Collection and Analysis of Soil Organic Carbon from TOF (Non-Forest)



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MINISTRY OF ENVIRONMENT, FOREST & CLIMATE CHANGE

GOVERNMENT OF INDIA



Collection and Analysis of Soil Organic Carbon from TOF (Non-Forest)

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Preface

Climate change has emerged as the leading environmental issue in the recent past. It is posing a serious threat to the environment and the quality of human life all over the world. Forests play an important role in mitigation and adaptation of climate change. Forests sequester and store more carbon than any other terrestrial ecosystem. Carbon sequestration by forest has attracted much interest as a mitigation approach as it has been considered a relatively inexpensive means of addressing climate change immediately. UNFCCC monitors the Green House gases through the process of National Communication (NATCOM).

India is a Party to the United Nations Framework Convention on Climate Change and report the GHG inventory on a regular basis.

Forest Survey of India has been providing the information of forests sub-sector for preparation of GHG inventory of LULUCF sector to the Ministry for reporting to various NATCOMs. As per the latest report, LULUCF sector is offsetting about 14% of CO_2 from the atmosphere. The carbon stock is estimated by FSI from two regular activities of FSI *viz.* Forest Cover Mapping and National Forest inventory. FSI reports the carbon stock for all the five carbon pools namely AGB, BGB, Deadwood, Litter and Soil Organic Carbon (SOC). Out of five carbon pools, SOC contributes the maximum carbon stock.

As SOC is an important Carbon pool and FSI provides regular estimates of SOC only for Forest area, it was felt that the estimation of SOC is non Forest Area under different land use category will be important for improvement of SOC estimates for NATCOM. Accordingly, MoEF & CC has given a project to FSI for estimation of SOC in non-forest areas. Under this project, FSI has collected soil sample from different land categories (As required in IPCC GPG) in non-forest areas spread over different agro climatic zones of the country. The data has been analysed and results are given in the report.

Anoop Singh



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NFI

Executive Summary

"Soil Organic Matter" is composed mainly of hydrocarbons. Therefore, carbon, hydrogen and oxygen are their major constituents. It has also small amount of other elements, such as nitrogen, phosphorous, sulphur, potassium, calcium, magnesium etc. Among, all the elements of soil organic matter, the soil organic carbon is omnipresent and work as a crucial indicator of the same. In forest environments, the biomass carbon is categorised in five major pools: the 'above ground biomass' (AGB), 'below ground biomass' (BGB), dead wood, litter and 'Soil Organic Carbon' (SOC). Among which, SOC accounts for nearly 50% of the total organic carbon locked in forests.

Tree Outside Forests (TOF) refers to all trees growing outside Recorded Forest Area (RFA) irrespective of patch size which, may or may not be larger than 1 ha. The TOF, having tree clusters of less than one (01) ha is classified under non-forest. The lesser abundance of bigger trees and their deep roots make the soil organic carbon more relevant in the TOF. Soil organic carbon is the basis of soil health *vis-a-vis* sustainable agriculture. Therefore, the loss of soil organic carbon by any means is detrimental to soil health and affects agricultural production. Moreover, soil carbon is the major active pool of terrestrial carbon; therefore, policies and measures will be pivotal not only to sustainable agricultural production but also to achieve global climate targets.

Trees outside forests (TOFs) are important natural resources that contribute substantially to national biomass and carbon stocks and to the livelihood of people in many regions of the world. Over the last decades, decision makers have become increasingly aware of the importance of TOF, and consequently, these tree resources are often considered in forest monitoring systems. Therefore, the inter-relations between Trees and Soil are symbiotic in nature, in terms co-existence and mutual dependence on carbon sequestration.

Agriculture being the mainstay of Indian Economy; it is occupying the highest land use coverage of the country. As a result, for agricultural resource development, India has been broadly divided into fifteen agricultural regions based on agro-climatic features, **particularly soil type**, **major land use classes**, climate including temperature and rainfall and its variation, availability of water resources.

These fifteen regions are given as follows:

1. Western Himalayan Region
2. Trans-Gangetic Plain Region
3. Upper Gangetic Plain Region
4. Central Plateau and Hills
5. Western Plateau and Hills
6. Southern Plateau and Hills
7. Middle Gangetic Plain Region
8. Lower Gangetic Plain Region
9. Eastern Coastal Plain and Hills
10. Eastern Plateau and Hills
11. Eastern Himalayan Region
12. Island Region
13. Western Coastal Plains and Ghats
14. Western Dry Region
15. Gujarat Plains and Hills

Land use pattern is the arrangement or layout of the uses of the land, which, may be used for forestry, agriculture, grasslands, wetlands, settlements and other lands. The factors for which the land can be used in various ways is determined by many factors like relief features, climate, the density of the population, **soil**, applicability, and socio-economy etc. Among which, the factor **"Soil"** is one of the most important one, as its properties are strongly influenced by land use and management practices. Therefore in the present study, along with fifteen agro-climatic-zones, five major land use classes (i) Agriculture, ii) Grass land, iii) Other land, iv) Settlement and v) Wetland) have been selected for soil organic carbon study.

The present study was aimed to attain the following objectives:

1. To determine the carbon stocks present in the soil under TOF, distributed under different land use classes other than forest.

2. To analyse the carbon stocks present in the soil under TOF, spread over various agro-climatic zones other than forest.

Visualizing the importance of "Soil Organic Carbon", in the TOF comprising of various "Agro-Climatic Zones" and "Land Use Classification", soil samples from the entire country were collected through stratified random sampling method. Out of designated 20,000 plus TOF plots as surveyed by FSI in two years, a total of 1602 plots have been selected for sampling to estimate country wide soil organic carbon.

The strata for soil sample collection have been created from all the intersections of 5 land use classes and 15 agro-climatic zones. Total 75 strata have been created with the intersection of land use classes and agro-climatic zones. However, in reality we could get 74 combined classes, since no (or negligible) 'Grassland' land use were marked in one of the agro-climatic zone, i.e. 'Island Region'.

From each of the combined classes number of points sampled are calculated based on the fraction of area exists with respect to the total area (excluding 'Forest' land use) in India. The survey points were selected from each of the combined classes or strata in such a way that the survey parties need to travel minimum number of States, with maximum land use coverage in all the agro-climatic zones, without altering the variability of the collected samples from respective strata. The number of samples obtained for each stratum was made in such a way that the minimum samples for each stratum should at least be five (5), so that proper mean and variance could be ascertained.

The sample plots of 10m X 10m were laid in such a way that the centre of the plot be the desired Geo-coordinate. In the centre, as well as, each of the four corners of the 10 m X 10 m plot, five smaller plots of 1 m X 1 m were laid. The soil samples were collected from all the sub-plots at a depth of 15 to 30 cm (sub-surface soil). The collected soil samples

from 5 subplots were mixed together over a clean paper and 250 g of the mixed sample was taken in order to minimize the local variability. The soil samples were then brought for "Soil Organic Carbon" analysis at the laboratory. The collected soil samples first dried and processed. The samples were thereafter analysed for soil organic carbon using the equipment that, records carbon from the carbon di-oxide (CO_2) peak by the Infra-Red (IR) detector, fitted inside the instrument.

Salient Findings of the Study:

- Agriculture is the backbone of Indian economy, as it is encompassing an area of 16,44,000 km^2; which, is nearly 50% of total geographical area of the country. The settlement area is presently around 3%, wetland is around 5% and the area of grassland in India is around 7% of country's total area.
- Most of the sample points 1027 in number out of 1602 are lying under agriculture land use, because agriculture being the dominant land use, covers nearly 50% of country's geographical area.
- In terms of areas, Agriculture, Grasslands and Settlements land uses are showing an increasing trend over the years, from 2005 to 2017. The other land, shows a constant decrease in area within the same time frame. There is a jump of nearly 10 to 11% of land use area for the settlement. In comparison to that, forest and agricultural land is increased around 2 to 3 % in the same time-period. The population rise in the country is definitely a concern, as it may rise the settlement sprawl further. This exponential rise in population is therefore, creating a constant depletion of cultivable land and man ratio.
- The "Western Himalayan Region" agro-climatic zone covers maximum area of 3,11,688 km^2, without forest cover and were having maximum of 194 soil sample points. Since, a major portion of "Western Himalayan Region" is under snow cover and devoid of any soil, therefore, the number of sample points were reduced in practical scenario to 164.
- The area of the non-forest area of "Island region" is negligible in comparison to the main land India. Therefore, the number of soil sample from any agro-climatic zone was calculated as only "One". However, for any reasonable estimate generation

only one sample point is absurd. Hence, in reality 20 soil sample points were collected from "Island region".

- The per hectare figure of carbon stock is very high in the settlements (35.25 t/ha) and other land (34.62 t/ha). In case of agricultural lands, the soil organic carbon content per ha land (29.55 t/ha) is relatively lower than settlement and the other land. One of the reason of this may be due to the fact that in many cases settlements and other lands are associated with many agro-based industries like: sugar mill, paper mill, distillery plant and municipal sewage treatment plant; which, deposits their organic carbon rich wastes in those lands.
- The estimated soil carbon stock in agricultural land is the maximum (4,858 Mt). This is due to the reason of maximum coverage of agricultural land use in India, followed by other land (1,329 Mt) and Grassland (648 Mt).
- The mean soil organic carbon stock per hectare is maximum in the "Western Coastal Plains and Ghats" (57.68 Tonnes/Ha), followed by "Gujarat Plains and Hills" (48.20 t/ha) and "Western Himalayan Region" (45.41 t/ha). The "Western Dry Region" (16.18 t/ha) is having very less organic carbon content. The Gangetic Plain Regions (Trans - 12.34 t/ha, Upper - 21.29 t/ha, Middle - 22.23 t/ha and Lower – 21.49 t/ha) also contains relatively lower carbon content. The rise in population in the "Indo-Gangetic Plains" may have cause the depletion of fertile agricultural lands. Moreover, the need for excess utilization of agricultural fields for raising cropping intensity to feed large population may have caused the lesser time in managing soil organic carbon resources.



Glossary

Aboveground biomass (AGB): The AGB carbon pool consists of all living vegetation above the soil, inclusive of stems, stumps, branches, bark, seeds and foliage.

Agriculture Land: These are the lands primarily used for farming and for production of food, fibre, and other commercial and horticultural crops. It consists of Cropland, Plantations, Fallow and Current Shifting Cultivation areas.

Agro-Climatic Zones: The Planning Commission after examining the earlier studies on the regionalisation of the agricultural economy has recommended that agricultural planning be done based on agro-climatic regions. For resource development, the country has been broadly divided into fifteen agricultural regions (mentioned within the report) based on agro-climatic features such as; soil type, climate including temperature and rainfall and its variation in the water resources availability

Base: A specification or product that has been formally reviewed and agreed upon, that thereafter serves as the basis for further development.

Belowground biomass (BGB): The BGB carbon pool consists of the biomass contained within live roots.

Benchmark: Something that serves as a standard by which others may be measured or judged.

Biodiversity: It refers to the variety of life on Earth at all its levels, from genes to ecosystems, and can encompass the evolutionary, ecological, and cultural processes that sustain life.

Biomass: Biomass is the organic material that comes from plant or animal and can used as renewable bioenergy sources.

Biomass Expansion Factor (BEF): The ratio of aboveground biomass and bole biomass (defined by a merchantable measure or a minimum DBH). It is used to quantify carbon stock in forests.

Block Plantation: Tree plantations in compact blocks of more than 0.1 ha on lands outside recorded forest areas.

Canopy: The cover of branches and foliage formed by crowns of trees.

Canopy Cover: The percentage of ground covered by a vertical projection of outermost perimeter of natural spread of foliage of plants.

Canopy Density: Percent area of land covered by canopy of trees. It is expressed as a decimal coefficient, taking closed canopy as unity.

Carbon dioxide equivalent (CO_2 eq.): It is a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential, by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential. (***Note:*** *In the present study, only the carbon is considered and CO_2 eq. is calculated by multiplying their molecular ratio).*

Carbon Pool: Carbon pools are major components of an ecosystem that can either accumulate or release carbon.

Carbon Sequestration: Process by which, Carbon dioxide is removed from the atmosphere and remain in solid or liquid form by a natural or artificial process.

Carbon Sink: A carbon sink is a carbon pool from which more carbon flows in than out. Soils can act as sink through the process of leaf drips from trees, crop residues and resultant microbiological interaction as a process of sequestration.

Cartographic Limit: The minimum area of a feature, which can be presented on a map at a given scale.

Climate change: Refers to any significant change in the measures of climate lasting for an extended period of time.

Coastal Region: Coastal areas are local administrative units that are bordering or close to a coastline. A coastline is the line where land and bay, sea or ocean water surfaces meet with each other.

Combustion: Combustion is a chemical process in which a substance reacts rapidly with oxygen and gives off heat. If the substance is organic matter, which, is largely made of hydrocarbons; then after combustion Carbon dioxide (CO_2) will be a major product.

Cropland: This includes all croplands and fallow land area. (As per India's Second Biennial Update Report).

Crown Area: It is the area of horizontal projection of a tree crown on the ground.

Dead Organic Matter: The DOM carbon pool contains all non-living woody biomass and can be divided into wood (fallen trees, roots and stumps with diameter over 10cm) and litter (greater than 2mm and less than 10cm diameter) components.

Ecosystem: An ecosystem consists of all the organisms and the physical environment with which they interact. These biotic and abiotic components are linked together through nutrient cycles and energy flows.

Emissions: Release of greenhouse gases and/or their precursors into the atmosphere over a specified area and period of time.

Emissions factor: Emissions factor gives gains and losses in carbon stock as a standard rate of emissions per unit activity.

Error: Error describes the difference between a value obtained from a data collection process and the 'true' value for the population. The greater the error, the less representative the data are of the population. (***Note***: The data collected from population is called "Sample" and the procedure for collecting sample data from population is called "Sampling").

False Colour Composite: The image generated by projecting any three spectral bands of the satellite data on the red, green and blue channels and does not show features in true colours.

Farm Forestry: The practice of cultivating and managing trees in compact blocks on agricultural lands.

Forest Area: The area recorded as a forest in the Government records. It is also referred to as "Recorded Forest Area".

Forest Blank: A patch within a forest, which bears few or no trees.

Forest Cover: All lands, more than one hectare in area, with a tree canopy density of more than 10 percent irrespective of ownership and legal status. Such lands may not necessarily be a recorded forest area. It also includes orchards, bamboo and palm.

Forest Inventory: The measurement of certain parameters of forests to assess the growing stock and other characteristics of forests.

Gain Loss Approach: A method to estimate annual emissions or removals of CO_2 as the sum of gains and losses in carbon pools occurring on areas of land subject to human activities.

Gangetic Plain: The Gangetic Plain, also known as the ***"Indo-Gangetic Plain"***, is a stretch of fertile plain on the Indian subcontinent encompassing the immediate branches and tributaries of river Ganges.

Geographic Information System: A computer based system for capturing, storing, manipulating, analysing and displaying data, which are spatially referenced to the earth.

Ghats: This term is used in the Indian subcontinent, depending on the context, that could refer to a range of stepped hills with valleys ("*Ghati"* in Hindi), such as the Eastern Ghats and Western Ghats.

Grassland: The areas of natural grass along with other vegetation, predominantly grass-like plants (Monocots) and non-grass-like herbs (except Lantana species, which are to be

classified as scrub). It includes natural/semi-natural grass/ grazing lands of Alpine / Sub-Alpine or temperate or subtropical or tropical zones, desert areas and manmade grasslands.

As per As per India's Second Biennial Update Report: Grassland are the areas covered with grassy and herbaceous growth as well as degraded forests with less than 10% tree canopy density.

Greenhouse gases: Gases that has the property of absorbing infrared radiation (net heat energy) emitted from Earth's surface and reradiating it back to Earth's surface, thus contributing to the greenhouse effect.

Hydrology: Hydrology is the study of the distribution and movement of water both on and below the Earth's surface, as well as the impact of human activity on water availability and conditions.

Land Cover: Broad land use classes interpreted from satellite data. It includes very dense forest, moderately dense forest, open forest, scrub and non-forest for the purpose of this report.

Litter: Woody material of trees having diameter <5cm which is not decomposed.

Land Use, Land-Use Change and Forestry: It is a category within UNFCCC accounting framework for greenhouse gas (GHG) emissions. It includes carbon pools of living biomass (above and below ground), dead organic matter (dead wood and litter) and organic soil carbon.

Mitigation: Mitigation in context of climate change refers to efforts to reduce or prevent emission of greenhouse gases.

National Aeronautics and Space Administration (NASA): The National Aeronautics and Space Administration is an independent agency of the U.S. federal government responsible for the civil space program, aeronautics research, and space research.

Nationally Determined Contributions (NDC): NDC articulates commitments by each country to reduce its national emissions and adapt to the impacts of climate change. Countries across the globe adopted this international climate agreement at UNFCCC Conference of the Parties (COP21) in Paris in December 2015.

Net Change (in Forest Cover): The sum of positive and negative changes in forest cover over a period of two assessments for a given area.

Non Forest Land: Land without forest cover.

Open Forest: Lands with forest cover having a canopy density between 10 to 40 percent.

Other land: In the present study, "Other land" is considered as the combination of Wasteland, Scrub, Rann and Snow Cover.

Parent Material: Parent material is the underlying geological material (generally bedrock) in which soil horizons form. Soils typically inherit a great deal of texture, structure and minerals compositions from their parent material. They are often classified based upon their contents of mineral material that has undergone some degree of physical or chemical weathering.

Physiographic Division: Physiographic divisions separate the Earth into different areas based on the predominant types of landforms found in each region. As example: Mountain, Plain, Plateau, Desert, Islands etc. are different physiographic divisions. In early 20^{th} century geomorphology is renamed as physiography at regional scale.

Phytomass: It is the quantitative estimate of the total mass of plants in a stand, population, or within a given area, at a given time.

Plateau: A plateau is a flat, elevated landform that rises sharply above the surrounding area on at least one side.

Precipitation: Precipitation is rain, snow, sleet, or hail — any kind of weather condition where something's falling from the sky.

Protected Forest: An area notified under the provisions of the Indian Forest Act or other State Forest Acts, having limited degree of protection. In protected forest all activities are permitted unless prohibited.

Recorded Forest Area: Forest Area recorded as forests in Government records.

Remote sensing: Remote sensing is the acquisition of data, such as total forest area, forest type, canopy cover and height, from sensors on board aircraft or space-based platforms.

Reserved Forests: An area so constituted under the provisions of the Indian Forest Act or other State Forest Acts, having full degree of protection. In Reserved forests all activities are prohibited unless permitted.

Scrub: Degraded forestlands having canopy density less than 10 percent.

Sample (Statistics): A sample refers to a smaller, manageable version of a larger group. It is a subset containing the characteristics of a larger population. Samples are used in statistical testing when population sizes are too large for the test to include all possible members or observations. A sample should represent the population as a whole and not reflect any bias toward a specific attribute.

Sampling (Statistics): Sampling is the selection of a subset of individuals from within a statistical population to estimate characteristics of the whole population. Statisticians attempt to collect samples that are representative of the population in question.

Settlement: It is an area of human habitation developed due to non-agricultural use and that has a cover of buildings, transport and communication, utilities in association with water, vegetation and vacant lands.

As per As per India's Second Biennial Update Report: Settlements Include major built-up areas and human habitations - both rural and urban.

Source (of carbon): A carbon source is a carbon pool from which more carbon flows out than flows in: forests can often represent a net source of carbon due to the processes of decay, combustion and respiration.

Soil Organic Carbon (SOC): Soil organic carbon is a measureable component of soil organic matter. Soil carbon provides source of nutrients through mineralisation, helps to aggregate soil particles (structure) to provide resilience to physical degradation, increases microbial activity, increases water storage and availability to plants, and protects soil from erosion.

Soil Organic Matter (SOM): It is the organic component of soil containing small plants residues, small living soil organism and decomposed organic matter.

Soil Health: Soil health is defined as the "the continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, promote the quality of air and water environments, and maintain plant, animal, and human health".

Spatial Resolution: The minimum area on earth's surface that can be captured by a satellite sensor as being separate from its surroundings and is represented by a "pixel".

Spectral Resolution: It refers to the width and number of spectral bands. The range of wave lengths that a satellite imaging system can detect. The narrower the bands, the greater the spectral resolution.

Strata (Singular: **Stratum):** Stratification is the division of the area into more homogenous units of similar land use and agro-climatic zone. The purpose of stratification is to increase the accuracy and precision of accounting by reducing field data variability.

Sustainable Development Goals: It is known as global goals, and are adopted as a universal call to action to end poverty, protect the planet and ensure that all people enjoy peace as well as prosperity by 2030. These goals are adopted by all United Nations Member States in 2015.

Terrestrial: Anything related with the Planet Earth.

Thematic Maps: Maps, generally showing forest cover, forest types, major species composition, crown density, other land uses etc. themes; prepared by interpretation of satellite images and verified by ground truth checking are commonly designated as thematic maps in forestry sector.

Trees Outside Forests: It refers to all trees growing outside recorded forest areas irrespective of patch size.

Trend (Statistics): A trend is a pattern found in time series datasets; it is used to describe if the data is showing an upward or downward movement for part, or all of, the time series.

Vulnerability: Vulnerability refers to the inability (of a system) to withstand the effects of a hazard (or hostile environment).

Wetland (NRSC/ISRO Definition): All submerged or water-saturated lands, natural or man-made, inland or coastal, permanent or temporary, static or dynamic, vegetated or non-vegetated, which necessarily have a land-water interface, are defined as wetlands.

Units Used

Sl. No.	Name of Unit	Symbol	Value
1.	metre	m	1 m = 100 cm
2.	centimetre	cm	
3.	tonnes	t	1 t = 1,000 kg
4.	hectare	ha	1 ha = 0.01 km^2
5.	million hectare	m ha	100 ha = 1 km^2
6.	square Kilometre	km^2	1 km^2 = 1000 m X 1000 m
7.	million tonnes	Mt	1 m t = 1,000,000 t
8.	CO_2 equivalent	CO_2 eq.	1 C = 44/12 CO_2 eq. = 3.67 CO_2 eq.
9.	centigrade	°C	0°C = 32° Fahrenheit = 273 K

Table of Contents

Preface 5

Acknowledgements 7

Executive Summary 9

Glossary 15

Units Used 22

1. Introduction 29

1.1 Soil Organic Carbon and Its Significance 29

1.2 Tree Outside Forest (TOF) – Land Uses Other than Forest 31

1.3 Importance of TOF 32

1.4 Soil and Its Importance for Trees 33

1.5 Agro-Climatic Zones of India and Its Significance 33

1.6 Land Use Trends Over the Years in India 50

1.7 Land Use and its Significance with Soil 52

1.8 Importance of Organic Carbon 53

1.9 Objective 55

2. Materials, Methods and Field Studies 59

2.1 Sampling Scheme 59

2.2 Land Use Classes 60

2.3 Agro-Climatic Zones 61

2.4 Creation of Strata and Its Validation 62

2.5 Software Used 63

2.6 Usual Sampling Procedures Follow by FSI during TOF Inventory 63

2.6.1 Methodology followed from 1991 to 2001 65

2.6.2 Methodology followed from 2001 to 2016 66

2.6.3 Methodology adopted from 2016 onwards 67

2.7 Plot Laying & Soil Sample Collection from TOF by FSI in the Present Study 67

2.8 Laboratory Analysis of Collected Soil Samples 69

3. Results and Discussion 75

3.1 Identified Major Land Use Classes 76

3.2 Identified Major Agro-Climatic Zones 82

3.3 Soil Organic Carbon Content in Various Land Use Classes 86

3.4 Soil Organic Carbon Content in Various Agro-Climatic Zones 90

4. Conclusion and Future Vision 99

5. References 103

6. Annexure 111

List of Tables

Table 1: Year wise Trend of Land Use Area Pattern (Area in m ha) 50

Table 2: Various Major Land Use Classes in India 76

Table 3: Distribution of Collected Soil Sample Points Across Various Agro Climatic Zones 84

Table 4: Estimated Soil Organic Carbon in Various Land Use Classes in TOF 89

Table 5: Estimated Soil Organic Carbon in TOF of Various Agro-Climatic Zones 91

Table 6: One way ANOVA Table of Soil Organic Carbon across various Land Use Classes 111

Table 7: One way ANOVA Table of Soil Organic Carbon across various Agro-Climatic Zones 111

List of Figures

Fig. 1: Scattered Trees Outside Forest as Agroforestry 32

Fig. 2: Landscape in Western Himalayan Region (Himachal Pradesh) 34

Fig. 3: Tea Garden in Eastern Himalayan Region (Assam) 35

Fig. 4: Agriculture in Lower Gangetic Plain Region (West Bengal) 36

Fig. 5: River Bed in Middle Gangetic Plain Region (Uttar Pradesh) 37

Fig. 6: Agriculture in Upper Gangetic Plain Region (Uttar Pradesh) 38

Fig. 7: Agriculture and Agroforestry in Trans Gangetic Plain Region (Haryana) 39

Fig. 8: Agriculture in Eastern Plateau and Hill Region (Odisha) 40

Fig. 9: Permanent Fallow in Central Plateau and Hill Region (Madhya Pradesh) 41
Fig. 10: Black Soil in Western Plateau and Hill Region (Maharashtra) 42
Fig. 11: Coconut Plantation in Southern Plateau and Hill Region (Tamil Nadu) 43
Fig. 12: Cultivation in East Coast Plain and Hill Region (Coastal Odisha) 44
Fig. 13: Western Ghats in West Coast Plain and Hill Region (Maharashtra) 45
Fig. 14: Gujarat Plain and Hill Region (Gujarat) 46
Fig. 15: Western Plain and Hill Region (Rajasthan) 47
Fig. 16: Island Region (Andaman) 48
Fig. 17: Agro-Climatic Zones of India 49
Fig. 18: Trend of Land use Area (m ha) from the year 2005 to 2017 in India 51
Fig. 19: Alternate Crop growth and Tillage for Improving Soil Organic Carbon 53
Fig. 20: Entire 20,000 Point Population Overlaid On Agro-Climatic Zones of India 64
Fig. 21: Pictorial Representation of Various Forms of TOF 66
Fig. 22: Schema Showing the Laying of Plots 68
Fig. 23: Mixing of Soil Samples in the Field 69
Fig. 24: Plot Laying and Soil Sample Collection 69
Fig. 25: Weighing, Drying and Carbon Measuring Instruments Used for TOC Analysis 70
Fig. 26: Distributed Soil Sample Points Across TOF In India 71
Fig. 27: Distributed Soil Sample Points Across TOF In India 73
Fig. 28: Distribution of Area under Different Land Use Classes 77
Fig. 29: A Typical Agricultural Land Use in India 77
Fig. 30: A Typical Settlement Land Use in India 78
Fig. 31: A Typical Marshy Wetland Land Use in India 78
Fig. 32: A Typical Grassland in India 79
Fig. 33: A Typical Other Land Use in India (A permanent fallow, scrub) 79
Fig. 34: Distribution of Soil Sample Collection Points Across Various Land Uses 81
Fig. 35: Distribution of Soil Sample Collection Points in Various Agro-Climatic Zones 85
Fig. 36: Distribution of Soil Sample Collection Points in Various Agro-Climatic Zones 86
Fig. 37: Soil Organic Carbon (Tonnes/Ha) in Various Land Use Classes 90
Fig. 38: Soil Organic Carbon (Tonnes/Ha) in Various Agro-Climatic Zones 93
Fig. 39: Range of Estimated Soil Organic Carbon (%) in the TOF Soils of India 94



CHAPTER ONE

Introduction



Collection and Analysis of Soil Organic Carbon from TOF (Non-Forest)

1. Introduction

1.1 Soil Organic Carbon and Its Significance

Organic matter makes up just a small fraction of most soil mass and the major portion of soil is made up of inorganic minerals. However, in smaller percentage "Soil Organic Matter" remains in soil; it has extremely important role in building the physical, chemical and biological function of the same. Organic matter contributes to soil health by nutrient retention and its turnover. It also makes proper soil structure, greater moisture retention capacity and its availability, quick decay of pollutants, and carbon sequestration. "Soil Organic Matter" is composed mainly with carbon, hydrogen and oxygen, and has small amounts of other elements, such as nitrogen, phosphorous, sulphur, potassium, calcium, magnesium etc. It is divided into 'living' and 'dead' components and can range from very recent inputs, such as stubble, fresh leaf drip to largely decayed materials that might be of many hundreds years old. Among, all the elements of soil organic matter, the soil organic carbon is omnipresent and work as a crucial indicator of the same. Therefore, in order to get the closest quantitative estimates of soil organic matter, soil organic carbon is measured **(Edward, 2022)**[1]. Therefore, managing soil organic carbon by alternate cropping, tillage are the key to maintain the soil health in sustainable manner.

In forest ecosystems, enormous carbon is stored which, is divided into five carbon pools **(GPG, 2003)**[2]. In forest environments, the living portion of biomass carbon is categorised in two pools: the 'above ground biomass' (AGB) and 'below ground biomass' (BGB) and are stores of significant amount of carbon. The 'dead organic matter' (DOM) is also categorised in two pools: 'dead wood' and 'litter'. The fifth pool is 'Soil Organic Carbon' (SOC) which, accounts for nearly 50% of the total carbon locked in forests **(FSI, 2019)**[3].

[1] Edward T. (2022). Agriculture and Food. Department of Primary Industries and Regional Development. Government of Western Australia. https://www.agric.wa.gov.au/measuring-and-assessing-soils/what-soil-organic-carbon

[2] GPG (2003). Good Practices Guidance for Land Use, Land-Use Change and Forestry (2003), Intergovernmental Panel on Climate Change, Japan.

[3] FSI (2019). India State of Forest Report 2019. Forest Survey of India. Ministry of Environment, Forest and Climate Change. Government of India. ISBN 978-81-941018-0-2.

However, in the TOF, the lesser abundance of bigger trees and their deep roots make the soil organic carbon more relevant. Soil organic carbon is the basis of sustainable agriculture. Farmers are interested in retaining and increasing soil organic carbon for individual fields in order to improve soil health and yield. The increasing pools of soil organic carbon in agricultural ecosystems is very important for restoring soil health and sustainable crop production **(Gabreyes, 2019)**[4]. Soil organic carbon is the key factor in maintaining soil pH, which, thereby, augments the supply of floral nutrients by improving soil aeration, water retention capacity and drainage. It also immobilizes pollutants and heavy metals and enhances soil microbial growth.

Therefore, the loss of soil organic carbon by any means is detrimental to soil health. The loss of soil organic carbon happens due to adverse climate change, fire incidences, harvesting and thinning of plants, livestock grazing, over use of pesticides that kills soil microorganisms, tree mortality and presence of invasive species **(Berryman *et al.*, 2020)**[5]. Soil scientists therefore have long advocated that increased soil organic matter *vis-a-vis* soil organic carbon is beneficial for soil fertility and resilience to changing adverse climatic conditions **(White, 2015)**[6].

A number of global initiatives reflects recent attention and raised expectations about soil organic carbon's (SOC) potential to contribute to climate change mitigation and adaptation. Soil carbon being the major active pool of terrestrial carbon, thus, policies and measures will be pivotal in achieving global climate targets. As per research findings, SOC sequestration may reduce the net annual greenhouse gas emissions from Agriculture, Forestry and Other Land Use by between 3% and 71%, while simultaneously supporting

[4] Gebreyes G. (2019). Soil Organic Matter and its Role in Soil Health and Crop Productivity Improvement. *Academic Research Journal of Agricultural Science and Research*. **Vol.7** (7): 475-483.
[5] Berryman E., Hatten J., Dumroese D.S.P., Heckman K.A., D'Amore D.V., Puttere J., SanClements M., Connolly S.J., Perry C.H.,and Domke G.M. (2020). Forest and Rangeland Soils of the United States under Changing Conditions. Chapter 2: Soil Carbon. Eds. Pouyat R.V. *et al.* (eds.). pp: 9-31.
[6] White R. (2015). Soil Carbon, the Backbone of Soil Fertility. Feature Interview (24th September, 2015). Future Directions International Pvt. Ltd., Australia.

various ecosystem services **(Wiese et al., 2021)**[7]. Therefore, accounting soil organic carbon throughout the country is extremely significant in the present scenario.

1.2 Tree Outside Forest (TOF) – Land Uses Other than Forest

The National Forest Policy 1988 aims at bringing 33% of the geographical area of the country under forest and tree cover. Forest Survey of India (FSI) assesses forest and tree cover of the country in biennial cycle. The forest cover assessment, which, includes all areas more than 1 hectare in extent and having tree canopy density of 10% and more irrespective of land use, legal status and ownership, is done using satellite data. However, there are many small patches of trees, which are less than 1 ha in extent, such as trees in village woodlots, homesteads, trees along linear features such as roads, canals, bunds, trees in urban areas, scattered trees etc. These smaller patches of trees are not included in the forest cover due to technological limitations of spatial resolution of satellite data used for the forest cover mapping. These widely spread patches of trees in the rural and urban landscapes play significant socio-economic, cultural and ecological roles.

Tree cover is more precisely defined as all tree patches of size less than 1 ha, occurring outside the recorded forest area. Tree cover includes trees in all formations including scattered trees. In colloquial, TOF and tree cover appear as similar terms but they are two different entities as defined in the FSI's assessment, though closely related to each other.

TOF refers to all trees growing outside Recorded Forest Area (RFA) irrespective of patch size which, may or may not be larger than 1 ha **(FSI, 2021)**[8]. Even the TOF patches more than size of 1 ha, comes within forest, irrespective of their legal status. On the other hand TOF of size less than 1 ha comes under Non-Forest, consisting of tree covers. Different countries and international agencies have defined trees outside forests differently. In India, TOF is defined as all trees found outside the recorded forest, in line with the FAO's

[7] Wiese L., Wollenberg E., Viridiana A.S., Richards M., Shelton S., Honle S.E., Heideckee C., Madarif B.E. and Chenug C. (2021). Countries' commitments to soil organic carbon in Nationally Determined Contributions. *Climate Policy*. DOI: 10.1080/14693062.2021.1969883

[8] FSI (2021). India State of Forest Report 2021. Forest Survey of India. Ministry of Environment, Forest and Climate Change. Government of India. ISBN 978-81-950073-1-8.

definition of TOF as trees available on lands which is not defined as 'forests' or 'other wooded land'.

1.3 Importance of TOF

Trees Outside Forests (TOF), are found in diverse formations in the rural and urban landscapes of the country like small woodlots, block plantations, trees along linear features such as roads, canals, bunds, etc. and scattered trees on farmlands, agricultural lands, homesteads, community lands and urban areas. **(Figure) Fig. 1** shows the Scattered Trees Outside Forest as Agroforestry. TOF plays a significant role in livelihood of rural and urban people of the country. They also act as important source of timber and fuel wood, contribute in carbon sequestration, conservation of biodiversity, provide habitat for wildlife, stabilize microclimate etc. They make critical contribution to the sustainable agriculture, food security and rural household economies.



Fig. 1: Scattered Trees Outside Forest as Agroforestry

They supply many products and services similar to forests. They protect crops and the soil against water and wind erosion, thus combating drought and desertification by protecting water resources. TOF in India have emerged as the major source of wood-based

industries, including plywood and wood panel also. TOF resources are important not only from the national perspective but also from the part of the strategies for combating ecological problems globally **(Ashutosh *et al.* 2020)**[9].

1.4 Soil and Its Importance for Trees

Soil is a heterogeneous mixture of rocks particles, sand and decaying dead matters. Based on the genesis, parent materials, particle size distribution (texture) etc. soils are classified into different types. However, the well-established fact about soil is that it provides the habitat for the flora and fauna, which, in turn, form the foundations of terrestrial ecosystems.

The inter-relations between Trees and Soil are symbiotic in nature. Soil provides the necessary nutrients, water and support to the plants to stand. On the other hand, Trees help to improve soil health. The tree roots improve the ability and capacity of soil to absorb water, reducing the risk of wind erosion. Fallen leaf litters from the trees create new organic matter in the soil, which, in turn become a significant source of plant nutrient as well as soil organic matter, responsible for the creation of new topsoil. Additionally, the shade created by trees helps to moderate soil temperature. In addition to creating plus protecting soil, trees benefit the health of both flora and fauna, through carbon sequestration, in order to control the potential hazards of climate change.

1.5 Agro-Climatic Zones of India and Its Significance

An "Agro-Climatic Zone" is a land unit in terms of major climates, suitable for a certain range of crops and cultivars. The Planning Commission of India (presently, NITI AAYOG) in the year 1989 **(Planning Commission, 1989)**[10], after considering several studies related to the regionalisation of the agricultural economy, recommended that agricultural planning be done on the basis of agro-climatic regions. The planning aims at scientific management of regional resources to meet the food, fibre, fodder and fuel wood without adversely affecting the status of natural resources and environment. Agro-climatic conditions mainly refer to soil types, major land use, rainfall, temperature and water availability,

[9] Ashutosh S., Lakhchaura P, Pandey K., Sourav Ghosh, Tripathi S. and Tripathi H.K. (2020). Trees Outside Forest Resources in India. *FSI Technical Information Series*. **Vol 2** (1): 1-30. ISBN: 978-81-941018-4-0.
[10] Planning Commission (1989). Annual Report. Government of India.

which, influence the type of vegetation **(Ministry of Jal Shakti, 2023)**[11]. For resource development, India has been broadly divided into **fifteen agricultural regions based on agro-climatic features**, particularly **soil type, major land use classes,** climate including temperature and rainfall and its variation of the availability of water resources **(Pradhan *et al.*, 2014)**[12]**.** The highlights of different agro-climatic zones are discussed below.

1. **Western Himalayan region**

   The Western Himalayan Region covers Jammu and Kashmir, Himachal Pradesh and the hill region of Uttarakhand. It has snow - covered peaks, dissected topography, steep slopes, perennial rivers, evergreen and deciduous forests, and thin cover of soils on undulating slopes. Summer season is mild (July average temperature 5°C to 30°C) but the winter season experiences severe cold conditions (January temperature 0°C to -4°C). The low temperatures, snowing and extreme weather in



Fig. 2: Landscape in Western Himalayan Region (Himachal Pradesh)

[11] Ministry of Jal Shakti (2023). Department of Water Resources, River Development & Ganga Rejuvenation. Ministry of Jal Shakti. Government of India. https://jalshakti-dowr.gov.in/agro-climatic-zones

[12] Pradhan R., Goroshi S. and Singh R.P. (2014). Spatial and Seasonal Characterization of Terrestrial Biospheric Carbon Flux Over India Using GOSAT Data. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. **Volume XL-8**: 617-621.

winters hinder the intensification of agriculture. A typical landscape in "Western Himalayan Region" is shown in **Fig. 2**.

2. **Eastern Himalayan region**

The Eastern Himalayan Region includes Arunachal Pradesh, the hills of Assam, Sikkim, Meghalaya, Nagaland, Manipur, Mizoram, Tripura, and the Darjeeling district of West Bengal. Average rainfall is ranging from 200 - 400 cm. The red-brown soil is moderately productive. Jhuming /shifting cultivation prevails in the hilly areas. **Fig. 3** shows a typical image of Tea Garden in "Eastern Himalayan Region" in the State of Assam.



Fig. 3: Tea Garden in Eastern Himalayan Region (Assam)

3. **Lower Gangetic Plain region**

West Bengal (except the hilly areas), eastern Bihar and the Brahmaputra valley lie in this region. Average annual rainfall lies between 100 - 200 cm. Temperature in July varies from 26°C to 41°C and for January from 9°C to 24°C. The region has adequate storage of ground water with high water table. Rice is the main crop which, at times yields three successive crops (Aman, Aus and Boro) in a year.

Picture of a typical inundated agricultural land of "Lower Gangetic Plain Region" of West Bengal is depicted in **Fig. 4**.



Fig. 4: Agriculture in Lower Gangetic Plain Region (West Bengal)

4. Middle Gangetic plain region

The Middle Gangetic Plain region includes large parts of Uttar Pradesh and Bihar. It is a fertile alluvial plain drained by the Ganga and its tributaries. The average temperature in July varies from 26°C to 41°C and that of January 9°C to 24°C, average annual rainfall is between 100 - 200 cm. Rice, maize, millets in Kharif, wheat, gram, barley, peas, mustard and potato in Rabi are important crops. Fig. 5 in this context shows a riverbed existing in the "Middle Gangetic Plain" of Uttar Pradesh.



Fig. 5: River Bed in Middle Gangetic Plain Region (Uttar Pradesh)

5. Upper Gangetic plain region

The Upper Gangetic Plains region comes in the central and western parts of Uttar Pradesh and the Haridwar as well as Udham Nagar districts of Uttarakhand. Climate is sub-humid continental with temperature in July between 26°C to 41°C and the same in January between 7°C to 23°C. Average annual rainfall is between 75 cm - 150 cm. This is an intensive agricultural region wherein wheat, rice, sugarcane, millets, maize, gram, barley, oilseeds, pulses and cotton are the main crops. A luxuriant crop growing agricultural field is depicted through **Fig. 6,** in the "Upper Gangetic Plain Region" of Uttar Pradesh.



Fig. 6: Agriculture in Upper Gangetic Plain Region (Uttar Pradesh)

6. Trans-Gangetic plain region

This region (also called the Sutlej-Yamuna Plains) extends over Punjab, Haryana, Chandigarh, Delhi and the Ganganagar district of Rajasthan. Semi-arid characteristics prevail over the region, with July's mean monthly temperature between 25 °C and 40 °C and that of January between 10°C and 20°C. The average annual rainfall varies between 65 cm - 125 cm. The soil is alluvial which is highly productive. The cultivators and the governments have installed canals, tube-wells as well as pumping sets. The intensity of agriculture is the highest in the country. Important crops include wheat, sugarcane, cotton, rice, gram, maize, millets, pulses, oilseeds etc. The region have the credit of introducing Green Revolution in the country, by adopting modern methods of farming with greater degree of mechanisation and excessive inorganic soil fertilization. The region is also facing the menace of water logging, salinity, alkalinity, soil erosion and falling water table. **Fig. 7** shows a combination of agriculture and agroforestry in the "Trans Gangetic Region" of Haryana State.



Fig. 7: Agriculture and Agroforestry in Trans Gangetic Plain Region (Haryana)

7. Eastern plateau and hill region

This region includes the Chotanagpur Plateau, extending over Jharkhand, Orissa and Chhattisgarh. The region enjoys 26°C to 34°C of temperature in July, 10°C to 27°C in January and 80 cm - 150 cm of annual rainfall. The region is deficient in water resources due to plateau structure and non-perennial streams. Soils are red and yellow with occasional patches of lateritic and alluviums. Rain fed agriculture is practised in this region. Crops like rice, millets, maize, oilseeds, ragi, gram and potato are mostly cultivated. **Fig. 8** shows a typical picture of agricultural cultivation in the "Eastern Plateau and Hill Region" in the State of Odisha.



Fig. 8: Agriculture in Eastern Plateau and Hill Region (Odisha)

8. Central plateau and hill region

This region is spread over the plateau regions of the States of Madhya Pradesh, Chattisgarh, Telengana and Northern Odisha. Semi-arid climatic conditions prevail over the region with temperature in July 26°C to 40°C, in January 7°C to 24°C and average annual rainfall from 50 cm - 100 cm. Soils are mixed red, yellow and black. There is scarcity of water. Crops grown are millets, wheat, gram, oilseeds, cotton and sunflower in this challenging conditions. A typical permanent fallow land in the "Central Plateau and Hill Region" of Madhya Pradesh is shown as **Fig. 9**.



Fig. 9: Permanent Fallow in Central Plateau and Hill Region (Madhya Pradesh)

9. Western plateau and hill region

This region comprises of southern part of Malwa and Deccan plateau (Maharashtra), this is a region of the regur (black) soil. The July temperature between 24°C and 41°C, January temperature between 6°C and 23°C and average annual rainfall of 25 cm - 75 cm. Wheat, gram, millets, cotton, pulses, groundnut, and oilseeds are the main crops in the rain-fed areas, while in the irrigated areas, sugarcane, rice, and wheat, are cultivated. Oranges, grapes and bananas are also grown in this region. **Fig. 10** shows the typical black Soil in "Western Plateau and Hill Region", in the State of Maharashtra.



Fig. 10: Black Soil in Western Plateau and Hill Region (Maharashtra)

10. Southern plateau and hill region

This region falls in interior Deccan and includes parts of southern Maharashtra, the greater parts of Karnataka, Andhra Pradesh, and Tamil Nadu uplands from Adilabad District in the north to Madurai District in the south. It is an area of dry-zone agriculture where millets, oilseeds, and pulses are grown. Coffee, tea, cardamom and spices are grown along the hilly slopes of Karnataka plateau. Coconut plantations, especially closer to the coastal agro-climatic belts are extremely common in the "Southern Plateau and Hill Region" of Tamil Nadu. A typical picture of the same is presented in the **Fig. 11**.



Fig. 11: Coconut Plantation in Southern Plateau and Hill Region (Tamil Nadu)

11. East coast plain and hill region

This region comprises of the Coromandel and northern Circar coasts of Andhra Pradesh and Orissa. The mean July temperature ranges between 25 °C and 35 °C and the mean January temperature varies between 20 °C and 30 °C. The mean annual rainfall varies between 75 - 150 cm. The soils are alluvial, loam and clay and are troubled by the problem of alkalinity. Main crops include rice, jute, tobacco, sugarcane, maize, millets, groundnut and oilseeds. **Fig. 12** shows a typical flooded land, ready for cultivation in “East Coast Plain and Hill Region” of coastal Odisha.



Fig. 12: Cultivation in East Coast Plain and Hill Region (Coastal Odisha)

12. West coast plain and hill region

This zone extends over the Malabar and Konkan coastal plains along the hills of Sahyadris. The region is humid with the mean July temperature varying between 25°C and 30°C and mean January temperatures between 18°C and 30°C. The mean annual rainfall is more than 200 cm. The soil is lateritic and coastal alluvial. Rice, coconut, oilseeds, sugarcane, millets, pulses and cotton are the main crops. The region is also famous for plantation crops and spices, which are raised along the hill slopes of the Western Ghats. A typical landscape of Western Ghats in "West Coast Plain and Hill Region" is exhibited through **Fig. 13**.



Fig. 13: Western Ghats in West Coast Plain and Hill Region (Maharashtra)

13. Gujarat plain and hill region

This region includes the hills and plains of Kathiawar, and the fertile valleys of Mahi and Sabarmati rivers. It falls under arid and semi-arid region. The mean July temperature reads 30°C and that of January is about 25°C. The mean annual rainfall varies between 50 cm - 100 cm. Soil is *"Regur"* in the plateau region, alluvium origin in the coastal plains. In Jamnagar area patches of red and yellow soils are observed. Groundnut, cotton, rice, millets, oilseeds, wheat and tobacco are the main crops. It is an important oilseed producing region. A typical sloping terrain is shown in **Fig. 14.** Of "Gujarat Plain and Hill Region" in the State of Gujarat.



Fig. 14: Gujarat Plain and Hill Region (Gujarat)

14. Western plain and hill region

This region spreads over Rajasthan, especially, in the west of Aravallis. This region has an erratic rainfall of an annual average of less than 25 cm. The desert climate further causes high evaporation and contrasting temperatures of 28°C to 45°C in June and 5°C to 22°C in January. Bajra, jowar, wheat and gram are the crops cultivated in this region. Livestock contributes greatly in desert ecology. The major thrust areas need to be addressed for development is rainwater harvesting for developing soil health and increase in crop production. A typical scrubland in the deserts of "Western Dry Region" is presented in **Fig. 15**.



Fig. 15: Western Plain and Hill Region (Rajasthan)

15. Island region

The island region includes Andaman-Nicobar and Lakshadweep, which have typically equatorial climate. Mean annual rainfall of the region is around 300 cm; the mean July and January temperature of Port Blair being 30°C and 25°C respectively. The soils vary from sandy along the coast to clayey loam in valleys and lower slopes. The main crops are rice, maize, millets, pulses, areca nut, turmeric and cassava. Nearly half of the cropped area is under coconut. The area is covered with thick forests and agriculture is in backward stage. **Fig. 16** shows small flowing creek in “Island Region” of the Union Territories of Andaman.



Fig. 16: Island Region (Andaman)

The main objectives of delineating agro-climatic regions are:

- To optimize agricultural production
- To increase farm income
- To generate more rural employment
- To make a judicious use of the available irrigation water
- To reduce the regional inequalities in the development of agriculture.

Robust soil health being one of the key parameter for the sustainable agricultural production **(Tahat *et al.*, 2020)**[13]. Agro-climate on the other hand is the important combination of factors, including soil for agriculture, as discussed in this section. Therefore, measuring soil health through a critical indicator like soil organic carbon brings the key essence to the present study. **Fig. 17** shows agro-climatic zones of India.

[13] Tahat M.M., Alananbeh K.M., Othman Y. A. and Leskovar, D.I. (2020). Soil Health and Sustainable Agriculture. *Sustainability*. **12: 4859**: 1-26.

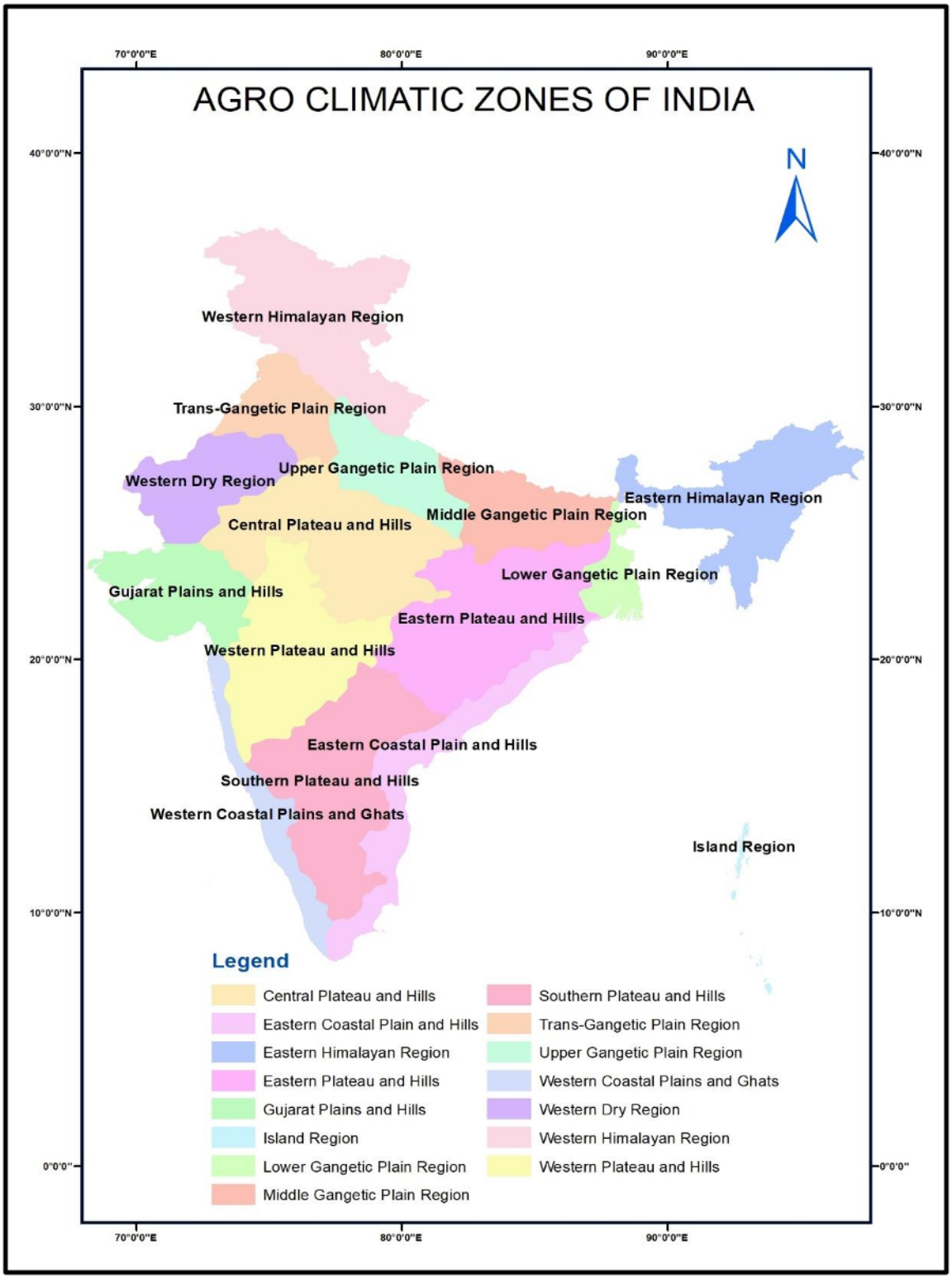


Fig. 17: Agro-Climatic Zones of India

1.6 Land Use Trends Over the Years in India

The **"India-Third Biennial Update Report" (BUR III),** which, was submitted to the "United Nations Framework Convention on Climate Change", in the year 2021, quoted the year wise distribution of land uses, since the year 2005.

Table 1: Year wise Trend of Land Use Area Pattern (Area in m ha)

Year	Forest	Agriculture	Grasslands	Settlements	Other land (Includes Wetland)	Total Area (Truncated to 2nd Place of Decimal)
2005	69.16	160.65	20.35	8.61	69.97	328.74
2006	69.24	160.94	20.42	8.72	69.42	328.74
2007	69.25	161.23	20.48	8.84	68.94	328.74
2008	69.27	161.53	20.55	8.96	68.43	328.74
2009	69.44	161.82	20.62	9.08	67.78	328.74
2010	69.50	162.12	20.69	9.20	67.23	328.74
2011	69.79	162.41	20.75	9.31	66.48	328.74
2012	69.98	162.71	20.82	9.43	65.80	328.74
2013	70.15	163.00	20.89	9.55	65.15	328.74
2014	70.49	163.29	20.89	9.55	64.52	328.74
2015	70.83	163.85	21.65	9.56	62.85	328.74
2016	71.03	164.40	22.42	9.57	61.32	328.74
2017	71.22	164.40	22.42	9.57	61.13	328.74

MoEFCC (2021). India: Third Biennial Update Report to the United Nations Framework Convention on Climate Change. Ministry of Environment, Forest and Climate Change, Government of India.

Table 1 clearly shows that the land use classes like: Forest (we are not considering in the present study), Agriculture, Grasslands and Settlements land uses are showing an increasing trend over the years, from 2005 to 2017. The other land, shows a constant decrease in area within the same time frame. This implies that the availability of spared other land, for raising forest cover, agricultural land and grasslands are also facing immense pressure. If may not create acute land shortage in recent future, but it certainly will after, few more decades. Although, numerically it looks very small rise in settlement area since 2005, but in reality, there is a jump of nearly 10 to 11% of land use area for the

same. In comparison to that, forest and agricultural land is increased around 2 to 3 % in the same time-period. The population rise in the country is definitely a concern, as it will continuously rise the settlement sprawl. This exponential rise in population is creating a constant depletion of cultivable land: man ratio **(Sourav Ghosh, 2008)[14].** The trend of land use in terms time series graph is also shown hereunder in **Fig. 18**.

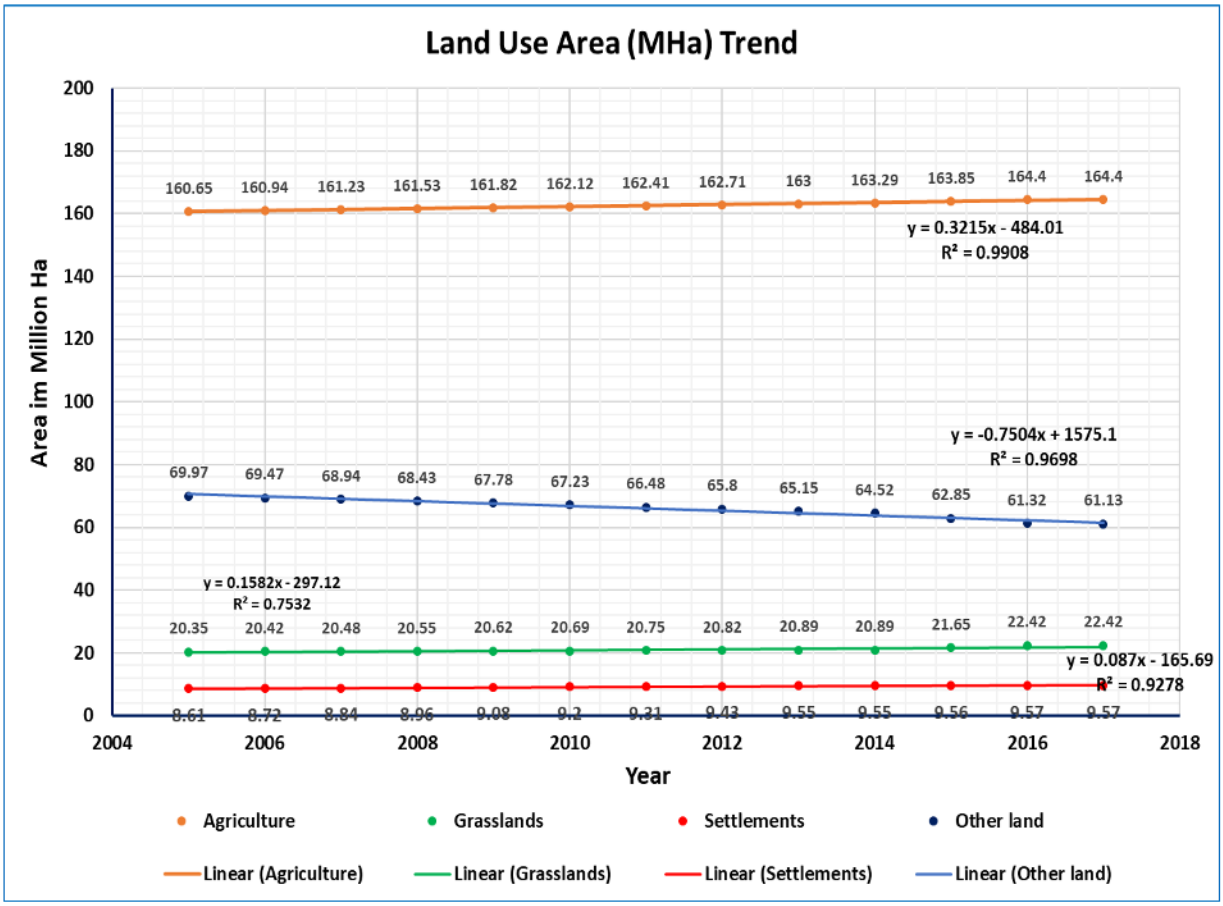


Fig. 18: Trend of Land use Area (m ha) from the year 2005 to 2017 in India

The above trend lines show that grassland, agriculture and settlement areas are significantly correlated with R^2 values of more than 0.75. Therefore, the increase of those land use area over the time is substantial. The negative linear slope, with square of correlation coefficient (R^2) more than 0.9 for other land implies that the said land use area is diminishing amply over the year, as analysed from 2005 to 2017; which, is noteworthy.

[14] Sourav Ghosh (2008). Soil Resource Mapping and Suggested Land Use for a Selected Watershed. *PhD Thesis*. Awarded in Agricultural Chemistry and Soil Science. University of Calcutta.

1.7 Land Use and its Significance with Soil

The land is a resource that is the most important for the survival of human beings. Land use pattern is the arrangement for the uses of land for different purposes. Land use pattern is the arrangement or layout of the uses of the land, which may be used for forestry, agriculture, pasture, settlements etc. Beside these, land covers like wetlands and any other lands may also be considered as a land use. However, there is a thin line of difference exists between 'Land Cover' and 'Land Use'. Land Cover refers to the observed physical and biological cover of the Earth's surface and includes natural vegetation and abiotic (non-living) surfaces. Land use on the other hand, reflects both **(a)** *the activities undertaken* and **(b)** *the institutional arrangements put in place* for a given area for the purposes of economic production, or the maintenance and restoration of environmental functions.

The factors for which the land can be used in various ways is determined by many factors like relief features, climate, the density of the population, **soil**, applicability, and socio-economy etc. Due to the rapid industrialization and population growth, land resources are under pressure from physical, human and global causes such as soil erosion, desertification, pollution, food shortage, land conflict, water shortage and climate change **(MoSPI, 2012)**[15]. Among which, the factor "**Soil"** is one of the most important one. Therefore, the soil properties are strongly influenced by land use and changes in management practices. Consequently, to conserve soil resources, policymakers need to implement appropriate land conservation strategies based on land-use structure **(Assefa *et al.*, 2020)**[16]. **Fig. 19** shows that the alternate crop growth and tillage practices used for Improving Soil Organic Carbon.

[15] MoSPI (2012). Land-The Base, The Foundation, Ministry of Statistics and Programme Implementation. Government of India.

[16] Assefa F., Elias E., Soromessa T., Ayele G.T. (2020). Effect of Changes in Land-Use Management Practices on Soil Physicochemical Properties in Kabe Watershed, Ethiopia. *Bio One Complete*. **Vol 13** (1).



Fig. 19: Alternate Crop growth and Tillage for Improving Soil Organic Carbon

1.8 Importance of Organic Carbon

Trees outside forests (TOFs) are important natural resources that contribute substantially to national biomass and carbon stocks and to the livelihood of people in many regions of the world. Over the last decades, decision makers have become increasingly aware of the importance of TOF, and consequently, this tree resource nowadays, often considered in forest monitoring systems **(Yadav *et al.*, 2017)**[17]. TOF also provide a unique way of combating climate change in cities by trapping carbon under urban forestry in the form of urban woodlots, roadside plantations, and trees inside urban parks, thereby, making their assessment extremely important in view of harnessing benefit under different climate change programs. With the existing area under wastelands, there is a huge potential to increase TOF through plantation drives involving local communities, non-governmental organizations (NGOs), and State forest department officials **(Wani *et al.*, 2021)**[18]. The efficient estimation of TOF carbon stock was successfully performed by several

[17] Yadav Y., Chhetri B.B.K., Raymajhi S., Tiwari K.R. and Sitaula B.K. (2017). Importance of Trees Outside Forest (TOF) In Nepal: A Review. *Octa Journal of Environmental Research.* **Vol 5** (2): 070-081.

[18] Wani A.A., Mehraj B., Masoodi T.H., Gatoo A.A. and Mugloo J.A. (2021). Assessment of Trees Outside Forests (TOF) with Emphasis on Agroforestry Systems. J. C. Dagar *et al.* (eds.), Chapter 4: Agroforestry for Degraded Landscapes.

organizations. **Singh and Chand, 2012[19];** estimated above-ground TOF phytomass and the carbon content of TOF in a semiarid region of the southern Haryana, India. The study results conclude that the classification of TOF and estimation of phytomass as well as carbon content in TOF can successfully be achieved through the combined approach of Remote Sensing and GIS based spatial technique with the supplement of field data. A research funded by the Land Cover and Land Use Change (LCLUC) Program at the National Aeronautics and Space Administration (NASA), USA, and University of Michigan, observed that Mapping related to individual trees outside forests in sparse landscapes in West Africa revealed more tree cover count by high resolution data, which, implies more carbon storage than is often expected. The study also showed the importance of considering TOF in carbon measurement and climate change mitigations actions. The use of VHR data for individual tree carbon estimation also revealed more carbon and a more robust spatial heterogeneity than the often-used coarse resolution global datasets having coarser resolution **(Skole, 2021)**[20]. However, under Indian scenario using very high-resolution satellite data is quite challenging, in terms of time, labour and money due to the vast extent of the country.

It is therefore widely accepted that TOFs can efficiently fix atmospheric CO_2 in its woody biomass and fulfil the timber demands. Hence, TOFs need to be managed and monitored properly for which local, regional or national level inventory is required. TOF is becoming an unavoidable part of existing national forest inventory systems. Only the Indian and FAO inventories are including trees growing in all land uses. However, harmonization in analysing and reporting is still not advanced, like in forestry sector, thereby creating difficulties locating the results from TOF assessments. **(Chakravarty *et al.*, 2019)**[21]. Therefore, it is evident that soil organic carbon is closely associated with any plant growth, even within TOF.

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[19] Singh K. and Chand P. (2012). Above-ground tree outside forest (TOF) phytomass and carbon estimation in the semi-arid region of southern Haryana: A synthesis approach of remote sensing and field data. *Journal of Earth System Science*. **Vol 121**(6): 1469-1482.

[20] Skole D.L., Samek J.H., Dieng M. and Mbow C. (2021). The Contribution of Trees Outside of Forests to Landscape Carbon and Climate Change Mitigation in West Africa. *Forests*. **12:**1652.

[21] Chakravarty S., Pala N. A., Tamang B. Sarkar B.C., Manohar A.K., Rai P. Shukla V.G., and Puri A. (2019). Ecosystem Services of Trees Outside Forest. M. K. Jhariya et al. (eds.), Sustainable Agriculture, Forest and Environmental Management. Springer Nature, Singapore.

1.9 Objective

It has been understood from the above-discussion that beside forests, TOF also plays significant role in carbon sequestration. Soil being one of the major pool of carbon in the natural ecosystem, it is having a great significance in contributing towards carbon storage. The density of trees in TOF being much lesser than forest; therefore, soil acts as the major sink of carbon.

Agriculture being the mainstay of Indian Economy; it is occupying the highest land use coverage of the country. The agro-climatic zones were therefore, delineated for judiciously boosting Indian agriculture production based on delineated various agro-climatic zones, suggested by Planning Commission of India (Presently, NITI AAYOG).

Soil fertility is the most crucial component of any crop production activities. Moreover, one of the key factor of soil fertility is soil organic carbon. Therefore, measuring soil organic carbon in the Non-Forests within TOF, with respect to various land use and agro-climatic zones are extremely important. FSI biennially monitors soil organic carbon of only the forest cover of TOF by taking samples from "Recorded Forest Area".

There is no such country level study has been performed to determine the soil organic carbon in TOF (excluding forest cover), based on land use as well as agro-climatic zone.

Moreover, for reporting GHG (Green House Gas) inventory under the "**National Communication" (NATCOM)**; the soil organic carbon present in different land uses existing under TOF are also extremely important. This is very much pertinent under the present scenario, when adverse climate change mitigation strategies across the country is widely under progress to understand the carbon sink potential of various land uses.

In the contexts of what have been stated above, the present study had been performed to attain the following objectives:

1. To determine the carbon stocks present in the soil under TOF, distributed under different land use classes other than forest.

2. To analyse the carbon stocks present in the soil under TOF, spread over various agro-climatic zones other than forest.



CHAPTER TWO

Materials, Methods & Field Studies



2. Materials, Methods and Field Studies

In the incidence of climate change, land degradation and biodiversity loss, soils have become one of the most vulnerable resources in the world. Soils are a major carbon reservoir containing more carbon than the atmosphere and terrestrial vegetation combined. Soil organic carbon is dynamic; however, any anthropogenic impacts on soil can turn it into either a net sink or a net source of GHGs. Enormous scientific progress have been achieved in understanding and explaining the dynamics of soil organic carbon. Yet, protection and monitoring of SOC stocks at national and global levels still face complicated challenges impeding effective on-the-ground policy design and regionally adapted implementation.

As SOC is a prime indicator of overall soil health and a healthy soil is the key productivity factor of Trees and Forests. Therefore, proper nurturing of soil would certainly enhance the growth of plants; thereby, it will facilitate in achieving an additional carbon sink.

2.1 Sampling Scheme

The soil samples from the entire country were collected through stratified random sampling method. Out of designated 20,000 plus TOF plots (**Fig. 19**) as surveyed by FSI in two years, a total of 1602 plots have been selected for country wide soil organic carbon estimation.

Since, the population size is finite i.e. 20,000; therefore, the Cochran's formula **(Cochran, 1977)**[22], has been used at 95% level of confidence, to calculate the sample size. i.e.

$$n = \frac{Z^2 \left(\frac{CV}{AE}\right)^2}{1 + \left(\frac{1}{N}\right).\left(\frac{CV}{AE}\right)^2}$$

Where, Z=Value of Z distribution at 95% level of significance,

n = Sample size, N = Population size, CV = Coefficient of Variation, AE = Acceptable Error.

[22] Cochran, W.G. (1977). Sampling Techniques. 3rd Edition, John Wiley & Sons, New York.

2.2 Land Use Classes

The soil organic carbon is very much dependent on the land use and land cover pattern of the place from where the soil samples are collected. As a thumb rule, greater vegetation and proper soil management improve the soil organic carbon status, beside its core genetic factors. **Fiener *et al.* (2014)**[23] successfully showed the spatial distribution pattern and sequestration potential of soil organic carbon in various soil developed under different land use classes.

In the present study, we have utilized the latest 1:250000, land use map of India as received from NRSC. The NRSC map contains 18 land use classes, which, are then clubbed into six major groups. The six (6) major classes are as follows:

a) Settlement: *Built Up*

It is an area of human habitation developed due to non-agricultural use and that has a cover of buildings, transport and communication, utilities in association with water, vegetation and vacant lands.

As per As per India's Second Biennial Update Report: Settlements Include major built-up areas and human habitations - both rural and urban.

b) Agriculture: *Kharif Crop, Rabi Crop, Zaid Crop, Double/ Triple Crop, Current Fallow, Shifting Cultivation*

These lands are primarily used for farming and for production of food, fibre, and other commercial and horticultural crops. It consists of Cropland, Plantations, Fallow and Current Shifting Cultivation areas.

c) Grassland: *Grassland*

The areas of natural grass along with other vegetation, predominantly grass-like plants (Monocots) and non-grass-like herbs (except Lantana species, which are to be classified as scrub). It includes natural/semi-natural grass/ grazing lands of Alpine / Sub-Alpine or temperate or subtropical or tropical zones, desert areas and manmade grasslands.

[23] Fiener P., Gottfried T., Sommer M. and Steger K. (2014). Soil organic carbon patterns under different land uses in South India. *Geoderma Regional*, **Vol (2-3)**: pp 91-101.

As per As per India's Second Biennial Update Report: Grassland are the areas covered with grassy and herbaceous growth as well as degraded forests with less than 10% tree canopy density.

d) Wetland: *Water Bodies Max, Water Bodies Min*

All submerged or water-saturated lands, natural or man-made, inland or coastal, permanent or temporary, static or dynamic, vegetated or non-vegetated, which necessarily have a land-water interface, are defined as wetlands.

e) Other land: *Wasteland, Scrub, Rann, Snow Cover*

Lands which do not fall under above-mentioned categories.

f) Forest: *Plantation, Evergreen Forest, Deciduous Forest, Degraded Forest, Littoral Swamp*

Having canopy covering more than 1 ha area with density of more than 10%.

In the present study five land use classes have been selected out of six major groups, **excluding 'Forest'**. The selected five land use classes within TOF are**: i) Agriculture, ii) Grassland, iii) Other land, iv) Settlement** and **v) Wetland**.

2.3 Agro-Climatic Zones

The Planning Commission of India has categorised 15 agro-climatic zones in India, taking into account the physical attributes and socio-economic conditions prevailing in the regions. The agro-climatic zone map reference of planning commission has been obtained from the site of Vikaspedia (an online information guide launched by the Government of India). It was later digitally converted into attributed vector, using Geospatial software.

The 15 agro-climatic zones are as follows:

1. Western Himalayan Region
2. Trans-Gangetic Plain Region
3. Upper Gangetic Plain Region
4. Central Plateau and Hills
5. Western Plateau and Hills
6. Southern Plateau and Hills
7. Middle Gangetic Plain Region
8. Lower Gangetic Plain Region

9. Eastern Coastal Plain and Hills
10. Eastern Plateau and Hills
11. Eastern Himalayan Region
12. Island Region
13. Western Coastal Plains and Ghats
14. Western Dry Region
15. Gujarat Plains and Hills

The study of soil organic carbon and physiographic zones of few selected sites has already been done by **Bhattacharyya *et al.* (2000)**[24]. The status of soil macro-nutrients like nitrogen (N), phosphorus (P), potassium (K) as well as organic carbon and its dependence on agro-climatic zones has already been highlighted and discussed **(Sharma *et al.*, 2012)**[25]. However, until now there is no such pan India based study has been performed which can correlate SOC with various broad land use classes present in different agro-climatic zones, under TOF. The attempt of FSI through this project is to fulfil this existing gap.

2.4 Creation of Strata and Its Validation

The strata have been created from all the intersections of 5 land use classes and 15 agro-climatic zones. Thus 75 strata have been created. However, in reality we could get 74 combined classes, since no 'Grassland' land use were marked in one of the agro-climatic zone, i.e. 'Island Region'.

From each of the combined classes, number of points sampled are calculated based on the fraction of area exists with respect to the total area excluding 'Forest' land use in India.

i.e. **$n = (a / (A - F)) \times 1602$**

Where, n = Number of sample points for any stratum

a = Area of the respective combined class or stratum

A = Total area of the country (32,87,469 km^2)

F = Area under forest land use as per FSI (ISFR, 2019) (7,12,249 km^2)

[24] Bhattacharya T., Pal D.K., Mandal C. and Velayutham M. (2000). Organic carbon stock in Indian soils and their geographical distribution. *Current Science*, **79** (5): pp 655-660.

[25] Sharma B.D., Sidhu G.S., Sarkar D. and Kukal S.S. (2012). Soil Organic Carbon, Phosphorous, and Potassium Status in Rice–Wheat Soils of Different Agro-climatic Zones in Indo-Gangetic Plains of India. *Communications in Soil Science and Plant Analysis.* **Vol (43)**: 10, pp: 1449-1467.

The number of survey point are allotted as per the proportion of the respective area. The points are selected from each of the combined classes or strata in such a way that the survey parties need to travel minimum distance, with maximum land use coverage in all the agro-climatic zones, without altering the variability of the collected samples from each strata.

The number of samples obtained for each stratum is made in such a way that the minimum samples for each stratum should at least be five (5), so that proper mean and variance could be ascertained.

The stratification has been validated with One-Way "Analysis of Variance" (ANOVA), considering 5 (five) land use classes and 15 (fifteen) agro-climatic zones **(Annexure)**, by considering the two null hypothesis:

$H_{0\ (Land\ Use)}$: All Means ('Soil C' t /ha) obtained from different land uses are equal.

$H_{0\ (Agro\ Climate)}$: All Means ('Soil C' t /ha) obtained from different Agro-climates are equal.

2.5 Software Used

The software ArcGIS and QGIS were used for GIS related activities. For image processing, raster classification concerned works ERDAS Imagine software was used. The MS-Office software is used for documentation and for preparing charts, diagrams as well as complex calculations and statistical analysis, MS-Excel software was used.

2.6 Usual Sampling Procedures Follow by FSI during TOF Inventory

In India FSI assesses forest cover of the country in biennial cycle. **Forest cover includes all patches of tree formations, which, are of size 1 ha or more, with more than 10% canopy cover. It does not discriminate whether the tree patch is within the recorded forest area or outsides.** Therefore, forest cover map of the country also includes TOF, which, occur in tree patch size of one ha or more. Apart from this, there is significantly large extent of TOF resource, which, occurs in the patch size less than 1 ha or in the scattered form. The distribution of entire population points are distributed across the country is presented in **Fig. 20**. This segment of TOF resource is assessed by FSI through sampling techniques following stratified random sampling design and is assessed as tree cover in terms of extent, growing stock etc. The methodology in detail is given in the following sub-sections.

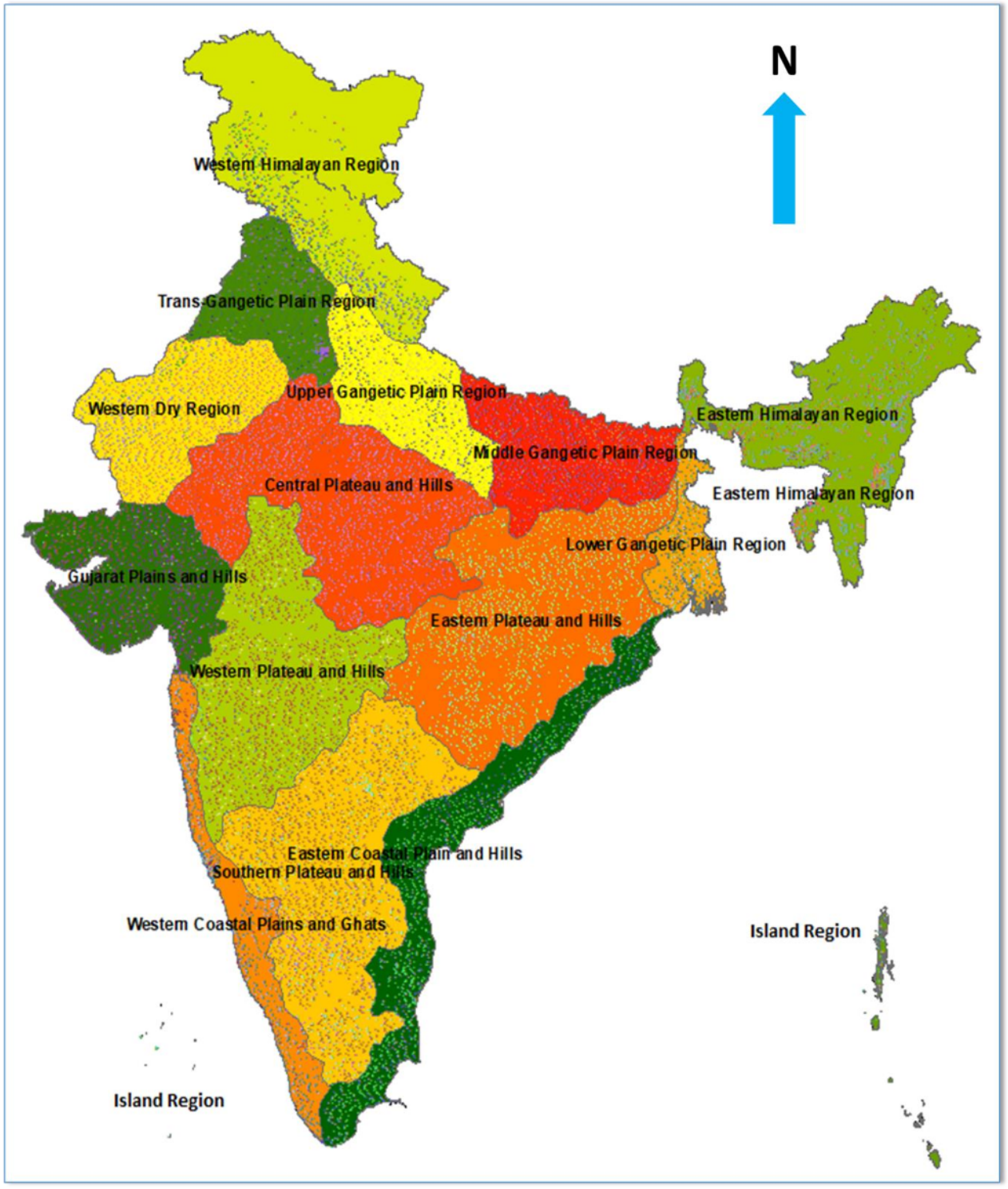


Fig. 20: Entire 20,000 Point Population Overlaid On Agro-Climatic Zones of India

2.6.1 Methodology followed from 1991 to 2001

The inventory of TOF started by FSI in 1991 was confined to the States or group of districts. Multistage stratified sampling design was used for the selection of samples. Separate methodology was followed for inventory of rural and urban TOF. As per the sampling design, the study area was stratified according to agro-ecological zones (AEZ). Districts, the basic planning and administrative units, which have significant influences on TOF and their resources, are considered for further stratification of these AEZs. The villages within these stratified areas are the sampling units selected, through stratified random sampling. The number of sample villages to be surveyed were decided by conducting a pilot study in 20-25 randomly selected villages with 10 to 15 percent permissible error, at 95 percent probability level. A complete inventory is conducted for all the trees of 10 cm DBH (Diameter Breast Height) and above in the randomly selected villages. For the inventory of TOF in urban areas, UFS (Urban Frame Survey) blocks maps of National Sample Survey Organization (NSSO) were taken as sampling unit. The number of sample blocks in the district was determined through a pilot study in randomly selected blocks with 10 to 15 percent permissible error, at 95 percent probability level. The randomly selected blocks in selected district were used for conducting a complete enumeration of the trees of 10 cm DBH and above.

The trees in the TOF area were classified into nine categories for the purpose of data recording, processing and analysis. These categories were as follows **(Fig. 21)**:

1. **Farm forestry:** Trees along farms and in small patches up to 0.1 ha in area.
2. **Woodlot:** Naturally growing and planted trees on community land (e.g. parks, gardens, and institutional plantation).
3. **Block plantation:** Patches covering areas of more than 0.1 ha and not considered in the above categories.
4. **Roadside windbreaks:** Trees planted along roadsides.
5. **Pond side plantation:** Trees planted in and around water bodies.
6. **Railway windbreaks:** Trees planted along railway lines.
7. **Canal side plantations:** Trees planted along canals.

8. **Homestead:** Trees appearing in the house area and not covered in the first three categories above.
9. **Others:** Trees not falling in any of the above categories.



Fig. 21: Pictorial Representation of Various Forms of TOF

2.6.2 Methodology followed from 2001 to 2016

The methodology adopted during 1991 to 2001 was not suitable for generating national level estimates of growing stock and other parameters as the inventory was confined to only group of districts or State at different point of time. Therefore, to generate the national level estimates of TOF, the sampling design was modified in 2001. As per the modified design, the country was stratified into 14 physiographic zones based on the similarities in vegetation, climate, soil etc. Sixty districts spread over the entire country representing all the physiographic zones were selected for the detailed inventory of TOF in a cycle of 2 years. Separate methodology was used for the inventory of rural and urban areas. The sampling frame for inventory of TOF (Rural) was created using the high resolution satellite data to stratify TOF resources of the selected districts into three strata, namely block, linear and scattered. Thereafter, simple random sampling was followed to select optimum number of sample points from each stratum. The optimum number of sample points and plot size in each stratum were determined with the help of the pilot study. Inventory was carried out in all the selected sample points in each stratum. Remote

sensing based methodology used for inventory of rural area was not followed for urban areas because the geo-referenced boundaries of urban areas were not available. Moreover, it was not possible to layout plots of desired size in urban areas due to tree pattern and residential configuration. Therefore, a different sampling design, based on the UFS block maps of NSO, as was done earlier, was adopted for inventory of urban TOF.

2.6.3 Methodology adopted from 2016 onwards

The district based methodology adopted in 2001 was again modified in 2016 to meet the data requirement at national and international levels. As per the modified design, FSI has switched over from district to grid based design. The country has been stratified into uniform grids of size 5 km x 5 km. This grid layer has been obtained from NRSC. The cycle for the TOF inventory in the new design has been kept at 10 years. All TOF grids are marked with numbers 1 to 10. Grids of a particular number are taken for inventory in a particular year. TOF grids consist of both TOF (Rural) and TOF (Urban). As generation of State level estimates is one of the main objectives of the new sampling design, the optimum sample size has been calculated at State level separately for rural and urban areas using past inventory data. For rural grids, remote sensing based methodology, as described earlier, was used for stratification of TOF resources into block, linear and scattered stratum and inventory is carried out in each selected grids. Similarly, for the urban inventory, UFS block maps of town falling in the selected grids are used for inventory of TOF in urban areas.

2.7 Plot Laying & Soil Sample Collection from TOF by FSI in the Present Study

- A plot of 10 m X 10 m was marked in such a way that the centre of the plot be the desired Geo-coordinate (**Fig. 22**).
- In the each of the four corners of the 10 m X 10 m plot, four smaller plots of 1 m X 1 m were laid.
- In the centre of the 10 m X 10 m plot, where, the Geo-coordinate lies, there also a 1 m X 1 m plot was placed.
- Therefore, in the entire 10 m X 10 m plot there will be 5 subplots of size 1 m X 1 m should exist as shown in the figure below.

Note: *Plots only laid to those locations, which were accessible through walking by a normal person and having at least more than 15 cm soil depth.*

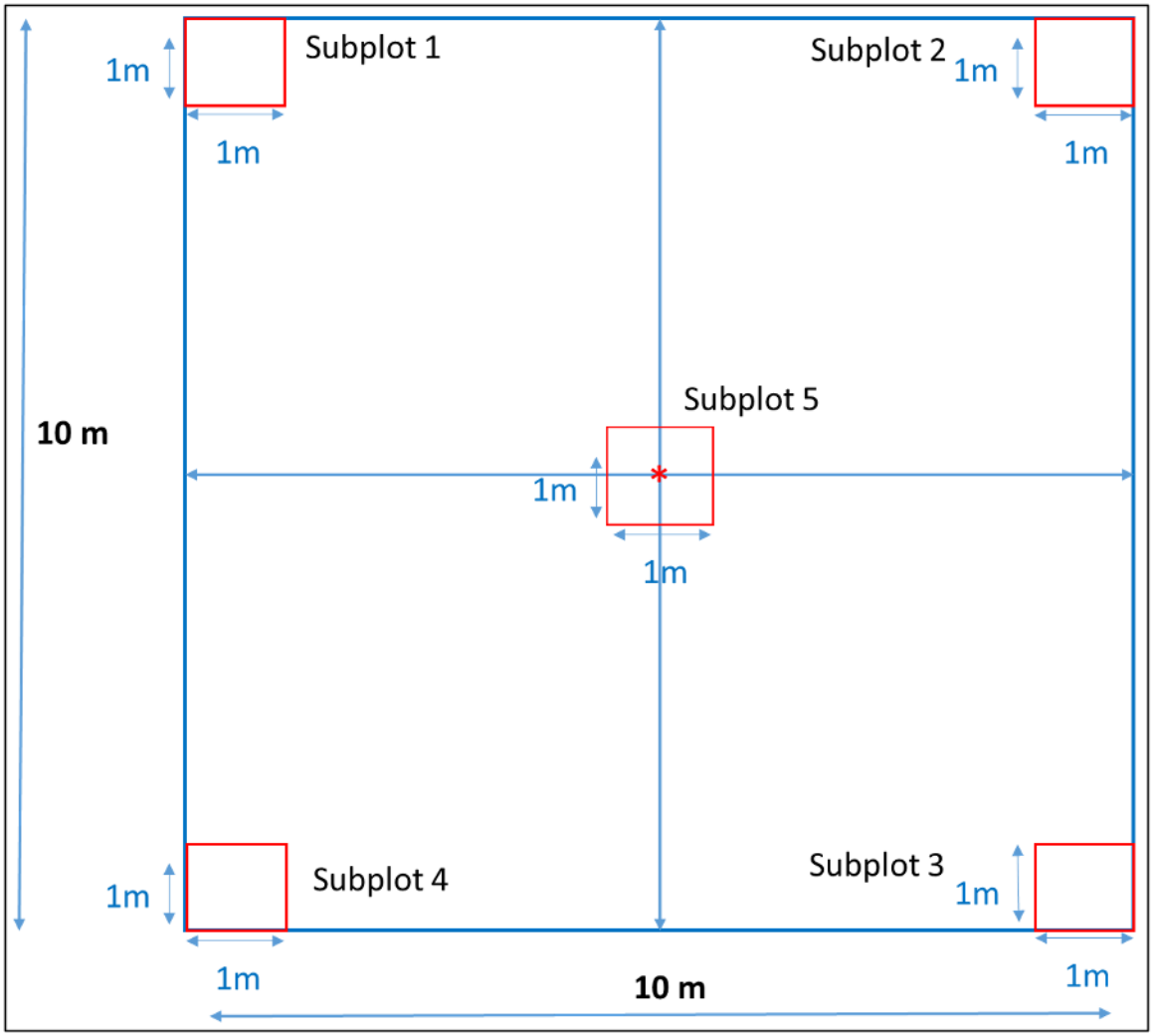


Fig. 22: Schema Showing the Laying of Plots

The soil samples were collected from all the sub-plots at a depth of 15 to 30 cm **(sub-surface soil)**. This was done because the surface soil undergoes frequent changes due to natural and anthropogenic interactions. The sub surface soils are devoid of any frequent external interference. The collected soil samples from 5 subplots were mixed together over a clean paper and 250 g of the mixed sample was taken for "Soil Organic Carbon" analysis at the laboratory **(Fig. 23 & Fig. 24)**. This mixing action reduces the chances of local variation within a laid plot of sub-surface soils.



Fig. 23: Mixing of Soil Samples in the Field



Fig. 24: Plot Laying and Soil Sample Collection

The strata wise distribution of soil sample distribution across the country is shown in **Fig. 26**. The soil samples collected from field, were kept in an air tight packet with proper numbering. The Unique ID of each of the packet were marked properly and sent to the laboratory at Forest Survey of India (FSI), HQ.

2.8 Laboratory Analysis of Collected Soil Samples

The collected soil samples (as instructed in the 'Field Form' (**Fig. 27**) of Soil Sample Collection) were then air dried for 24 hours and followed by oven-dried for 4 hours at controlled temperature of 50°C to evaporate moisture only, without disturbing the soil organic carbon content.

The dried soil samples were there after crushed in mortar-pestle and passed through 2mm sieve to remove gravels and the gravel percentage in the soil sample was also noted.

The prepared soil samples are then weighed properly in weighing machine, having accuracy level of 1/10th of 1 milligram and analysed for 'Total Organic Carbon' (percentage) by 'Elementar Rapid CS Cube' instrument by batch process method (**Fig. 25**).

To enhance the forward reaction rate Al_2O_3 (Aluminium Oxide, i.e. commonly called as Corundum Balls) and CuO (Cupric Oxide) were also used for complete combustion at prescribed temperature. The excess moisture is absorbed by P_2O_5 (Phosphorus Pentoxide, i.e. commonly called as Sicapent). The other precautionary processes like requirement of acidification was performed accordingly.

In this method, the equipment records Carbon from the Carbon Di-Oxide (CO_2) peak detected by the Infra-Red (IR) detector, fitted inside the instrument. The IR-detector was specially designed to detect the CO_2 peak, within a concealed furnace at 930°C.



Fig. 25: Weighing, Drying and Carbon Measuring Instruments Used for TOC Analysis

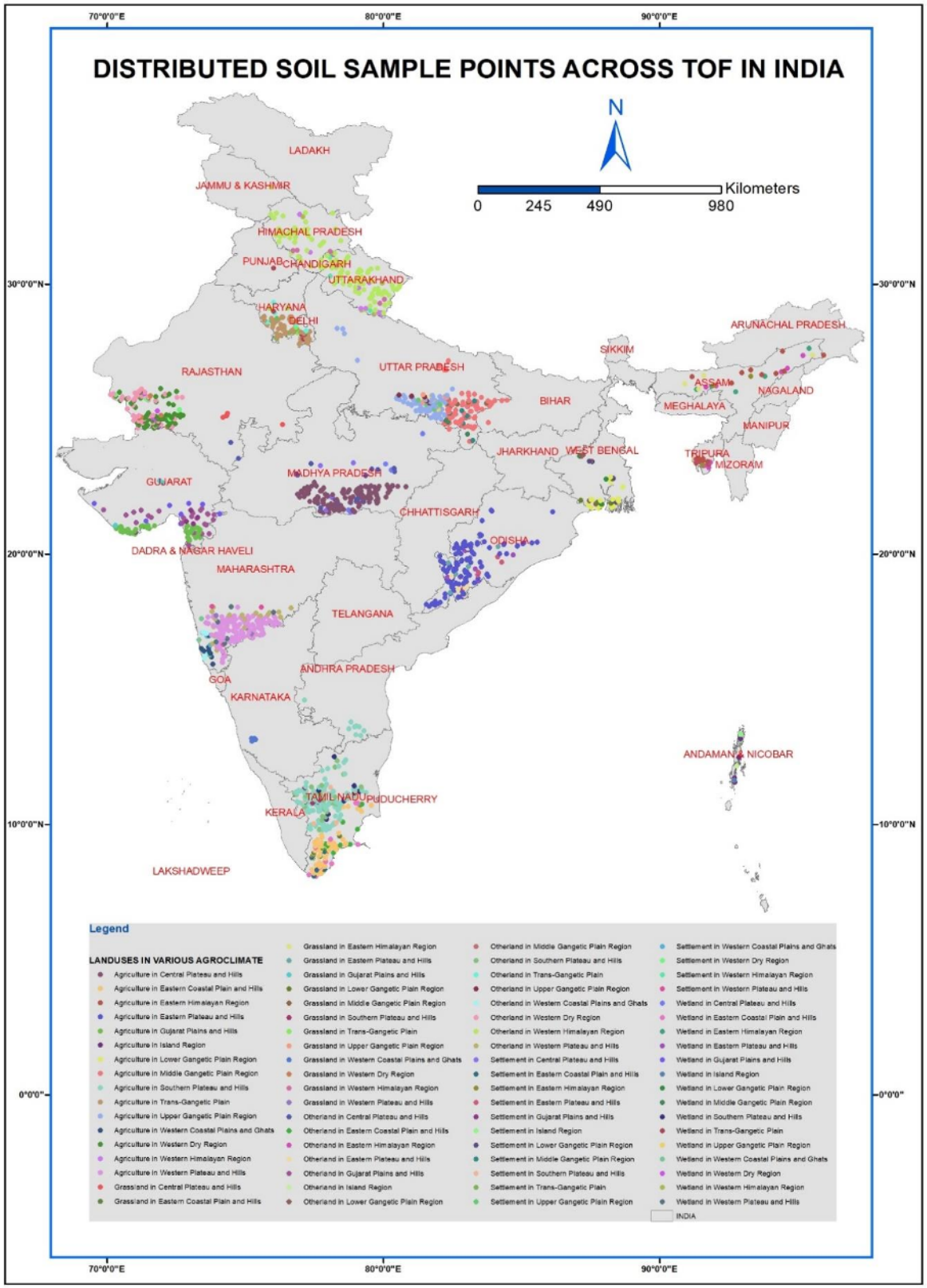


Fig. 26: Distributed Soil Sample Points Across TOF In India

SOIL SAMPLING FORM

Plot ID	FSI Zone	State Code	Dist. Code	Locality Type	Location Name	Land Cover	Latitude (ddmmss.ss)	Longitude (ddmmss.ss)
1 (4)	2 (1)	3 (2)	4 (2)	5 (1)	6	7 (1)	8 (8)	9 (8)

Soil Colour	Percentage Soil (upto 3 digit)	Percentage Gravel (upto 3 digit)	Photographs of Landscape Plot ID with Sl. No. (1, 2)
10 (1)	11 (3)	12 (3)	13 (5)

Date…….. Signature of the Crew Leader……

Note:

i) First Number in the row below the field headings represents the column number and the number inside the bracket represents the column width.

ii) For Lat & Long, seconds to be recorded upto two decimal places, no need to put the decimal points more than two digits.

Fig. 27: Distributed Soil Sample Points Across TOF In India

CHAPTER THREE

Results & Discussion



3. Results and Discussion

Carbon stored in soils worldwide exceeds the amount of carbon stored in phytomass and the atmosphere. Despite the large quantity of carbon stored as soil organic carbon (SOC), there is still a lot of debate is existing on the size of global SOC stocks, their spatial distribution, and the carbon emissions from soils due to periodic changes in land use and land cover **(Scharlemann *et al.*, 2014)**[26].

Ever since attention had increased overtime on carbon sequestration in the mitigation of climate change, an enormous focus on all possible carbon sources and sinks started receiving attentions. Therefore, carbon storage potential for TOF other than forest should always be kept in an accountable position **(Muriga *et al.*, 2014)**[27].

Trees outside Forests (TOF) have assumed importance in view of their economic, ecological, and climatic role. There is a strong recognition of trees outside forests by policy makers, planners, and forest managers because of its pivotal role in sustainable development. Trees outside forests (TOF) are attracting attention in view of pressure mounting on the existing forests due to increasing population and greater resource consumption **(Plieninger *et al.*, 2015)**[28]. Unlike forests, TOF are present on all non-forest lands having varying uses, in varying densities and configurations, which, makes them a resource rather than an area category.

Land use affects soil carbon dynamics, which influence the global carbon cycle **(Jha *et al.*, 2012)**[29]. Understanding the response of soil organic carbon (SOC) dynamics, in diversifying climatic conditions and various land uses requires systematic studies.

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[26] Scharlemann J.P.W., Tanner E.V.J., Hiederer R. and Kapos V. (2014). *Carbon Management*. **Vol. 5** (1): 81-91. ISSN: 1758-3004 (Print) 1758-3012 (Online).

[27] Muriga C.B., Malimbwi R. E., Zahabu E. (2014). Carbon Storage Potential of Trees Outside Forests under Private and Communal Tenure Regimes in Ng'iresi Village, Arumeru District, Tanzania. *International Journal of Science and Research*. **Vol 3** (10): 567-579. ISSN (Online): 2319-7064.

[28] Plieninger T, Hartel T., López B.M., Beaufoy G., Bergmeier E., Kirby K., Montero M.J., Moreno G., Rozas E.O. and Uytvanck J.V. (2015). Wood-pastures of Europe: Geographic coverage, social–ecological values, conservation management, and policy implications. *Biological Conservation* **190**: 70–79.

[29] Jha P., De A., Lakaria B.L., Biswas A.K., Singh M., Reddy K.S. and Rao A.S. (2012). Soil Carbon Pools, Mineralization and Fluxes Associated with Land Use Change in Vertisols of Central India. *National Academy of Science Letters*. **Vol 35**: 475-483.

3.1 Identified Major Land Use Classes

Land use is one of the major governing factor of soil health *vis-à-vis* soil organic carbon, therefore, its area wise distribution has been considered from the latest reports published by Government of India.

Table 2: Various Major Land Use Classes in India

Sl. No.	Major Land Use	Area in km^2 *(% of Area, rounded off to Whole Number)*	Calculated Points	Actually Collected Sample Points	Cited From
1	Forest	7,12,249 *(21%)*	Not Surveyed	Not Surveyed	India State of Forest Report (2019), FSI
2	Settlement	95,700 *(3%)*	60	81	MoEFCC, 2021[30]
3	Grassland	2,24,200 *(7%)*	139	74	-
4	Wetland	1,59,815 *(5%)*	99	92	ISRO, 2021[31]
5	Agriculture	16,44,000 *(50%)*	1023	1027	MoEFCC, 2021
6	Other land	4,51,505 *(14%)*	281	328	MoEFCC, 2021
Total Area (in km^2)		32,87,469 ***(100%)***	**1602**	**1602**	

Agriculture is the backbone of Indian economy, as it is encompassing an area of 16,44,000 km^2; which, is nearly 50% of total geographical area of the country **(Table 2)**. However, the recent report of **Ministry of Agriculture, 2021[32],** mentioned that agricultural area is nearly 53% of the country. Forest area is presently occupying the second position with 7,12,249 km^2 coverage, which is nearly 21% (**Fig. 28**) of the India's geographical area. The area of grassland in India is around 7% of total country's geographical area. In terms of practicality, it is actually extremely difficult; to distinguish between grassland and scrubs with satellite data of lower spatial resolution, therefore, the exact area figure of grassland and other land may vary. The minor variability may occur due to the use of different resolution satellite data, interpreter's bias and intensity of ground verification.

[30] MoEFCC (2021). India: Third Biennial Update Report to the United Nations Framework Convention on Climate Change. Ministry of Environment, Forest and Climate Change, Government of India.

[31] ISRO (2021). Gupta P.K., Patel J.G., Singh R.P., Bahuguna I.M., Raj Kumar *et al.* Space based observation of Indian wetlands, Space Applications Centre, Indian Space Research Organization, Ahmedabad, India. Pp-92. ISBN: 978-938-276-0436.

[32] Ministry of Agriculture (2021). Annual Report, 2020-21. Department of Agriculture, Cooperation & Farmers' Welfare. Ministry of Agriculture & Farmers' Welfare. Government of India. Krishi Bhawan, New Delhi-110 001.

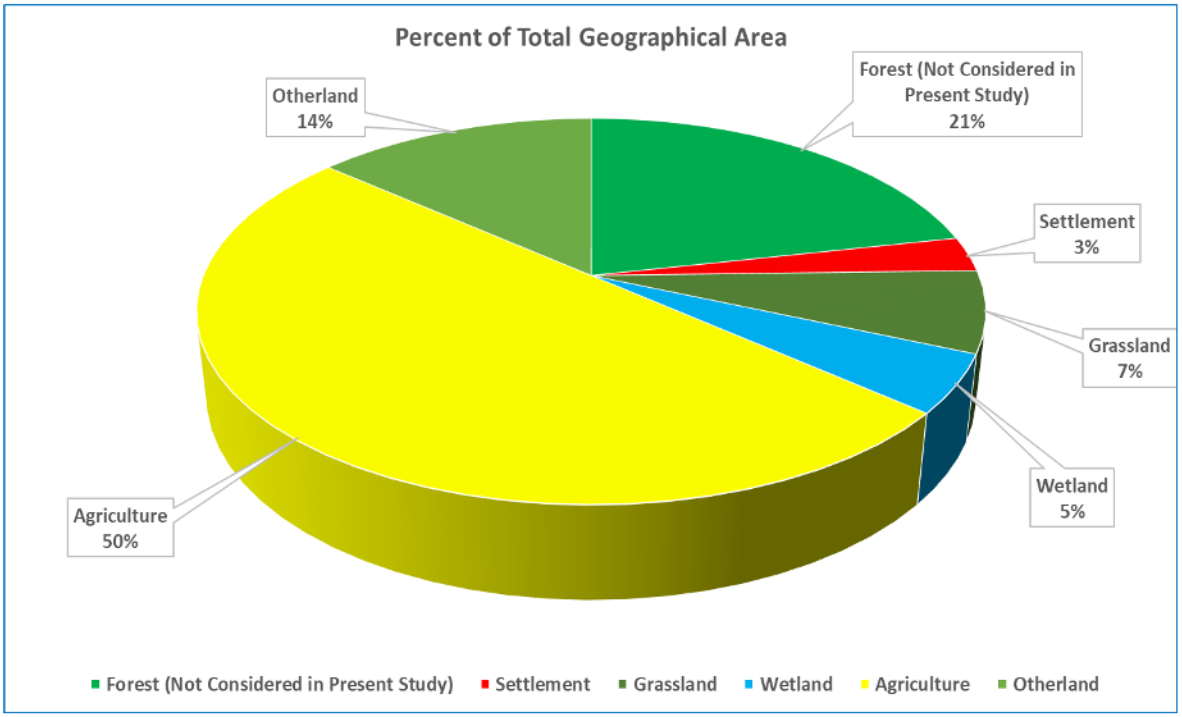


Fig. 28: Distribution of Area under Different Land Use Classes



Fig. 29: A Typical Agricultural Land Use in India



Fig. 30: A Typical Settlement Land Use in India



Fig. 31: A Typical Marshy Wetland Land Use in India



Fig. 32: A Typical Grassland in India



Fig. 33: A Typical Other Land Use in India (A permanent fallow, scrub)

As per the report of **NITI AAYOG (2021)**[33], the urban population of India has raised from 31.1% (2011 Census) to 34.03 % in 2018. The settlement area (presently around 3%) is also increasing day by day for accommodating larger population. Therefore, rapid population outburst and consequent need for urbanization is constantly changing the settlement area percent of the country too.

In the present study, since the focus was concentrated only on TOF area, therefore, the area covered by Forest cover was subtracted from the total study area. The total study area therefore, becomes 25,75,220 km^2. Therefore, the sample points, have only been distributed as per area proportion, across the other five land use classes; i.e. Settlement, Grassland, **Wetland** (**Fig. 31**), Agriculture and Other land. The detailed description of each one of them has already been mentioned in the section 2.2 (in the Materials and Method part).

It is also observed that most of the points (1027 in Number) are lying under agriculture land use (depicted in **Fig. 29**), because of the spatial extent wise dominance of the same**.** Agriculture land use covers nearly 50% of country's geographical area. In contrast to that, settlement (as shown in **Fig. 30**) covers only around 3% of country's area. Therefore, it contains only 81 points out of selected 1602. Nevertheless, as per the obtained study design, the minimum number of points under each stratum should be minimum of five (5) and the total number of sample points should be around 1600 plus, in order to keep the error level below acceptable range. Therefore, for 15 agro-climatic zones, 15 X 5 =75 plus settlement points (actually, 81) have been selected and proportionately, redistributed in different land use classes. Therefore, a minor difference could be observed in "Calculated Points" and "Actually Collected Sample Points" columns of the above-mentioned table. Majority of the points have been relocated from majorly uniform "Grassland class" (**Fig. 32**) and were placed in the variable "Other land" (**Fig. 33**) class (281 to 328), because of the wide variability, of the later, starting from scrub, industrial dump yard to other wastelands. **Fig. 34** shows land use wise total sample point distributions, across the country in various land use classes.

[33] NITI AAYOG (2021). Reforms in Urban Planning Capacity in India. Final Report.

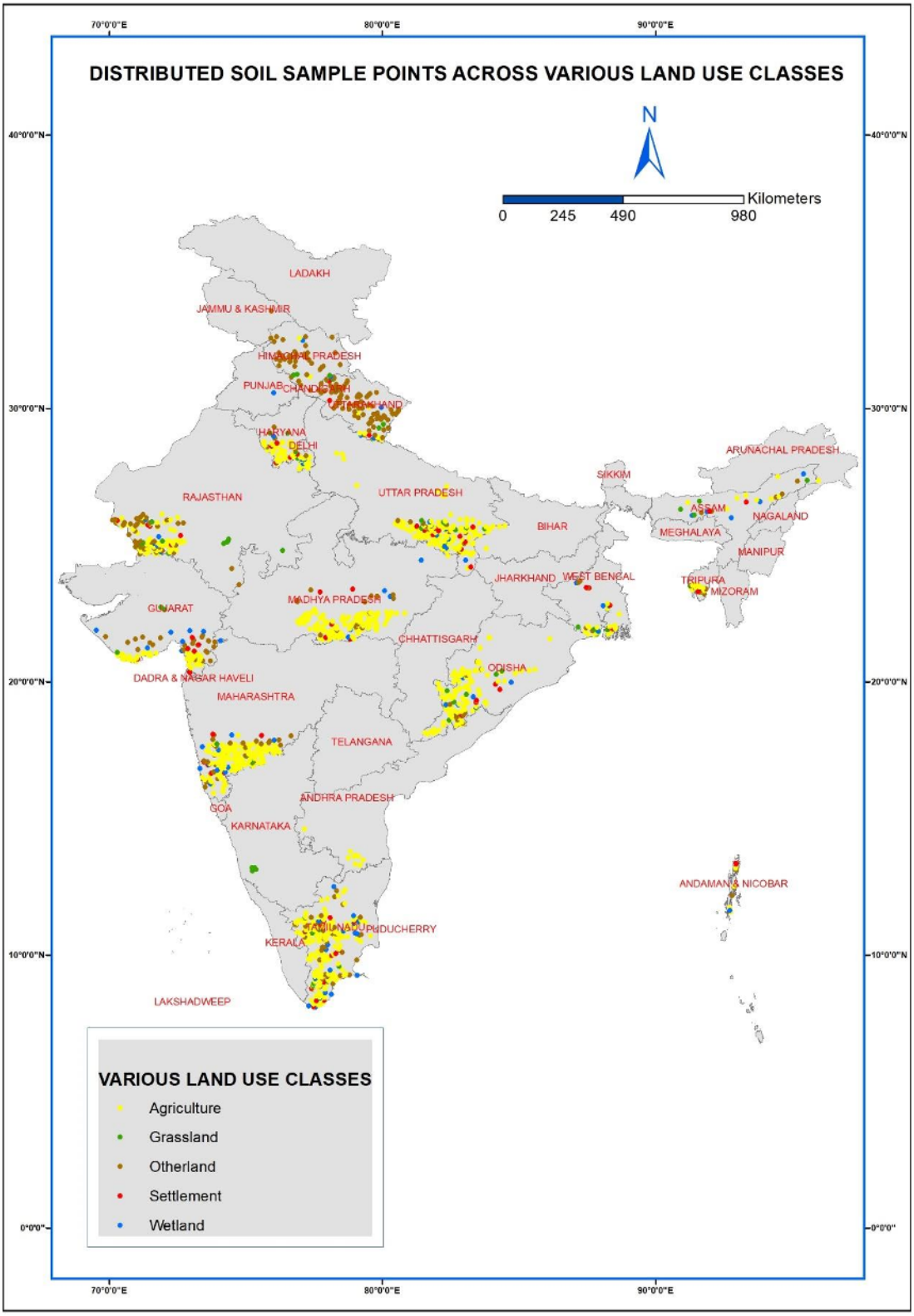


Fig. 34: Distribution of Soil Sample Collection Points Across Various Land Uses

3.2 Identified Major Agro-Climatic Zones

In order to maximize the agricultural production from the available resources, with the prevailing climatic conditions; delineation of agro-climatic zones based on soil, water, rainfall, temperature etc. was devised by planning commission of India (Presently, NITI AAYOG) in the year 1989, with the help of National Remote Sensing Agency (NRSA) (Presently, known as National Remote Sensing Centre i.e. NRSC) . Agro-climatic zones are divided in such a way, that it gives idea that how the vegetation is getting influence from the climate, soil and water. The delineation was based on land survey, soil survey and agricultural survey of rural India. Therefore, an "Agro-climatic zone" is a land unit in terms of major climates, suitable for a certain range of crops and cultivars to be produced over soil. The planning aims at scientific management of regional resources to meet the food, fibre, fodder and fuel wood without adversely affecting the status of natural resources and environment.

Several authors have performed researches based on agro-climatic zones. **Singh (2014)**[34], worked on the effect of population pressure, on major land use practices in agro-climatic zones. The said author emphasized his work in the State of Uttar Pradesh, where two major agriculture dominated agro-climatic zones like: "Upper Gangetic Plain" and "Middle Gangetic Plain" exists. It has been shown by the said authors that per capita net sown area has been decreased in the region over past two decades, resulting an immense pressure on these agriculturally dominated areas.

Sandhu *et al*. (2016)[35]**,** published a report of brainstorming symposium on Agro-climatic Region Centred Research and Development Planning for the "Central Plateau and Hill Region". In the symposium, scientists and researchers have identified several issues those are responsible for lesser agricultural output, than the potential of the said agro-climatic zone. Those concerns, which need to be addressed, are the delivery system of agricultural livestock, large share of unproductive livestock, exodus of rural youth from the region in

[34] Singh P. (2014). Population and agro climatic zones in India. The 3rd International Geography Symposium. *Procedia – Social and Behavioural Sciences*. **120:** 268-278.

[35] Sandhu J.S., Gautam, U.S., Ghosh P.K., Dubey S.K., Singh A., Kumar R.V. and Singh S.V. (2016). Agro-climatic Region Centred Research and Development Planning (Central Plateau and Hill Region), Brainstorming jointly organized by: i) ICAR-Agricultural Technology Application Research Institute (ATARI) & ii) Kanpur and ICAR-Indian Grassland and Fodder Research Institute (IGFRI), Jhansi. Held at: IGFRI, Jhansi.

search of white colour job, only a smaller area centric natural resource management, lack of knowledge and information about modern agricultural practices etc.

Under the context of present study, the two above-mentioned reviews may apparently seem to be irrelevant. However, it has a great significance, while, the area coverage of the agro climatic zones of India be discussed. In reality, it is extremely difficult to demarcate any specific agro climatic zone with exact demarcation boundary. The reason is that the climate and agricultural practices does not change rapidly in either side of the border of any two agro climatic zones; unless, there is a sudden and tremendous alteration of physiography. Moreover, studies have shown that the purpose with which, the agro climatic zones were proposed, that worked extremely beneficial to attain its objective in its initial phases. In contrary to that, in the present scenario the border of agro climatic zone are under challenge, primarily due to enormous population pressure, inefficient resource management and alteration of focus of the youth population towards non-agricultural sectors. Therefore, quoting an exact area of agro climatic zone is really challenging and should be used with caution in future research purposes. The above-mentioned two citations are therefore suitable examples of the present challenges being faced by the delineated agro-climatic zones more than three decades back.

Table 3 shows that there is a minor difference in the calculated points and the actually visited points from where the soil samples have been collected over different agro-climatic zones. The main reason is that the area of the non-forest of “Island region” is negligible in comparison to the main land India. The number of soil sample from any agro-climatic zone cannot be only “One” (as per theoretical estimation), for any reasonable estimate generation, which was calculated as per the area true proportion. As per the adopted methodology, the total number of points per land use class should at least be five (05) for better Statistical accuracy, therefore, from four (04) land use classes (except, grassland land use class, which, is not or negligibly present in Island region, as per the scale of study) 5 X 4 = 20, soil samples have been collected. In order to keep the total number of sample points around 1600 plus, and error below acceptable limit. The points those were placed in difficultly accessible area in the other agro climatic zones, have randomly been selected and adjusted with the Island agro climatic zones. The distribution of soil sample collection points in various agro-climatic zones are presented in **Fig. 35**.

The "Western Himalayan Region" covers maximum area of 3,11,688 km^2 and were having maximum of 194 soil sample points with 12.10% of area coverage (**Fig. 36**). Since, a major portion of "Western Himalayan Region" is under snow cover and devoid of any soil layer, therefore, the number of sample points were reduced in practical scenario to 164. The "Southern Plateau and Hills" of area coverage 3,10,259 km^2 is having 193 soil sample points and all of those sample points have been collected from the ground .

Table 3: Distribution of Collected Soil Sample Points Across Various Agro Climatic Zones

Sl. No.	Agro Climatic Zones	Area in km^2 (Excluding Entire Forest Area)	% of Area (Rounded off to 2nd Place of Decimal)	Rounded Off Number of Soil Sample Points (Calculated)	Rounded Off Number of Soil Sample Points (Collected)
1	Western Himalayan Region	3,11,688	12.10	194	164
2	Trans-Gangetic Plain Region	1,13,685	4.41	71	80
3	Upper Gangetic Plain Region	1,32,282	5.14	82	89
4	Central Plateau and Hills	2,86,374	11.12	178	175
5	Western Plateau and Hills	2,78,478	10.81	173	179
6	Southern Plateau and Hills	3,10,259	12.05	193	193
7	Middle Gangetic Plain Region	1,49,303	5.80	93	98
8	Lower Gangetic Plain Region	50,632	1.97	31	44
9	Eastern Coastal Plain and Hills	1,61,866	6.29	101	102
10	Eastern Plateau and Hills	2,29,105	8.90	143	148
11	Eastern Himalayan Region	1,11,088	4.31	69	51
12	*Island Region	1,507	0.06	1	20
13	Western Coastal Plains and Ghats	46,571	1.81	29	31
14	Western Dry Region	2,07,443	8.06	129	119
15	Gujarat Plains and Hills	1,84,939	7.18	115	109
Total Forest Area (FSI, 2019, India State of Forest Report) (Not considered in the present study)		**7,12,249**	**-**	**Not Applicable**	**Not Applicable**
TOTAL GEOGRAPHICAL AREA		**32,87,469**	**100.00**	**1602**	**1602**

*** Note**: In case of Island Agro Climatic Region, only the non-forest area under Andaman and Nicobar Islands as well as Lakshadweep Islands have been considered

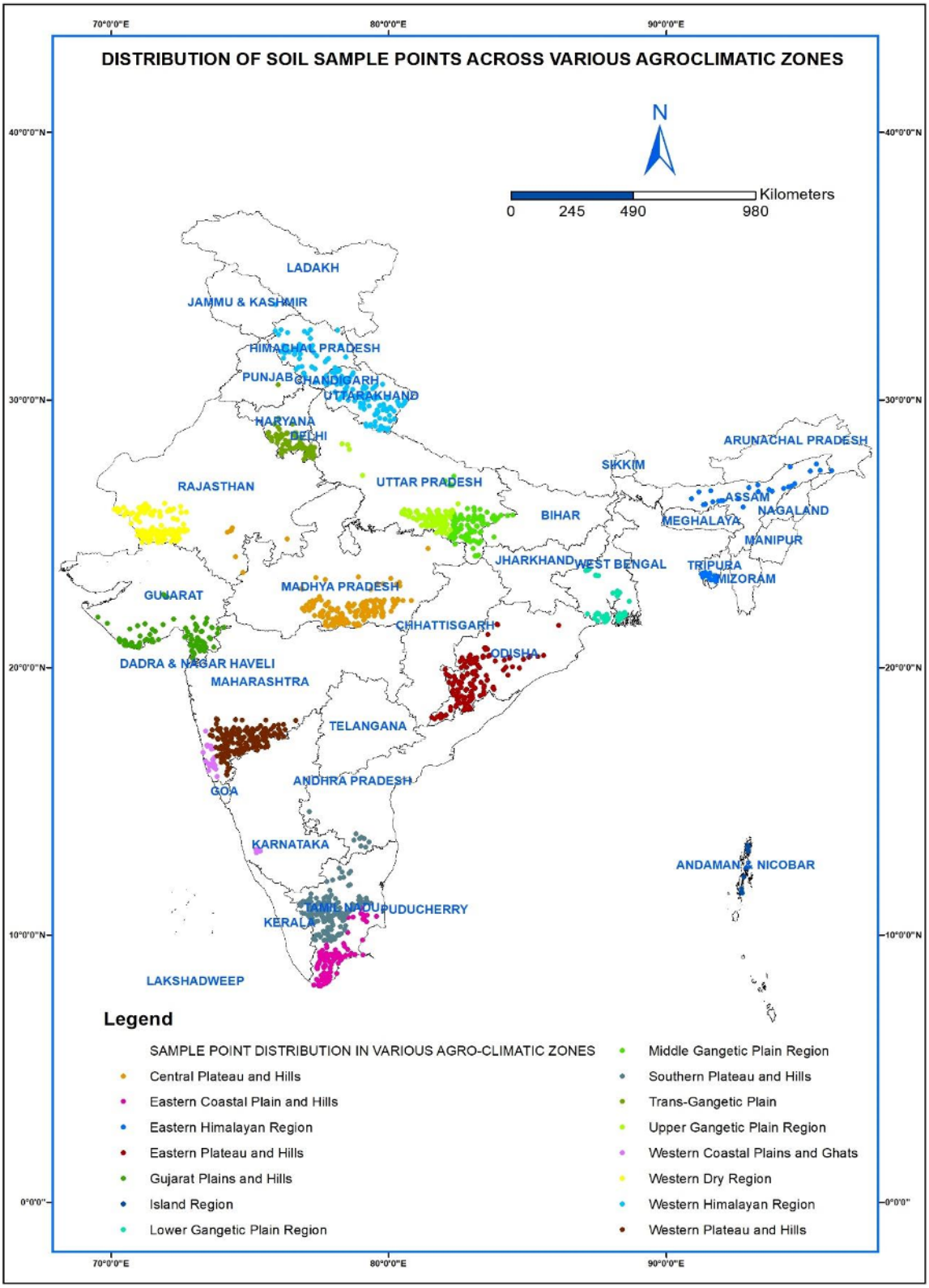


Fig. 35: Distribution of Soil Sample Collection Points in Various Agro-Climatic Zones

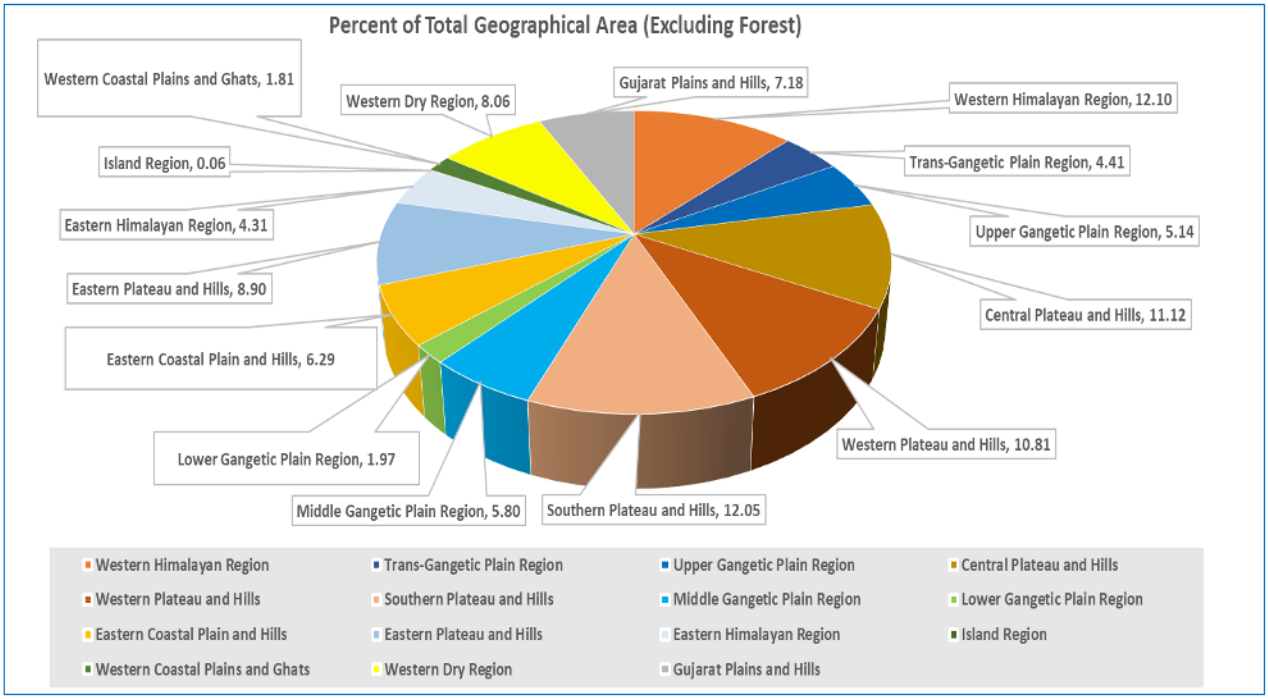


Fig. 36: Distribution of Soil Sample Collection Points in Various Agro-Climatic Zones

3.3 Soil Organic Carbon Content in Various Land Use Classes

Land use pattern, is one of the major indicator of the possible behaviour of soil or its quality. Land use pattern and any change on it also affects the soil organic carbon content. Changes in soil carbon pools and properties were more pronounced in surface (0–15 cm) soils than in the subsurface (15–30 cm) **(Padbhushan *et al.*, 2021)[36].** Therefore, in the present study also the subsurface soils were collected, because the surface soils are more vulnerable to alluviation by water flow and colluviation due to gravity or wind. In contrary, the characteristic behaviour of sub-surface soil is much stable than the surface one.

Several authors have studied land use specific effects on soil organic carbon. However, most of the researches of soil organic carbon have so far been done in India, with the aim to assess soil quality in agricultural lands and thereby to enhance the crop productivity of the respective soil with various agro-management practices. **Yadav *et al.* (2020)[37]**, studied

[36] Padbhushan R., Kumar U., Sharma S., Rana D.S., Kumar R., Kohli A., Kumari P., Parmer B., Kaviraj M., Sinha A.K., Annapurna K., Gupta V. (2021). Impact of Land-Use Changes on Soil Properties and Carbon Pools in India: A Meta-analysis. *Frontiers of Environmental Science & Engineering*. **Vol – 9**.

[37] Yadav S., Kumar R., Sharath Chandra M., Abhineet, Singh S., Yadav R.B. and Kumar M. (2020). Soil Organic Carbon Sequestration and Carbon Pools in Rice Based Cropping Systems in Indo-Gangetic Plains: An Overview, *International Research Journal of Pure & Applied Chemistry,* **21**(24): 122-136. ISSN: 2231-3443.

Soil Organic Carbon Sequestration and Carbon Pools in rice based cropping systems in Indo-Gangetic Plains. The Western world always blames the Asian countries for their intense rice cultivation system for their contribution in the methane emission and associated climate change. Therefore, the authors suggested for Integrated Nutrient Management, by promoting mycorrhiza symbiosis in aerobic rice system besides enhancement of stable phytolith-occluded carbon for enhancing carbon sequestration in rice production system. However, in the present context, we are only considering the carbon storage in the subsoil of agricultural land use in India, without considering the adopted management practices in the selected plot through stratified random sampling.

Authors like **Vasenev *et al.* (2013)[38],** studied soil organic carbon (SOC) pools in mega cities and in small settlements, with due account for the natural, economic, and historical heterogeneity of urban territories in and around the city of Moscow, Russia. Although, in agricultural point of view it appears irrelevant to measure soil organic carbon from built up area. However, in terms of carbon sequestration through urban plantation, this study obviously keeps its significance. In the present study, we could observe the potential of soil organic carbon in the settlement area.

Grassland soils are high in soil organic carbon and contain an extensive fibrous root system that creates an environment, ideal for soil microbial activity. Accurate quantification of SOC pool is needed to generate benchmark information for the present and to determine the changes in future, especially for grassland areas **(Gupta and Sharma, 2013)[39].**

It is well documented that the land use class of wetland is having utter significance since, the ancient period. Wetlands have always been the sites of sources of water and consequently the development of various renowned civilisations. Wetlands are among the most productive ecosystems and play a significant role in the eco hydrological sustainability of a region.

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[38] Vasenev V.I., Prokof'eva T.V. and Makarov O. A. (2013). The Development of Approaches to Assess the Soil Organic Carbon Pools in Megapolises and Small Settlements, *Eurasian Soil Science,* **Vol 46** (6): pp. 685–696. ISSN: 1064-2293. © Pleiades Publishing, Ltd., 2013.

[39] Gupta M. and Sharma S.D. (2013). Sequestered Organic Carbon Status in the Soils under Grassland in Uttarakhand State, India. *Applied Ecology and Environmental Sciences*. **Vol 1**: 7-9.

Until date, researchers are constantly working on various aspects of wetland ecosystem. Among them, studying the soil organic carbon is utterly important for us. **Sharma *et al.* (2022)**[40] performed a detailed study on surface and sub-surface soil organic carbon content of "Tidal Wetlands" and observed that the soil organic carbon content of surface and subsurface are positively as well as significantly correlated. They have also shown that the soil organic carbon gradually decreases with the increase in soil depth. However, in the current study, the emphasis have been given to the sub-surface (15-30 cm) soils. Obviously, it is quite possible of inter-mixing of the soil sample fraction of surface (0-15 cm) with the sub-surface one.

Among, all the land use classes' wastelands or degraded permanent fallow lands are probably the most neglected one in terms of the study of soil organic carbon. Due to the persistent non-productivity for any other issues like water shortage, industrial toxicities to those lands, the soil organic carbon potential have seldom been tested. However, still researchers have shown their interest in the study of the potential for carbon accumulation in the wastelands having depleted nutrients, soil structure and microbial population, yet, retaining the requisites to add to the sequestered carbon pool **(Rajalekshmi and Bastin, 2020)**[41].

Table 4 represents the soil organic carbon in tonnes per hectare as well as the total estimated soil organic carbon stock under different land use classes in India. It can be observed that the carbon stock per hectare is comparatively high in the settlements (35.25 t/ha) and other land (34.62 t/ha). The other land considered are dominated by wasteland and scrublands. The wastelands and scrubs may include the permanent fallow lands alongside of agricultural and allied industries like sugar mill, paper mill, distillery plant and municipal sewage treatment plant in several cases, which, deposits their organic carbon rich wastes in those lands **(Reddy, 2014)**[42]. Therefore, the study of wasteland as a meaningful sink of soil organic carbon is noteworthy. The scrubland if kept for a longer

[40] Sharma R., Mishra D.R., Levi M.R. and Sutter L.A. (2022). Remote Sensing of Surface and Subsurface Soil Organic Carbon in Tidal Wetlands: A Review and Ideas for Future Research. *Remote Sensing*. **Vol 14**: 2940.
[41] Rajalekshmi K. and Bastin B. (2020). Potential of wastelands for carbon sequestration- A review, *International Journal of Chemical Studies.* **Vol 8** (3): 2873-2881. P-ISSN: 2349–8528. E-ISSN: 2321–4902.
[42] Reddy P. (2014). Influence of Nutrient Rich Organic Wastes in Wastelands Reclamation. *PhD Thesis*. ISBN (eBook): 9783656596134, ISBN (Printed Book): 9783656596967. Munich, GRIN Verlag.

time, it shows a slow rise in the stock of Soil Organic Carbon Pool **(Romero *et al.*, 2021)[43].** This may be another probable reason for getting higher carbon content per ha land in the other land use class.

The settlement also rises near these industrial bases for better job opportunity , where soil is filled with industrial carbon rich wastes; thereby making the soil organic carbon content much richer than our expectation. For better comparative visualization, Soil Organic Carbon (t/ha) in various land use classes are pictorially represented in **Fig. 37**.

In case of agricultural lands, intensive cultivation of crops without providing proper compost to the soil is the reason behind the fall in soil organic carbon content **(Business Standard, 2022)[44]**. This may be the reason of lesser soil organic carbon content per ha land (29.55 t/ha) in agricultural land use.

However, the estimated soil carbon stock in agricultural land is the most (4,858 Mt). This is due to the reason of maximum coverage of agricultural land use in India.

Table 4: Estimated Soil Organic Carbon in Various Land Use Classes in TOF

Sl. No.	Land Use Classes	Mean Soil Organic Carbon (C) (in t/ha)	Standard Error (SE) of Soil Organic (C) (in t/ha)	Mean CO_2 eq. (in t/ha)	Estimated Soil Organic Carbon (Mt) *(CO2 eq. is in Parenthesis)*
1	Agriculture	29.55	0.69	108.45	4,858 *(17,829)*
2	Grassland	28.91	2.63	106.10	648 *(2,379)*
3	*Other land	34.62	1.48	127.06	1,329 *(4,876)*
4	Settlement	35.25	3.61	129.37	337 *(1,238)*
5	Wetland	26.52	2.15	97.33	424 *(1,555)*
Weighted Mean of Soil Organic Carbon		**30.67**	**Overall SE = 0.60**	**112.56**	**7,596 *(27,877)***
Note: $Weighted\ Mean\ of\ Soil\ Organic\ Carbon = \frac{\Sigma(\mu i.fi)}{\Sigma fi}$, **where, μi = Average of the ith class and fi = Number of observations in ith class**					
* The **"Other land"** includes Rann and Snow covers where soils do not exists below 15 cm depth, therefore, during ***Soil Carbon Stock Estimation*** the area of Rann and Snow cover has been adjusted.					

[43] Romero E.N., Rubio P., Kremyda V., Absalah S., Cammeraat E., Jansen B., Lasanta T. (2021). Effects of agricultural land abandonment on soil organic carbon stocks and composition of soil organic matter in the Central Spanish Pyrenees. *Catena,* **205:** 105441.

[44] Business Standard (2022). Soil organic carbon content fell from 1% to 0.3% in 70 years in India: NRAA. Published on: Sat, March 26 2022.

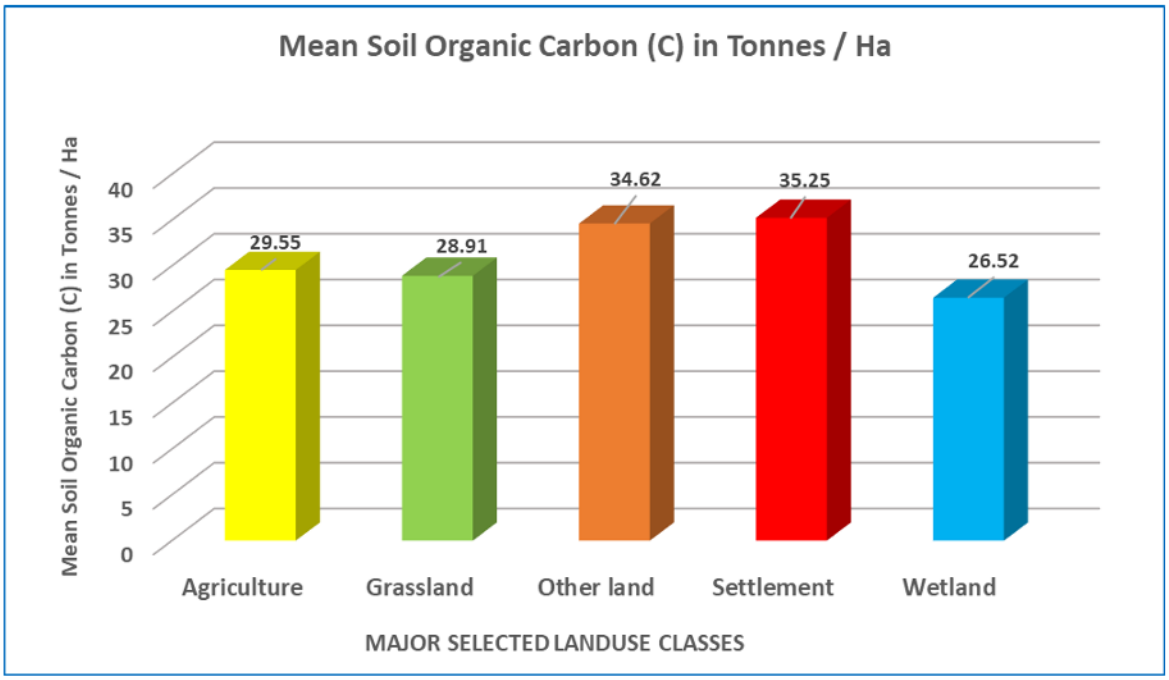


Fig. 37: Soil Organic Carbon (Tonnes/Ha) in Various Land Use Classes

3.4 Soil Organic Carbon Content in Various Agro-Climatic Zones

Soil quality assessment through soil organic carbon (SOC) measurement has always remained the major concern for soils, in terms of its fertility and productivity. Important factors controlling soil organic carbon levels include climate, hydrology, parent material, vegetation patterns and land use **(Jenny, 1941)**[45]. Climate being one of the major factors affecting soil formation; therefore, in the present study fifteen agro-climatic zones of India were taken care off, for soil organic carbon estimation. The scientists of "National Bureau of Soil Survey and Land Use Planning also performed similar study, considering the major physiographic zones of India, namely: (i) the Northern Mountains, (ii) the Great Plains, (iii) the Peninsular Uplands, and (iv) the Indian Coasts and (v) Islands.

However, the collection and analysis of soil organic carbon according to agro-climatic zone distribution for the entire country; especially, for the TOF is one of the pioneering approach in this field of study.

[45] Jenny, H., Factors of Soil Formation, McGraw-Hill, New York, 1941, p. 281.

Table 5: Estimated Soil Organic Carbon in TOF of Various Agro-Climatic Zones

Sl. No.	Agro Climatic Zones	Mean Soil Organic Carbon (C) (in t/ha)	Standard Error (SE) of Soil Organic (C) (in t/ha)	Mean CO_2 eq. (in t/ha)	Estimated Soil Organic Carbon (Mt) *(CO2 eq. is in Parenthesis)*
1	Western Himalayan Region	45.41	2.34	166.65	1,169 *(4,292)*
2	Trans-Gangetic Plain Region	12.34	1.37	45.29	139 *(509)*
3	Upper Gangetic Plain Region	21.29	1.64	78.13	278 *(1023)*
4	Central Plateau and Hills	28.80	1.12	105.69	816 *(2995)*
5	Western Plateau and Hills	40.53	1.67	148.74	1,117 *(4098)*
6	Southern Plateau and Hills	30.29	1.31	111.15	930 *(3412)*
7	Middle Gangetic Plain Region	22.23	1.69	81.58	328 *(1205)*
8	Lower Gangetic Plain Region	21.49	1.68	78.86	108 *(395)*
9	Eastern Coastal Plain and Hills	26.67	1.64	97.88	427 *(1567)*
10	Eastern Plateau and Hills	24.76	1.39	90.87	561 *(2059)*
11	Eastern Himalayan Region	28.71	4.09	105.37	316 *(1157)*
12	Island Region	36.21	5.09	132.88	5 *(20)*
13	Western Coastal Plains and Ghats	57.68	6.19	211.68	266 *(975)*
14	Western Dry Region	16.18	0.91	59.37	332 *(1219)*
15	Gujarat Plains and Hills	48.20	3.58	176.89	804 *(2951)*
Weighted Mean of Soil Organic Carbon		**30.67**	**Overall SE = 0.60**	**112.56**	**7,596 *(27,877)***

Note: $Weighted\ Mean\ of\ Soil\ Organic\ Carbon = \frac{\Sigma(\mu i.fi)}{\Sigma fi}$,
where, μi = Average of the i^{th} class and fi = Number of observations in i^{th} class

The **"Other land"** includes Rann and Snow covers, is falling in the agro-climatic zones of "Gujarat Plains and Hills" and "Western Himalayan Region", respectively, where, soils do not exists below 15 cm depth, therefore, during ***Soil Carbon Stock Estimation*** the area of Rann and Snow cover has been adjusted.
* The Estimated Soil Organic Carbon has been normalized as per area proportion.

Table 5 represents the mean soil organic carbon stock per hectare. It is maximum in the "Western Coastal Plains and Ghats" (57.68 t/ha), followed by "Gujarat Plains and Hills" (48.20 t/ha) and "Western Himalayan Region" (45.41 t/ha). On the other side, the "Western Dry Region" (16.18 t/ha) and Gangetic Plain Regions (Trans - 12.34 t/ha, Upper - 21.29 t/ha, Middle - 22.23 Tonnes /Ha and Lower - 21.49 t/ha) contains relatively lower carbon content per ha. The comparative representation of the Soil Organic Carbon (t/ha) in various agro-climatic zones are presented in **Fig. 38**.

The "Western Coastal Plains and Ghats", has received 1.5 to 2 times the magnitude of rainfall with each passing decade during the second half of the 20th century **(Marar, 2022)[46].** Moreover, the increased precipitation is considerably responsible for keeping soil microbial diversity and health stable **(Li *et al.*, 2022)[47].** The Soil microbial community play a major role in C-cycling and these microbial activities has been considered as the main driver of differences in the potential to store C in soils **(Bhattacharyya, 2022)[48]**. Therefore, these combining effect may be the significant reason for achieving highest soil organic carbon content per hectare soil in the "Western Coastal Plains and Ghats".

In contrary to that the "Western Dry Region" is vastly covered with deserts and semi deserts. The area is therefore facing severe scarcity of rainfall. These factors causes the depletion of soil microbial activities and thereby, causing low soil organic carbon content per hectare.

The soil organic carbon in the Indo-Gangetic plain (Trans, Upper, Middle and Lower) showed low to moderate in range. The data corroborates with the findings provided by the scientists of "National Bureau of Soil Survey and Land Use Planning" (under Indian Council of Agricultural Research). The rise in population, especially in the fertile Indo-Gangetic Plain Region, depletes the fertile land availability and thereby, decreases the soil fertility in the long-run. The process of natural chemical degradation in soils in parts of the Indo-Gangetic Plain Region is also proceeding at a faster rate, thereby, diminishing its soil microbiological activities **(Bhattacharyya *et al.*, 2004)[49]**. Therefore, the soils of Indo-Gangetic Plains have a lot of potential to sequester more carbon by properly managing the soils of the vast agricultural belt existing in this region.

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[46] Marar A. (2022). Western Ghats received more rain in last few decades due to changes in Pacific Ocean: Study. *Indian Express.* Published on: February 24, 2022.

[47] Li1 J., Benti G., Wang D.,Yang Z. and Xiao R. (2022). Effect of Alteration in Precipitation Amount on Soil Microbial Community in a Semi-Arid Grassland. *Frontiers in Microbiology*. **Vol. 13:** 842446.

[48] Bhattacharyya S.S., Ros G.H., Furtak K., Iqbal H.M.N., Saldívar R.P. (2022). Soil Carbon Sequestration – An Interplay between Soil Microbial Community and Soil Organic Matter Dynamics. *Science of the Total Environment.* **Vol 815**: 152928.

[49] Bhattacharyya, T., Pal D.K., Chandran P., Mandal C., Ray, R.K. Gupta and Gajbhiye K.S. (2004). Managing Soil Carbon Stocks in the Indo-Gangetic Plains, India, Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi-110 012, India. pp 44.

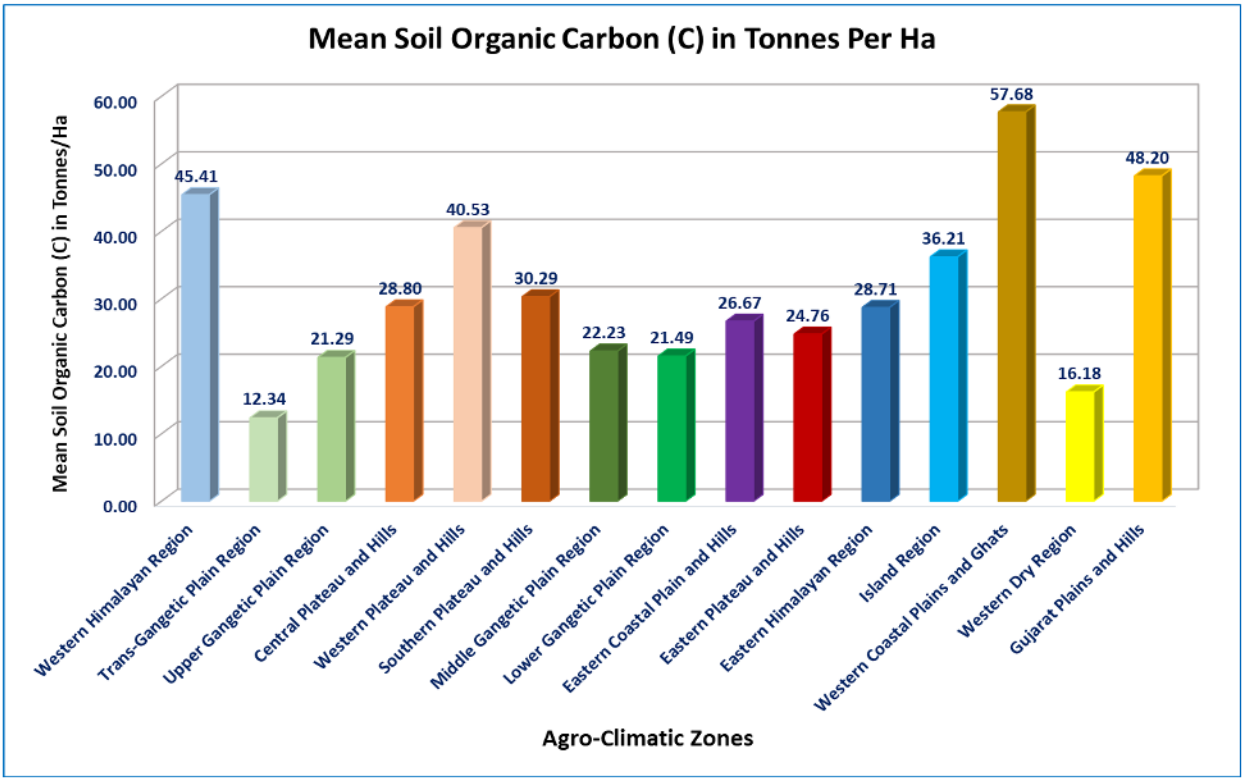


Fig. 38: Soil Organic Carbon (Tonnes/Ha) in Various Agro-Climatic Zones

Different authors have so far been studied the distribution of soil organic carbon in Indian soil. **Ravikumar and Somashekhar (2013)**[50] have studied soil physical and chemical properties including soil organic carbon, in the soils of "*Varahi river basin*", Udupi district, Karnataka. In a broader context, **Babu *et al.*, 2017**[51]**,** studied the soil organic carbon across the country by giving a special focus on rice cultivating agricultural field, with more than 500 soil sample points. Unlike, the present study, the authors also expressed their concern regarding the depletion of soil organic carbon across "Indo-Gangetic Plain". As per usual expectation the soils of dry desert of Rajasthan showed low (less than 0.5%) soil organic carbon percent, due to less soil microbial activities in dry soil. In this study, the range of soil organic carbon percent of TOF (excluding forest) was sub-divided and mapped **(Fig. 39)** into four major categories; such as: High (> 1%), Medium to High (0.75 to 1%), Medium (0.5 to 0.75%) and Low (<0.5%).

[50] Ravikumar P. and Somashekhar (2013). Evaluation of nutrient index using organic carbon, available P and available K concentrations as a measure of soil fertility in Varahi River basin, India. *Proceedings of the International Academy of Ecology and Environmental Sciences*. **3** (4): 330-343. ISSN 2220-8860.

[51] Babu V.R., Sailaja B. and Brajendra (2017). Soil Organic Carbon Mapping and Estimation of Stock in Rice Soils of India. *Global Symposium on Soil Organic Carbon.* Rome, Italy, 21-23 March 2017.

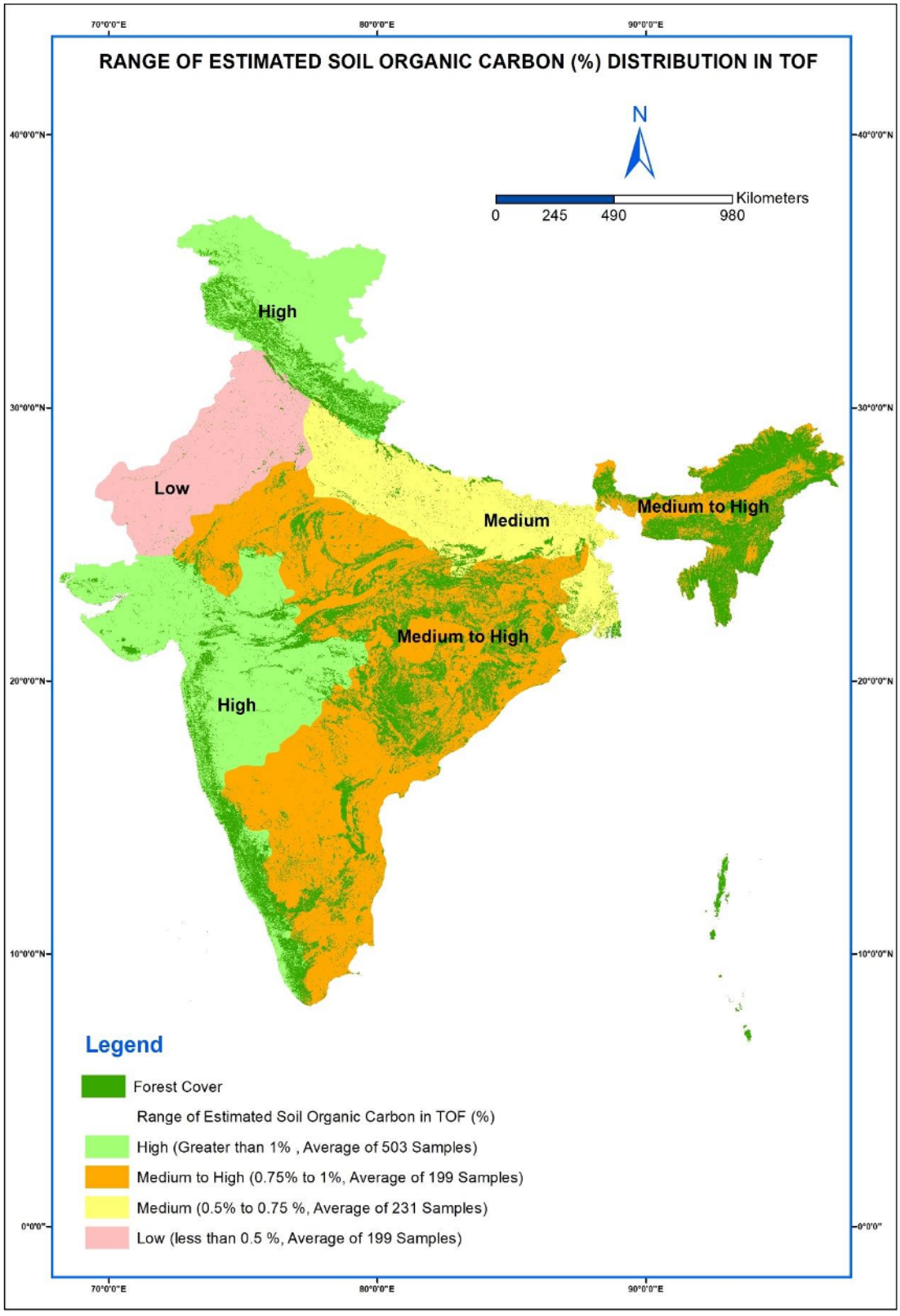


Fig. 39: Range of Estimated Soil Organic Carbon (%) in the TOF Soils of India





CHAPTER FOUR

Conclusion & Future Vision



4. Conclusion and Future Vision

Soil organic carbon (SOC) plays an important role in soil fertility and productivity. It is an extremely crucial indicator of "Soil Health". Soils hold the largest biologically and geochemically active terrestrial carbon pool on Earth, which, are critical for stabilizing atmospheric CO_2 concentrations. Therefore, soil organic carbon is a vital indicator of climatic impact on the environment. FSI, in tune of its mandate estimated the forest carbon content in the five organic carbon pools of forests regular interval of alternate year. Those are AGB, BGB, dead wood and litter. However, the soil organic carbon estimation in TOF, devoid of forestland was yet to be carried out by FSI. The lesser abundance of dense bigger trees and their deep roots make the soil organic carbon more relevant in term of its contribution to the carbon pools. Therefore, soil organic carbon in TOF, without forestland became the need of the hour.

All total 1602 number of soil sample points were identified from a population of 20,000 TOF points and they were proportionately distributed in five (5) identified land use classes such as agriculture, Grassland, Wetland, Settlement and Other land (except, forest) and 15 agro-climatic zones of India (as per NITI AAYOG's definition). The points were distributed in various strata according to the respective area proportion, with necessary adjustment.

As per the mandated objective, the soil organic carbon of five (05) land use classes have been analysed. It was observed that per ha soil organic carbon is highest in the settlement (35.25 C t/ha) and in the other land (34.62 C t/ha); although the estimated stock of soil organic carbon is highest in agricultural land use (4,858 Mt) owing to its vast area coverage of around 50% of the country. Therefore, there is potential in terms of soil organic carbon, for the soils of settlement and other land for using the same in plantation or agricultural purposes, provided the other parameters remain favourable.

Moreover, the soil samples were also collected from the 15 agro-climatic regions of India. The soils of "Western Coastal Plains and Ghats" (57.68 t/ha), "Gujarat Plains and Hills" (48.20 t/ha) and "Western Himalayan Region" (45.41 t/ha) have higher range of soil organic carbon on an average (>1%). This was probably due to the presence of adequate

soil moisture and favourable temperature throughout the year with undisturbed soil condition in most of the region. The Plateaus of Indian subcontinent and "Eastern Himalayan Region" is having "Medium to High" soil organic carbon content (0.75 to 1%). In contrary, the most of the soils of "Indo-Gangetic Plain" is excessively utilized for over the year crop production. Continuous cropping practices with minimum soil health management may be the reason of its depleted average soil organic carbon content (0.5 to 0.75%). Low soil organic carbon content of less than 0.5% has been observed in the "Western Dry Region", mostly covered with the "*Thar"* desert of Rajasthan. Therefore, there is a huge potential to improve the soil health by improving soil organic carbon in the regions of "Indo Gangetic Plains". Moreover, the intersecting area between the agro-climatic zones of "Indo Gangetic Plains" and utilizable other land use could be treated as the most priority area, where potential to enhance either cropland or plantation is possible.

Thus, utilization of greater area for crop production and plantation with proper soil organic carbon management will certainly have the capability to reduce the food insecurity of the Nation and the forest area enhancement of the country respectively.

The higher the forested area of the country implies the greater potential to sequester more and more atmospheric CO_2. This in turn will certainly be a step forward to achieve "Nationally Determined Contribution" and a way ahead in inching towards "Carbon Neutrality" by our country.

CHAPTER FIVE

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5. References

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CHAPTER FIVE

Annexure



6. Annexure

The one-way analysis of variance (ANOVA) is used to determine whether there are any statistically significant differences of a single independent variable between the means of that variable obtained from more than one independent (unrelated) groups or strata.
In the present study mean 'Soil Organic C' in t/ha is analysed for finding its variation across five (5) land use classes and fifteen (15) agro-climatic zones. The obtained ANOVA tables are shown as below.

Table 6: One way ANOVA Table of Soil Organic Carbon across various Land Use Classes

SUMMARY OF LULC CLASSES

Groups	*Count*	*Sum*	*Average*	*Variance*
Agriculture	1027	30343.58	29.54584	491.2935
Grassland	74	2139.049	28.90606	512.3268
Other land	328	11354.64	34.6178	721.9572
Settlement	81	2855.357	35.25133	1056.005
Wetland	92	2439.88	26.52044	424.3323

ANOVA OF LULC CLASSES

Source of Variation	*SS*	*df*	*MS*	*F observed*	*P-value*	*F critical*
Between Groups	9924.235	4	2481.059	4.399365	0.001537	2.3775
Within Groups	900641.6	1597	563.9584			
Total	**910565.8**	**1601**				

Table 7: One way ANOVA Table of Soil Organic Carbon across various Agro-Climatic Zones

SUMMARY OF AGRO-CLIMATIC ZONES

Groups	*Count*	*Sum*	*Average*	*Variance*
Western Himalayan Region	164	7446.717	45.40681	894.7643
Trans-Gangetic Plain Region	80	987.484	12.34355	150.2457
Upper Gangetic Plain Region	89	1894.726	21.28906	239.1952
Central Plateau and Hills	175	5039.477	28.79701	219.0418
Western Plateau and Hills	179	7254.264	40.52662	497.2789
Southern Plateau and Hills	193	5845.06	30.28528	332.68
Middle Gangetic Plain Region	98	2178.529	22.22989	280.7992
Lower Gangetic Plain Region	44	945.3858	21.48604	123.7028
Eastern Coastal Plain and Hills	102	2720.681	26.67334	273.9495
Eastern Plateau and Hills	148	3664.431	24.75967	286.836
Eastern Himalayan Region	51	1464.433	28.71438	856.1921
Island Region	20	724.109	36.20545	519.1039
Western Coastal Plains and Ghats	31	1788.014	57.67786	1187.325
Western Dry Region	119	1925.118	16.17746	100.6203
Gujarat Plains and Hills	109	5254.076	48.20253	1397.962

ANOVA OF AGRO-CLIMATIC ZONES						
Source of Variation	*SS*	*df*	*MS*	*F observed*	*P-value*	*F critical*
Between Groups	187761.2	14	13411.51	**29.44651**	7.4042E-70	**1.698004**
Within Groups	722804.6	1587	455.4534			
Total	**910565.8**	**1601**				

The **table 6** and **table 7** depict the "One Way Analysis of Variance" (ANOVA), for the variable Soil Organic Carbon distributed across various ***Land Use Classes*** (05 in number) and ***Agro-Climatic Zones*** (15 in number) respectively.

For both the cases, observed F - statistic exceeds F - Critical value at 95 % level of significance (confidence) at 4 (5-1 = 4) and 14 (15 – 1 = 14) degrees of freedom for land use and agro-climatic zones respectively.

These implies that the variability among the means of the selected 5 land use classes and 15 agro-climatic zones significantly differs with each other. Therefore the null hypothesis were:

$H_{0\ (Land\ Use)}$**:** All Means ('Soil C' t /ha) obtained from different land uses are equal, and

$H_{0\ (Agro\ Climate)}$**:** All Means ('Soil C' t /ha) obtained from different Agro-climates are equal;

Both of the have null hypothesis been rejected.

Therefore, the creation of strata as per land use classes and agro-climatic zones were proven to be valid according to the test of hypothesis by one way ANOVA.

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About FSI

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

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

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



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