1.1. Overview of the Study

The aboveground biomass (AGB) of trees has the largest pool of stored carbon and is directly impacted by deforestation and degradation (Gibbs et al., 2007). It is reported (Reichstein et al., 2013) that sensitivity of the forest biome to climate extremes (such as drought, heavy precipitation) strongly affects standing biomass and carbon fluxes. Behaviour of these major carbon sinks in the near future is uncertain as erratic rainfall pattern is seriously affecting most of these mechanistic processes of forests in an unprecedented manner. The first decade of the 21st century has experienced a major magnitude of human induced climate change. Massive industrial and other developmental activities followed by rapid deforestation with improper implementation of forest management activities during 20th century became some of the many major causes for the climate change. Alterations in seasonal pattern and erratic rainfall are functioning as triggers for altering forest ecosystems' equilibrium and biogeochemical cycles, specifically for carbon cycle. Estimating aboveground forest biomass carbon is the most critical step in quantifying carbon stocks and fluxes from tropical forests (Gibbs et al., 2007). Given the implications of Kyoto Protocol and the imminent need to determine sources and sinks of carbon resulting from land-use change (and, perhaps, from natural processes as well), methods that can determine biomass accurately, repeatedly, and inexpensively are desperately needed (Houghton et al., 2001). The United Nations Convention on Climate Change and its Kyoto Protocol, and other United Nations Conventions to Combat Desertification and on Biodiversity all recognize the importance of soil organic carbon (SOC) and point to the need for quantification of SOC stocks and changes. An understanding of SOC stocks and changes at the national and regional scale is necessary to further elaborate our understanding of the global carbon cycle, to assess the responses of terrestrial ecosystems to climate change and to aid policy makers in making land use/management decisions (Milne et al., 2007). Demand of the time is to have biomass inventories of forests across gradient ecosystems (like tropics, temperate) and climate range (like semi-arid, arid). Fast developing countries like India have to address these issues as a priority as they are more severely affected by these changes. It is therefore logical to assume that changes in climate would alter the distribution of forest ecosystems (Gopalkrishnan et al., 2011) which has a sizeable impact in altering the forest's ability to store carbon.

Tropical forests cover most of the earth's terrestrial biodiversity and account for a large proportion of terrestrial carbon stored. AGB and SOC are the two major terrestrial carbon sinks. Soils are the largest source of uncertainty in the terrestrial carbon balance. Movement of carbon inside the soil, across different physical and chemical pools is crucial to maintain the soil as a sink or turn it into a source (Dinakaran and Krishnayya, 2008). According to Schwendenmann and Pendall (2008), SOC is a complex mixture of carbon compounds derived from plants, animals and microbes, which vary greatly in their amount and decomposition dynamics. SOC is a quantifiable parameter, along with AGB, to address the effects of climate change and land use & land cover (LULC) changes on tropical forests' ability to hold carbon. Improved understanding of SOC dynamics is needed to assess soil quality and its ability to support vegetation. It also helps in providing directions to accelerate recovery of degraded soils.

1.2. Carbon Cycle

One of the most profuse chemical elements of the Universe, 'Carbon' is the second most abundant element of living organisms on the Earth. Carbon is non–metallic element with atomic number 6. The word carbon comes from the Latin word '*carbo*' which means 'Coal/charcoal' (West, 2008). Carbon forms a large number of compounds, more than any other element. Softer Graphite to much harder Diamonds are basically made up of carbon. Carbon exists throughout the planet in several reservoirs and in a variety of forms (The Royal Society, 2005). Carbon is present in all living things and is often referred to as the building block of life. The oil, coal and natural gas we burn for energy are made up mostly of carbon. Our dependence on these fuels has, in recent years, caused both economic and environmental problems, and even more importantly, it has contributed to the worldwide problem of global warming (West, 2008). Scientists now believe that an increase in burning of carbon–based fuels has hiked the concentration of CO_2 in the atmosphere, and this, in turn, has resulted in rising global temperatures (West, 2008).

There are three forms of carbon present on the Earth viz., 1. Elemental (e.g. charcoal, graphite, soot etc.) 2. Inorganic (e.g. gaseous forms like carbon dioxide, carbon monoxide, methane; minerals like carbonates, bicarbonates etc.) and 3. Organic (e.g. carbohydrates, amino acids, carboxylic acids, alcohols, aldehydes, phenols, almost all the structural and functional compounds necessary for life) (Schumacher, 2002; Korhonen et al., 2002; Nieder and Benbi, 2008). These three forms of carbon are recycled between different reservoirs such as hydrosphere, biosphere, atmosphere and lithosphere by different processes as photosynthesis, respiration, burning, burial of organic matter, decomposition, and weathering processes (West, 2008). In soils, a wide variety of organic carbon forms are present, ranging from freshly deposited litter to highly decomposed forms such as humus (Buringh, 1984). In nature, SOC is mainly derived from biodegradation of plant and animal litter in soil. Thus major source of SOC is coming from the decomposition of fallen leaves, twigs & branches, fruits, dead roots, fine root exudates, dead insects & animals, animal excreta etc. Plant litter and microbial biomass are the major parent materials for soil organic matter (SOM) formation (Kogel–Knabner, 2002; Kramer and Gleixner, 2006).

Chemical elements (Carbon, Hydrogen, Nitrogen, Oxygen etc.) in their ionic form or as molecules continually get reused and recycled across Biosphere, Atmosphere, Hydrosphere, and Geosphere. These Biogeochemical cycles are having vital importance to life on the Earth. Owing to its great significance in organic life form on the Earth, regulating CO_2 levels, carbon cycle has attracted importance in recent scientific ecological studies (Fig. 1).

The circulation of carbon is mainly comprised of two different processes viz. the exchange of carbon between the atmosphere and the sea and the binding and release of carbon in conjunction with photosynthesis and respiration in terrestrial ecosystems (Korhonen et al., 2002). Carbon flows between each reservoir in an exchange called the carbon cycle, which has slow and fast components (Fig. 2). Any change in the cycle that shifts carbon out of one reservoir puts more carbon in the other reservoirs. Changes that put carbon gases into the atmosphere result in warmer temperatures on Earth. Without human interference, the carbon in fossil fuels would leak very slowly into the atmosphere through volcanic activity over millions of years in a relatively slower carbon cycle. By burning coal, oil, and natural gas, humans have accelerated the process, releasing vast amounts of carbon into the atmosphere every year. In 2009, humans released about 8.4 billion tons of carbon into the atmosphere by burning fossil fuel. In the atmosphere, carbon exists primarily in the form of carbon dioxide, carbon monoxide, and methane. The global concentration of carbon dioxide in the atmosphere – the primary driver of recent climate change – has reached 400 parts per million (ppm) for the first time in recorded history, according to data from the Mauna Loa Observatory in Hawaii. Mean global temperature has been significantly increased with respect to increasing concentration of carbon dioxide (CO_2) (Fig. 3). Since 1958, carbon dioxide has increased by about 24 percent, the beginning of this record (http://climate.nasa.gov/). Ocean waters contain dissolved carbon dioxide, and calcium carbonate shells in marine organisms store about 38,000 to 40,000 gigaton carbon. Carbon stored in Lithosphere (Earth's crust) consists of fossil fuels and sedimentary rock deposits, such as limestone, dolomite, and chalk. This is the largest carbon pool on earth. The amount of carbon in the lithosphere varies about 66 to 100 million gigatons. Of this, only 4,000 gigatons consists of fossil fuels (http://soilcarboncenter.k-state.edu/carbcycle.html). Pidwirny (2010) reported that globally soil organic matter contains more than three times as much carbon as terrestrial forests' vegetation contain as biomass carbon (Table 1).

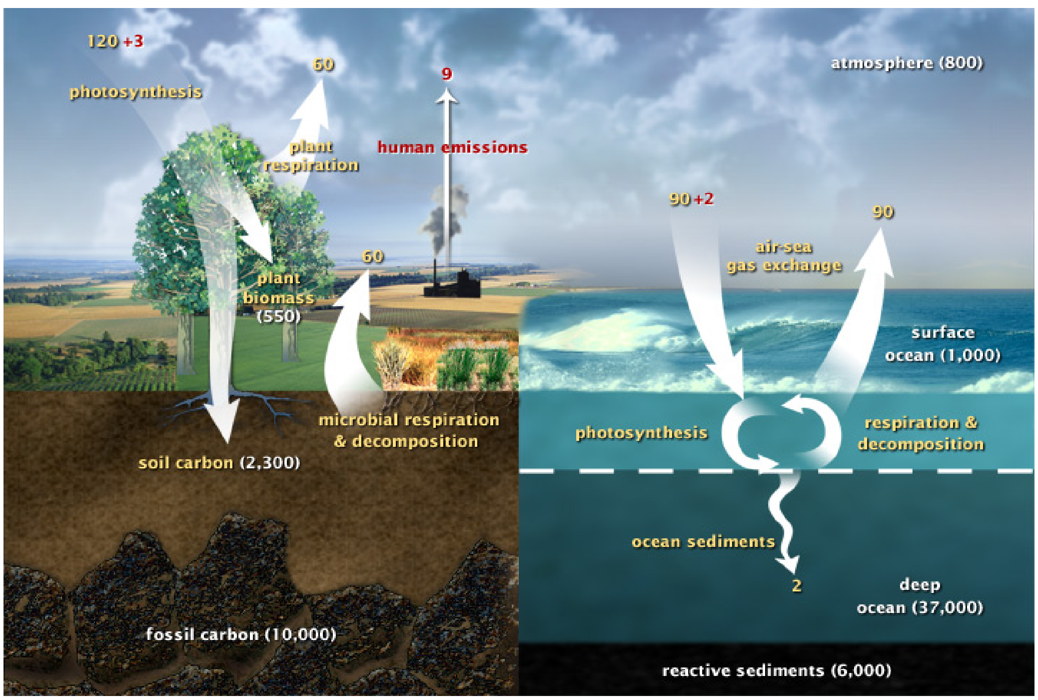

Figure 1: Graphical representation of the movement of carbon between land, atmosphere, and oceans. Yellow numbers are natural fluxes, and red are human contributions in gigatons of carbon per year. White numbers indicate stored carbon (U.S. Department of Energy, http://science.energy.gov/; NASA, USA, http://earthobservatory.nasa.gov/).

Oceans play a vital and dominant role in the Earth's carbon cycle. The total amount of carbon in the ocean is about 50 times greater than the amount in the atmosphere, and is exchanged with the atmosphere on a time-scale of several hundred years (http://science.nasa.gov/). At least 1/2 of the oxygen we breathe comes from the photosynthesis of marine plants (http://science.nasa.gov/). Oceans are biggest sink of the carbon (Pidwirny, 2010). Currently, 48% of the carbon emitted to the atmosphere by fossil fuel burning is sequestered into the ocean (http://science.nasa.gov/). But the future fate of this important carbon sink is quite uncertain because of the potential climate change impacts on ocean circulation, biogeochemical cycling, and ecosystem dynamics (http://science.nasa.gov/).

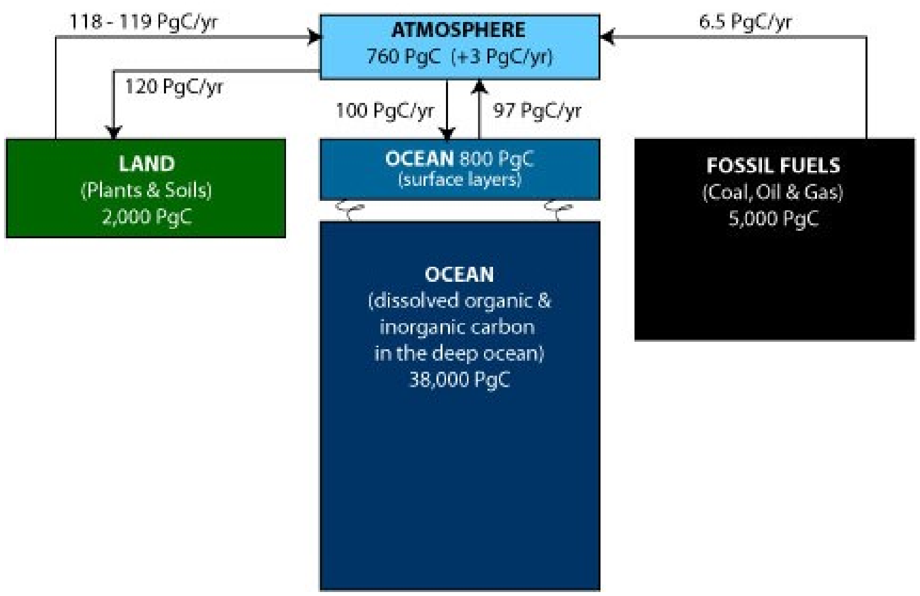

Figure 2: Global Flow of Carbon (http://science.nasa.gov/). (** 1 Pg = 10^{15} g)

The climate and the terrestrial carbon cycle will be key determinants of the dynamics of the Earth System over the coming decades and centuries (Smith et al., 2013). The terrestrial carbon cycle has major effects on the dynamics of the Earth System over decadal or longer timescales and in this, terrestrial vegetation currently accounts for approximately 60% of the total annual flux in atmospheric carbon dioxide (Denman et al., 2007). There is great uncertainty about how the balance between CO_2 emissions and its uptake by vegetation will change in the future (Cramer et al., 2001; Friedlingstein et al., 2006; Denman et al., 2007; Satchi et al., 2008). Terrestrial cycling of carbon takes place across atmosphere, vegetation and soil. Plants, during photosynthesis absorb gaseous form of CO_2 and convert it to carbon rich chemical compounds. Metabolism and physiology allow the plant to produce plenty of different carbon rich organic compounds. About half of the fraction in dry weight of plant is carbon. A fraction gets into the soil as plant litter (senescent leaves, dried pieces of stems, fallen flowers and fruits, root exudates) periodically, where it is decomposed and stored as organic carbon. Each year, photosynthesis by terrestrial plants moves about 110 Pg (1 Pg = 10^{15} g) of carbon from the atmosphere to the biota (Pidwirny, 2010). Terrestrial uptake of CO_2 is governed by net biome production, which is the balance of gross primary production (GPP), carbon losses due to heterotrophic respiration forest fire, harvested biomass. The effectiveness of terrestrial uptake as a carbon sink depends on the transfer of carbon to various forms with relatively longer residence times (wood or modified soil organic matter).

The United Nations Framework Convention on Climate Change (UNFCCC) aims to stabilize greenhouse gas concentrations in the atmosphere at a level that limits adverse impacts on global climate. Potential mechanisms cover emission reductions and activities that increase carbon sinks, including terrestrial sinks. The Kyoto Protocol of the UNFCCC (http://unfccc.int/kyoto_protocol/items/2830.php) provides a mechanism to address issues related to the impact of afforestation, reforestation and deforestation on carbon sinks (Article 3.3).

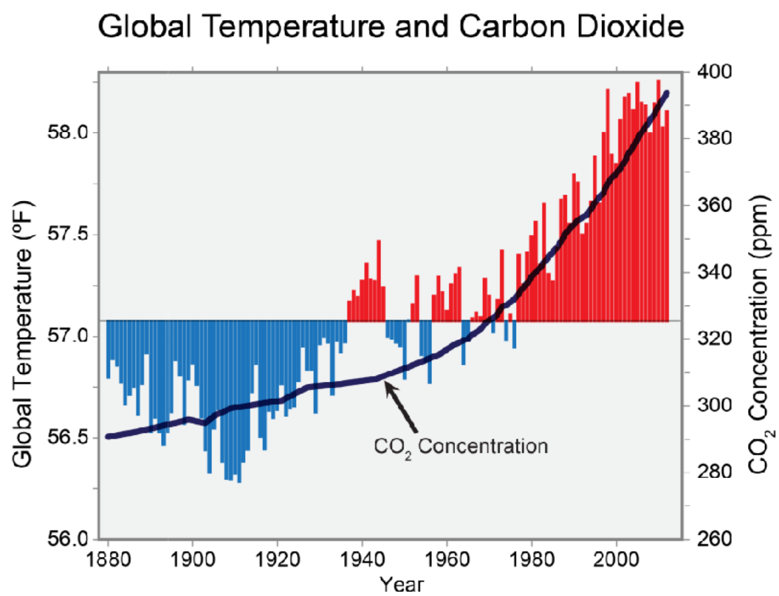

Figure 3: Mean Global Temperature (1 °F = -17.22 °C) and Global CO_2 levels (climate.nasa.gov/vital-signs/global-temperature/)

Another aspect looked at is, categories such as grazing land management, cropland management, forest management and revegetation under Article 3.4 (Smith, 2004) acting as carbon sinks. This applies to the first commitment period, 2008–2012. According to the Kyoto Protocol, countries must reduce total greenhouse gas emissions by 2012, compared to 1990 levels. In order to correctly account for soil carbon sinks, a commonly agreed system of assessing soil carbon stocks and changes are needed. This system needs to be generically applicable, being as relevant to soil and climatic conditions in tropical and arid areas as it is to conditions in temperate areas (Milne et al., 2007). A country has various options for measures to meet the Kyoto standards. Examples are: i) Afforestation and social forestry activities to remove more CO_2 from the air. ii) Sustainable management practices in forestry and on farms. iii) Joint Implementation by countries to earn credits when through emission reduction projects. iv) Clean development mechanisms; industrialized nations earn credits for projects implemented in developing countries. v) Buying emission allowances from other operators which have excess emissions credits. The Sustainable Innovation Forum (SIF15) held during the 21st annual Conference of Parties (COP21), took place recently in December, 2015 at Paris. The summit proposed that by the second half of this century, there must be a balance between the emissions from human activity such as energy production and farming, and the amount that can be captured by carbon-absorbing "sinks" such as forests or carbon storage technology. It was discussed that, developing nations (like India) which still need to burn coal and oil to power growing populations, are encouraged to enhance their efforts to cuts in absolute emissions. India took leading steps during the summit. Coal ministry of India has reported that, India has plans to add 30 times more solar-powered generation capacity by 2022 (http://www.cop21paris.org/).

Table 1: Major stores of carbon on the Earth (Pidwirny, 2010; http://www.eoearth.org/). (** 1 Pg = 10^{15} g)

Store	Amount in petagram (Pg)
Atmosphere	~578 (as of 1700) – ~766 (as of 1999)
Soil Organic Matter	1500–1600
Ocean	38000–40,000
Marine Sediments and Sedimentary Rocks	66,000,000–100,000,000
Forests' vegetation biomass	540–610
Fossil Fuel Deposits	4000

1.3. Alterations to carbon cycle

1.3.1. The human influence

Changes in the amount of carbon stored in forests can result from a variety of anthropogenic and natural influences. For example, carbon is removed or emitted from forests when trees are harvested, when forest land is cleared for other uses such as agriculture or development, or as a result of disturbances such as wildfire, insects, and disease. Net storage of carbon can result from afforestation, and natural reforestation of land (U.S. EPA, 2015).

The dynamics of terrestrial ecosystems depend on interactions between a number of biogeochemical cycles, particularly the carbon cycle, nutrient cycles, and the hydrological cycle, all of which may be modified by human actions. Terrestrial ecological systems, in which carbon is retained in live biomass, decomposing organic matter, and soil, play an important role in the global carbon cycle. Carbon is exchanged naturally between these systems and the atmosphere through photosynthesis, respiration, decomposition, and combustion. Human activities change carbon stocks in these pools and exchanges between them and the atmosphere through land use, land-use change, and forestry, among other activities. Substantial amounts of carbon have been released from forest clearing at high and middle latitudes over the last several centuries, and in the tropics during the latter part of the 20th century (http://www.ipcc.ch/ipccreports/sres/land_use/index.php?idp=3). Anthropogenic activities lead the world in altered climatic conditions during past century. Altered NASA's strategy for reducing climate change uncertainty includes improving land, ocean, and atmosphere carbon cycling models, and, more importantly, providing the new observations required to locate global sources and sinks of carbon, quantify their strengths, and understand how they depend on environmental factors that are rapidly changing (http://science.nasa.gov/). In what way this current trend in atmospheric CO_2 is unique? Bala (2013) has reported that in the past several million years, in the absence of human influence, CO_2 has naturally fluctuated between 180 and 280 ppm during glacial and interglacial periods. Thus, the current level of CO_2 is unusual and signifies the footprint of human civilization on this planet.

One might even wonder if we have taken the destiny of the planet in our hands. People could be endlessly debating the role of humans on the recent global warming because of the inherent variability in surface temperature, but there can be very little doubt that anthropogenic emissions are responsible for the atmospheric CO_2 rise and humans are changing the chemical composition of the atmosphere. The annual mean CO_2 values for 2011 and 2012 were 390.48 and 392.5 respectively (Bala, 2013). The CO_2 levels in the atmosphere are increasing since the start of industrial revolution from 280 ppm to the level ~385 ppm (Houghton, 2003 and 2005) which is recently estimated at a severely high level of 400 ppm as a daily concentration (Monastersky, 2013). The steady increase in atmospheric carbon dioxide, which is the main driver of global climate change, has fortunately been slowed by a simultaneous rise in CO_2 absorption by land plants, termed the land CO_2 sink (Metcalfe, 2014; Ballantyne et al., 2012). Ehlers et al. (2015) have reported that terrestrial vegetation currently absorbs approximately a third of the annual anthropogenic CO_2 emissions, mitigating the rise of atmospheric CO_2. However, terrestrial net primary production is highly sensitive to atmospheric CO_2 and associated climatic changes. In C_3-plants, net photosynthesis depends on the ratio between gross photosynthesis and photorespiration, which strongly depends on CO_2. Each year, on an average, land and ocean carbon sinks absorb the equivalent of about half of the global fossil fuel emissions, thereby providing a critical service that slows the rise in atmospheric CO_2

concentrations (Poulter et al., 2014; Ballantyne et al., 2012). The Industrial Revolution increased the use of coal, oil, and natural gas. In 2000, humans burned about 4.6 billion metric ton of coal, 28.1 billion barrels of oil, and 89 trillion cubic feet of natural gas, which caused about 6.5 petagram of carbon to flow from the fossil fuel storage pool to the atmosphere. Human activity has disturbed the biotic storage pool. By reducing the number of trees through burning and/or chopping them down, deforestation reduces the amount of carbon stored in the biota. Deforestation and other changes in land use of the 1990's caused 1–2 petagram of carbon to flow from the biota to the atmosphere annually (Pidwirny, 2010).

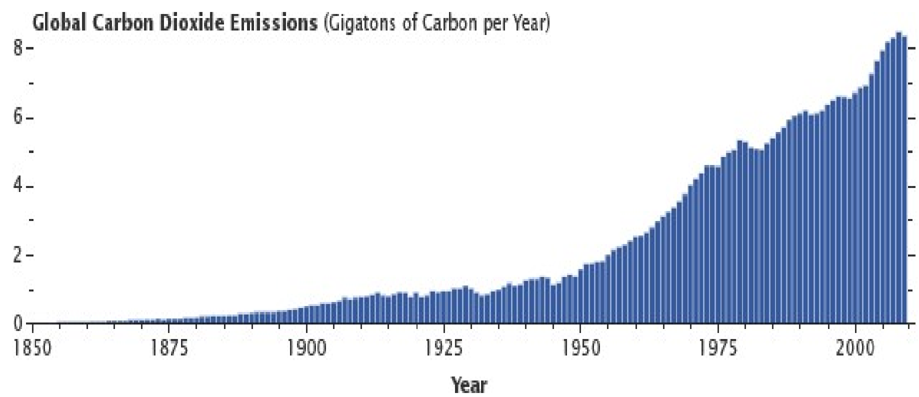

Figure 4: Emissions of carbon dioxide by human activities have been growing steadily since the onset of the industrial revolution. (http://science.energy.gov/; http://earthobservatory.nasa.gov/)

Rising CO_2 levels have increased aboveground net primary productivity (NPP) in tropical forests, which is estimated to sequester 1.3×10^9 t C yr^{-1} (Lewis et al., 2009; Malhi, 2010), but it is unclear whether this has increased or decreased carbon storage in the soil. Alterations to vegetation covers because of deforestation, reforestation, and agriculture are prone to alter carbon storage of soils (Bashkin and Binkley, 1998; Post and Kwon, 2000; Paul et al., 2002; Paul et al., 2003; Degryze et al., 2004;

Richards et al., 2007). The affects of land use changes on soil carbon stocks are of concern in the context of international policy agendas on greenhouse gas emissions mitigation (Guo and Gifford, 2002).

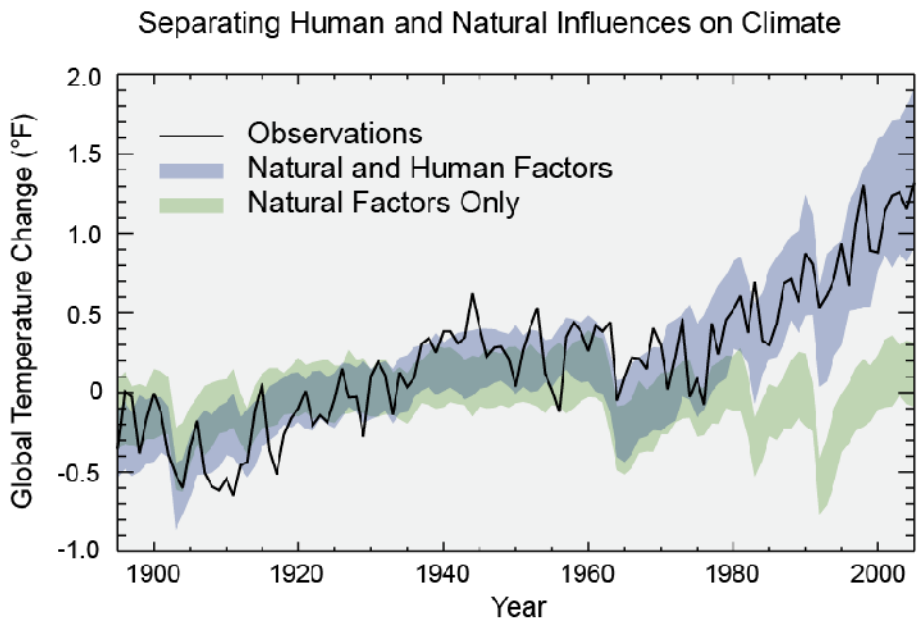

Figure 5: Separating Human and Natural Influences on Climate: The green band shows how global average temperature would have changed due to natural forces only, as simulated by climate models. The blue band shows model simulations of the effects of human and natural factors combined. The black line shows observed global average temperatures. As indicated by the green band, without human influences, temperature over the past century would actually have cooled slightly over recent decades. The match up of the blue band and the black line illustrate that only the inclusion of human factors can explain the recent warming. (Figure & caption source: adapted from Huber and Knutti, 2012; http://nca2014.globalchange.gov/highlights/overview/overview).

The mean rate of soil carbon change after 40 years of afforestation was 0.09 % per year (0.006 t C ha^{-1} per year) (Paul et al., 2003). Soil organic matter dynamics following land-use change remains difficult to predict because of the complex biological (microbial), physical (soil texture), and chemical (enzymes, organic matter) mechanisms of soil that control carbon turnover (Grandy et al., 2009). Significant change in carbon stock followed by LULC change has been reported earlier for global data (Haberl et al., 2007; Don et al, 2011) as well as in India (Ravindranath et al., 1997; Ravindranath et al., 2001; Chhabra and Dadhwal, 2004; Bijalwan et al., 2010).

1.3.2. Influence of global climate change

Apart from above mentioned human induced alterations in carbon cycle, global and regional changes in climate play considerable role in regulating ecosystems' equilibrium. Extreme temperatures, erratic rainfall, seasonal shifts making alterations in natural carbon cycle and carbon stocks through altered ecosystem processes. According to various predictions, a global warming by 1.8–4.0 °C is projected by 2100 with land surface warmer than oceans, along with regional changes in precipitation and sea level rise (IPCC, 2007a). Scientific evidence suggests that the projected climate change is likely to lead to increased water scarcity, droughts and high rainfall events, loss of biodiversity, shifts in forest types and reduction in food production in dry tropics with increased risk of hunger and flooding due to sea level rise. Some of the impacts such as loss of biodiversity and wetlands are irreversible (IPCC, 2007b). Water-limited ecosystems are likely to be highly responsive to altered precipitation regimes (Thomey et al., 2011). Rapid alterations to natural rainfall pattern can alter forest ecosystem dynamics and related carbon cycle processes. The episodic nature of water availability has significant consequences on belowground carbon and nutrient cycling (Austin et al., 2004). Increases in the frequency, duration, and/or severity of drought and heat stress associated with climate change could fundamentally alter the composition, structure, and biogeography of forests in many regions (Allen et al., 2010). These are likely to have a significant impact on the 'carbon' sink potential of forests. Relative importance of climate on tree growth has been highlighted (Go´mez-Aparicio et al., 2011). They also reported about the limited understanding of how growth of coexisting tree species varies along environmental gradients in Mediterranean water-limited forest ecosystems, and its implications for species interactions and community assembly under current and future climatic conditions. This is likely to alter the standing biomass. According to Aanderud et al. (2010) shifts in the seasonal timing of rainfall have the potential to substantially affect the immense terrestrial stores of SOC. Schmidt et al. (2011) reported that the feedbacks between soil organic carbon and climate are not fully able to answer questions like, whether the major pool of soil organic carbon is sensitive to changes in climate or local environment; how and on what time scale will it respond to such changes? It is important to understand the contribution of easily measurable parameters (rainfall, aboveground biomass or soil characteristics) in explaining the relationship between soil carbon and standing biomass in tropics. Existing knowledge is quite blurred for the tropical forests' responses to the altered rainfall patterns.

1.4. Forest carbon stocks

Forests play a significant role in capturing carbon dioxide from the atmosphere through photosynthesis, converting it to forest biomass and releasing into atmosphere through plant respiration and to soils through decomposition. Therefore forests contribute positively to global carbon balance. Forests store more carbon dioxide than the entire atmosphere and the role of forests is more critical (Stern, 2006).

1.4.1. Global and regional status

Globally, forest vegetation carbon constitutes nearly three-fourth, therefore, it is important to understand vegetation carbon cycle (IPCC 2003). Forests of tropical ecosystems are considered as a potential sink of carbon (Lewis et al., 2009). They store a large quantity of carbon in vegetation and soil. Food and Agricultural Organization (FAO, UN) classified tropical forests into six ecofloristic zones (the tropical rain forests, the moist deciduous forests, the dry zone, the very dry zone, the desert zone and the hill and mountain forests). These regions have a major impact on global biodiversity and carbon cycling. Tropical forest carbon stocks include biomass and soil carbon pools. Accurate estimation of biomass is required for accounting carbon stocks and their monitoring. Total biomass of each forest varies in different forest types, such as natural or planted forests and closed or open forests. Merchantable bole forms about 60% of the total aboveground biomass and leaves for fodder form about 3-5% of closed forests (Brown, 1997).

To know the role of vegetation in global carbon cycle, biomass and productivity estimations are the intermediate steps (Kale et al., 2001). When being disturbed by human or natural causes, forests can behave as sources of atmospheric CO_2. Thereafter they become atmospheric carbon sinks during their regrowth after disturbance, and hence they can be managed to alter the magnitude and direction of their carbon fluxes (Brown and Gaston, 1996). Forests as well as soils, oceans and the atmosphere store carbon, which moves among those different stores over time through several processes. Consequently, forests can act as sources or sinks at different times: Sources release more carbon than they absorb while sinks soak up more carbon than they emit.

Table 2: An overview of the magnitude of global carbon stocks in terrestrial systems (vegetation and soil carbon pools) down to a depth of 1 m. (http://www.ipcc.ch/ipccreports/sres/land_use/index.php?idp=3)

Biome	**Area (10^9 ha)**	**Global Carbon Stocks (Gt C)**		
		Vegetation	Soil	Total
Tropical forests	1.76	212	216	428
Temperate forests	1.04	59	100	159
Boreal forests	1.37	88	471	559
Tropical savannas	2.25	66	264	330
Temperate grasslands	1.25	9	295	304
Deserts and semideserts	4.55	8	191	199
Tundra	0.95	6	121	127
Wetlands	0.35	15	225	240
Croplands	1.60	3	128	131
Total	**15.12**	**466**	**2011**	**2477**

The concept of carbon sinks is based on the natural ability of trees, other plants and the soil to soak up carbon dioxide and temporarily store the carbon in wood, roots, leaves and the soil. An assessment of carbon pool can be provided by estimating the biomass of forests because significant percentage of the carbon is stored by the forest vegetation. Carbon sequestration refers to the removal and long-term storage of CO_2 from the atmosphere through the use of natural carbon sinks, primarily in forests by increasing AGB. In this process, CO_2 from the atmosphere is absorbed by vegetation through photosynthesis, and stored as carbon in biomass (tree trunks, branches, foliage and roots) and also in soils as SOC. Globally, soil organic matter contains more than three times as much carbon as either the atmosphere or terrestrial vegetation (Schmidt et al., 2011). Tropical forests show a different pattern of distribution as the carbon is partitioned more or less equally between the vegetation and soil (Malhi et al., 1999). Pan et al. (2011) reported that tropical forests have 56% of carbon stored in biomass and 32% in soil, whereas boreal forests have only 20% in biomass and 60% in soil. Piao et al. (2009) reported that ~58% of carbon sink lies in biomass and the rest in soil organic matter. Thus, various forest types show differences in the allotment of carbon between AGB and SOC.

A number of studies have been carried out on the carbon captured and storage in the forests of different regions of the world (Brown and Lugo, 1982; Dixon et al., 1994; Lal and Singh, 2000; Cairns et al., 2003; Sierra et al., 2007; Sheikh et al., 2011; Hoover et al., 2012; Zhang et al., 2013). Estimates of carbon cycling in India are in infancy. Preliminary estimate for major pools and fluxes of carbon cycle of India in 1985-86 has been made by Dadhwal and Nayak (1993). There are reports available on carbon stock and storage in the Indian forests (Haripriya, 2000; Chhabra et al., 2002; Chaturvedi et al., 2011; Sharma et al., 2011 and Devagiriet al., 2013) but there is limited information coming from field based studies on the carbon capture and storage in the forest ecosystems of Gujarat, India. 'Forest' area in India has traditionally been defined as land controlled by the Forestry Department, rather than as land actually under tree cover. Forest Survey of India (FSI, http://fsi.nic.in/) defined 'Forest cover' as, an area of more than 1 ha in extent and having tree canopy density of 10 percent and above. Total forest cover in India had been reduced from about 23% (2001) to about 21% (FSI, State of Forest Report, 2001 & 2009) of total geographical area. Declining forest area significantly alter the carbon storage ability of both biomass and soil. Studies report different statistics for mean AGB carbon pool in India, e.g. 2,587 Tg C (Hingane, 1991), 3,117 Tg C (Dadhwal et al., 1998), 3,017 Tg C (Dadhwal and Shah, 1997). The numbers reported on mean AGB carbon density in India are quite variable, e.g. 49.2 Mg C ha^{-1} (Hingane, 1991), 60.2 Mg C ha^{-1} (Dadhwal et al., 1998), 63.6 Mg C ha^{-1} (Dadhwal and Shah, 1997). These variability in estimates is mainly due to different methodologies followed. The study by Flint and Richards (1991) on historical forest/vegetation carbon pool in 1880 in India indicates that total carbon pool and density in AGB was about 7,940 Tg C and 77.3 Mg C ha^{-1} respectively with total forest area of 102.68 Mha. Ravindranath et al. (1995) estimated the standing biomass (both above and below ground) of forests as 8,375 million tons for the year 1986 in India. In this carbon storage was reported to be 4,178 million tons. Forest covers in India store 3.43 Pg C in above ground biomass while it is 20.99 Pg C in soil (up to 30 cm depth) (Ravindranath et al., 1997; Lal, 2004). The major carbon pools in India are estimated based on very coarse resolution data and extrapolation because the primary data for many regions of the country are non-existed or over-estimated (Dadhwal and Nayak, 1993). Most of the studies related to volume and AGB at national level are based either on raw data from state forest department or growing stock estimates. Due to the lack of reliable data on standing biomass and rates of forest degradation, the net carbon emission estimates for India are highly variable (Ravindranath et al., 1997). Thus, improved quantification of carbon pools and their fluxes in forest ecosystems is important for understanding the contribution of forests to net carbon emissions and their potential for carbon sequestration.

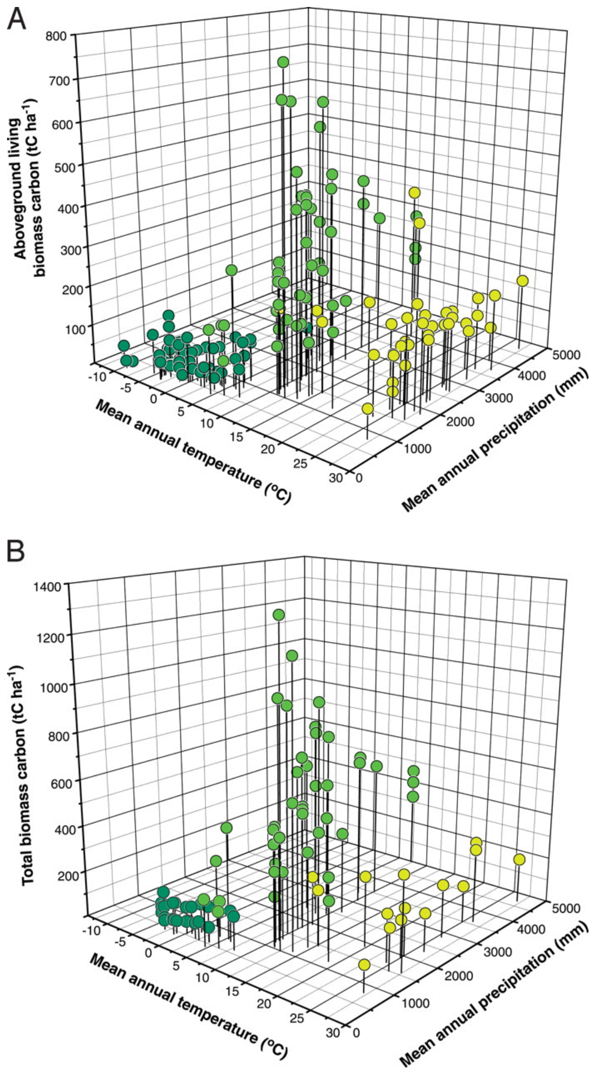

Figure 6: Global forest site data for above-ground living biomass carbon (t C ha^{-1}) (A), and total biomass carbon (t C ha^{-1}) (B), in relation to mean annual temperature and mean annual precipitation. (Keith et al., 2009)

1.4.2. Aboveground biomass (AGB) and soil organic carbon (SOC) relationship

Carbon storage in forest ecosystems involves numerous components including biomass carbon and SOC (Lal, 2005). The total ecosystem carbon stock is large and in dynamic equilibrium with its environment. The biomass pool includes living above-ground biomass, living below-ground biomass, dead organic matter, mineral soil organic carbon, and deadwood (IPCC, 2006). Biomass pool studies through carbon inventories include estimation of stocks and fluxes of carbon from different land-use systems in a given area over a time and space. It is important to study the relationship between carbon in land area consisting of biomass and the soil carbon pools. Estimating aboveground forest biomass carbon is the most critical step in quantifying carbon stocks and fluxes from tropical forests (Gibbs et al., 2007). The aboveground biomass of trees has the largest pool of stored carbon and is directly impacted by deforestation and degradation (Gibbs et al., 2007). Chaturvedi *et al.* (2011) reported the significance of relationship between the pattern of aboveground vegetation carbon density, and carbon stored in the soil. Evaluating the role of tropical soils (as a component of soil-vegetation system) in the carbon cycle is very important. Because of the large areas involved at regional/global scale, forest soils play an important role in the global carbon cycle (Detwiler and Hall, 1988; Bouwman and Leemans, 1995; Richter et al., 1995; Sedjo, 1992; Jobbágy and Jackson, 2000). Changes in vegetation covers alter inputs of organic matter into the top layers of soil (Mehta et al., 2013). Li et al. (2010) have reported a strong relationship of SOC with aboveground vegetation properties. Any change in the abundance and composition of soil carbon can substantially affect the global carbon cycle and many other important processes (Li et al., 2010; Batjes, 1996). Similarly, changes in climate and land use will likely change the abundance and composition of soil organic carbon (e.g. Cramer et al., 2001; Berthelot et al., 2002; Lal, 2005; Schulp et al., 2008). Assessing changes in carbon flux depends on reasonable estimates of the soil carbon stocks at plot, regional, national, and global levels (Batjes, 1996; Morisada et al., 2004; Wang et al., 2004). Although 40% of soil carbon is found beneath forests, carbon pools in forest soils (especially in mountainous areas) are under-sampled and under-studied compared to aboveground carbon pools (Lal, 2005; Peltoniemi et al., 2007). The carbon stock in terrestrial ecosystems represents difference between the gain from net primary production (in terms of quality and quantity) and the loss through decomposition (Couteaux et al., 1995; Amundson, 2001). Moorhead and Sinsabaugh (2006) affirmed that soils may sequester more carbon either by slower litter decay rates or by larger litter inputs. Carbon sequestration into soil through decomposition is influenced by quality and quantity of litter (aboveground vegetation characteristic), climatic and edaphic characters. However the decomposition process is slower in temperate forests and faster in tropics as soil biological activity across top profile differs widely in tropics and temperate system. Hence it is important to correlate the aboveground vegetation mass with corresponding soil organic carbon at various depths of soil.

Globally, the organic carbon content of mineral forest soils (up to 1 m depth) vary between less than 10 to almost 20 kg C m^{-2}, with large standard deviations (Jobbágy and Jackson, 2000). Mineral forest soils to that depth contain approximately 700 Pg C (Dixon et al., 1994). Because the input of organic matter is largely from aboveground litter, forest soil organic matter tends to concentrate in the upper soil horizons, with roughly half of the soil organic carbon of the top 100 cm of mineral soil being held in the upper 30 cm layer. The carbon held in upper profile is often the most chemically decomposable, and directly exposed to natural and anthropogenic disturbances. Plant functional types, through their differences in carbon allocation, help to control SOC distributions with depth in the soil (Jobbágy and Jackson, 2000). Fontaine et al. (2007) reported that stability of organic carbon in deep soil layers is controlled by fresh carbon supply. Tropical forests show a different pattern of distribution as the carbon is portioned more or less equally between the vegetation and soil (Malhi et al., 1999). Luyssaert et al. (2008) reported that the old-growth forests continue to accumulate carbon, contrary to the earlier view that they are carbon neutral, and will lose much of this carbon to the atmosphere if they are disturbed. Pande (2005) reported that the disturbed and mature plots showed less tree density than the undisturbed and younger plots for tree species. Thus, estimating aboveground forest biomass carbon is the most critical step in quantifying carbon stocks and fluxes from tropical forests (Gibbs et al., 2007).

1.5. Soil properties and microbial activities

Soil carbon sequestration assists in restoring degraded soils, enhances biomass production, purifies surface and ground waters, and reduces the rate of enrichment of atmospheric CO_2 by offsetting emissions due to fossil fuel (Lal 2004). Dinakaran and Krishnayya (2008) showed that physical properties of soil like particle size influence SOC content. Dan-Dan et al. (2010) reported that understanding how spatial scale influences commonly-observed effects of soil texture on SOC storage is important for accurately estimating the SOC pool at different scales. The physical disconnection between decomposer and organic matter is likely to be one reason for persistence of deep soil organic matter (Schmidt et al., 2011). It is important to evaluate how changes in AGB (because of precipitation fluctuations) impact organic matter and particle size of tropical soils.

The carbon stock in terrestrial ecosystems represents the difference between the input from net primary production (in terms of quality and quantity) and the output through decomposition (Couteaux et al., 1995). Soil microbes play a pivotal role in litter decomposition processes. Hattenschwiler et al. (2005) reported that soil organisms process litter that enters the detrital system not only from above ground but also from below ground. Schmidt et al. (2011) reported that environmental change can influence soil carbon cycling through changes in both metabolic activity and community structure of soil micro-organisms. Schmidt et al. (2011) reported that environmental (local climatic conditions, physico–chemical properties of surrounding environment, physical disconnection between decomposer and organic matter) and biological (microbial activities) controls influence SOC stability. Climatic factors such as precipitation and temperature have influence on decomposition and microbial activities in soil (Aerts, 1997; Berg, 2000). Mehta et al. (2013) showed that vegetation type influences the SOC input through selective decomposition by microbes. Study of soil microbial biomass carbon (MBC) along with SOC, would be indicative of microbial activities at different depths in soil. It helps in understanding the role of AGB, SOC, and MBC in regulating carbon dynamics of tropical soils.

1.6. Significance of the Study

Forests cover approximately 30% of the earth's land surface (nearly 4 billion hectares). Singh et al. (2011) reported that, the total carbon content of the world's forest ecosystems in 2010 was estimated at 652 Gt, including storage in biomass, soil and dead wood. They also reported that current deforestation rates and forest degradation, however, pose serious threats to the world's forests and undermine their ability to contribute to climate change mitigation besides adding to GHG emissions. Estimating above-ground forest biomass carbon is the critical step in quantifying carbon stocks and fluxes from tropical forests. It is very challenging to monitor changes in forests as they are continuously exploited for different resources such as timber, fuel, and fodder. Currently, forest resource exploitation is relatively higher in tropics. Rapid pace of industrialization and related landscape changes in tropical countries are putting tremendous pressure on the existing forest covers. Ethnic people's dependency on these resources is ever increasing. Demands of urban dwellers are augmenting the problem. Federal forest agencies are trying to mitigate the negative impacts of these activities by plantation of economically important trees at many of the deforested areas. They are also promoting social forestry program as an important management approach. It is vital to evaluate how these activities are affecting AGB and SOC of these regions. Most developing countries currently have limited data on carbon stocks of forests which can assist in developing estimates of historic carbon emissions from past deforestation and degradation (Saatchi et al., 2011). While several studies on the status of carbon stocks and forest biomass have been done earlier in Indian forests (Ravindranath et al., 1997; Ravindranath et al., 2001; Chhabra and Dadhwal, 2004; Lal, 2004; Das et al., 2008; Ravindranath et al., 2008; Patil et al., 2012), the impact of rainfall variation on AGB and SOC of tropical forests, how carbon flux is dependent on AGB and SOC has not been addressed specifically. Records currently available are restricted to fewer sites, coupled with lack of uniform methodology and chronological variations of data generation leading to misinterpretations of carbon models. Several studies on status of carbon stocks and forest biomass have been done earlier in Indian forests but very few researchers have made an attempt to estimate and compare different soil parameters and its correlation with aboveground biomass in explaining carbon sink potential of forests of Gujarat. The total area under forests cover in India is estimated as 77.82 mha while Gujarat state has a forest cover of 1.20 mha. These forest covers hold carbon in vegetation (above-ground and below-ground biomass) and in soils. Gujarat forests biomass represents a significant pool of carbon. The rate of cycling of carbon in soils and in different pools across different vegetation covers is still not clear for the fast growing tropical systems. This study makes measurements of AGB, SOC, MBC, and soil physical properties to ask, how these parameters are related, and what are the implications of their relationship across forest covers of Gujarat?

Hofhansl et al. (2015) reported that the proportion of carbon allocated to wood biomass is an important determinant of the carbon sink strength of global forest ecosystems. The significance of climate change as a factor on forest vegetation and on soil carbon dynamics is still not clear for the economically fast growing tropical countries. Impacts of Human pressure, management activities of federal departments, scale and magnitude of seasonal rainfall variation on AGB and SOC of tropical forests has not been addressed specifically. As growing attention is paid in a changing climate and land use pressure, studies that link carbon dynamics to precipitation in tropical forests are required. Reichstein et al., (2013) reported that climate extremes have the potential to significantly affect the carbon cycle regionally and globally and even a small shift in the frequency and severity of climate extremes could subsequently reduce carbon sinks and may result in sizeable positive feedbacks to climate warming. Human pressure on the existing tree cover coupled with the dynamics of Indian monsoon are potentially future tipping elements that affects carrying capacity of the Indian subcontinent region (Lenton et al., 2008; Ahlstrom et al., 2015). Gopalkrishnan et al. (2011) reported that low tree density, low biodiversity status as well as higher levels of fragmentation, in addition to climate change, contribute to the vulnerability of many of the Indian forest covers. Chaturvedi et al. (2011) reported the need for developing and implementing adaptive strategies to reduce vulnerability of forests to projected climate change. The assessment of climate impacts in India showed that at the national level, about 45% of the forested grids are projected to undergo change (Gopalkrishnan et al., 2011). Policy makers find that carbon sequestration by the sink approach is a relatively inexpensive tool for climate change mitigation (Singh et al., 2013). Hence, these issues are to be deftly addressed. These help in the better implementation of international agreements such as the Kyoto Protocol and can take advantages of programmes like Reducing Emissions from Deforestation and Forest Degradation (REDD) and Reducing Emissions from Deforestation and Degradation and Enhancement of Carbon Stocks (REDD+).

Keeping the above perspectives in focus, this study has been carried out with the following objective,

to correlate the aboveground biomass (AGB) and corresponding soil organic carbon content (SOC) across forest covers of Gujarat.