximum AGB C stock in forest lands in tropical Asia of 185 Mg C/ha with a range of 25 to more than 300 Mg C/ha.

Forest vegetation represents a major pool in the global C cycle and alone contains over 350,000 Tg of C (Dixon *et al.* 1994). Studies carried out by different scientists for different countries on the earth showed that United States forests 12.1 Pg (Turner *et al.* 1995), European forests accumulated 7.5 Pg of carbon (Kauppi *et al.* 1992), Chinese forests stocked 4.63 Pg (Fang *et al.* 2001) and Japanese forests accumulated 1.39 Pg carbon (Alexandrov *et al.* 1999). At the global scale, the forest phytomass carbon pool has been estimated as 359 Pg (Pg = 1015 g) (IPCC 2000). Malaysian forests have C densities ranging from 100 to 160 Mg/ha and from 90 to 780 Mg/ha in vegetation and soils, respectively (Abu Bakar 2000). For Thailand, various forest types have a C density in AGB ranging from 72 to 182 Mg/ha (Boonpragob 1998). In the 1990s the biosphere sink was estimated to be sequestering 3.2 Pg C/yr (Malhi *et al.* 2002). The global net terrestrial carbon sink averaged 0.8 (± 0.8) Pg C/yr during the 1990s (Houghton, 2005a). Justin *et al.* (2006) quantify the whole ecosystem C storage (soil + plant) in grazed and ungrazed sites at three distinct locations along an east-west environmental gradient in the North American Great Plains. The grazed site of the short grass community had 24% more whole-ecosystem carbon storage compared to the ungrazed site (4022 vs. 3236 g C m^2). Terakunpisut *et al.* (2007) assessed the potential of carbon sequestration in the different forest ecosystems in Thong Pha Phum National Forest, Thailand. As the result, tropical rain forests had higher carbon stock than dry evergreen forests and mixed deciduous forests at 137.73± 48.07, 70.29± 7.38, and 48.14 ± 16.72-ton C/ha, respectively. Among tree size classes in this study area the >4.5- 20 cm trees potentially provided greater carbon sequestration in the tropical rain forest and dry evergreen forest while the size of >20- 40 cm gave potentially high carbon sequestration in mixed deciduous forest. Sandstrom *et al.* (2007) assessed the relationships between volume, biomass, and C in dead wood per decay class for Norway spruce, Scots pine, and birch, the most common tree species in Scandinavia. The amount of C in dead wood per hectare, including logs and snags, was estimated to be 0.85 Mg C/ha. Supawan *et al.* (2007) have carried out work to compare aboveground carbon content in mixed deciduous forests and teak plantations. The aboveground carbon content found in the teak plantation trees aged 6,10,15,23 and 24 years old and in the mixed deciduous forest was 39.51,40.82,33.87,55.23,41,13 and 71.60 per ha, respectively. Fan Jing-Yun *et al.* (2007) estimated total carbon storage in the biomass of the grasslands of China was 3.32 Pg C. Ordonez *et al.* (2008) estimated the carbon content in vegetation, litter, and soil, under 10 different classes of LULC in the Purepecha Region, located in the Central Highlands of Mexico. Carbon content in vegetation ranged from 0.2 (grasslands) to 169.7 (for forest) Mg C ha^{-1} and carbon content in litter ranged from 0.6 (agriculture) to 4.1 (for forest) Mg C/ha. The Pacific Coast region of the US has the highest forest down and dead woody C stocks on average exceeding 15 Mg/ha (Woodall *et al.* 2008). Keith *et al.* (2009) determined forest biomass carbon stocks in the highlands of victoria, which is located in the south-eastern part of Australia. They found that the *Eucalyptus regnans* forest in the O'Shannassy catchment of the Central Highlands contains an average of 1053 t C/ha in living AGB and 1867 t C/ha in living plus dead total biomass. Jeanine *et al.* (2009) reconstruct pre-Euro-American settlement (1850's) forest carbon in the state of Wisconsin. Results suggest that total aboveground live forest carbon (AGC) fell from 434 Tg C before settlement to 120 Tg C at the peak of agricultural clearing in the 1930s and has since recovered to approximately 276 TgC. Nsabimana and Wallin (2009), examined carbon stocks in Ruhande Arboretum and Nyungwe forest in Rwanda. Total carbon storage was found to be between 356-1252 Mg C/ha in the Ruhande Arboretum and between 382-798 Mg C/ha in the Nyungwe forest. Maria *et al.* (2010) examined the relative importance of environment, space, and diversity on ecosystem function, specifically tree carbon storage in four plant types (understory/canopy; trees/palms), in a tropical forest in central Panama. They estimated tree carbon storage at the subplot level ranging from 26.1 to 284 Mg C/ha. Rodrigo *et al.* (2010) compared above and below-ground responses of control and experimental plots that had been thinned five years before Hurricane Wilma hit the northern Yucatan Peninsula in October of 2005. These plots had similar aboveground carbon but differed in structure (i.e. basal area and tree density) before the hurricane. Djomo *et al.* (2011) estimated the carbon biomass in Cameroon and the average carbon biomass is 264±48 Mg/ha. Martin and Thomas (2011), assessed the empirical data from stem cores of 59 Panamanian rainforest tree species to demonstrate that wood C content is highly variable among co-occurring species, with an average (of 47.46 $\pm$ 51% S.D.). The CO_2 sequestration capacity of *Quercus ilex*, an evergreen species widely distributed in the Mediterranean Basin, has been analyzed by Loretta *et al.,* 2011 and found per shrub corresponds to 1.4 kg of C^{-1} and the CO_2 sequestration per shrub decreased by *77%* during drought.

3.4.1.2 National level estimation:

Hingane (1991), estimated the total phytomass carbon pool as 2587 Tg C and 49.2 Mg C/ha of phytomass carbon density in two forest types in India. Richards and Flint (1994), estimated the carbon present in Indian forests for the year 1880, with a total forest area of 102.68 M/ha, as 7940 Tg C. Dadhwal *et al.* (1998) estimated the total carbon pool as 3117 Tg C and carbon density as 60.2 Mg C/ha using FAO inventory for ecological zones in India. Dadhwal and Shah (1997), estimated total carbon pool is 4071 Tg C and carbon density was 63.6 Mg C/ha in 64.2 M/ha of Indian forests. According to Ravindranath *et al.* (1997), the standing biomass (Both above and below ground) in India was estimated to be 8,375 million tons for the year 1986, of which the carbon storage was reported to be 4,178 million tons. The total carbon stored in forests of India including soil was estimated to be 9578 million tonnes. Quantification of Carbon fluxes in tropical deciduous forests using satellite data was done by (Prasad *et al.* 2000). The average mean carbon storage is 64.34 t/ha C for deciduous forests, 129.0 t/ha C for mixed dry deciduous forests and 0.02 t/ha C for mixed scrub forests. Later on, a spatial analysis of phytomass carbon in Indian forests for the period (1988-94) was carried out at the district level by Chhabra *et al.* (2002b).

This data was computed by combining remote sensing-based forest area inventories on a 1:250,000 scale, field inventories of growing stock volume by FSI, and crown density-based biomass expansion factor. The total phytomass pool in Indian forests was estimated at 4.3 Pg C (Chhabra *et al.* 2002a). The total carbon stock in Indian forests is 2940 Tg with a carbon density of 45.8 Mg C/ha (Haripriya 2002). Prasad *et al.* (2003), estimated that the Indian forests have a potential net sink of 0.94 Gt carbon from 1997 to 1999, and based on Markov modeling their projected estimated for the year 2050 is 20.59 Mt Carbon. Singh *et al.* (2003), studied carbon sequestration potential in arid and semi-arid regions of Northwestern India and reported carbon stock in vegetation ranges from 1.96 to 2.83 Mg/ha in Gujarat and 0.24-1.73 Mg/ha in Rajasthan. Chhabra and Dadhwal (2004), estimated the Indian forest phytomass was in the range of 3.8-4.3 Pg C based on information on state and union-territory field inventory based growing stock volume and the corresponding area under three different crown density classes grouped under four major forest categories by Forest Survey of India (FSI 1995). The total litter fall C flux in India is estimated as 210 ± 20 Tg C/yr, of which leaf litter fall contributes 150 ± 13 Tg C/yr (Chhabra and Dadhwal, 2004). Manhas *et al.* (2006), estimated the wood (stem) carbon stock of Indian forests for 1984 and 1994. The forest area and carbon stock were 63.86 Mha, and 1085.06 Mt respectively in 1984 and with the reduction in forest area, 63.34 Mha, in 1994 and carbon stock (1083.69 Mt) also reduced subsequently. A total of 24.75 Mt C was lost during 1984-1994 and 21.35 Mt C during 1991-94 at a rate of 2.48 Mt C yr^{-1} and 5.35 Mt C/yr respectively (Manhas *et al.* 2006). According to Singh (2008), in low biomass Indian forests, a total of 833.8 Tg of carbon can be sequestered by protecting refugees, restoring bio-diversity, providing connectivity, mimicking nature in plantations, and controlling man-made fires through community-based forest management (CBFM). Singh *et al.* (2009), recorded the total carbon as 96.44 Mg ha^{-1} in the natural forest followed by 47.80 Mg/ha in 32 years old converted forest, 42.88 Mg ha^{-1} in 23 years old converted forest, and 46.25 Mg ha^{-1} in the 15-year old converted forest of Bamawapara Wildlife Sanctuary. Kaul *et al.* (2009), estimated carbon flux caused by deforestation and afforestation in India separately for two time periods, 1982-1992 and 1992-2002, using the IPCC 2006 guidelines for greenhouse gas inventories and estimated the cumulative net carbon flux due to land use change as 45.9 Tg C. Manish *et al.* (2009), estimated the total carbon sequestration by forests of the Radhanagari wildlife sanctuary between 2004 and 2006 as 78742.09 tonnes. Baishya *et al.* (2009), compared the carbon storage potential of natural semi-evergreen forests and sal plantation forests in the humid tropical region of northeast India. Their results suggest that the natural forest had a lower AGB (324 Mg/ha) than the plantation forest (406.4 Mg/ha). Bipal *et al.* (2009), measured carbon stock per hectare as estimated for *Shorea robusta, Albizzia lebbek, Tectona grandis,* and *Artocarpus integrifolia* were 5.22, 6.26, 7.97, and 7.28 t C/ha, respectively in these forest stands. Using recent remote-sensing-based estimates of tree cover and growing stock outside forests in India, the estimated 2.68 billion trees outside forests contribute to an additional national average tree carbon density of 4 Mg C/ha in non-forest areas, in comparison to an average density of 43 Mg C/ha in forests (Kaul *et al.* 2010). Kaul *et al.* (2010) estimated the carbon sequestration potential of Sal (*Shorea robusta),* Eucalyptus (*Eucalyptus tereticomis),* Poplar (*Populus deltoides*), and Teak (*Tectona grandis)* forests in India by using a dynamic growth model (CO_2FIX). The results indicate that long-term total carbon storage ranges from 101 to 156 Mg C/ha. Arvind *et al.* (2010), estimated AGB and carbon storage varied from 45.94 to 78.31 Mg/ha, and 22.97 to 33.27 Mg/ha, respectively among different forest types of dry tropical forest in the Raipur district of Chhattisgarh. Nirmal Kumar *et al.* (2011), conducted a study to measure carbon stocks in the forest of Rajasthan, western India. Results revealed that the amount of total carbon stock of forests was 533.64±37.54 Mg/ha. Sharma *et al.* (2010), estimated total carbon ranged from 59 and 245 Mg/ha from four forest stands each of twenty major forest types in sub- tropical to temperate zones of Garhwal Himalaya. The study of total carbon sequestered in selective trees grown on the campus of Dr. B. A.M. University, Aurangabad is conducted by Chavan and Rasal (2010). They reported mean above-ground organic carbon ranges between 0.15-4.27 Mg/tree, followed by a mean below-ground range of 0.020.641 Mg/tree and mean organic carbon of 0.17-4.91 Mg/tree. Bhat and Ravindranath (2011), monitored above-ground standing biomass and carbon-stock dynamics for 25 years (from 1984 to 2009) in six 1-ha permanent forest sites subjected to different levels of anthropogenic pressure in tropical rain forests of Uttara Kannada district, Western Ghats, south India. In their study, it was observed that the carbon accumulation rate ranged from 0.31-3.19 t/ha. Kaul *et al.* (2011), estimated the above-ground phytomass carbon pools in Indian forests for 1992 and 2002 using two different methodologies. The first estimate was derived from remote sensing-based forest area and crown density estimated, and growing stock data for 1992 and 2002, and the estimated pool size was in the range of 2,626-3,071 Tg C (41 to 48 Mg C/ha) and 2,660- 3,180 Tg C (39 to 47 Mg C/ha) for 1992 and 2002, respectively. The second methodology followed IPCC 2006 guidelines and using an initial 1992 pool of carbon, the carbon pool for 2002 was estimated to be in the range of 2,668-3,112 Tg C (39 to 46 Mg C/ha), accounting for biomass increment and removals for the period concerned. The estimated total biomass increment was about 458 Tg over the period 1992-2002. Mitra *et al.* (2011) evaluated carbon stocks in the AGB of three dominant mangrove species in the Indian Sundarbans. Among the three studied species, *Sonneratia apetala* showed the maximum above-ground carbon storage (15.39-84.79 t/ha) followed by *Avicennia alba* (10.95-11.02 t/ha) and *Excoecaria agallocha* (6.05-23.32 t/ha). Mohanraj *et al.* (2011), estimated existing carbon stock in the AGB of different forest types of Kolli forest, located in the Eastern Ghats of Tamilnadu, India, and reported above ground carbon stock of Kolli hills was 4.49 Tg C. Sharma *et al.* (2011), conducted a study on seven major forest types of the temperate zone of Garhwal Himalaya to understand the effect of slope aspects on carbon (C) density.

They reported that total C density (SOC+TCD) ranged between 118.1 C Mg/ha on the SW aspect (Himalayan *Finns roxburghii* forest) and 469.1 C Mg/ha on the NE aspect (moist *Cedrus deodara* forest). Sumeet *et al.,* (2011) studied the live tree biomass and carbon variation along an altitudinal gradient in moist temperate valley slopes of the Garhwal Himalaya (India); they reported total live tree carbon density varied from 107.8 to 234.1 Mg C/ha. Piyaphongkul *et al.* (2012) sampled 75 and 47 tree species in the primary and the secondary forests of Khao Yai National Park and estimated the carbon stocks of 342.29 and 99.10 tons C/ha, respectively. Yu (2012), after a thorough review of the literature, found the carbon stocks are most likely 500 (±100 range) Gt in northern peat lands; and the greatest uncertainty for all the approaches attributed to lack or insufficient representation of data, including depth, bulk density, and carbon accumulation data, especially from the world's large peat lands.

3.5 Methodology for Measurement of Bulk Density:

Soil bulk density is defined as the oven-dry weight of the soil unit of its bulk volume. The bulk volume includes the volume of soil solids and pore spaces, and bulk density is expressed as grams/cubic cm. The bulk density of soil indicates the degree of compactness and aeration, which is necessary for estimating the weight of soil per unit area per hectare. The bulk density is calculated from the bulk volume and weight of the dried soil (Ravindranath and Ostwald 2008).

The location for sampling sites for the estimation of soil organic carbon (SOC) was selected. The dimensions of tin like height and diameter were noted. The core tin box was weighed. The soil samples were sampled vertically at 10cm depth. Without disturbing the soil inside the core tin was extracted and removed the extra adhered soil with core tin and along with the soil the sample tin was weighed. The soil with core tin was dried at 105^0C inside the oven and weighed the dried soil.

The soil with core tin was dried at 105^0C inside the oven and weighed the dried soil. The bulk density (g/cm3) of soil was calculated by dividing the weight of the oven-dry soil by the volume of the tin.

$$\text{Bulk density}\left(\frac{g}{cm3}\right) = \frac{\text{Weight of dry soil}}{\text{Volume of tin}}$$

3.5.1 Soil Analysis:

Soil samples from LULC categories such as Agricultural land (Current Fallow Land, Barren Land, Paddy fields, Coconut plantations, and Cashew plantations), Wetlands, Mangroves, and Forest areas (Semi-Evergreen, Moist Deciduous, and Open forests) were collected. The soil samples were obtained from 0-10cm depth. Collected samples were dried at room temperature for 8-10 days. Dried samples were crushed into fine pieces using mortar and pestle. The fine pieces were passed through 40mm sieves using an electrical sieve shaker. The bulk density of each soil sample was estimated using standard procedure. The sieved samples were analyzed in the soil laboratory for the estimation of Soil Organic Carbon (SOC) and Soil Organic Matter (SOM) through two different methods i.e. (a) Loss on Ignition (LOI) (Storer *1984*) and (b) Revised Walkley -Black rapid titration (W-B) method (Trivedi and Goel, 1986).

3.5.1-A. Loss on Ignition (LOI)

- Place the dry empty crucibles in a hot air oven at 50^0C for 15-20 mins.
- Record the weight of the empty crucible (**A**).
- Scoop 5-10 g of dried soil into tarred crucibles.
- Dry for two hours at 105^0C in a hot air oven.
- From the oven, immediately place the crucibles in the desiccator for 5 mins.
- After 5 mins, record the weight of the soil sample with a desiccator (**B**).
- Place the crucible at 360^0C for two hours in a muffle furnace.
- After two hours, immediately place the crucibles in the desiccator for 15 mins.
- Weigh in a draft-free environment to ±0.001 g (**C**).

$$LOI(\%) = \frac{B\_C}{A}\ X\ 100$$

- The above result provides SOM.
- The SOM is then converted to SOC by using the conversion value of 0.58.

3.5.1.-B Revised Walkley Black Titration method (W-B method)

- Weigh out 0.10 to 2.00 g dried soil samples and transfer them to a 500ml conical flask.
- Add 10 ml. of 1N potassium dichromate solution.
- Add 20 ml. sulfuric acid and mix by gentle rotation for 1 minute, taking care to avoid throwing soil up onto the sides of the flask.
- Let stand for 30 minutes.
- Dilute to 200 ml. with deionized water.
- Add 10 ml. phosphoric acid, 0.2g ammonium fluoride, and 8-10 drops of diphenylamine indicator.
- Titrate with 0.5 N Ferrous Ammonium Sulfate solution (FAS) until the color changes from dull green to turbid blue.
- Add the titrating solution drop by drop until the endpoint is reached when the color shifts to a brilliant green.
- Prepare and titrate a blank in the same manner.

$$\%\ Organic\ Carbon = \frac{B - S\ x\ 0.5\ x 0.001}{Weight\ of\ Soil\ Sample}\ x100$$

Where B: Blank titration
S: Sample titration
0.5: Normality of Ferrous Ammonium Sulphate
0.001: Milli equivalents of Carbon

$$\textbf{Organic matter } (\%) = \textbf{Total organic carbon } (\%) \textbf{ x 1.72}$$

For comparative purposes, both methods were used for the estimation of SOC and SOM.

Goa distribution of forest

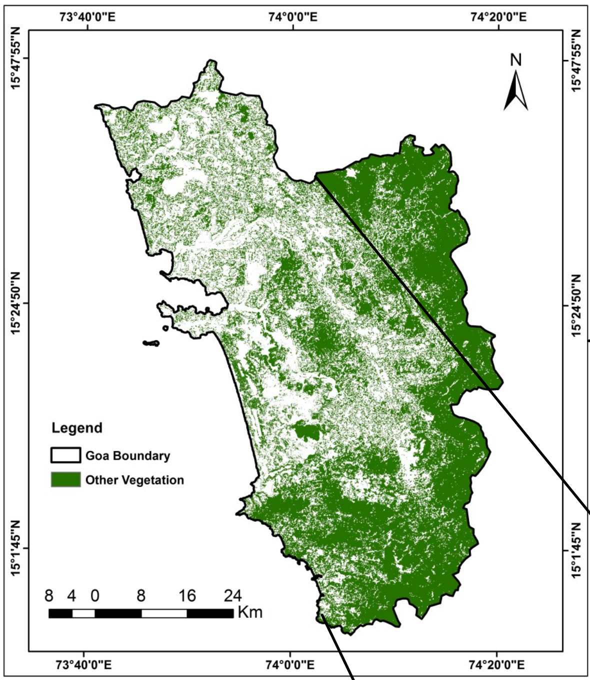


Figure 3.1 Goa Distribution of Evergreen and dense Forest

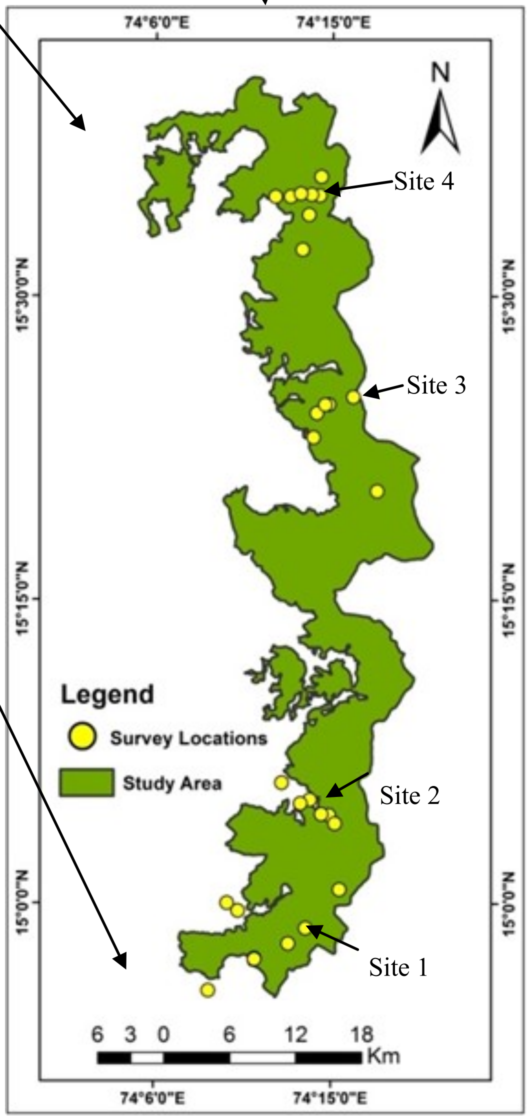


Figure 3.2 location of Samples for forest inventory

Out of this, the W-B method proved to be efficient for its accurate reading and consumes less time when compared to the LOI method (Ismael *et al.* 2017).

The % of SOC value obtained from the W-B method was multiplied by a standard correction factor of 1.32 (De Vos *et al.* 2007) to obtain the corrected SOC. The SOC stock was computed by multiplying the SOC values (g/kg) with bulk density (g/cm^3) and depth (cm) and was expressed in ton/ha (Joao Carlos *et al.* 2001).

3.6 Analysis of Biomass (Estimation)

Biomass represents Above-Ground Biomass (AGB) and Below-Ground Biomass (BGB). The parameters to be considered for the estimation are height (H), diameter at breast height (DBH), and basal area (Ab). Error in the above parameters leads to inaccurate biomass estimation.

3.6.1 Sampling Inventory of Plant Taxa:

The Biomass of tree species was estimated from four different forest sites (Figure 3.1) such as Cotigao Wildlife Sanctuary (CWS), Netravali Wildlife Sanctuary (NWS), Bh 3.agwan Mahaveer Wildlife Sanctuary (BMWS), and Mhadei Wildlife Sanctuary (MWS) (Table 3.1 to 3.7). The present forest sites were further classified into three forest covers i.e. Semi-Evergreen (SE), Moist Deciduous (MF), and Open Forest (in some cases Plantations) (OF/PT). A total of 35 dominant tree species were recorded from four forest sites in Goa (Table 3.1). Of the 35 species, 11 species belonging to 8 families are registered in Semi-Evergreen forests; 16 species belong to 11 families in Moist Deciduous forests; 8 species belong to 7 families in sites of Open forest/ Plantation areas (Table 3.2). In Site 1, a total of 22 tree species from 13 families were identified, in which 7 species of 6 families from SE forest; 9 species of 8 from MD forest, and 6 species of 5 families from OF/PT were registered. In Site 2, a total of 26 tree species from 16 families were identified, in which 6 species of 5 families from SE forest; 13 species of 10 from MD forest, and 7 species of 6 families from OF/PT were registered. In Site 3, a total of 20 tree species from 14 families were identified, in which 8 species of 6 families from SE forest; 8

species of 7 from MD forest, and 4 species of 4 families from OF/PT were registered. In Site 4, a total of 26 tree species from 14 families were identified, in which 9 species of 6 families from SE forest; 10 species of 7 from MD forest, and 7 species of 6 families from OF/PT were registered (Table 3).

Tree species such as *Anacardium occidentale* L, and *Leea indica* (Burm.f.) Merr, *Tectona grandis* L.f, *Terminalia bellerica* (Gaertn.) Roxb, *Terminalia paniculata* Roth and *Xylia xylocarpa* (Roxb.) Taub was predominantly present in all the forest sites. Species for example *Atalantia racemosa* Wight & Arn and *Diospyros montana* Roxb were observed only in one site. In SE forest, tree species such as *Mangifera indica* L and *Xylia xylocarpa* (Roxb.) Taub was present in all four sites whereas *Atalantia racemosa* Wight & Arn was found to be registered in CWS. In MD forest, *Leea indica* (Burm.f.) Merr, *Tectona grandis* L.f, *Terminalia bellerica* (Gaertn.) Roxb and *Terminalia paniculata* Roth were dominantly forests and *Diospyros montana* Roxb was found in CWS. In OF/PT type, *Anacardium occidentale* L and *Cocos nucifera* L were present dominantly in all the forest sites of Goa.

3.6.2 Above Ground Biomass (AGB):

The average height and DBH of the tree species present in the forest sites of Goa are 14.50 $\pm$ 6.63 m^2 and 0.84 $\pm$ 0.46 m^2 respectively. The mean height (m) and DBH (m) of the tree species in SE, MD, and OF/PT are 21.20 $\pm$ 5.27σ, 132.84 $\pm$ 31.57σ; 12.15 $\pm$ 5.41σ, 70.20 $\pm$ 33.39σ and 10 $\pm$ 2.22σ, 42.8 $\pm$ 21.84σ m^2 respectively. The mean height (m) and DBH (m) of the tree species present in the three forest cover types from the four forest sites are as follows:

Site 1: The average tree height and DBH of the tree species present in SE, MD, and OF/PT forest type are 21.97 $\pm$ 5.41σ, 134.77 $\pm$ 36.65σ; 11.77 $\pm$ 6.67σ, 65.71 $\pm$ 36.28σ and 10.75 $\pm$ 2.0σ, 46.50 $\pm$ 23.84σ m^2 respectively.

Site 2: The mean tree height and DBH of the tree species present in SE, MD, and OF/PT forest type are 20.97 $\pm$ 6.33σ, 145.57 $\pm$ 24.82σ; 12.18 $\pm$ 5.0σ, 72.46 $\pm$ 36.74σ

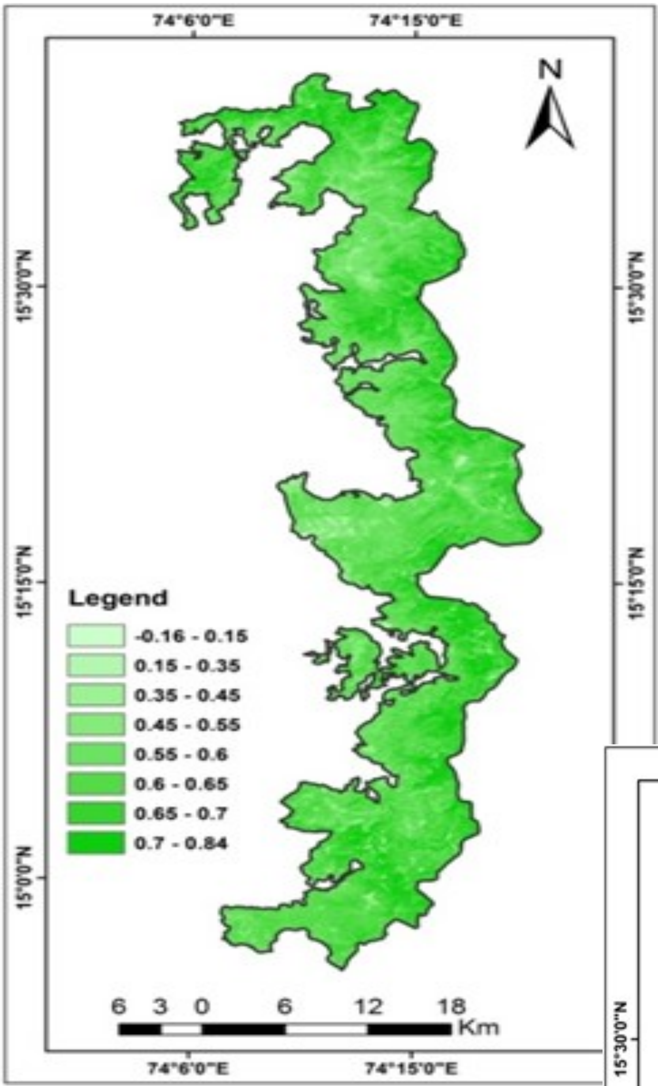


Figure 3.2 Goa Forest NDVI

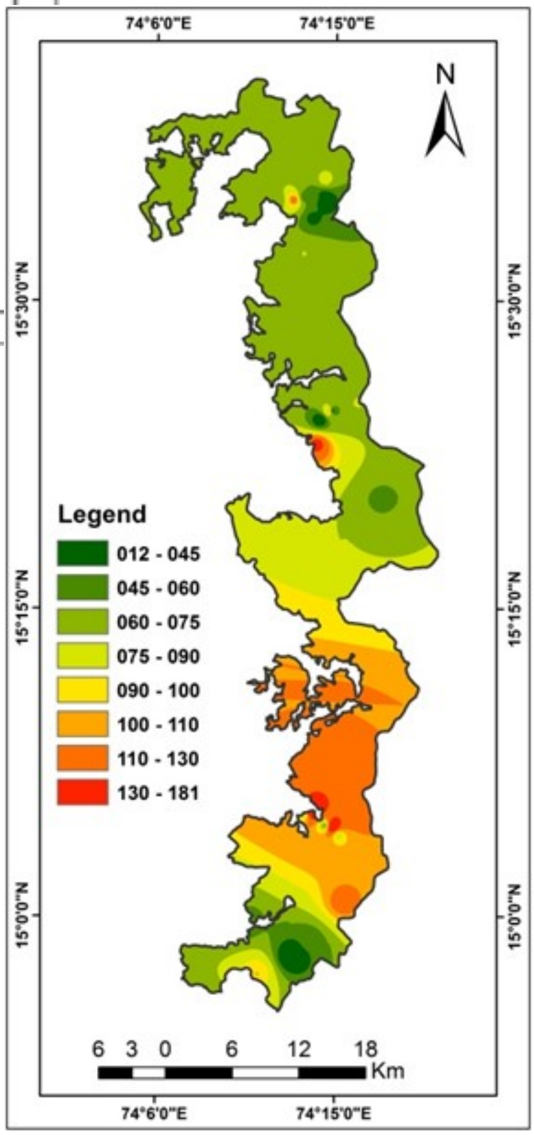


Figure 3.3 Goa Forest distribution of SOC in Tons

and 10.4 $\pm$ 2.0σ, 43.09 $\pm$ 23.6 σ m^2 respectively.

Site 3: The mean tree height and DBH of the tree species present in SE, MD, and OF/PT forest type are 20.68 $\pm$ 5.66σ, 136.45 $\pm$ 23.12σ; 12.10 $\pm$ 5.98σ, 68.68 $\pm$ 35.77σ and 8.85 $\pm$ 2.5σ, 36.62 $\pm$ 11.9σ m^2 respectively.

Site 4: The average tree height and DBH of the tree species present in SE, MD, and OF/ PT forest types are 22.32 $\pm$ 5.15σ, 135.09 $\pm$ 34.72σ; 12.85 $\pm$ 4.66σ, 81.8 $\pm$ 34.6σ and 10.23 $\pm$ 2.3σ, 45.64 $\pm$ 21.9σ m^2 respectively.

In forest areas, trees are the major contributors to above-ground biomass. The mean Above-ground tree biomass (Mg) in SE, MD, and OF/PT forests are 14.66 $\pm$ 8.08σ, 3.01 $\pm$ 2.34σ, and 0.83 $\pm$ 0.89σ respectively. In the SE forest type, *Ficus bengalensis* L showed high content of Above-Ground Biomass (Mg) i.e. 26.85 whereas *Syzgium cumini* (L) Skeels registered the least value of 4.38. In the MD forest type, *Tectona grandis* L.f reported 6.94 while *Tabernaemontana alternifolia* L enclosed 0.03Mg of AGB. In OF/PT type, *Alstonia scholaris* (L.) R.Br showed 2.80 and *Zanthoxylum rhetsa* (Roxb.) DC 0.16 Mg of AGB. Few trees registered approximately similar AGB content for example species of *Vitex altissima* L.f and *Artocarpus integrifolia* L which belongs to the Plantation type showed the same AGB content i.e. 0.43 Mg, in Semi-Evergreen forest type Ficus bengalensis L. and Ficus religiosa L. had AGB content of 26.85 Mg and 26.57 Mg in that order and moist deciduous forest, two tree species not only registered same AGB value but they were the species which proved to have least AGB value compared to other trees i.e. 0.03Mg

The ΔAGB i.e. carbon amount in above-ground biomass per forest area (Mg /ha) has been calculated by multiplying the above-ground biomass by the default value of carbon fraction i.e. 0.50. It has been estimated for all four forest sites of Goa.

The ΔAGB (Mg C/ha) content is 621.5, 1681.8, 1680.4, and 2059.22 from CWS, NWS, BMWS, and MWS respectively.

3.6.3 Below-Ground Biomass (BGB):

The Below-Ground Biomass (BGB) is an important carbon pool for many vegetation types and accounts for 20% of the total biomass (Santantonio *et al.* 1997). The mean below-ground biomass of the tree species present in the forest sites of Goa is 1.23 $\pm$ 1.50σ Mg. The average BGB of tree species present in SE, MD, and OF/PT is 2.93 $\pm$ 1.62σ; 0.60 $\pm$ 0.47σ and 0.17 $\pm$ 0.18σ Mg respectively. In the SE forest type, *Ficus bengalensis* L registered a maximum value of 5.37 Mg whereas *Syzgium cumini* (L.) Skeels showed a minimum value of 0.88 Mg. In MD forest cover, *Tectona grandis* L.f has a high value of 1.4 Mg while *Leea indica* (Burm.f.) Merr has a low value of 0.003. In OF/PT forest type, *Alstonia scholaris* (L.) R.Br indicated higher content of BGB i.e. 0.56 Mg whereas *Zanthoxylum rhetsa* (Roxb.) DC registered lower content of BGB i.e. 0.03 Mg.

3.6.3.1 Basal area (BA):

The basal area (BA) is the cross-sectional area of the tree's stem (trunk) at breast height. It is being calculated using the same formula for the area of a circle i.e. multiplying π by the square of the radius (DBH) where π stands for the value of 3.14. The overall mean basal area of the tree species present in the forest areas of Goa is 2.63 $\pm$ 1.45σ m^2. The mean BA (m^2) in SE, MD, and OF/PT is 4.17 $\pm$ 1.0σ; 2.2 $\pm$ 1.0σ and 1.34 $\pm$ 0.7σ respectively. While comparing among the tree species in the forest areas, *Ficus bengalensis* L from the SE forest type registered a maximum basal area i.e. 5.21 $m^{2,}$ and *Leea indica* (Burm.f.) Merr from the MD forest type showed the least value i.e. 0.3 m^2.

3.6.3.2 Volume estimation:

The Volume of the tree trunk was calculated by multiplying the basal area by the height of the tree and the site-dependent constant (0.5 - default conversion factor). On the whole, the mean volume density of the tree species is 2.22 $\pm$ 1.9σ m^3. The average volume density of the tree species found in the forest of SE, MD, and OF/PT is 4.42 $\pm$ 1.63σ; 1.48 $\pm$ 0.9σ and 0.67 $\pm$ 0.37σ m^3. On comparing the volume among the tree species, *Ficus bengalensis* L registered the maximum value of 68.8 m^3 while *Leea indica* (Burm.f.) Merr enclosed the leas value of 0.64 m^3.

3.7 Biomass Estimation Allometric Equations:

Biomass was calculated using allometric equations where the volume of a tree and the wood density of the tree are being used. The wood density of the individual tree species was obtained through worldagroforestry.org but in some cases where the wood density was not obtained, the constant factor of 0.6 g/cm3 is taken into consideration. The total biomass of the forest sites of Goa is 4.79 million tonnes. The mean biomass estimated from the tree species is 0.14 $\pm$ 0.10 million tonnes. The biomass estimated in all the forest covers types i.e. SE, MD, and OF/PT is 0.25 $\pm$ 0.07σ; 0.11 $\pm$ 0.07σ, and 0.04 $\pm$ 0.02σ million tonnes. In forest sites, the biomass of the entire site is calculated by multiplying the mean biomass (million tons) content by the area of the site (ha). This equation has been applied to all the forest sites of Goa.

Site 1 (CWS): The mean biomass content in the site is 0.13 $\pm$ 0.09σ million tonnes. The total area of the site is 8,817 ha therefore the total biomass content in CWS is 1162.36 million tonnes. In the present site, tree species such as *Mangifera indica* L registered high biomass content while *Leea indica* (Burm.f.) Merr showed a lower value.

Site 2 (NWS): The average biomass content in the site is 0.13 $\pm$ 0.10σ million tonnes. The total area of the site is 22,058 ha so the total biomass content in NWS is 2784.10 million tonnes. In NWS, tree species such as *Ficus bengalensis* L showed maximum biomass content whereas *Tabernaemontana alternifolia* L registered the minimum.

Site 3 (BMWS): The mean biomass content in the site is 0.15 $\pm$ 0.12σ million tonnes. The total area of the site is 22,951 ha hence the total biomass content in this forest site is 3415.16 million tonnes. Here, the tree species for example *Schleichera oleosa* (Lour.) Oken has high biomass content whereas *Anacardium occidentale* L. is the lower one.

Site 4 (MWS): The average biomass content in the present site is 0.15 $\pm$ 0.11σ million tonnes. The total area of the site is 21,830 ha hence the total biomass content in this forest site is 3331.98 million tonnes. In MWS, tree species such as *Ficus hispida* L.f showed maximum biomass content while *Areca catechu* L. had the minimum value.

The above results reveal that comparative site 3 has shown high biomass content while site 1 showed the least. In terms of tree species, *Schleichera oleosa* (Lour.) Oken proves to contain maximum biomass content whereas *Leea indica* (Burm.f.) Merr the minimum value. In the case of forest cover, tropical semi-evergreen forest proves to enclose high biomass content whereas Open forest areas reveal a low biomass value.

3.7.1 Carbon Stock through Soil Analysis:

A total of 280 soil samples were analyzed for SOC%, Bulk Density, and SOCS, which includes 160, 50, and 45 from 25 soil samples from agroecosystems, forests, wetlands, and mangrove areas respectively. The mean SOC content (%) in agro-ecosystems, wetlands, and mangrove and forest areas are 3.19%$\pm$1.93σ; 4.06%$\pm$1.18σ; 4.73%$\pm$2.24σ and 6.24%$\pm$3.28σ with B.D (g cm^{-3}) of 1.40, 1.15, 1.09 and 1.46 respectively. The average SOCS (t ha^{-1}) of agroecosystems, wetlands, mangrove, and forest areas are 44.84, 46.72, 51.62, and 86.42 respectively. While comparing, soil samples collected from forest areas have shown higher mean SOC content followed by mangroves, wetlands, and agroecosystems.

3.7.2 Soil Organic Carbon Stock of Goa:

The soils collected from 280 sites in Goa consisting of agroecosystems, wetlands, and mangrove and forest areas were used for the estimation of SOCS using the W-B method. Results are used for spatial interpolation using the Inverse Distance Weighted (IDW) interpolator to generate the spatial distribution patterns of SOCS over the study region (Fig 3.8). The analysis reveals that there are three pockets of SOCS ranging from 6 to 191 t ha^{-1}. First, the low SOCS which ranges from 6 to 47 t ha^{-1} were observed mostly in areas of arable land. Secondly, regions with moderate concentration i.e. 47 to 65 t ha^{-1} cover the areas of wetlands and mangrove areas. Wetlands and mangrove soil samples show evidence of low organic carbon content compared to agricultural soil samples (Gaikwad S. *et al* 2018). And lastly, the highest concentration of SOCS ranges from 65 to 191 t ha^{-1} which mostly encloses the forest areas of Goa. The carbon stock is found maximum in forest soil and minimum in agricultural land. The higher percent of soil organic carbon in the forest may be due to dense canopy and higher input of litter which results in maximum storage of carbon stock (Bhandari S & Bam S, 2013). The SOCS map of Goa was overlaid on the extracted LULC classes to view the spatial distribution patterns of agro-ecosystems, wetlands, and mangrove and forest areas which are discussed further.

3.8 Spatial distribution patterns of SOCS from Agro-ecosystems

The spatial distribution patterns of SOCS from Agro-ecosystems (Fig.3.4) reveal that the SOCS which ranges from 6 to 191 t ha^{-1} can be classified into three major compartments i.e. low (6 to 47 t ha^{-1}), moderate (47 to 65 t ha^{-1}) and high (65 to 191 t ha^{-1}). The low concentration of SOCS ranging from 6 to 47 t ha^{-1} was observed in areas of vast agricultural tracts. Arable soils have the lowest SOCS concentration. The two reasons are the repeated disturbance & breakdown of soil aggregates during tilling and the reduced inputs of organic material due to the harvesting of crops. The land which is being left fallow for 1-2 years (i.e. current fallow land) shows a low presence of SOCS. There was an initial rapid loss of SOCS associated with the loss of SOM when natural land cover is converted to arable land (Eaton J *et al.* 2008). The land which was exposed to fire to burn up the weeds and grass showed minimum SOCS. Accelerated land clearing and implementation of degradative agricultural practices (e.g. burning of crop residues etc.) lead to a rapid decline in soil carbon reserves (Nachimuthu and Hulugalle, 2016). The soil samples that were also collected from the coconut plantations showed a low concentration of SOCS. Regions with moderate SOCS concentration (47 to 65 t ha^{-1}) are mostly found in the land are which are being left fallow for more than 8-10 years (i.e. fallow and barren land) where the grass cover was with an approximate height of 2-3ft. Barren land unlike croplands, maintain a partial vegetation cover and a high root turnover leading to higher SOC input (Graham *et al.* 2002). The highest concentration of SOCS (65 to 191 t ha^{-1}) represents the agricultural land which is close to the wetlands and Khazan lands. Wetlands are recognized for their ability to act as C sinks, mostly via their soils storing larger amounts of C (Passos *et al.* 2016) which can be noticed in the present study. Paddy fields soil samples revealed the maximum SOCS.

The soil sample collected from paddy fields was clayey and crop residues were present which enhances the soil fertility and increases the OC content. The soil samples collected from the cashew plantations showed a high concentration of SOCS. The litterfall from the cashew plantations can increase SOC (Ogeh *et al.* 2015). The presence of higher OC content can be attributed to the rapid decomposition of forest litter (Dar *et al.* 2013).

3.9 Spatial distribution patterns of SOCS from Wetlands

The spatial distribution patterns of SOCS from wetlands (figure 3.7) reveal that the SOCS which ranges from 6 to 125 t ha^{-1} can be classified into two major compartments i.e. low (6 to 50 t ha^{-1}) and high (50 to 125 t ha^{-1}). The low concentration of SOCS ranging from 6 to 50 t ha^{-1} was observed in those areas which are located near farmland, open lake, reservoir, and the coastal body. The high concentration of SOCS ranging from 50 to 125 t ha^{-1} was observed in areas that are associated with the mangroves, where there is a continuous flow of backwater and salt marshes. The wetland bodies found in reserved forest areas showed the presence of a high concentration of SOCS. Recent reports have indicated that wetland ecosystems especially peat bogs have a high carbon storage value (Clark *et al.* 2007; Mariusz *et al.* 2008; Mcnamaran *et al.* 2008). Salt marshes have shown a presence of high carbon content than coastal wetlands (Dodla *et al.* 2008; Wang *et al.* 2007; Wang *et al.* 2003). The soil found in mangrove-associated wetlands was clayey and clayey soil show more carbon content than the other as they accumulate high amounts of carbon in their soils because of anaerobic conditions produced by the presence of water which enhances the carbon storage (Meyers *et al,* 2016 & Gaikwad *et al.* 2018).

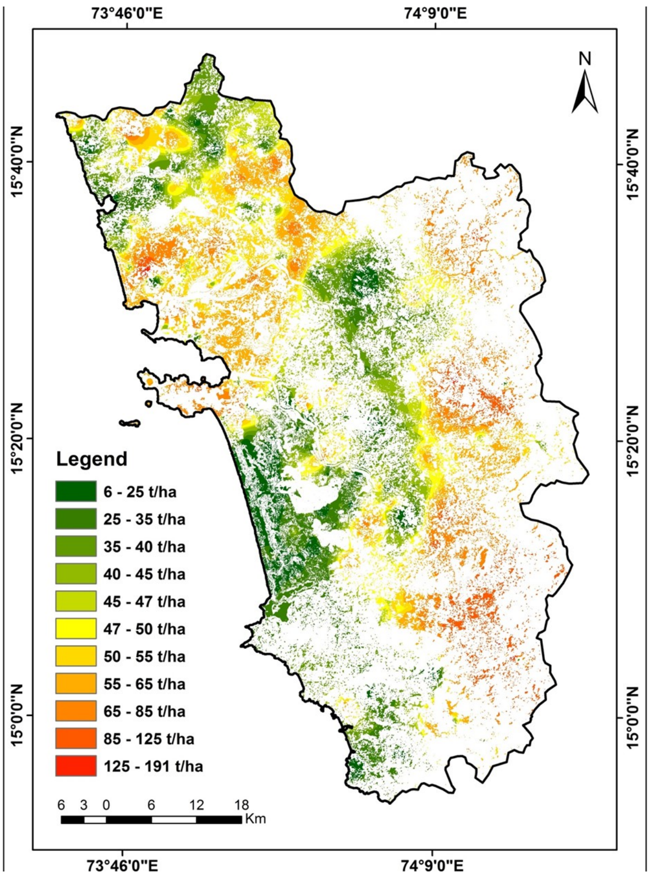


Figure 3.4 Goa SOC form Agri-culture

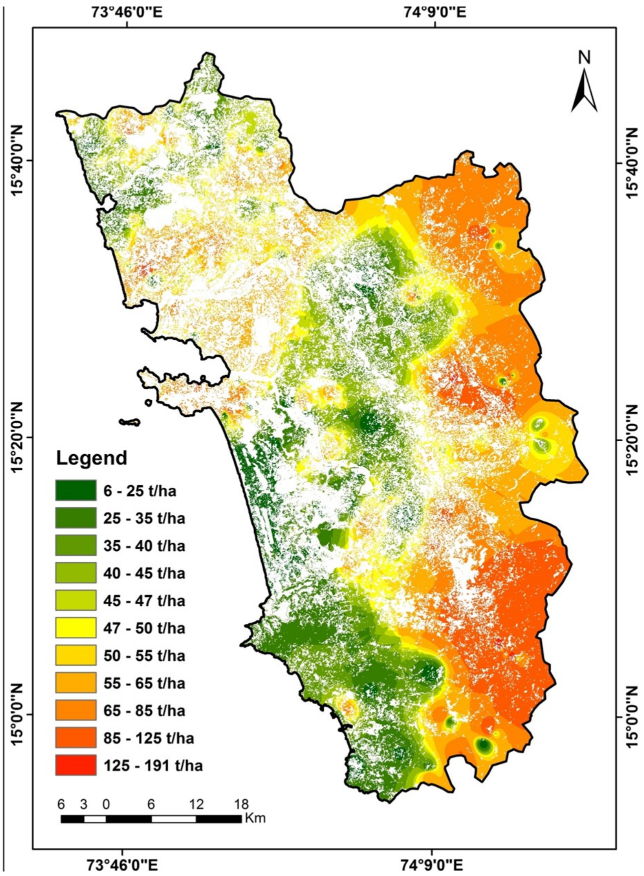


Figure 3.5 Goa SOC from Forest and other vegetation

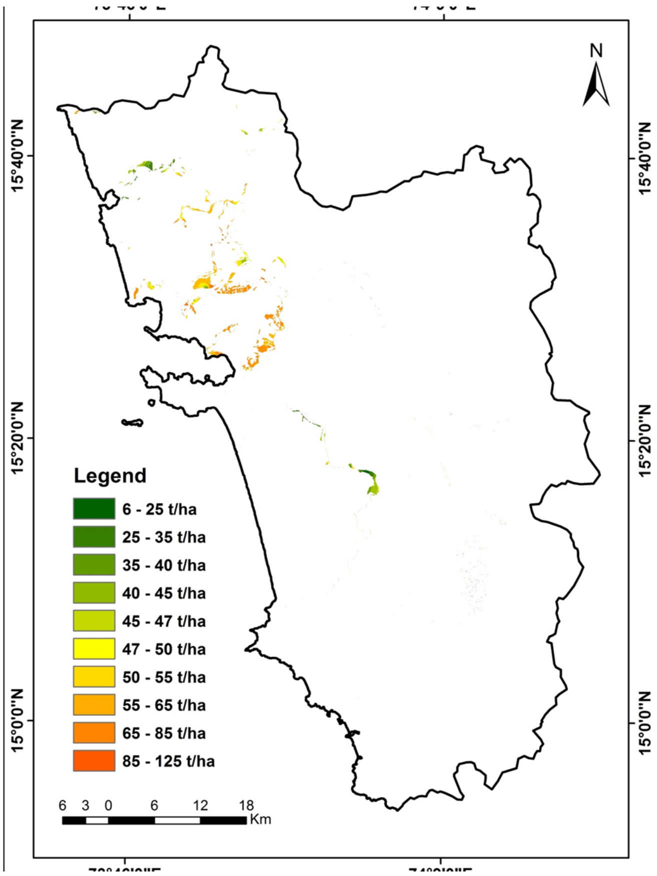


Figure 3.6 Goa SOC from Mangroves

Figure 3.7 Goa SOC from Wetlands

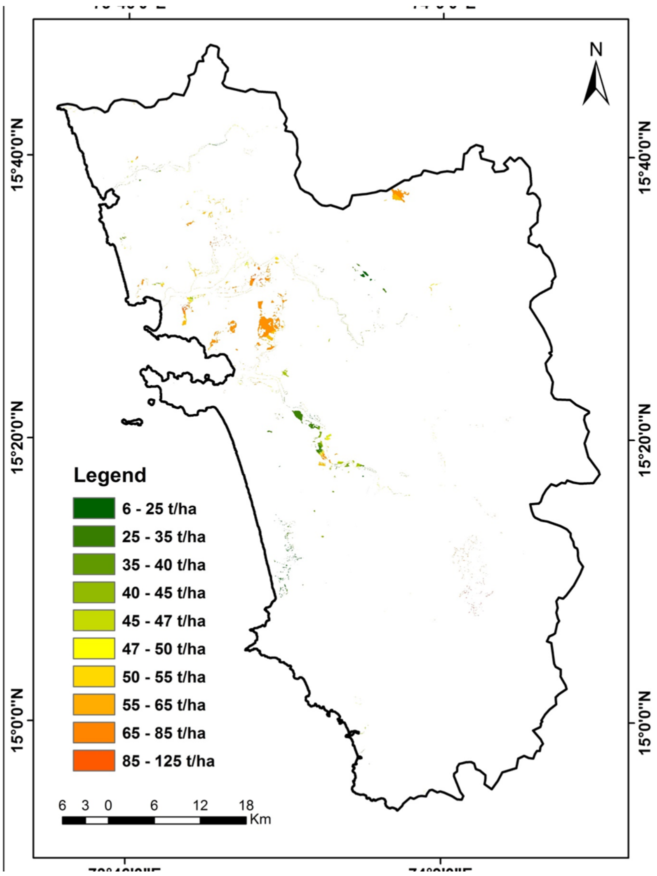
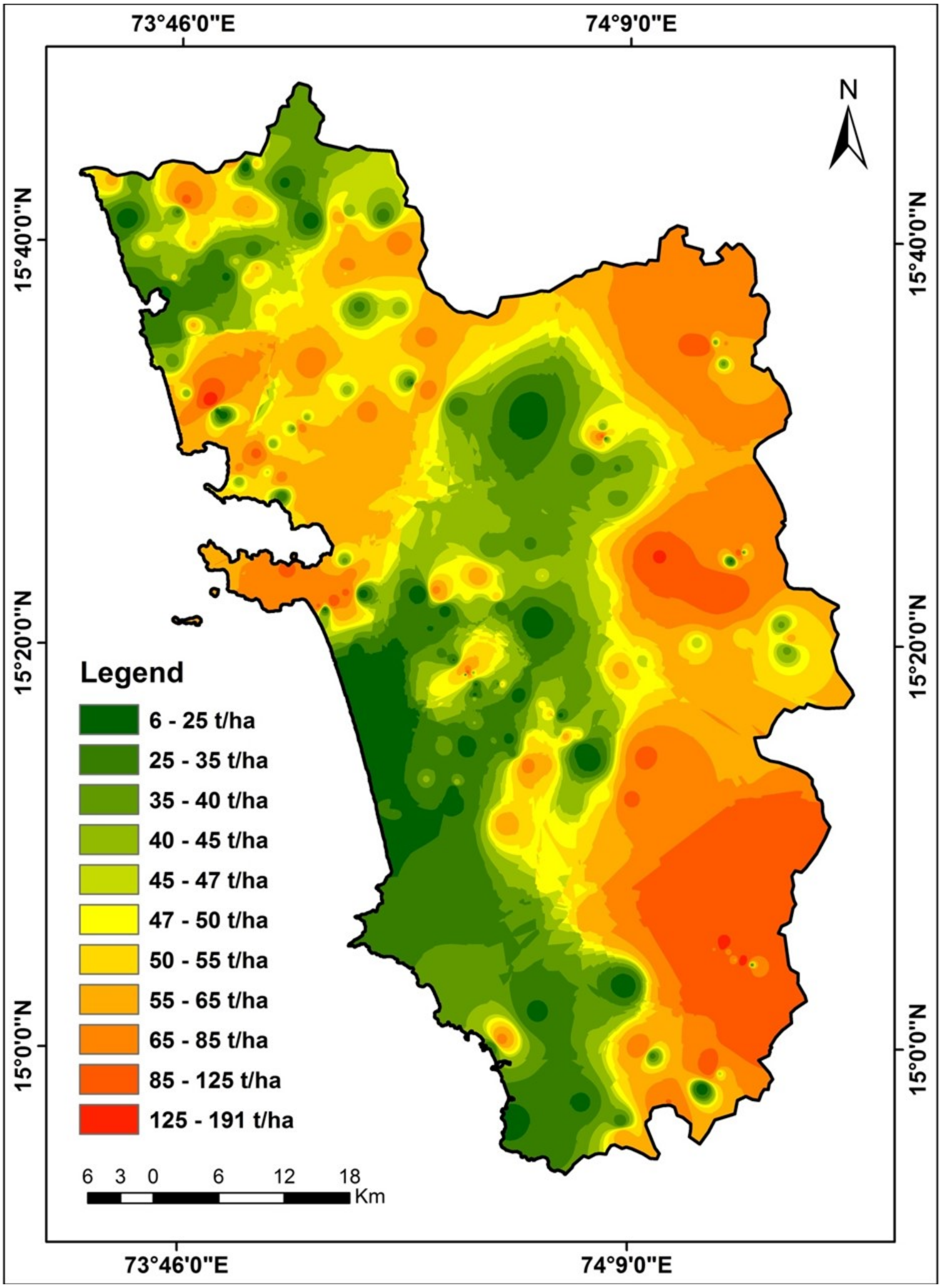


Figure 3.8 Goa SOC stock

Based on IDW interpolation and data derived from lab test of soil samples collected from 280 locations



Source : Compiled by Researcher

3.10 Spatial distribution patterns of SOCS from Mangroves

The spatial distribution patterns of SOCS from mangroves (Fig. 10.c) reveal that the SOCS which ranges from 6 to 125 t ha^{-1} can be classified into two major compartments i.e. low (6 to 50 t ha^{-1}) and high (50 to 125 t ha^{-1}). Mangrove soil samples mostly showed the presence of high OC content but the low concentration of SOCS ranging from 6 to 50 t ha^{-1} was observed in those areas which were not maintained accordingly and have been considered degraded mangrove forests. The high SOCS ranging from 50 to 125 t ha^{-1} were seen in preserved mangrove forests such as Chorao Island. The mangrove associated with the backwater or river bodies such as rivers Zuari and Mandovi indicated high SOCS. It has been also noticed that the soil samples collected from the mangrove forest which has high litter fall indicated high organic content compared to those areas having a low rate of litterfall and decomposition.

3 .11 Spatial distribution patterns of SOCS from Forest

The spatial distribution patterns of SOCS from Forest (Fig. 3.5) reveal that the SOCS which ranges from 6 to 191 t ha^{-1} can be classified into three major compartments i.e. low (6 to 45 t ha^{-1}), moderate (45 to 65 t ha^{-1}) and high (65 to 191 t ha^{-1}). The low concentration of SOCS ranging from 6 to 45 t ha^{-1} was observed mostly in open forest areas. Regions with a moderate concentration of SOCS which ranges from 45 to 65 t ha^{-1} were seen in plantation areas and the high concentration of SOCS ranging from 65 to 191 t ha^{-1} have been noticed in the reserved forest areas. In reserved forest areas, the forest type such as semi-evergreen forest showed maximum organic carbon content than dry deciduous followed by open and degraded forest (Chrips, 2014) which has been observed in the present study.

3.12 Total carbon stock of Goa

The carbon stock of Goa was estimated through chemical and spatial analysis. In chemical analysis, the mean SOCS (t ha^{-1}) was multiplied by the area (ha) of the LULC class which includes the area of agro-ecosystems, wetlands, and mangrove and forest areas from chemical analysis.

The total carbon stock of Goa from chemical analysis resulted in a total of 16.50 million tons. From spatial interpolation, it has been revealed that the carbon stock of agro-ecosystems, wetlands, mangroves, and forests are 5.32, 0.15, 0.15, and 11.44 million tons respectively which accounts for a total of 17.06 million tons of carbon stock of Goa. Hence, while comparing both the techniques i.e. chemical and spatial analysis used for the estimation of the carbon stock of Goa approximately 96.70% of accuracy has been found concerning the total carbon stock of Goa.

CHAPTER 4:
CARBON SEQUESTRATION SCENARIO THROUGH LAND USE CHANGE

4.1 Introduction to Carbon Sequestration:

Understanding the concept, factors, and processes driving and influencing the cycle of carbon in a particular ecosystem is critical to achieving proper management of the aboveground biomass in plants and organic matter in the soil, both for reducing greenhouse gas emissions and improving soil quality. Carbon sequestration is a generalized term for the common process involving the long-term storage of carbon in oceans, soils, and vegetation (especially forests), and carbon capture in geologic formations. The oceans store most of the Earth's carbon (Negi *et al.* 2003). The soils contain approximately 75% of the carbon pool in terrestrial regions three times more than the amount of carbon stored in living plants and animals. Therefore, soil plays a major role in maintaining a balanced global carbon cycle in nature.

Carbon sequestration in the terrestrial ecosystem is the major route for the absorption of CO_2 from the atmosphere by photosynthesis (Matthews *et al.* 2000). Carbon sequestration is the process of carbon capture and secure storage that would otherwise be emitted to or remain in the atmosphere. Trees in the forests, vegetation as well as forest products, are primarily responsible for carbon sequestration mechanisms (Hairiah 2009; Bass *et al.* 2000). Carbon sequestration through forestry is based on two premises. First, that carbon dioxide is an atmospheric gas that circulates globally; consequently, efforts to remove greenhouse gases (GHGs) from the atmosphere will be equally effective whether they are based next door to the source or across the globe. Second, green plants take CO_2 gas out of the atmosphere in the process of photosynthesis and use it to make sugars and other organic compounds used for growth and metabolism. Long-lived woody plants store carbon in their wood. The other tissues until they die and decompose at which time the carbon in their wood may be released to the atmosphere as carbon dioxide, carbon monoxide, or methane, or may be incorporated into the soil as organic matter (Anderson and Spencer 1991; Pedro 1996).

4.2 Terrestrial Carbon Sequestration:

Carbon sequestration refers to the transfer of atmospheric CO_2 into lived terrestrial pools like biotic, soil so that CO_2 sequestered is not immediately released into the atmosphere. Three predominant components of terrestrial Carbon (C) sequestration include soil, biota, and bio-fuel. The increase in Soil Organic Carbon (SOC) pool must be assessed to a depth of up to 2m as significant management-induced changes in the SOC pool can occur deep in the subsoil (Lorenz and Lal 2005). Any increase in SOC pool is assessed in terms of either fixed soil depth or on equal soil mass basis for major land use and soil management systems (Matthews *et al.* 2000; Lal 2007). Trees use photosynthetic processes for absorbing carbon dioxide from the atmosphere. The carbon from this carbon dioxide is sequestered and used to grow leaves, stems, bark, roots, and other plant parts. While the system with the tree parts that are growing and sequestering carbon is termed a carbon sink. The rate at which trees grow and sequester carbon is influenced by site productivity and local characteristics such as climate, topography, and soils. For a typical tree plantation, tree growth tends to be slow in the early years as the trees establish themselves by adapting to the surrounding. The sequestration rates peak in many areas when trees are of about 10 to 20 years old as earlier in faster-growing species and then slow down or get loosened (Wardlaw 1990; Vina 2004; Gorte 2007; Lal 2007; Ugle *et al.* 2010). A carbon sequestration rate at different periods in the life of a tree depends on several factors. Thus the carbon sequestration of a forest ultimately depends on the number of trees planted per hectare, climatic factors, soil type, and the quality of site preparation and management to ensure seedling survival and ongoing protection from fire, pests, and disease (McCarty 2000; Lal 2007; Deo 2008). If trees are not harvested after maturity, they will continue to sequester carbon at a declining rate. The age of maturity of trees varies from species to species, generally at around 100 or 200 years. During the stage of maturity, the tree growth is balanced by decay with no net carbon assimilation (Ravindranath and Ostwald 2008).

The common activities sequestering the carbon include the planting of trees, changing agricultural tillage or cropping practices, and re-establishing grasslands (Pearson *et al.* 2005). Soil is the largest reservoir of carbon. It accounts for 2011 Gt C or 81% of the total carbon in the terrestrial biosphere (WBGU 1998; Ravindranath and Ostwald 2008). The net long-term CO_2 sink dynamics of forests or urban areas change through time as trees grow, die, and decay. In addition, human activities influence forests. These further can affect CO_2 sink dynamics of forests through factors such as fossil fuel emissions and harvesting of biomass (Nowak and Crane 2002). As the tree biomass grows, the carbon held by the plant also increases as carbon stock. The rate of carbon storage increases in young stands but then declines as the stand ages (Jana *et al.* 2009; Chavan and Rasal 2011a, b).

4.3 Forest and Carbon Sequestration:

Forests play an important role in the global carbon cycle. The growing forests not only have a significant impact on climate change but also influence ecosystem productivity, nutrient cycling, and environmental sustainability with stability. The temporal carbon dynamics are characterized by long periods of gradual build-up of biomass acting as a sink and alternated with short periods of massive biomass loss as the source. Forests thus switch between being a source or a sink for carbon (IPCC 1995). It is believed that the goal of reducing carbon sources and increasing the carbon sink can be achieved efficiently by protecting and conserving the existing forests as carbon pools (Brown *et al.* 1996b). The destruction of forests can be a serious source of greenhouse gases due to enhancing rates and quantities of organic decay. The forests through their sustainable management can be important sinks of the same gases. It has been proved that the lands where the stocks are highest had the highest stocks of soil organic carbon in comparison to other land use systems (McCarty 2000; Deo 2008). The forests act as natural storage for carbon at the global scale, contributing approximately 80% of terrestrial above-ground, and 40% of terrestrial belowground carbon storage, in addition to various goods and services being provided to human beings (Kirschbaum 1996).

Overall, forest ecosystems store 20–100 times more C per unit area than croplands. Therefore, they play a critical role in reducing ambient CO_2 levels, by sequestering atmospheric C in their growth forming woody biomass through the process of photo-synthesis and thereby increasing the SOC content (Brown and Pearce 1994).

4.4 Carbon Sink and Source:

A carbon sink is a process or an activity that removes greenhouse gases from the at-mosphere and sequestered in the carbon pools. Within the carbon cycle, a sink is any location where carbon is stored like vegetation or soil (Brown 1997; Chavan and Rasal 2010). A source is any location in the carbon cycle where carbon in any form is re-leased or made available for chemical reaction. Some examples of carbon sinks are forests, soil, and the ocean. Carbon sinks can turn into carbon sources like fossil fuels. These are sinks buried in the Earth's interior and hence, clear that wood is act as a sink. When fossil fuels or wood are burned, carbon is released into the atmosphere and it is now referred to as a carbon source. Trees, act as a sink of atmospheric carbon, as they grow in the process they absorb more CO_2 and store it (Chavan and Rasal 2010; Jana *et al.* 2009). The number of urban trees has the potential to reduce the accumulat-ed atmospheric carbon and can contribute to maintaining the equilibrium by reducing atmospheric CO_2 (*Chavan and Rasal, 2009*).

4.5 Carbon Pools:

The flowing of carbon through the different reservoirs such as Above-ground biomass, Below-ground biomass, dead wood, litter, and soil organic matter are the major carbon pools in the terrestrial ecosystem (FAO 2005; IPCC 2003; IPCC 2006; Chavan and Rasal 2012).

4.5.1 Above-Ground biomass (AGB):

According to IPCC (2006), above-ground biomass consists of all living biomass above the soil including stems, stumps, branches, bark, seeds, and foliage. Above-ground bi-omass is the most important and visible carbon pool and the dominant carbon pool in forests and plantations.

Above-ground biomass is the most important carbon pool for all land-use systems and involves trees, and is likely to change frequently, even annually, much faster than other carbon pools for all projects involving tree planting. Above-ground biomass has been given the highest importance in carbon inventory and most mitigation projects (Ravindranath and Ostwald 2008). It is the most important pool in afforestation and reforestation through CDM projects under the Kyoto Protocol as well as any inventory or mitigation project related to forest lands, agro-forestry and shelter belts in croplands. Above-ground biomass is commonly expressed as tones of biomass or carbon per hectare. The methods and models for measuring and projecting above-ground biomass are also well developed as compared to other carbon pools. In non-forest land -use systems such as cropland and grassland, biomass predominantly consists of non-woody perennial and annual vegetation. It makes up a much smaller part of the total carbon stock in the ecosystem than that in forest lands.

4.5.2 Below-Ground Biomass (BGB)

According to IPCC (2006), belowground biomass consists of all living roots excluding fine roots of sizes less than 2mm in diameter. Roots of terrestrial vegetation play important role in the carbon cycle as they transfer considerable amounts of carbon to the ground, which may be stored for a relatively long period. Belowground or live root biomass is expressed as tonnes of biomass or carbon per hectare. Although roots can extend to great depths, the greatest proportion of the total root mass is confined to the top 30 cm of the soil surface. Carbon loss and accumulation in the ground are intense in the top layer of the soil profile, which indicates that this should be the focus of sampling (Ponce-Hernandez *et al.* 2004; Ravindranath and Ostwald 2008). In many land-use systems like grasslands and croplands, this pool may not be important. The below -ground biomass in grassland and cropland under crops is part of the annual carbon cycle, and need not be measured.

4.6 Soil Organic Carbon (SOC)

According to IPCC (2006), soil carbon sequestration is an important strategy for enhancing soil quality, increasing agronomic productivity, reducing risks of soil erosion and sedimentation, decreasing eutrophication and contamination of water, reducing net CO_2 emission by off-setting those due to fossil fuel combustion, and mitigating the climate change (Lal 2004). According to IPCC (2006), Soil organic matter is the organic carbon in mineral soils to a specified depth. The generic term for all organic compounds in the soil is particles that are not living roots or animals. As dead organic matter is fragmented and decomposed, it is transformed into soil organic matter. There are wide varieties of materials that differ greatly in their residence time in soil. Some of them are easily decomposed by microbial organisms and return the carbon to the atmosphere. Some of the soil's organic carbon is converted into recalcitrant compounds as organic-mineral complexes that decompose slowly and may remain in the soil for decades or centuries or even longer. Fires often result in the production of small amounts. These are called black carbon. The inert carbon fraction with turnover time has spanned several thousand years (IPCC 2006). Management practices and other forms of disturbances can alter the net balance of carbon input and carbon losses from the soil (Nakane 1995). Input to soil carbon stock can balance between carbon input and carbon losses from the soil and can come from higher plant production. When native grassland or forest land is converted into cropland, 20-40% of the original soil carbon stock can be lost (Davidson and Ackerman 1993; Ravindranath and Ostwald 2008). Both organic and inorganic forms of carbon are found in soil. Land use and management typically have larger impacts on the organic form of carbon. Since most of the soil carbon is in the form of organic matter, management practices that promote an increase in soil organic matter have a positive carbon sequestration effect (Dixon *et al.* 1994; Lugo and Brown 1993). Removing crop residue can harm soil quality, water quality, and agronomic production and also cause depletion of the soil carbon pool (Ravindranath and Ostwald 2008). The soil C sequestration is not a universal remedy for all environmental issues, but it is certainly a step in the right direction to restore degraded soils, increase agronomic yields, improve water quality, reduce erosion along with suspended and dissolved loads, reduce anoxia in coastal ecosystems, and is useful to mitigate climate change through reduction in net anthropogenic emission of CO_2 into the atmosphere.

4.7 Carbon Sequestration by Cropping:

Tropical alley cropping systems, and the cultivation of arable crops between tree hedgerows, represent a low end concerning the potential for C storage. Vegetation in urban areas furnishes many benefits. Vegetation contributes significant aesthetic value to urban communities (McCarty 2000). Vegetation can create a sense of well-being and foster an environment where people can function more effectively (Kaplan and Ryan 1998). In addition, vegetation helps rainwater to infiltrate the ground and reduction of the flow of water into storm sewers (*Dwyer et al., 1992*).

4.7.1 Above-Ground Biomass (AGB):

Globally, each cubic meter of growing stock equals, on average, 1 ton of aboveground biomass, 1.3 tonnes of total biomass, and 0.7 tons of carbon in biomass (FAO 2006). Estimates of carbon stocks and stock changes in tree biomass (above and belowground) are necessary for reporting to the United Nations Framework Convention on Climate Change (UNFCCC). It is required for Kyoto Protocol reporting in forthcoming years (Almgir and Amin 2008). Aboveground plant biomass stores carbon in all woody stems, branches, and leaves of living trees, creepers, climbers, and epiphytes as well as understorey plants and herbaceous growth (Hairiah *et al.* 2009). The Guidelines have been published for setting up permanent plots, censuring trees correctly to measure the biomass of trees (Sheil 1995; Condit 1998), and for actual estimating above-ground biomass (AGB) stocks and related changes (Brown 1997; Clark *et al.* 2001). It is hardly ever possible to measure all biomass on a sufficient sample area by destructive sampling.

Therefore some form of allometry is used to estimate the biomass of individual trees to an easily measured property such as its stem diameter. Equations with more sigmoid form can be used with confidence, even beyond the given maximum bounds (Brown *et al.* 1989). The assessment of biomass equations for the efforts to improve carbon budget estimates is based on the link between individual-tree and whole-stand biomass estimates (Parresol 1999). It is coupled with the assumption that wood mass is about 50% carbon (Montagnini and Porras 1998; Montagu *et al.* 2002). Experience to date with the development of generic regression equations, for both tropical and temperate forests, has indicated that measurements of diameter at breast height, are typical for trees and explain more than 95% of the variation in tree biomass. There is a need to develop species-specific equations (Brown 1997; Clark *et al.* 2001). The local regression equations are developed in two pilot projects in the tropics, local regression equations were developed for *Cecropia spp.* (Early colonizers) and several species of palms (Brown and Delaney 2001, unpublished report). Murray (2003) used an analytical model of timber and carbon rotation and data from different forest settings to examine the effects of carbon sequestration incentives on the optimal management of an individual forest stand. Biomass equations are most commonly expressed in polynomial, power, and combined variable model forms (Brown 1997; de Gier 2003; Parresol 1999; Zianis *et al.* 2004). The mathematical equation has been developed and used by many researchers for biomass estimation of trees in an urban environment (Brown *et al.* 1989; Negi *et al.* 1980). These equations are species specific and the general equation has been developed in modified forms (Brown 1997) which are applicable in the field. Considering the mathematical terms, the models are developed by FAO (1997), Negi *et al.* (1980), and Brown *et al.* (1989). The literature revealed that this method is non-destructive and is the most suitable method (Brown 1997; FAO 1997). Species and DBH (at 1.3 m above the ground) of each standing tree above a minimum DBH of 10 cm were recorded in each separate plot by many researchers (Brown, 1997; Foody *et al.* 2003; Deo, 2008).

Smaller trees <10cm DBH are generally neglected since they contribute a relatively small quantity of biomass (Brown 1997). The studies in both primary and secondary forests in Southeast Asia reported the importance of site-specific equations for accurate biomass estimation based on application and/or comparison of the proposed pan-tropic general models (Brown 1997) and observed biomass data sets for each forest type (Bauki *et al.* 2009; Kenzo *et al.* 2009).

4.7.2 Below-Ground Biomass (BGB):

Below Ground Biomass (BGB) includes all the plant biomass of live roots excluding the fine roots of sizes <2mm diameter (Ravindranath and Ostwald 2008). The importance of roots as structural, storage, and physiological organs has been acknowledged for quite some time (Harris 1971; Santantonio 1977). The development and build-up of the roots' biomass are more complex than some of the above-ground components. DBH is readily available and provides good estimates for woody root biomass. The study of below-ground biomass is complicated due to the inaccessibility of the roots (Whittaker and Marks 1975). Therefore, most of the estimation of below-ground production has been based on empirical allometric relations with the aboveground biomass like root/shoot ratios. These are vegetation-type dependent, and thus difficult to apply in diverse ecosystems (Santantonio 1977; Monk 1966). Total root biomass is another important carbon pool and can represent up to 40% of total biomass (Cairns *et al.* 1997). However, for quantifying this pool no practical standard field techniques yet exist (Korner, 1993; Kurz *et al.* 1996; Cairns *et al.* 1997). Belowground biomass comprises roots, soil fauna, and the microbial community (Hairiah *et al.* 2009). As the measurement of root biomass is not simple, normally default assumptions are used for the shoot: root ratio in many studies (Cairns *et al.* 1997; Mokany *et al.* 2005).

4.8 Soil Carbon Sequestration:

The flow of carbon between soil and the atmosphere is a continuous process, highly influenced by land use and management (Paustian *et al.* 1997). Soil carbon storage potential depends on climates such as temperature and precipitation, the nature of parent geological materials, vegetation type, and land management practices (McCarl 2007). Soil is the largest reservoir of carbon, accounting for 2011 Gt C, or 81% of the total carbon in the terrestrial biosphere (Ravindranath and Ostwald 2008; WBGU 1998). The ability to measure soil-carbon pools is a source of contention in forestry however, as for vegetation; there is a well-established set of methods and documentation for measuring soil-carbon pools (Garten *et al.* 1999). Soil carbon stock is the highest in the upper soil profile (0-15cm), which should be sampled most intensively (Richter *et al.* 1995; Ravindranath and Ostwald 2008). Soil organic carbon is routinely estimated for all forestry, grassland, and cropland conservation and developmental projects by various methods (IPCC 2003). The total carbon stored in forests, including soil is estimated to be 9578 Mt (Ranabhat *et al.* 2008). Soil bulk density expressed as the oven-dry weight of soil unit of its bulk volume indicates the degree of compactness and aeration, which is necessary for estimating the weight of soil per unit area, such as per hectare (Ravindranath and Ostwald 2008).

4.9 Spatial Interpolation and Extrapolation:

Spatial interpolation was conducted on the data to quantify the patterns of spatial variation in carbon stock using ERDAS IMAGINE software. The total 280 sample data points and about 7834 sample data entries from ICAR Govt. India portals were considered to interpolate SOCS using Inverse Distance Weighted (**IDW**) and **Kriging** interpolation techniques. The power value for IDW is optimized by considering the root mean square (**RMS**) error. SOCS classes were created using the geometric data distribution technique and class-wise, SOCS data was extracted using LULC classes. Statistics were generated using spatial analysis tools from ARC-GIS, and QGIS to estimate the carbon stock of Goa.

Figure 4.1 represent the distribution of the SOCs sample collected and tested in the departmental labs during the project work. In total 280 samples consisting of 160 from ag ricultural regions, and 50 from different sites of forested areas. Researchers have also collected a sample of soil from the wetland (45) and Mangroves ecosystems (25) of Goa. Researchers have also collected soil OC gridded data for the State of Goa from the online portal of the Department of Agriculture and Farmers Welfare, Ministry of Agriculture and Farmers Welfare, Government of India (https://soilhealth.dac.gov.in/PublicReports/GridFormNSVW). The data is sorted for location and cycles of which major data sample localities were available for the cycles of 2017-18 (2047 entries), 2018-19 (2074 entries), and 2019-20 (3474 entries). Whereas, a few samples from 2015-16 (2),2016-17 (20), and 2020-21 (217) were used while estimating SOCs.

Table 4.1: Soil Samples Collected for the LULC Class from field visit.

Sr. No.	LULC Classes	No. of Soil Samples
1	Agriculture	160
2	Forest	50
3	Wetlands	45
4	Mangroves	25
	Total	***280***

Source: Fieldwork carried during 2015-17, and samples tested in departmental lab.

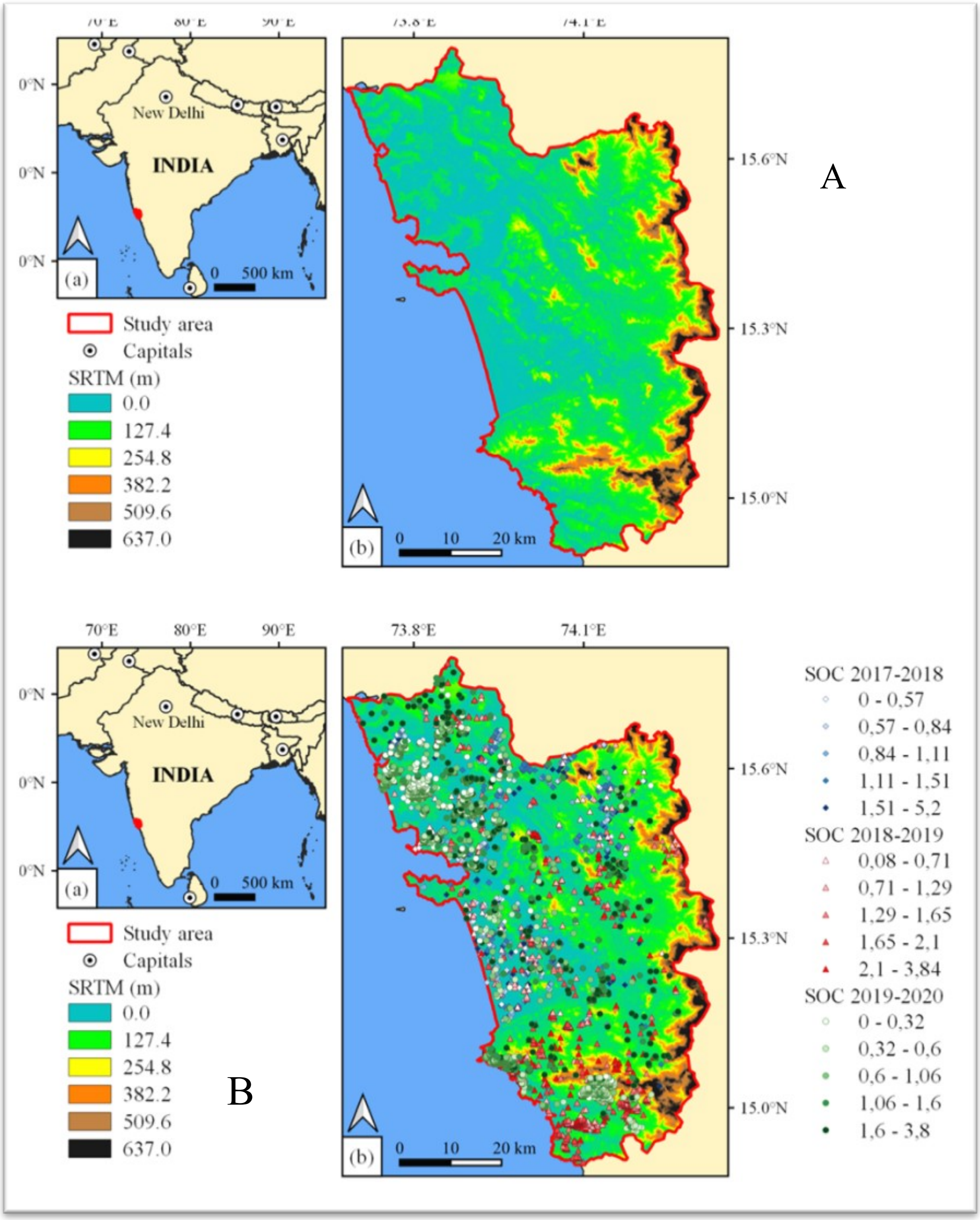
Table 4.2: Cycles of SOC data collection, samples, and average SOC for Goa

CYCLES	No OF SAMPLES	Minimum	Maximum	STD	Average
2015-16	2	0.13	3.38	1.63	1.76
2016-17	20	0.32	3.85	0.99	1.64
2017-18	2047	0.00	5.20	0.54	1.05
2018-19	2074	0.08	3.84	0.72	1.05
2019-20	3474	0.00	3.80	0.64	0.93
2020-21	217	0.10	3.15	0.64	0.96
Total	7834				

Source: Compiled by Researcher, Based on the data acquired form https://soilhealth.dac.gov.in/PublicReports/GridFormNSVW

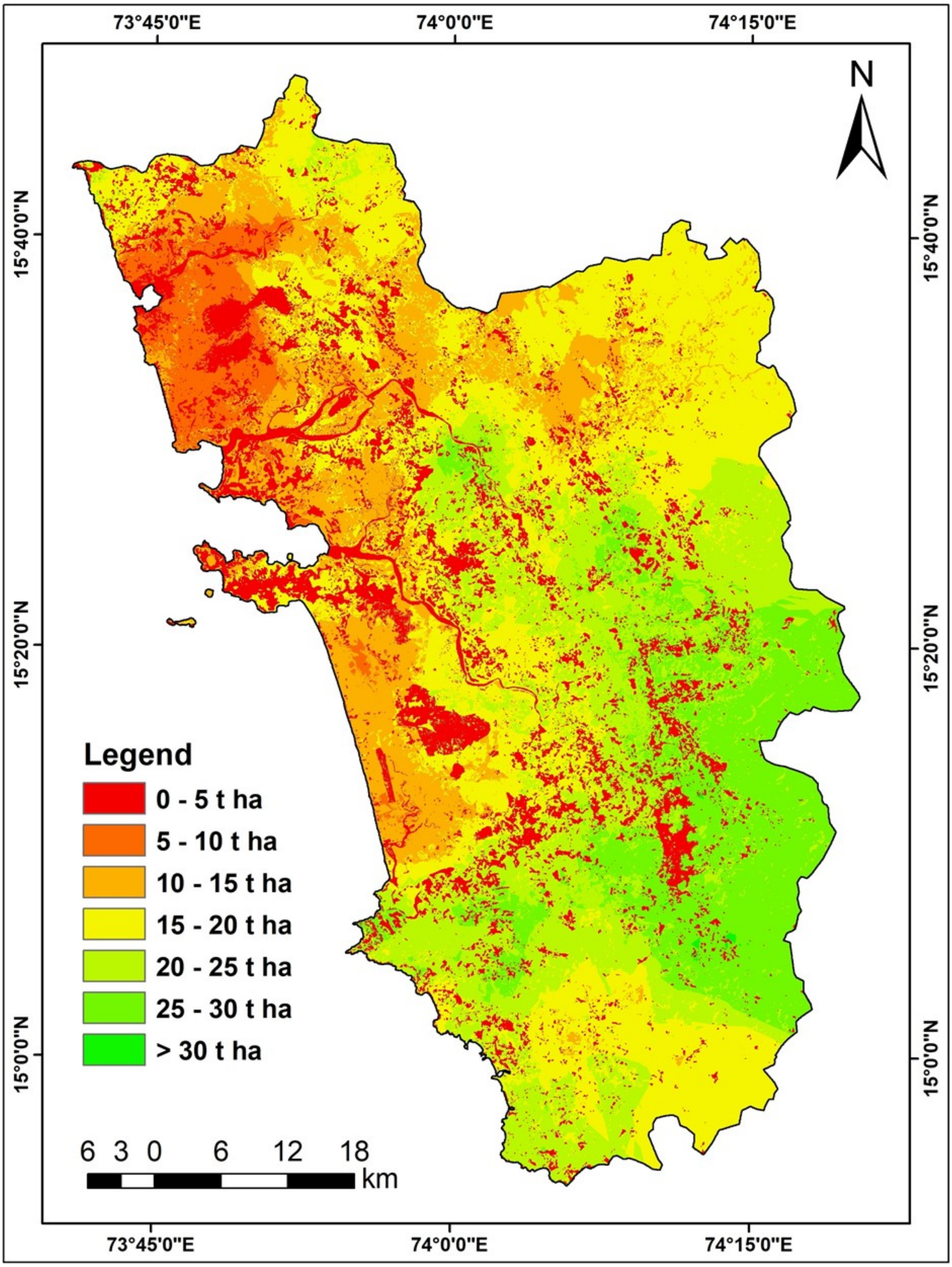
The above tables and figure 4.1 & 4.2 shows that the sample points used for spatial interpolation are distributed over all the parts and are representative of almost all sorts of geophysical setups. Overall 7834 reference points are used for spatial Kriging.

Figure 4.1 Goa Location, Physiography and Distribution of SOC sample Locations of major cycles obtained form /https//soilhealth.dac.gov.in/PublicReports/



Source : Compiled By researcher *https://soilhealth.dac.gov.in/PublicReports/GridFormNSVW*

Figure 4.2 Plot of SOCs (t/Ha) based on Kriging interpolation



Source : Compiled by Researcher

4.9.1 Region of Very Low SOC

The SOC is Categorized into seven classes that are ranging from 0-5 t/hectare (Figure 4.2, Table 4.2) and covers most of the built-up area and rocky outcrops, barren and exposed areas, and the surfaces with very shallow soil surfaces. The pockets of such conditions are scattered all over the State and cover all together ~ 30 % of the geographical area and contribute 31944 Mt of OC to the carbon stock of the region.

Vast areas of coastal belt consisting of Pednem, Bardes, Tiswadi, Salcete tehsil, Bicholim, and Ponda tahsils are observed to have OC stock in the range of 5 to 10 and 10 to 15 tons per hectare of OC. The region in this range covers about 3043 and 2880 hectares of area and almost 30426 Mt and 43205 Mt of OC to the state carbon Stock

4.9.2 Regions of Moderate SOC Stock

The area belongs to the vast foothills and valley regions of eastern Pednem, Bardez, Bicholim, Ponda Sattari, and the Eastern part of Cantona tehsil. Mostly these areas are under intensive agriculture, forestry, and plantation agriculture where SOC ranges from 15 to 20 Mt per hectare (Figure 4.2, Table 4.2). This region contributes to 45369 Hectares (~12%) of geographical space and 907387 Mt (~9%) of OC to the carbon stock of the State. The region is quite critical from the transition from vegetation & forest dominating regions gaining commercial importance in the state.

4.9.3 Regions of High SOC stock

The region comprises the hilly area of Quepem, the Western part of Cancona, the southwester part of Sangues along the boundary of Quepem and Concona, and the major area of Dharbandona, Bicholim, and Ponda tehsil along the river Khandepar and its tributaries. This region contributes 111023 hectares of area (29%) of the State and contributes 27775584 tons (28.23 %) of State SOC stock.

4.9.4 Regions Very High SOC stock

This region of very high SOC stock of ~ 30 tons per hectare (Figure 4.2, Table 4.2), comprises part of Sanguem tehsil with Netravali Wildlife Sanctuary and some small pockets of intermountain valleys of Quepem and Ponda tehsil. This part covers 201496 hectares (~55 %) of the geographical area of the State and contributes about 6044871Mt (62 %) of SOC. Mostly the area belongs to a protected forest and wildlife Sanctuary and is part of Western Ghats biodiversity hotspots.

Table 4. 3 Goa SOC stock interpolation from Spatial Krigging

	SOC T / Hectare	Area Hectare	Total SOC in Tone
1	>5	6389 (1.73)	31944 (0.32)
2	5-10	3043 (0.82)	30426 (0.31)
3	10-15	2880 (0.78)	43205 (0.44)
4	15-20	45369 (12.26)	907387 (9.23)
5	20-25	111023 (29.99)	2775584 (28.23)
6	25-30	201496 (54.43)	6044871 (61.47)
		370200 (100)	9833416 (100)

Source: Compiled by the researcher

The SOC interpolated using kriging (figure 4.2) reveals the SOC range from 5 tons/ hectare to 30 tons/hectare. More than 54 % area has SOC in the range of 25-30 tons/ hectare which contributes to 61 % of States SOC stock. This trend is followed by SOC rage 20-25 by ~30 % area contributes by 28 % of SOC stock.

Median SOC for the under major land use and land cover categories reveals that forest has maximum median SOC (1.27 %) followed by bare land i.e. land which is not regularly cultivated or current fallow land. Due to minimum tillage practices or minimum disturbance to the natural setup barren, uncultivated and fallow lands considered in this group show a high concentration of SOC. Wetlands, agriculture, and water bodies also appear to be promising reservoirs of OC that exhibit the range of OC from 0.88 to 1.00. Observation also clarifies that there are seasonal variations in SOC, as the OC in consecutive cycle show change.

4.10 Data and classification

Satellite imagery used for this research consisted of cloud-free Landsat-5, Landsat-7,

Table 4.4 Median SOC computed based on the OC cycles

CYCLES	Water	Barren land	Urban	Forest	Agri-culture	Wetland
2017-2018	0.92	1.05	0.88	1.11	1.01	0.87
2018-2019	0.82	1.31	0.82	1.60	0.96	1.29
2019-2020	0.91	0.90	0.66	1.10	0.76	0.84
MEAN OC	0.88	1.09	0.79	1.27	0.91	1.00

Source: Compiled by researcher based on ICAR OC data for 2017-18 to 2019-20 cycles

Table 4. 5: Mean Soil Organic Carbon Stock from of the LULC Class and cycles of 2018-2020

LULC Class	Mean SOC value			number of SOC measurements per LU LC class		
	2018	2019	2020	2018	2019	2020
Water	0.92	0.82	0.91	27	40	33
Bare Land	1.05	1.31	0.90	956	885	1872
Urban	0.88	0.82	0.66	145	35	162
Forest	1.11	1.60	1.10	743	909	1028
Agriculture	1.01	0.96	0.76	95	57	247
Wetland	0.87	1.29	0.84	80	53	130

Source : Compiled by Researcher

Table 4. 6: Number of total acquired reference data (R), training (t), and validation (v) samples per class and researched year.

Year	1990			2000			2010			2020		
Class	R	t	V	R	T	V	R	T	V	R	t	V
Water	54	38	16	65	46	20	71	50	21	54	38	16
Bare land	57	40	17	40	28	12	54	38	16	29	20	9
Urban	26	18	8	20	14	6	24	17	7	26	18	8
Forest	62	43	19	49	34	15	62	43	19	47	33	14
Agriculture	22	15	7	20	14	6	8	6	2	18	13	5
Wetland	12	8	4	26	18	8	15	11	5	12	8	4
Total	233	163	70	220	154	66	234	164	70	186	130	56

Source: Compiled by researcher

and Landsat-8 imagery obtained during the observed year. Landsat-5 thematic mapper satellite data contains seven bands: four visible and near-infrared (NIR) bands, two shortwave infrared (SWIR) of 30-m spatial resolution, and one thermal infrared TIR band of 120-m spatial resolution. The Landsat-5 scene size is 180 km × 170 km (Kovalskyy and Roy, 2013). Landsat-7 enhanced thematic mapper plus satellite imagery contains eight bands: four visible and near-infrared (NIR) bands, two shortwave infrared (SWIR) of 30-m spatial resolution, and one thermal infrared TIR band of 120-m spatial resolution, and a panchromatic band of 15-m spatial resolution. The Landsat-7 scene size is approximately 185 km × 180 km (Roy et al. 2016). The Landsat-8 satellite consists of two scientific sensors: The Operational Land Imager and the Thermal Infrared Sensor. These two sensors provide imagery at a spatial resolution of 30 m for the five visible and near-infrared (NIR) bands, three shortwave infrared bands, two thermal infrared TIR bands of 120-m spatial resolution, and a panchromatic band of 15-m spatial resolution. The Landsat-8 scene size is approximately 185 km × 180 km (Roy et al. 2014). All Landsat satellite imagery used in this research was collected via Google Earth Engine, a similar approach used in the research Gašparović and Singh (2020). Based on the acquired Landsat imagery and collected reference training samples land cover maps for each decade were generated. Land cover maps were calculated based on the supervised satellite image classification algorithm Classification and regression trees (CART; Breiman et al. 1984). Satellite imagery was classified into six classes (water, bare land, urban, forest, agriculture, and wetland). The CART algorithm is based on a binary decision tree, and recursively examines the variables of each sample with logical if-then questions in the binary structure of the tree. Questions are asked at each node of the tree, and that usually represents one input variable. The variables are compared with a predetermined threshold so that the samples are divided into "cleaner" subsets (Myint et al. 2011). All samples are divided into a very large tree until they reach a terminal node until the nodes have less than a defined number of samples, or when further division will result in almost the same outcome. Furthermore, the tree is then pruned back by creating a nested row of less complex trees. Finally, the class is predicted at the terminal node according to the share of classes in the training samples that have reached that node (Goldblatt et al. 2016). The CART algorithm is one of the most used classifiers nowadays (Steinberg and Colla, 2009; Kaszta et al. 2016; Kobayashi et al. 2020) and find application in the Google Earth Engine platform (Goldblatt et al. 2016; Shelestov et al. 2017; Hird et al. 2017). The images have been classified using the Maximum Likelihood Classification Algorithm (MLC) which is a robust supervised classification method. Clusters are defined in feature space based on the training sets defined for each class by the analyst. MLC considers not only the cluster center but also its shape, size, and orientation. This is achieved by calculating a statistical distance based on the mean values and covariance matrix of the clusters. The statistical distance is a probability value, the probability that observation x belongs to a specific cluster. The pixel is assigned to the class (cluster) for which it has the highest probability. MLC follows the assumption that the spectral values in the clusters follow a 'normal' (Gaussian) distribution (Evans, 1998).

4.10.1: Training and validation reference data

For providing supervised image classification, training samples were needed. Furthermore, for the calculation, the accuracy assessments of the land cover maps made by supervised satellite imagery classification validation samples were required. Accordingly established and common practice training and validation samples were collected at the same time and randomly divided into training (70% of all samples) and validation (30% of all samples) datasets (Table 4.6). Samples were collected manually using the various available satellite data and historical maps (e.g., Google Earth Engine, Land Cover maps, etc.). The study site and acquired training and validation reference data for 1990 are sown in figure 4.1.

4.10.2 Accuracy Assessment:

LULC maps derived from the classification of images usually contain some sort of errors due to several factors that range from classification techniques to methods of satellite data capture. Hence, the evaluation of classification results is an important process in the classification procedure. In so doing among the common measures used for measuring the accuracy of thematic maps derived from multispectral imagery, an error/confusion matrix has been used (Congalton and Green, 1999). An error matrix is a square assortment of numbers defined in rows and columns that represent the number of sample units assigned to a particular category relative to the actual category as confirmed on the ground. The rows in the matrix represent the classes derived from LULC, while the columns represent the reference data that were collected from fieldwork. These tables produce many statistical measures of thematic accuracy including overall classification accuracy, percentage of omission and commission error, and kappa coefficient an index that estimates the influence of chance (Congalton and Green, 1999).

An error of omission is the percentage of pixels that should have been put into a given class but were not. The error of commission indicates pixels that were placed in a given class when they belong to another. These values are based on a sample of error-checking pixels of known land cover that are compared to their corresponding classification on the map. An error of commission and omission can be expressed in terms of the user's accuracy and the producer's accuracy (PA). User's accuracy (UA) represents the probability that a given pixel will appear on the ground as has been classified, while producer's accuracy represents the percentage of a given class that is correctly identified on the map. Overall accuracy is computed by dividing the total number of correctly classified pixels (i.e. the sum of the elements along the major diagonal) by the total number of reference pixels. Likewise, the accuracies of indicated categories can be calculated by dividing the number of correctly classified pixels in each category by either the total number of pixels in the corresponding row or column (Lillesand and Kiefer, 1994). On the other hand, the Kappa coefficient is a measure of the interpreter agreement. The Kappa statistics incorporate the off-diagonal elements of the error matrices (i.e., classification errors) and represents agreement obtained after removing the proportion of agreement that could be expected to occur by chance. One of the problems with the confusion matrix and the kappa coefficient is that it does not provide a spatial distribution of errors (Foody, 2002). For all classified maps an accuracy assessment was done by generating stratified random points for the classified images, using the accuracy assessment application in Erdas Imagine 50 points were taken per class (Congalton, 1991). The reference points were digitized manually on screen. An error matrix was produced for each classified map presenting the overall accuracy, class-wise UA and PA as well as the kappa coefficient.

The classification accuracy of each image was expressed in the form of an error matrix in terms of the producer's error, the user's error, and overall accuracy. Overall accuracy was calculated by adding the number of pixels classified correctly and dividing by the total number of pixels (sum of all pixels in all ground-truthed classes). Kappa Coefficient was also used as a measure of classification accuracy, subtracting the effect of random accuracy. Accuracy assessment has been performed for each classified image and quantified in terms of Overall accuracy and Kappa statistics. A wide set of band combinations were selected for supervised classification and their performance was evaluated.

The Kappa stat supports the good quality of the classification of LULC (Table 12). Overall accuracy is 0.82 (82.86%) which indicates a good classification. It is stated that Kappa values of more than 0.80 indicate good classification performance (Jensen 2005, Lillesand *et al.* 2004). Table 4.1 indicate that for the year 1990 overall accuracy is 91 % where other that wetland and agriculture have the least accuracy whereas forest, barren land, and built-up area exhibits the highest accuracy.

Table 4. 7 Accuracy assessment of the land cover maps 1990 to 2010
(Overall accuracy – AO; figure of merit – FoM; omission – O; commission – C)

Year	**1990**			**2000**			**2010**			**2020**		
Class	FoM	O	C	FoM	O	C	FoM	O	C	FoM	O	C
Water	95.5	0.0	4.5	95.0	5.0	0.0	100.0	0.0	0.0	91.3	8.7	0.0
Bare land	82.4	12.5	6.7	85.7	0.0	14.3	73.7	22.2	6.7	60.0	30.8	18.2
Urban	71.4	16.7	16.7	80.0	20.0	0.0	42.9	0.0	57.1	66.7	11.1	27.3
Forest	87.5	6.7	6.7	100.0	0.0	0.0	73.7	12.5	17.6	93.8	6.3	0.0
Agriculture	66.7	14.3	25.0	100.0	0.0	0.0	100.0	0.0	0.0	60.0	0.0	40.0
Wetland	50.0	50.0	0.0	87.5	0.0	12.5	66.7	33.3	0.0	57.1	20.0	33.3
OA	91.0			96.5			88.1			87.0		

Source : Compiled by Researcher

Classification data for the year 2000 gave the highest overall accuracy (96.5%) whereas forest and agriculture show the highest degree of agreement followed by other classes with < 85% accuracy. Classification of data for the years 2010 and 2020 exhibits < 85% overall agreement. Maximum errors of Omission and commission have occurred in the case of urban and barren land since the spectral signatures are almost similar in both cases therefore in further analysis researchers may club these two classes together while estimating the change in area and SOCs. Also, the Landsat data used here is from July month of the respective year, since July month is the monsoon season in the State of Goa, it has also created errors while estimating wetland and water resources of the region. Due to seasonal variation, the estimation of forest (1990 & 2010) and agriculture (1990 & 2020) is varying.

4.11 Land Use and Land Cover Change Modelling

The Markov Chain Model (MCM) predicts the probability between two different times and produces the transition probability matrix based on both times (Singh et al. 2015) whereas, the cellular automata (CA) provide the direction of development. Therefore, researchers have used the CA-MCM to predict the land use/land cover change of the Goa state. Researchers have adopted a three-map validation technique to identify the intensity of change in the category in size (Varga et al. 2019).

Land Use Land Cover Change CA-MCM model result show (table 4.8) that geographical coverage of important LU LC categories is likely to increase drastically by 2030

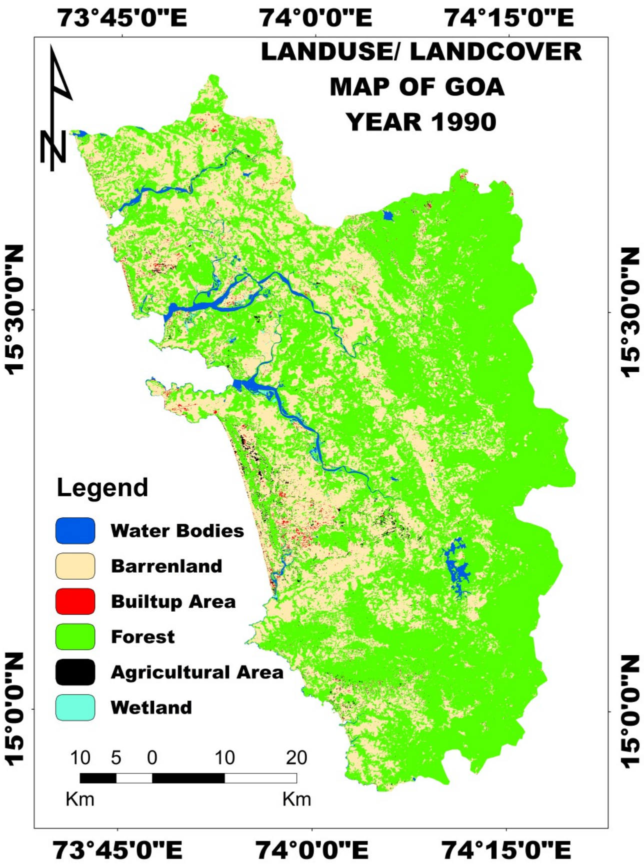
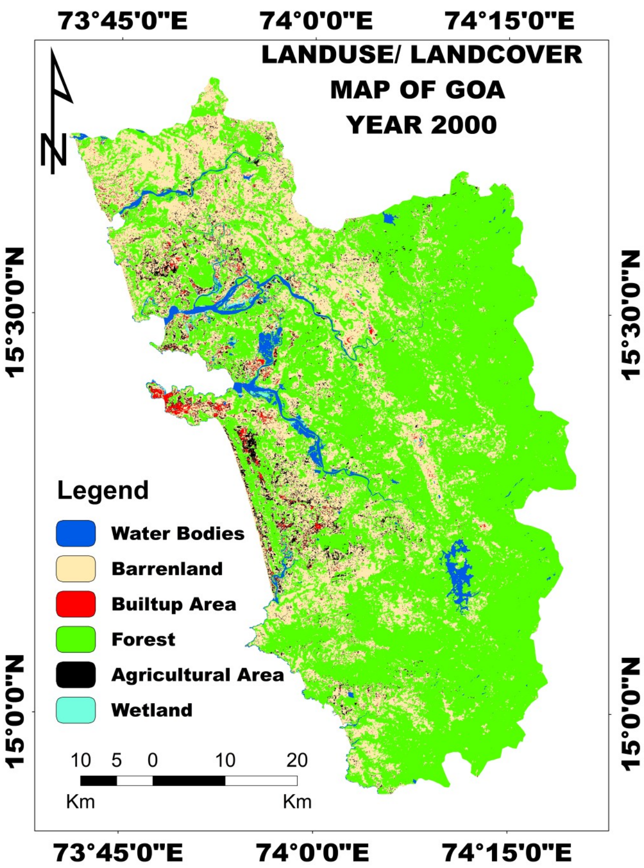


Figure 4.3 Goa Land use land cover 1990

Figure 4.4 Goa Land use land cover 2000



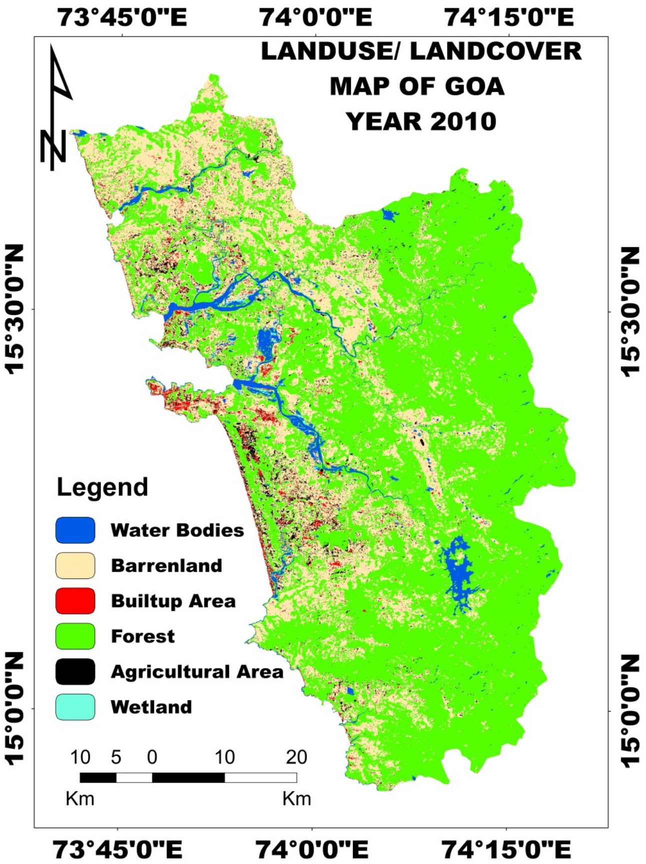
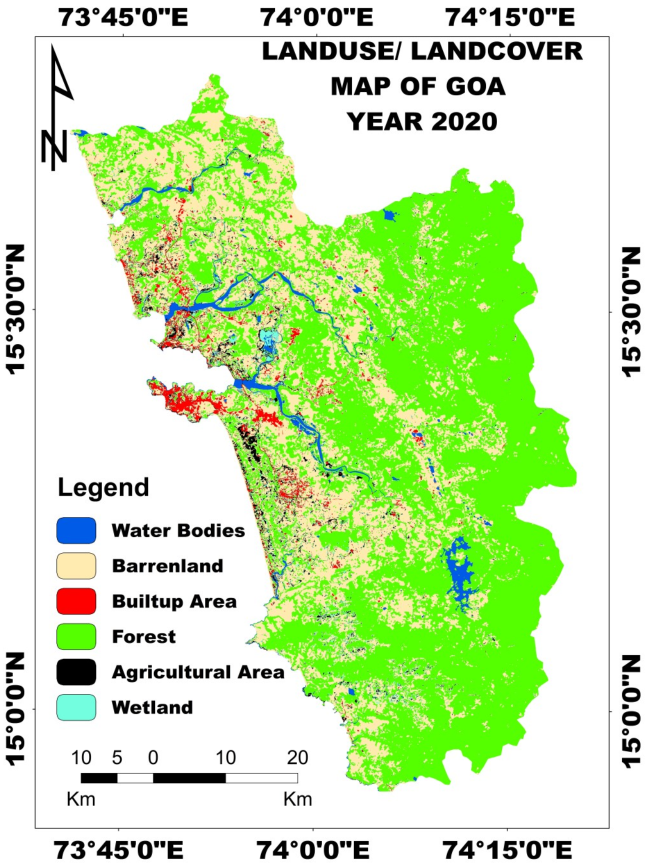


Figure 4.5 Goa Land use land cover 2010

Figure 4.6 Goa Land use land cover 2020



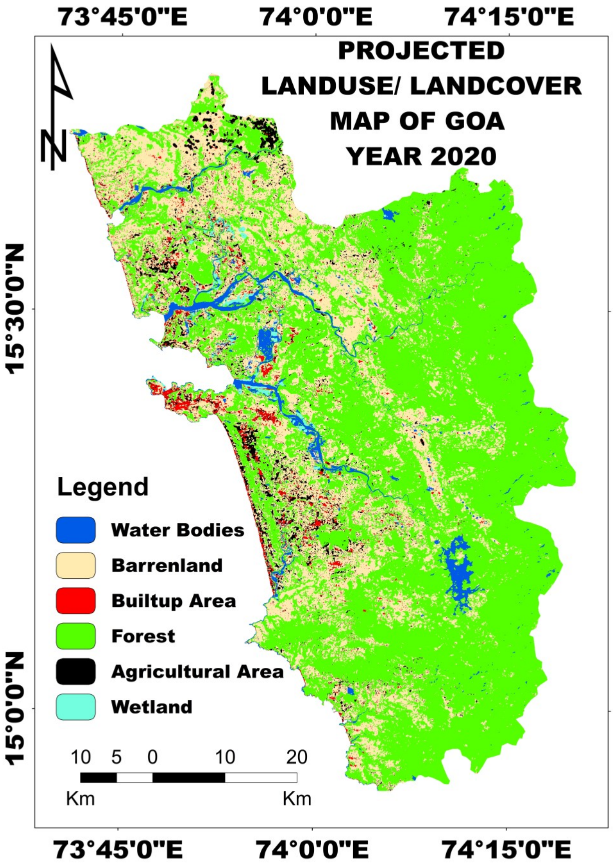


Figure 4.7 Goa
Projected land use land cover 2020

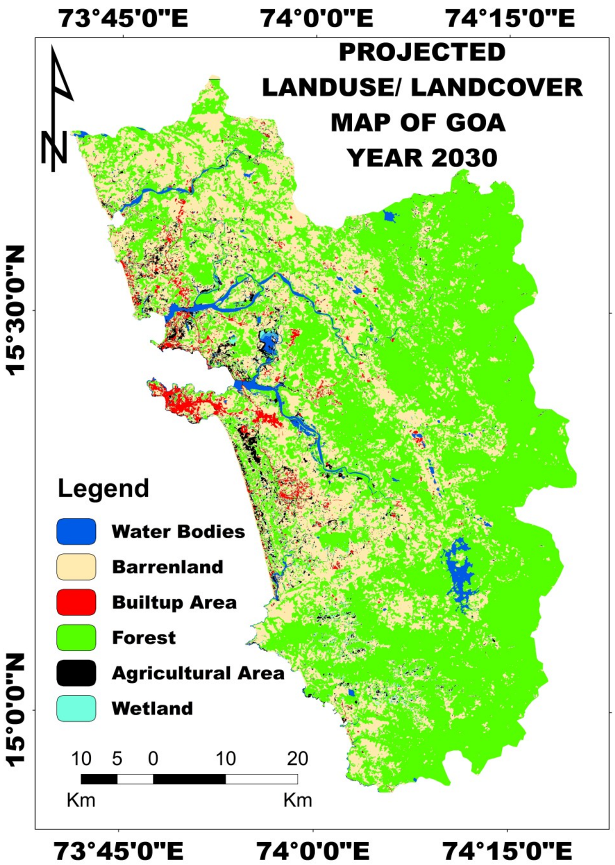


Figure 4.8
Goa
Projected land use land cover 2030

in barren land and built-up surfaces. The analysis predicts negative changes in the geographical coverage of forest and agricultural land. The analysis of the probability of change (table 4.9) through the CA-MCM model predicts (figures 4.3 to 4.8) the loss of forest land (~ 22 %) to the barren and exposed surface by the year 2030. Agriculture land will be lost to built-up (~12%) and barren land (~55%) by 2030. The model also predicts the possibility of an increase in wetlands by 17 % by 2030, as most of the areas of the coastal region are not cultivating the traditional Khazans.

Table 4.8 Land Use Land Cover Change from 1990 to 2020 and Projected Land Use Land Cover for 2020 and 2030, Based on three map validation technique

Category	Legend	Area 1990 (Ha)	Area 2000 (Ha)	Area 2010 (Ha)	Area 2020 (Ha)	Projected Area 2020 (Ha)	Projected Area 2030 (Ha)
1	Water	6856.65	10343.97	12253.23	7745.49	11469.15	8723.7
2	Barren land	121905.09 (33.03)	103548.78 (28.06)	106268.85 (28.80)	116703.72 (31.62)	101801.61 (27.59)	116755.38 (31.64)
3	Built-up	1996.29	4666.05	6269.67	7554.87	7330.86	7644.96
4	Forest	233976.69	238643.73	233920.98	223519.95	233887.32	223454.16
5	Agriculture	3390.66 (0.92)	10668.06 (2.89)	9312.21 (2.52)	6953.13 (1.88)	12218.49 (3.31)	7761.87 (2.10)
6	Wetland	935.37	1095.57	958.41	6578.73	2275.92	4715.82

Source: Compiled by researcher, based on LULC CA_MCM Model, derived from Landsat MSS, TM, ETM, ETM^+ data of July -1990, 2000, 2010, and 2020

Decadal change (table 4.10) in LULC reveals that there are consistent negative changes observed in the coverage of forests from the year 2000 onward. Similarly agricultural land has shown -12 to -27 percent changes. Barren land is likely to gain more area (+12) by 2030.

Table 4.9 Probability to change projected for year 2030 based on CA-MCM model.
(Area in hectare, figures in parenthesis indicates probability to change)

CLASS	Water	Barren land	Built up	Forest	Agri-culture	Wetland	Total
Water	3873 (49.17)	1014 (12.87)	92 (1.17)	1868 (23.71)	378 (4.8)	651 (8.27)	7877
Barren land	529 (0.46)	70115 (61.07)	6636 (5.78)	25469 (22.18)	5233 (4.56)	6836 (5.95)	114817
Built up	98 (1.16)	4349 (51.63)	1995 (23.69)	518 (6.16)	918 (10.9)	545 (6.47)	8423
Forest	93 (0.04)	51258 (23.11)	1616 (0.73)	161433 (72.8)	3058 (1.38)	4304 (1.94)	221762
Agriculture	25 (0.31)	4475 (55.86)	1021 (12.75)	628 (7.84)	1103 (13.76)	759 (9.47)	8011
Wetland	2671 (28.69)	1343 (14.43)	339 (3.64)	1673 (17.97)	1409 (15.14)	1875 (20.14)	9310
Total	7289	132554	11700	191589	12099	14970	370200

Source: Compiled by researcher, based on LULC CA_MCM Model, derived from Landsat MSS, TM, ETM and ETM$^+$ data of July -1990, 2000, 2010, and 2020

Table 4.10 Relative change in LULC from 1990 to 2030

Reference Years / Class	1990-2000	2000-2010	2010-2020	2020-2030	2010-2030	2000-2030	1990-2030
Water	50.90	18.45	-36.80	12.63	-28.82	-15.68	27.23
Barren land	-15.04	2.62	9.80	0.04	9.85	12.73	-4.22
Built-up	133.80	34.36	20.48	1.19	21.92	63.80	282.96
Forest	2.02	-1.98	-4.47	-0.03	-4.49	-6.39	-4.50
Agriculture	214.71	-12.71	-25.35	11.63	-16.66	-27.26	128.92
Wetland	17.16	-12.52	586.29	-28.32	391.94	330.34	404.17

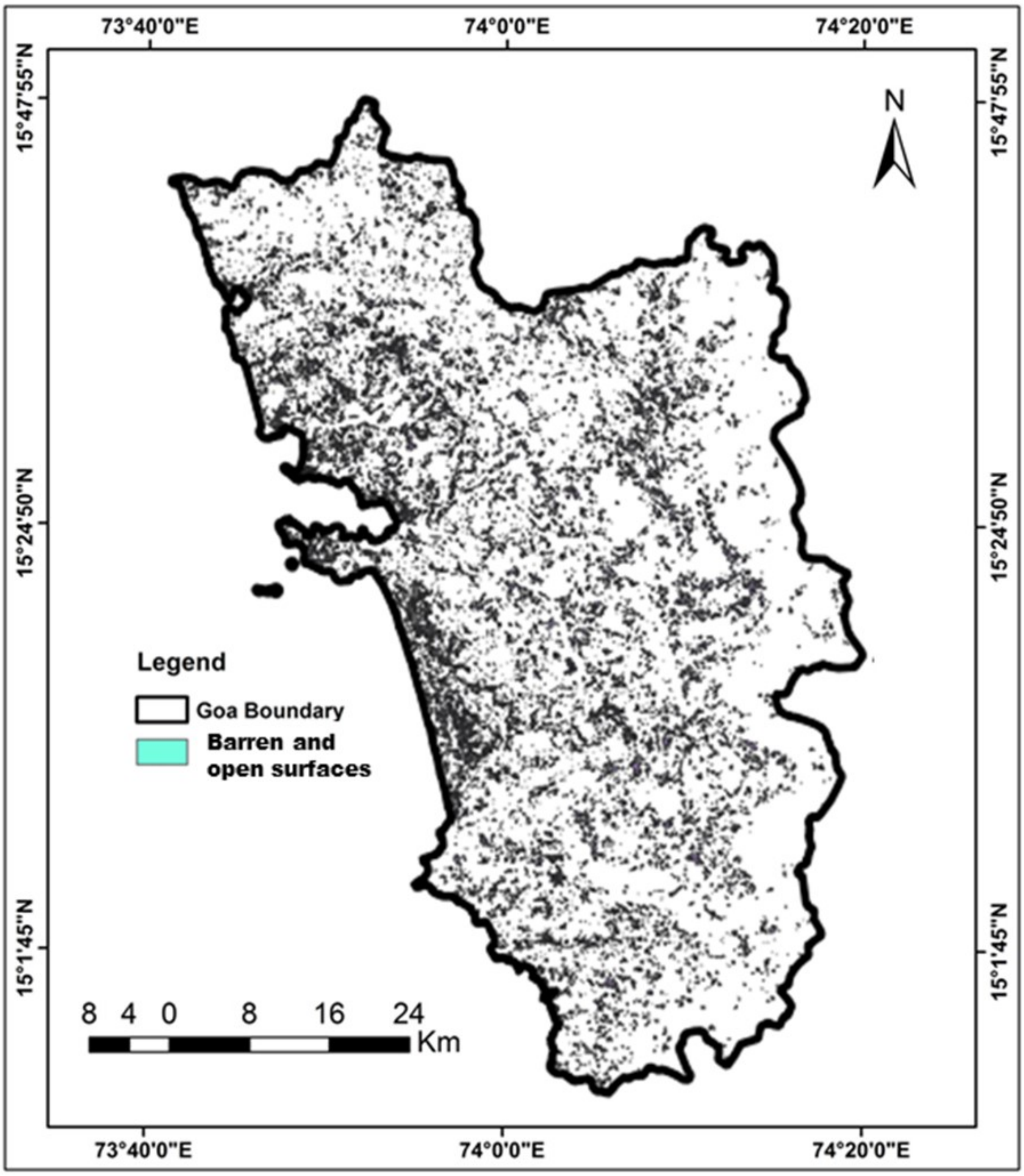
Source: compiled by researcher

Table (4.10) indicates a positive change in built-up land by 63 percent from the year 2000 to 2030. If compared with the base year (1990) it is likely to reach 280 times the area under built-up surfaces as the probability (table 4.10) of barren and built-up land is ~ <50 %.

4.12 Regional analysis of SOC stock and sequestration potential

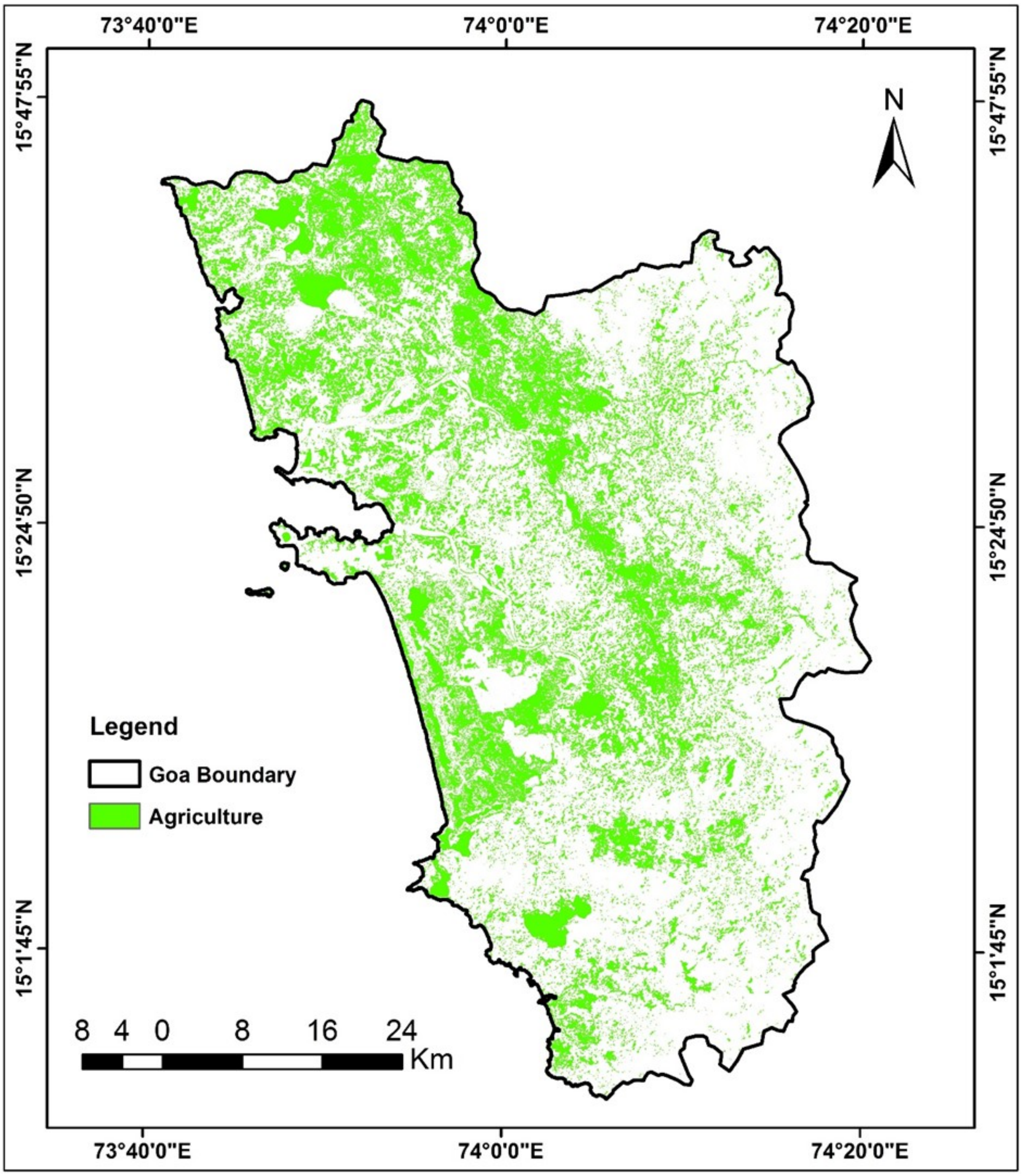
Probability and relative change analysis (figure 4.3 and table 4.11) clarified the possibility of change in area under agriculture, forest, wetland, Barren land, and Built-up land. The following discussion deals with the regional potential to sequester and store C in the region as SOC stock in the State of Goa.

Figure 4.9 Goa distribution of Barren and Bare surfaces 2020



Source : Compiled by research

Figure 4.10: Goa distribution of Agricultural Regions 2020



Source : Compiled by research

Table 4.11 Tehsil wise distribution of potential sites and predicted SOC potential form Barren land and wasteland

Tehsil	Area Computed Under Barred surfaces (H)	Area rescaled @ 60 % probability by CA-MCM Model Area in Hectare	Min. SOC @1.31 % potential by Interpolation	Max. SOC @1.6 % Potential by Interpolation	Max. SOC @6 % potential based on field samples 50% probability to sequester 30 ton/hectare
Sanguem	2063.81	1238.29	1622.15	1981.26	37148.58
Dharbandoda	1491.32	894.79	1172.18	1431.67	26843.82
Maomugao	890.92	534.55	700.26	855.28	16036.55
Quepem	1817.41	1090.44	1428.48	1744.71	32713.32
Ponda	1652.09	991.25	1298.54	1586.01	29737.61
Pednem	929.42	557.65	730.53	892.25	16729.63
Tiswadi	1690.92	1014.55	1329.06	1623.28	30436.59
Bardez	1690.92	1014.55	1329.06	1623.28	30436.59
Salcete	2246.64	1347.98	1765.86	2156.77	40439.51
Bicholim	918.81	551.28	722.18	882.06	16538.55
Cancona	1639.28	983.57	1288.47	1573.70	29506.97
Sattari	18400.32	11040.19	14462.65	17664.31	331205.80
	35431.86	21259.12	27849.44	34014.59	637773.52

Table 4.12 Predicted loss of SOC from agricultural land by 2030 by Tehsils of Goa

Region	Area in Hectare	Change in Area under agriculture			Maximum Possible SOC t/h 2020	Possible Loss of SOC from Agriculture @44t/h		
		Decadal (@ -30)	Predicted change by 2030 (-25%)	Probability to change from Agriculture to Barren/ fallow @ ~-55 %		Decadal Loss of SOC	Predicted loss by 2030 SOC	Loss of by probability of conversion
Tiswadi	2937	881	2203	1298	129227	96920	57118	519258
Sattari	5756	1727	4317	2544	253280	189960	111950	1017726
Sanguem	5510	1653	4132	2435	242429	181822	107154	974125
Salcete	1493	448	1120	660	65695	49271	29037	263975
Quepem	3026	908	2270	1338	133161	99871	58857	535065
Ponda	4920	1476	3690	2175	216494	162371	95690	869913
Pernem	1985	595	1488	877	87319	65489	38595	350864
Mormogao	1546	464	1159	683	68005	51004	30058	273258
Dharbandoda	3736	1121	2802	1651	164383	123287	72657	660521
Cancona	3286	986	2465	1453	144595	108446	63911	581007
Bicholim	1677	503	1258	741	73806	55354	32622	296566
Bardez	1889	567	1417	835	83128	62346	36743	334025
Total	37762	11329	28321	16691	1661523	1246142	734393	6676302

Source: Compiled by Researcher, Based on LULC, interpolation and results obtained from field samples and results of CA-MCM Model

4.12 .1 Predicted probable gain of SOC stock and sequestration potential of Barren land and wasteland

The analysis is based on the figures derived from the results of the CA-MCM model. The model defines the probability of an increase in the geographical coverage of barren and bare surfaces will ~60 percent by 2030. This in conjunction with the SOC stock and potential values analyzed by interpolation and fieldwork. (figure 4.9)

Overall State will gain an additional 6.3 lakh tons of SOC stock if bare surfaces (barren, wasteland) are brought under vegetation cover. Sub-divisional analysis indicates that Sattari tehsil alone will contribute an additional 3.3 lakh tons of stock (~52 %). Similarly Sanguem and Dharbandoda tehsils will contribute an additional 10% of SOC stock, whereas, Mormugao, Bicholim, and Pednem together will contribute about ~8 % of additional SOC to the potential SOC stock by 2030. The remaining 30 % contribution may come from Cancona, Ponda, Tiswadi, Bardez, Salcete, and Quepem tehsils. These tehsils are coastal and developing tehsils of the state.

4.12 .2 Predicted probable loss of SOC stock and sequestration potential from Agriculture land

The analysis (Figure 4.10 and Table 4.12) indicates that the area under agriculture is reducing at a very faster rate from 2010 to 2020 (30%). The CA-MCM probability analysis revealed that the area under agriculture will change by -25 % by 2030. This will contribute to the negative SOC stock of the state by 6.67 million tons by 2030. At present, the negative change in coverage of agricultural region shows a negative change of 16.6 million tonnes for the last decade.

Tehsil level variation shows that Sattari, Sanguem, Dharbandoda, and Ponda are the major losers on SOC stock by 2030. Those altogether contribute ~52 percent of the loss of the state being forest-dominated ecological setup. Urban tehsils like Tiswadi, Bardez, Salcete, and Mormugoa contribute ~-20 percent of the loss of SOC. Even the minimum rate of change predicted by the LULC change model indicates 0.7 million tons of SOC loss at the rate of 25 reductions in area.

Plate 1 : Field Photographs from Agricultural, Barren, Grazing and Grasslands of Goa

A

B

C

D

E

F

A: Paddy field; **B:** Current fallow land; **C:** Fallow land;
D: Barren land; **E:** Grazing land; **F:** Grassland

Plate 2 Photographs form Wetland and Mangroves of Goa

A: Marsh

B: Swamp

C: Bog

D: Fen

E: Chorao Island

F: Curtorim

G: Macazana

H: Tuem

Plate 3 : Photographs from Forests of Goa

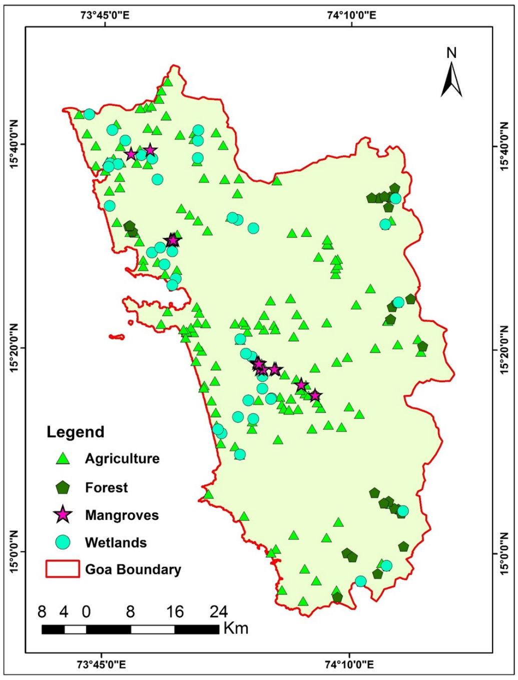
A: Semi-Evergreen forest

B: Moist Deciduous forest

C: Open forest

D: Plantation

Soil Sampling Points location from different LULC setup of Goa



Compiled by Researcher

CHAPTER 5:

FINDINGS AND CONCLUSION

Findings

- The Land Use and Land Cover (LULC) pattern of a region is an outcome of natural and socio-economic factors and their utilization by man in time and space. LULC change has become a central component in current strategies for managing natural resources and monitoring environmental changes.
- The LULC classes were agriculture, water bodies, wetlands, mangroves, and forests. The state of Goa encompasses a total area of 3,702 sq. km.
- The spatial extent of forest areas covers 2012.61 sq. km (54.37%), agriculture or agro-ecosystems covers 1094.17 (29.57%), settlements 481.1 (~13%), water bodies 60.13 (1.62%), wetlands 27.19 (0.73%) and mangrove cover 26.8 (0.72%).
- The Kappa stat supports the good quality of the classification with overall accuracy is 0.82 (82.86%) which indicates a good classification for LULC and CA MCM model from 85 to 95 %. The Kappa stat supports the good quality of the classification of LULC (. Overall accuracy is 0.82 (82.86%) which indicates a good classification. For the year 1990 overall accuracy is 91 % whereas classification data for the year 2000 gave the highest overall accuracy (96.5%) where forest and agriculture show the highest degree of agreement followed by other classes with < 85% accuracy. Classification of data for the years 2010 and 2020 exhibits < 85% overall agreement. Due to seasonal variation, the estimation of forest (1990 & 2010) and agriculture (1990 & 2020) is varying.
- Net change (loss) has been recorded in the categories of agriculture, wetlands, and water bodies with a decrease in an area (sq. km) of 32.13, 3.24, and 3.76 respectively whereas in the case of net change (gain) has been noted in the classes of forests, settlements, and mangroves with an increase in an area (sq. km) of 16.39, 18.54 and 4.2 correspondingly.
- Maximum gain in the area was observed in settlements however there was an extreme loss in agricultural areas. The present situation reveals 92.02% accuracy of

agroecosystems, 90.63% of wetlands, 88.89% of mangroves, and 75.51% accuracy of forest areas. The total forest cover of Goa has been increased by 20.59 sq. km which includes wildlife sanctuaries, a national park, a bird sanctuary, a mangrove forest, and the hilly regions which is a good addition to the contribution of Western Ghats. From 2007-2017, there has been an increase in forest area by ~16.4 sq. km.

- A total of 35 dominant tree species were recorded from four forest sites in Goa. Of the 35 species, 11 species belonging to 8 families are registered in Semi-Evergreen forests; 16 species belong to 11 families in Moist Deciduous forests; 8 species belong to 7 families in sites of Open forest/Plantation areas.
- Tree species such as *Anacardium occidentale* L, *Leea Indica* (Burm.f.) Merr, *Tectona grandis* L.f, *Terminalia bellerica* (Gaertn.) Roxb, *Terminalia paniculata* Roth and *Xylia xylocarpa* (Roxb.) Taub was predominantly present in all the forest sites.
- The average height and DBH of the tree species present in the forest sites of Goa are 14.50 $\pm$ 6.63σ m^2 and 0.84 $\pm$ 0.46σ m^2 respectively. The mean Above-ground tree biomass (Mg) in SE, MD, and OF/PT forests are 14.66 $\pm$ 8.08σ, 3.01 $\pm$ 2.34σ, and 0.83 $\pm$ 0.89σ respectively. The ΔAGB (Mg C/ha) content is 621.5, 1681.8, 1680.4, and 2059.22 from CWS, NWS, BMWS, and MWS respectively. The Below-Ground Biomass (BGB) is an important carbon pool for many vegetation types and accounts for 20% of the total biomass.
- The mean below-ground biomass of the tree species present in the forest sites of Goa is 1.23 $\pm$ 1.50σ Mg. The average BGB of tree species present in SE, MD, and OF/PT is 2.93 $\pm$ 1.62σ; 0.60 $\pm$ 0.47σ and 0.17 $\pm$ 0.18σ Mg respectively. The total biomass of the forest sites of Goa is 4.79 million tonnes.
- The mean biomass estimated from the tree species is 0.14 $\pm$ 0.10σ million tonnes. The biomass estimated in all the forest covers types i.e. SE, MD, and OF/PT is 0.25 $\pm$ 0.07σ; 0.11 $\pm$ 0.07σ, and 0.04 $\pm$ 0.02σ million tonnes.

- The results reveal that comparative site 3 has shown high biomass content while site 1 showed the least. In terms of tree species, *Schleichera Oleosa* (Lour.) Oken proves to contain maximum biomass content whereas *Leea Indica* (Burm.f.) Merr the minimum value.
- In the case of forest cover, tropical semi-evergreen forest proves to enclose high biomass content whereas Open forest areas reveal a low biomass value. The carbon content in the forest sites is 2.4 million tonnes which are obtained by multiplying total tree biomass by a default conversion factor of 0.5.
- The mean SOC content (%) in agro-ecosystems, wetlands, and mangrove and forest areas are 3.19%$\pm$1.93σ; 4.06%$\pm$1.18σ; 4.73%$\pm$2.24σ and 6.24%$\pm$3.28σ with B.D (g cm^{-3}) of 1.40, 1.15, 1.09 and 1.46 respectively. The average SOCS (t ha^{-1}) of agroecosystems, wetlands, and mangrove and forest areas are 44.84, 46.72, 51.62, and 86.42 respectively.
- While comparing, soil samples collected from forest areas have shown higher mean SOC content followed by mangroves, wetlands, and agroecosystems. The total carbon stock of Goa from chemical and spatial analysis resulted in a total of 16.50 million tonnes and 17.06 million tonnes. While comparing both the techniques i.e. chemical and spatial analysis used for the estimation of the carbon stock of Goa approximately 96.70% of accuracy has been found concerning the total carbon stock of Goa.
- The SOC is Categorized into seven classes that are ranging from 0-5 t/hectare and covers most of the built-up area and rocky outcrops, barren and exposed area, and surfaces with very shallow soil surfaces. The pockets of such conditions are scattered all over the State and cover all together ~ 30 % of the geographical area and contribute 31944 Mt of OC to the carbon stock of the region.
- Vast areas of coastal belt consisting of Pednem, Bardes, Tiswadi, Salcete tehsil, Bicholim, and Ponda tahsils are observed to have OC stock in the range of 5 to 10 and

10 to 15 tonnes per hectare of OC. The region in this range covers about 3043 and 2880 hectares of area and almost 30426 Mt and 43205 Mt of OC to the state carbon Stock.

- The area belongs to the vast foothills and valley regions of eastern Pednem, Bardez, Bicholim, Ponda Sattari, and the Eastern part of Cancona tehsil. Mostly these areas are under intensive agriculture, forestry, and plantation agriculture where SOC ranges from 15 to 20 Mt per hectare. This region contributes to 45369 Hectares (~12%) of geographical space and 907387 Mt (~9%) of OC to the carbon stock of the State. The region is quite a critical form the transition from vegetation & forest dominating regions is gaining commercial importance in the state.
- The region comprises the hilly area of Quepem, and Western part of Cancona, the southwestern part of Sangues along the boundary of Quepem and Cancona, and the major area of Dharbandona, Bicholim and Ponda tehsil along the river Khandepar and its tributaries. This region contributes 111023 hectares of area (29%) of the State and contributes 27775584 tons (28.23 %) of State SOC stock.
- This region of very high SOC stock of ~ 30 tonnes per hectare comprises part of Sanguem tehsil with Netravali Wildlife Sanctuary and some small pockets of inter-mountain valleys of Quepem and Ponda tehsil. This part covers 201496 hectares (~55 %) of the geographical area of the State and contributes about 6044871Mt (62 %) of SOC.
- The SOC interpolated using kriging reveals the SOC range from 5 t/h to 30 Ton/hectare. More than 54 % area has SOC in the range of 25-30 t/h which contributes to 61 % of States SOC stock. This trend is followed by SOC rage 20-25 by ~30 % area contributes by 28 % of SOC stock.
- Median SOC for the under major land use and land cover categories reveals that forest has maximum median SOC (1.27 %) followed by bare land i.e. land which is not regularly cultivated or current fallow land. Due to minimum tillage practices or

minimum disturbance to the natural setup barren, uncultivated and fallow lands considered in this group show a high concentration of SOC. Wetlands, agriculture, and water bodies also appear to be promising reservoirs of OC that exhibit the range of OC from 0.88% to 1.00%. Observation also clarifies that there are seasonal variations in SOC, as the OC in consecutive cycle show change.

- Land Use Land Cover Change CA-MCM model result show that geographical coverage of barren land and built-up surfaces is likely to increase drastically by 2030. The analysis predicts negative changes in the geographical coverage of forest and agricultural land.
- The analysis of the probability of change through the CA-MCM model predicts the loss of forest land (~ 22 %) to the barren and exposed surface by the year 2030. Agriculture land will be lost to built-up (~12%) and barren land (~55%) by 2030. The model also predicts the possibility of an increase in wetlands by 17 % by 2030, as most of the areas of the coastal region are not cultivating the traditional Khazans.
- Decadal change in LULC reveals that there are consistent negative changes observed in the coverage of forests from the year 2000 onward. Similarly agricultural land has shown -12 to -27 percent changes. Barren land is likely to gain more area (+12) by 2030.
- A positive change (~63%) is predicted in built-up land by the year 2030. If compared with the base year (1990) it is likely to reach 280 times the area under built-up surfaces as the probability to transform barren and bare open surfaces to built-up land is ~ predicted about 50 %.
- The analysis is based on the figures derived from the results of the CA-MCM model. The model defines the probability of an increase in the geographical coverage of barren and bare surfaces will ~60 percent by 2030. This in conjunction with the SOC stock and potential values analyzed by interpolation and fieldwork.

  Overall State will gain an additional 6.3 million tonnes of SOC stock if bare surfaces (barren, wasteland) are brought under vegetation cover. Sub-divisional analysis indicates that Sattari tehsil alone will contribute an additional 3.31million tonnes of stock (~52 %).

Sanguem and Dharbandoda tehsils will contribute an additional 10% of SOC stock, whereas, Mormugao, Bicholim, and Pednem together will contribute about ~8 % of additional SOC to the potential SOC stock by 2030. The remaining 30 % contribution may come from Cancona, Ponda, Tiswadi, Bardez, Salcete, and Quepem tehsils. These tehsils are coastal and developing tehsils of the state.

The area under agriculture is reducing at a very faster rate from 2010 to 2020 (30%). The CA-MCM probability analysis revealed that the area under agriculture will change by -25 % by 2030. This will contribute to the negative SOC stock of the state by 6.67 million tonnes by 2030. At present, the negative change in coverage of the agricultural region shows a negative change of 16.6 million tonnes of SOC for the last decade.

Tehsil level variation shows that Sattari, Sanguem, Dharbandoda, and Ponda are the major losers on SOC stock by 2030. Those altogether contribute ~52 percent of the loss of the state being forest-dominated ecological setup. Urban tehsils like Tiswadi, Bardez, Salcete, and Mormugoa contribute to a loss of 20 percent SOC predicted by LULC, CA & MCM models.

Conclusion:

The present study emphasizes three major aspects, i.e. LULC change, Biomass estimation, and Carbon stock of Goa.

From the LULC map a net change (loss) has been recorded in the categories of agriculture, wetlands, and water bodies with a decrease in an area (sq. km) of 32.13, 3.24, and 3.76 respectively whereas in the case of net change (gain) has been noted in the classes of forests, settlements, and mangroves with an increase in an area (sq. km) of 16.39, 18.54 and 4.2 correspondingly.

- The Kappa stat reveals the overall accuracy is 0.82 (82.86%). The biomass of the forest obtained through biometric measurement is 4.79 million tons. The carbon stock of forests obtained through soil analysis and biometric measurements is 14.18 million tonnes.
- The total carbon stock of Goa from chemical and spatial analysis resulted in a total of 16.50 million tonnes and 17.06 million tonnes. While comparing both the techniques i.e. chemical and spatial analysis used for the estimation of the carbon stock of Goa approximately 96.70% of accuracy has been found concerning the total carbon stock of Goa.
- CA and MCM predicted the Probability of change in area under agriculture, forest, wetland, Barren land, and Built-up land. This is going to bring a rapid change in the regional potential to sequester and store C as SOC stock in the State of Goa.
- Overall analysis indicates to undertake of afforestation and agroforestry to bring positive changes in the State. The areas like agriculture, mangrove, and forests are going through negative spatial changes whereas barren, bare, and non-productive surfaces are increasing at a rapid rate is an alarm to undertake such initiatives to bring positive change in the natural setup of the environment of the State of Goa.

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Table 3.1: Details of Tree Species Present in the Forest Sites of Goa

Sr. No.	Tree Species	Family	Common Name	Local Name
1	*Acacia auriculioformis* A.Cunn. Ex Benth	Fabaceae	Earleaf Acacia	Australia Babul
2	*Acacia catechu* (L.) Wild., Oliv	Fabaceae	Cutch Tree	Khair
3	*Alstonia scholaris*(L.) R.Br	Apocynaceae	Devil tree	Satvan
4	*Anacardium occidentale* L.	Anacardiaceae	Cashew tree	Kaju
5	*Aporosa cardiosperma*(Gaertn.) Merr	Phyllanthaceae	Lindley's Aporosa	Sali
6	*Areca catechu* L.	Arecaceae	Betel nut Palm	Pophala
7	*Artocarpus integrifolia* L.	Moraceae	Jackfruit tree	Phanas
8	*Atalantia racemosa* Wight & Arn.	Rutaceae	Bombay Atalantia	Makad limbu
9	*Buchanania lanzan* Spreng.	Anacardiaceae	Chironji tree	Char
10	*Careya arborea* Roxb.	Lecythidaceae	Wild Guava	Kumbyo
11	*Cocos nucifera* L.	Arecaceae	Coconut tree	Naal
12	*Dalbergia latifolia* Roxb.	Fabaceae	Indian rosewood	Shisham
13	*Dalbergia sissoo* Roxb.	Fabaceae	North Indian rose-wood	Siso
14	*Diospyros montana* Roxb.	Ebenaceae	Bombay ebony	Goiunda
15	*Ficus bengalensis* L.	Moraceae	Indian banyan tree	Vad
16	*Ficus hispida* L.f.	Moraceae	Devil fig tree	Kalaumbar
17	*Ficus religiosa* L.	Moraceae	Sacred fig	Pipal
18	*Flacourtia montana* J.Graham	Salicaceae	Mountain Sweet Thorn	Chafra
19	*Ixora elongata* B.Heyne ex G.Don	Rubiaceae	Rosy Ixora	Gulab kuda
20	*Lagerstroemia lanceolata* Wall.	Lythraceae	Nandi Tree	Nano
21	*Lagerstroemia parviflora* Roxb.	Lythraceae	Small Flowered crape Myrtle	Taman
22	*Leea indica* (Burm.f.) Merr.	Vitaceae	Bandicoot Berry	Jino
23	*Macaranga peltata* Roxb. Mueller	Euphorbiaceae	Chandada	Chandado
24	*Mangifera indica* L.	Anacardiaceae	Mango tree	Ambo
25	*Pavetta crassicaulis* Bremek.	Rubiaceae	Kankara	Papat
26	*Schleichera oleosa* (Lour.) Oken	Sapindaceae	Kusum Tree	Kasamb
27	*Syzgium cumini* (L.) Skeels.	Myrtaceae	Jambolan	Jambul
28	*Tabernaemontana alternifolia* L.	Apocynaceae	Nag Kuda	Nag Kuda
29	*Tectona grandis* L.f.	Lamiaceae	Teak	Saylo
30	*Terminalia bellerica* (Gaertn.) Roxb.	Combretaceae	Bahera	Goting
31	*Terminalia tomentosa (Roxb.) Wight & Arn*	Combretaceae	Indian laurel	Marat
32	*Terminalia paniculata* Roth.	Combretaceae	Kinjal	Kindal
33	*Vitex altissima* L.f.	Lamiaceae	Peacock chaste tree	Bavalgi
34	*Xylia xylocarpa* (Roxb.) Taub.	Fabaceae	Burma Ironwood	Zambo
35	*Zanthoxylum rhetsa* (Roxb.) DC.	Rutaceae	Indian Prickly Ash	Tirphal

Source : Compiled by Researcher, Based on fieldwork

Table 3.2: Distribution of Tree Species in Different Forest Covers of Goa

Sr. No.	Tree Species	Forest Cover
1	*Acacia auriculioformis* A.Cunn. Ex Benth	OF/PT
2	*Acacia catechu* (L.) Wild., Oliv	MD
3	*Alstonia scholaris* (L.) R.Br	OF/PT
4	*Anacardium occidentale* L.	OF/PT
5	*Aporosa cardiosperma* (Gaertn.) Merr	SE
6	*Areca catechu* L.	OF/PT
7	*Artocarpus integrifolia* L.	OF/PT
8	*Atalantia racemosa* Wight & Arn.	SE
9	*Buchanania lanzan* Spreng.	MD
10	*Careya arborea* Roxb.	MD
11	*Cocos nucifera* L.	OF/PT
12	*Dalbergia latifolia* Roxb.	MD
13	*Dalbergia sissoo* Roxb.	MD
14	*Diospyros montana* Roxb.	MD
15	*Ficus bengalensis* L.	SE
16	*Ficus hispida* L.f.	SE
17	*Ficus religiosa* L.	SE
18	*Flacourtia montana* J.Graham	MD
19	*Ixora elongata* B.Heyne ex G.Don	MD
20	*Lagerstroemia lanceolata* Wall.	SE
21	*Lagerstroemia parviflora* Roxb.	SE
22	*Leea indica* (Burm.f.) Merr.	MD
23	*Macaranga peltata* Roxb. Mueller	MD
24	*Mangifera indica* L.	SE
25	*Pavetta crassicaulis* Bremek.	MD
26	*Schleichera oleosa* (Lour.) Oken	SE
27	*Syzgium cumini* (L.) Skeels.	SE
28	*Tabernaemontana alternifolia* L.	MD
29	*Tectona grandis* L.f.	MD
30	*Terminalia bellerica* (Gaertn.) Roxb.	MD
31	*Terminalia tomentosa (Roxb.) Wight & Arn*	MD
32	*Terminalia paniculata* Roth.	MD
33	*Vitex altissima* L.f.	OF/PT
34	*Xylia xylocarpa* (Roxb.) Taub.	SE
35	*Zanthoxylum rhetsa* (Roxb.) DC.	OF/PT

OF/PT: Open Forest/Plantations

MD: Moist Deciduous Forest

SE: Semi-Evergreen Forest

Source : Compiled by Researcher, Based on fieldwork

Table 3.3: Distribution of Tree Species in the Forest Sites of Goa

Sr.no.	Tree Species	Site 1	Site 2	Site 3	Site 4
1	*Acacia auriculioformis* A.Cunn. Ex Benth	1	1	0	1
2	*Acacia catechu* (L.) Wild., Oliv	0	1	0	1
3	*Alstonia scholaris* (L.) R.Br	1	1	0	1
4	*Anacardium occidentale* L.	1	1	1	1
5	*Aporosa cardiosperma* (Gaertn.) Merr	0	1	1	0
6	*Areca catechu* L.	1	1	0	1
7	*Artocarpus integrifolia* L.	1	1	0	1
8	*Atalantia racemosa* Wight & Arn.	1	0	0	0
9	*Buchanania lanzan* Spreng.	0	1	1	1
10	*Careya arborea* Roxb.	1	1	0	0
11	*Cocos nucifera* L.	1	1	1	1
12	*Dalbergia latifolia* Roxb.	1	1	0	0
13	*Dalbergia sissoo* Roxb.	0	0	1	1
14	*Diospyros montana* Roxb.	1	0	0	0
15	*Ficus bengalensis* L.	0	1	1	1
16	*Ficus hispida* L.f.	1	0	1	1
17	*Ficus religiosa* L.	1	1	0	1
18	*Flacourtia montana* J.Graham	0	1	0	1
19	*Ixora elongata* B.Heyne ex G.Don	0	1	0	1
20	*Lagerstroemia lanceolata* Wall.	1	0	1	1
21	*Lagerstroemia parviflora* Roxb.	0	1	1	1
22	*Leea indica* (Burm.f.) Merr.	1	1	1	1
23	*Macaranga peltata* Roxb. Mueller	0	1	1	0
24	*Mangifera indica* L.	1	1	1	1
25	*Pavetta crassicaulis* Bremek.	1	0	1	0
26	*Schleichera oleosa* (Lour.) Oken	0	0	1	1
27	*Syzgium cumini* (L.) Skeels.	1	0	0	1
28	*Tabernaemontana alternifolia* L.	1	1	0	0
29	*Tectona grandis* L.f.	1	1	1	1
30	*Terminalia bellerica* (Gaertn.) Roxb.	1	1	1	1
31	*Terminalia tomentosa (Roxb.) Wight & Arn*	0	1	0	1
32	*Terminalia paniculata* Roth.	1	1	1	1
33	*Vitex altissima* L.f.	0	0	1	1
34	*Xylia xylocarpa* (Roxb.) Taub.	1	1	1	1
35	*Zanthoxylum rhetsa* (Roxb.) DC.	0	1	1	0

Site 1: Cotigao Wildlife Sanctuary

Site 2: Netravali Wildlife Sanctuary

Site 3: Bhagwan Mahaveer Wildlife Sanctuary

Site 4: Mhadei Wildlife Sanctuary

0= Not Observed
1= present and Observed

Source : Compiled by Researcher, Based on fieldwork

Table 3.4: Mean Height, Diameter at Breast Height (DBH) and Basal Area of the Tree Species

Sr. No.	Tree Species	Height (m)	DBH (cm)	Basal area (cm)
1	*Acacia auriculioformis* A.Cunn. Ex Benth	10.8	52.6	165.16
2	*Acacia catechu* (L.) Wild., Oliv	13.1	82.2	258.11
3	*Alstonia scholaris* (L.) R.Br	9.6	88.9	279.15
4	*Anacardium occidentale* L.	7.4	32.7	102.68
5	*Aporosa cardiosperma* (Gaertn.) Merr	14.9	116.8	366.75
6	*Areca catechu* L.	12.6	22.4	70.34
7	*Artocarpus integrifolia* L.	11.5	31.7	99.54
8	*Atalantia racemosa* Wight & Arn.	17.36	128.6	403.80
9	*Buchanania lanzan* Spreng.	12.8	79.6	249.94
10	*Careya arborea* Roxb.	13.6	66.7	209.44
11	*Cocos nucifera* L.	12.58	50.7	159.20
12	*Dalbergia latifolia* Roxb.	19.6	66.9	210.07
13	*Dalbergia sissoo* Roxb.	18.3	60.6	190.28
14	*Diospyros montana* Roxb.	15.3	69.7	218.86
15	*Ficus bengalensis* L.	26.4	166	521.24
16	*Ficus hispida* L.f.	24.3	162.4	509.94
17	*Ficus religiosa* L.	23.7	174.3	547.30
18	*Flacourtia montana* J.Graham	8.9	128	401.92
19	*Ixora elongata* B.Heyne ex G.Don	7.9	48.5	152.29
20	*Lagerstroemia lanceolata* Wall.	16.6	117.6	369.26
21	*Lagerstroemia parviflora* Roxb.	15.7	122.5	384.65
22	*Leea indica* (Burm.f.) Merr.	4.4	9.25	29.05
23	*Macaranga peltata* Roxb. Mueller	11.6	36.1	113.35
24	*Mangifera indica* L.	29.4	131.5	412.91
25	*Pavetta crassicaulis* Bremek.	2.5	51	160.14
26	*Schleichera oleosa* (Lour.) Oken	22.4	112.5	353.25
27	*Syzgium cumini* (L.) Skeels.	26.7	66.7	209.44
28	*Tabernaemontana alternifolia* L.	3.3	14.9	46.79
29	*Tectona grandis* L.f.	19.3	98.7	309.92
30	*Terminalia bellerica* (Gaertn.) Roxb.	14.6	104.7	328.76
31	*Terminalia tomentosa (Roxb.)Wight & Arn*	15.9	96.9	304.27
32	*Terminalia paniculata* Roth.	13.3	109.5	343.83
33	*Vitex altissima* L.f.	7.1	40.47	127.08
34	*Xylia xylocarpa* (Roxb.) Taub.	15.7	162.3	509.62
35	*Zanthoxylum rhetsa* (Roxb.) DC.	8.3	22.6	70.96
	Mean	***14.50***	***83.61***	***262.55***
	Standard Deviation	***6.63***	***46.31***	***145.41***

Source : Compiled by Researcher, Based on fieldwork

Table 3.5: Above-Ground (AGB) and Below-Ground Biomass (BGB) of the Tree Species

Sr. No.	Tree species	AGB (Kg)	BGB (Kg)
1	*Acacia auriculioformis* A.Cunn. Ex Benth	1102.82	220.56
2	*Acacia catechu* (L.) Wild., Oliv	3266.83	653.37
3	*Alstonia scholaris* (L.) R.Br	2800.18	560.04
4	*Anacardium occidentale* L.	292.04	58.41
5	*Aporosa cardiosperma* (Gaertn.) Merr	7502.10	1500.42
6	*Areca catechu* L.	233.33	46.67
7	*Artocarpus integrifolia* L.	426.51	85.30
8	*Atalantia racemosa* Wight & Arn.	10596.02	2119.20
9	*Buchanania lanzan* Spreng.	2993.28	598.66
10	*Careya arborea* Roxb.	2233.07	446.61
11	*Cocos nucifera* L.	1193.46	238.69
12	*Dalbergia latifolia* Roxb.	3237.57	647.51
13	*Dalbergia sissoo* Roxb.	2480.32	496.06
14	*Diospyros montana* Roxb.	2743.27	548.65
15	*Ficus bengalensis* L.	26849.19	5369.84
16	*Ficus hispida* L.f.	23653.17	4730.63
17	*Ficus religiosa* L.	26573.83	5314.77
18	*Flacourtia montana* J.Graham	5381.72	1076.34
19	*Ixora elongata* B.Heyne ex G.Don	685.84	137.17
20	*Lagerstroemia lanceolata* Wall.	8472.93	1694.59
21	*Lagerstroemia parviflora* Roxb.	8695.27	1739.05
22	*Leea indica* (Burm.f.) Merr.	13.89	2.78
23	*Macaranga peltata* Roxb. Mueller	557.93	111.59
24	*Mangifera indica* L.	18763.33	3752.67
25	*Pavetta crassicaulis* Bremek.	239.99	48.00
26	*Schleichera oleosa* (Lour.) Oken	10463.19	2092.64
27	*Syzgium cumini* (L.) Skeels.	4384.04	876.81
28	*Tabernaemontana alternifolia* L.	27.04	5.41
29	*Tectona grandis* L.f.	6939.09	1387.82
30	*Terminalia bellerica* (Gaertn.) Roxb.	5906.87	1181.37
31	*Terminalia tomentosa (Roxb.) Wight & Arn*	5510.05	1102.01
32	*Terminalia paniculata* Roth.	5885.60	1177.12
33	*Vitex altissima* L.f.	429.18	85.84
34	*Xylia xylocarpa* (Roxb.) Taub.	15263.28	3052.66
35	*Zanthoxylum rhetsa* (Roxb.) DC.	156.46	31.29
	Mean	***6170.08***	***1234.02***
	Standard Deviation	***7517.42***	***1503.48***

Source : Compiled by Researcher, Based on fieldwork

Table 3.6: Volume and Wood Density of the Tree Species

Sr. No.	Tree Species	Volume (m^3)	Wood Density (g/cm^3)
1	*Acacia auriculioformis* A.Cunn. Ex Benth	891.89	0.58
2	*Acacia catechu* (L.) Wild., Oliv	1690.61	0.93
3	*Alstonia scholaris* (L.) R.Br	1339.90	0.39
4	*Anacardium occidentale* L.	379.91	0.45
5	*Aporosa cardiosperma* (Gaertn.) Merr	2732.30	0.6
6	*Areca catechu* L.	443.12	0.6
7	*Artocarpus integrifolia* L.	572.34	0.53
8	*Atalantia racemosa* Wight & Arn.	3505.02	0.6
9	*Buchanania lanzan* Spreng.	1599.64	0.4
10	*Careya arborea* Roxb.	1424.18	0.77
11	*Cocos nucifera* L.	1001.36	0.61
12	*Dalbergia latifolia* Roxb.	2058.65	0.8
13	*Dalbergia sissoo* Roxb.	1741.10	0.82
14	*Diospyros montana* Roxb.	1674.26	0.7
15	*Ficus bengalensis* L.	6880.37	0.49
16	*Ficus hispida* L.f.	6195.72	0.4
17	*Ficus religiosa* L.	6485.53	0.44
18	*Flacourtia montana* J.Graham	1788.54	0.86
19	*Ixora elongata* B.Heyne ex G.Don	601.55	0.83
20	*Lagerstroemia lanceolata* Wall.	3064.89	0.6
21	*Lagerstroemia parviflora* Roxb.	3019.50	0.6
22	*Leea indica* (Burm.f.) Merr.	63.90	0.5
23	*Macaranga peltata* Roxb. Mueller	657.45	0.4
24	*Mangifera indica* L.	6069.78	0.5
25	*Pavetta crassicaulis* Bremek.	200.18	0.6
26	*Schleichera oleosa* (Lour.) Oken	3956.40	0.9
27	*Syzgium cumini* (L.) Skeels.	2796.00	0.7
28	*Tabernaemontana alternifolia* L.	77.20	0.5
29	*Tectona grandis* L.f.	2990.71	0.6
30	*Terminalia bellerica* (Gaertn.) Roxb.	2399.93	0.69
31	*Terminalia tomentosa* (Roxb.) Wight & Arn	2418.91	0.84
32	*Terminalia paniculata* Roth.	2286.47	0.66
33	*Vitex altissima* L.f.	451.12	0.9
34	*Xylia xylocarpa* (Roxb.) Taub.	4000.53	0.82
35	*Zanthoxylum rhetsa* (Roxb.) DC.	294.50	0.39
	Mean	***2221.53***	***0.63***
	Standard Deviation	***1890.63***	***0.17***

Source : Compiled by Researcher, Based on fieldwork

Table 3.7: Biomass Estimation of the Tree Species

Sr. No.	Tree species	Biomass (tons)	Biomass (million tons)
1	*Acacia auriculioformis* A.Cunn. Ex Benth	51729.36	0.052
2	*Acacia catechu* (L.) Wild., Oliv	157226.49	0.157
3	*Alstonia scholaris* (L.) R.Br	52256.13	0.052
4	*Anacardium occidentale* L.	17095.89	0.017
5	*Aporosa cardiosperma* (Gaertn.) Merr	163938.14	0.164
6	*Areca catechu* L.	26587.01	0.027
7	*Artocarpus integrifolia* L.	30334.21	0.030
8	*Atalantia racemosa* Wight & Arn.	210301.12	0.210
9	*Buchanania lanzan* Spreng.	63985.66	0.064
10	*Careya arborea* Roxb.	109661.74	0.110
11	*Cocos nucifera* L.	61082.68	0.061
12	*Dalbergia latifolia* Roxb.	164691.74	0.165
13	*Dalbergia sissoo* Roxb.	142770.09	0.143
14	*Diospyros montana* Roxb.	117198.46	0.117
15	*Ficus bengalensis* L.	337138.03	0.337
16	*Ficus hispida* L.f.	247828.90	0.248
17	*Ficus religiosa* L.	285363.26	0.285
18	*Flacourtia montana* J.Graham	153814.78	0.154
19	*Ixora elongata* B.Heyne ex G.Don	49928.28	0.050
20	*Lagerstroemia lanceolata* Wall.	183893.47	0.184
21	*Lagerstroemia parviflora* Roxb.	181170.15	0.181
22	*Leea indica* (Burm.f.) Merr.	3194.95	0.003
23	*Macaranga peltata* Roxb. Mueller	26298.13	0.026
24	*Mangifera indica* L.	303488.85	0.303
25	*Pavetta crassicaulis* Bremek.	12010.50	0.012
26	*Schleichera oleosa* (Lour.) Oken	356076.00	0.356
27	*Syzgium cumini* (L.) Skeels.	195719.81	0.196
28	*Tabernaemontana alternifolia* L.	3859.85	0.004
29	*Tectona grandis* L.f.	179442.52	0.179
30	*Terminalia bellerica* (Gaertn.) Roxb.	165595.40	0.166
31	*Terminalia tomentosa* (Roxb.) Wight & Arn	203188.83	0.203
32	*Terminalia paniculata* Roth.	150906.99	0.151
33	*Vitex altissima* L.f.	40600.72	0.041
34	*Xylia xylocarpa* (Roxb.) Taub.	328043.68	0.328
35	*Zanthoxylum rhetsa* (Roxb.) DC.	11485.52	0.011
	Total	***4787907.35***	***4.79***
	Mean	***136797.35***	***0.14***
	Standard Deviation	***104277.48***	***0.10***

Source : Compiled by Researcher, Based on fieldwork

Appendix

1. LULC CHANGE-1990-2000– MCM ITERATION RESULT

CrossClassCode	NewClass	ReferenceClass	Pixel Sum	Area [metre^2]
1	1	1	69437	62493300
2	1	2	15198	13678200
4	1	3	599	539100
7	1	4	23471	21123900
11	1	5	1073	965700
16	1	6	5138	4624200
3	2	1	1120	1008000
5	2	2	957590	861831000
8	2	3	13603	12242700
12	2	4	165540	148986000
17	2	5	12575	11317500
22	2	6	839	755100
6	3	1	233	209700
9	3	2	41861	37674900
13	3	3	3632	3268800
18	3	4	4577	4119300
23	3	5	1348	1213200
27	3	6	190	171000
10	4	1	1902	1711800
14	4	2	241311	217179900
19	4	3	1507	1356300
24	4	4	2388863	2149976700
28	4	5	17484	15735600
31	4	6	846	761400
15	5	1	136	122400
20	5	2	95510	85959000
25	5	3	2483	2234700
29	5	4	15675	14107500
32	5	5	4683	4214700
34	5	6	57	51300
21	6	1	3347	3012300
26	6	2	3025	2722500
30	6	3	355	319500
33	6	4	1612	1450800
35	6	5	511	459900
36	6	6	3323	2990700

2. LULC CHANGE-2000-2010– MCM ITERATION RESULT

Cross Class Code	New Class	Reference Class	Pixel Sum	Area[metre^2]
1	1	1	94700	85230000
2	1	2	8498	7648200
4	1	3	1381	1242900
7	1	4	15209	13688100
11	1	5	515	463500
16	1	6	5084	4575600
3	2	1	4140	3726000
5	2	2	202701	182430900
8	2	3	13839	12455100
12	2	4	31799	28619100
17	2	5	19211	17289900
22	2	6	1625	1462500
6	3	1	1012	910800
9	3	2	24809	22328100
13	3	3	8387	7548300
18	3	4	4087	3678300
23	3	5	4669	4202100
27	3	6	802	721800
10	4	1	10737	9663300
14	4	2	908044	817239600
19	4	3	25887	23298300
24	4	4	2599416	2339474400
28	4	5	92515	83263500
31	4	6	2060	1854000
15	5	1	45	40500
20	5	2	6078	5470200
25	5	3	1996	1796400
29	5	4	1009	908100
32	5	5	1621	1458900
34	5	6	202	181800
21	6	1	4291	3861900
26	6	2	1137	1023300
30	6	3	351	315900
33	6	4	397	357300
35	6	5	13	11700
36	6	6	2401	2160900

3. LULC CHANGE-2010-2020– MCM ITERATION RESULT

Cross Class Code	New Class	Reference Class	Pixel Sum	Area[metre^2]
1	1	1	76736	69062400
2	1	2	3481	3132900
4	1	3	720	648000
7	1	4	2017	1815300
11	1	5	273	245700
16	1	6	2830	2547000
3	2	1	13276	11948400
5	2	2	218080	196272000
8	2	3	20546	18491400
12	2	4	1039431	935487900
17	2	5	4088	3679200
22	2	6	1263	1136700
6	3	1	1173	1055700
9	3	2	19406	17465400
13	3	3	16206	14585400
18	3	4	41784	37605600
23	3	5	5027	4524300
27	3	6	345	310500
10	4	1	23204	20883600
14	4	2	18281	16452900
19	4	3	1364	1227600
24	4	4	2439945	2195950500
28	4	5	302	271800
31	4	6	441	396900
15	5	1	4398	3958200
20	5	2	8064	7257600
25	5	3	3370	3033000
29	5	4	59017	53115300
32	5	5	988	889200
34	5	6	1420	1278000
21	6	1	6536	5882400
26	6	2	5999	5399100
30	6	3	1554	1398600
33	6	4	56449	50804100
35	6	5	271	243900
36	6	6	2288	2059200

4.LULC CHANGE-1990-2020– MCM ITERATION RESULT

Cross Class Code	New Class	Reference Class	Pixel Sum	Area [metre^2]
1	1	1	60235	54211500
2	1	2	10867	9780300
4	1	3	455	409500
7	1	4	11646	10481400
11	1	5	505	454500
16	1	6	2349	2114100
3	2	1	3983	3584700
5	2	2	918809	826928100
8	2	3	13319	11987100
12	2	4	341253	307127700
17	2	5	17628	15865200
22	2	6	1692	1522800
6	3	1	449	404100
9	3	2	61822	55639800
13	3	3	3784	3405600
18	3	4	16005	14404500
23	3	5	1575	1417500
27	3	6	307	276300
10	4	1	6997	6297300
14	4	2	284554	256098600
19	4	3	2088	1879200
24	4	4	2177339	1959605100
28	4	5	10417	9375300
31	4	6	2138	1924200
15	5	1	1914	1722600
20	5	2	40870	36783000
25	5	3	1753	1577700
29	5	4	26173	23555700
32	5	5	5173	4655700
34	5	6	1374	1236600
21	6	1	2553	2297700
26	6	2	37564	33807600
30	6	3	780	702000
33	6	4	27297	24567300
35	6	5	2375	2137500
36	6	6	2528	2275200

5. LULC CHANGE DETECTION ANALYSIS : CHANGE MATRIX 1990-2000

V_ReferenceClass	Water	Bareland	Urban	Forest	Agriculture	Wetland	Total
Water	62.4933	1.008	0.2097	1.7118	0.1224	3.0123	68.5575
Bareland	13.6782	861.831	37.6749	217.1799	85.959	2.7225	1219.0455
Urban	0.5391	12.2427	3.2688	1.3563	2.2347	0.3195	19.9611
Forest	21.1239	148.986	4.1193	2149.9767	14.1075	1.4508	2339.7642
Agri-culture	0.9657	11.3175	1.2132	15.7356	4.2147	0.4599	33.9066
Wet-land	4.6242	0.7551	0.171	0.7614	0.0513	2.9907	9.3537
Total	103.4244	1036.1403	46.6569	2386.7217	106.6896	10.9557	3690.5886

6. LULC CHANGE DETECTION ANALYSIS : CHANGE MATRIX 2000-2010

ReferenceClass	Water	Barren land	Built-up	Forest	Agricul-ture	Wetland	Total
Water	85.23	3.726	0.9108	9.6633	0.0405	3.8619	103.4325
Barren land	7.6482	182.4309	22.3281	817.2396	5.4702	1.0233	1036.14
Built-up	1.2429	12.4551	7.5483	23.2983	1.7964	0.3159	46.6569
Forest	13.6881	28.6191	3.6783	2339.474	0.9081	0.3573	2386.725
Agriculture	0.4635	17.2899	4.2021	83.2635	1.4589	0.0117	106.6896
Wetland	4.5756	1.4625	0.7218	1.854	0.1818	2.1609	10.9566
Total	112.8483	245.9835	39.3894	3274.793	9.8559	7.731	3690.601

7. LULC CHANGE DETECTION ANALYSIS : CHANGE MATRIX 2010 –2020

ReferenceClass	Water	Bareland	Urban	Forest	Agriculture	Wetland	Total
Water	69.06	11.95	1.06	20.88	3.96	5.88	112.79
Bareland	3.13	196.27	17.47	16.45	7.26	5.40	245.98
Urban	0.65	18.49	14.59	1.23	3.03	1.40	39.38
Forest	1.82	935.49	37.61	2195.95	53.12	50.80	3274.78
Agriculture	0.25	3.68	4.52	0.27	0.89	0.24	9.85
Wetland	2.55	1.14	0.31	0.40	1.28	2.06	7.73
Total	77.45	1167.02	75.55	2235.18	69.53	65.79	3690.51570

8. LULC CHANGE DETECTION ANALYSIS : CHANGE MATRIX 1990-2020

V_ReferenceClass	Water	Barren	land	Built-up	Forest	Agriculture	Wetland
Water	54.2115	3.5847	0.4041	6.2973	1.7226	2.2977	68.5179
Barren land	9.7803	826.9281	55.6398	256.0986	36.783	33.8076	1219.037
Built-up	0.4095	11.9871	3.4056	1.8792	1.5777	0.702	19.9611
Forest	10.4814	307.1277	14.4045	1959.605	23.5557	24.5673	2339.742
Agriculture	0.4545	15.8652	1.4175	9.3753	4.6557	2.1375	33.9057
Wetland	2.1141	1.5228	0.2763	1.9242	1.2366	2.2752	9.3492
Total	77.4513	1167.016	75.5478	2235.18	69.5313	65.7873	3690.513