CHAPETER-I INTRODUCTION

Forest is one of the important renewable natural resources. It plays a crucial role in the human life and environment. Forest has been defined in several ways based on the objectives of management, land use, vegetation type, and composition. According to the widely accepted The United Nations Framework Convention on Climate Change (UNFCCC) definition, forest is an area of land 0.05-1 hectare in size, of which more than 10-30% is covered by tree canopy. Trees must also have the potential to reach a minimum height of 2-5 metres at maturity (Sasaki and Putz, 2009). Forests occupy one third of the Earth's land area and are found on all corners of the globe (FRA, 2010). Human society and the global economy are strongly linked to forests. Three hundred million people, worldwide, live in forests. About 1.6 billion people rely on forests for their livelihoods. Forests are home to 80% of the world's terrestrial biodiversity. Forests play a critical role in maintaining the ecological balance (Berlyn and Ashton, 1996) and providing wide range of economic and social benefits like food, water, wood products, and essential medicines (*Global Forest Resources Assessment, 2005: Progress towards Sustainable Forest Management,* 2006). Forests act as hydrologic flow modulators and help in conserving microclimate of the area. Trees and soil help regulate atmospheric temperature through evapotranspiration. The terrestrial biosphere is the second largest reservoir for carbon with much of it being stored in forests. Forests account for approximately 80% of all aboveground carbon and 40% of all belowground carbon in the entire terrestrial ecosystem (IPCC, 2001). Forests play an important role in mitigating climate change at the global scale as they potentially act as a sink for carbon dioxide and other greenhouse gases. The world's forests are unique sites to study impacts of climate change on terrestrial vegetation not only in terms of total carbon emission but also related to global carbon sequestration capacity, and for climate regulation. In one of the earlier studies (Ford and Teskey, 1991) it has been suggested that trees should be planted specially to sequester CO_2 and to mitigate the projected further increase in atmospheric CO_2 concentration.

Forests are seriously affected by timber harvesting, land use, climate change and other natural and human induced disturbances (Canadell et al., 2007). Recent global forest analysis reveals that during last two decades, agriculture expansion, logging, development, and other human activities caused the deforestation of more than 120,000

km^2 each year (Muthukrishnan, 2015). Depletion of forest cover affects several ecological, social and economic consequences leading to loss of biodiversity, soil erosion, global warming, threatening the well-being and livelihoods of people who heavily depend on forest resources (Panigrahy et al., 2010). Yet deforestation is occurring at alarming rates, more particularly in areas of the world that have high levels of human and animal population growth. Because of these changes, forests could turn from carbon sinks to carbon sources, threatening the quality and quantity of habitat available for existing species. Since forest ecosystems are dynamic and continuously changing, timely information on forest structure and function is vital for management of forests optimally. Accurate data gives a better understanding of the response of forest to climate dynamics, its share in global carbon cycle, and how that value is changing over time. Many critical questions about the forests remain understudied by researchers due to lack of accurate information on forest stand attributes and their extent of distribution. Determining the health and function of forest ecosystems requires a long-term inventory and monitoring effort (Brandeis and Rozo, 2005). Forests are recognized as a natural linkage between the pedosphere, atmosphere, and hydrosphere on the earth surface, therefore forests should be conserved on priority basis for sustainable environmental management (Panigrahy et al., 2010). Recent analysis of Global Forest Resources Assessments (GFRA, 2015) results suggests that over the past 25 years (1990-2015) the world's forest area has declined by 3.1% with most of the loss of forests continued to occur in countries and areas in the tropical regions (Keenan et al., 2015). From 2010 to 2015, tropical forest area declined by 5.5 Mha per year (Keenan et al., 2015). Decline in tropical forests cover can lead to unprecedented changes in global carbon cycle. Therefore, conservation of tropical forest is extremely important and improved knowledge of tropical forests and their relationship with climatic variables at regional and global scale is an important and desirable objective for projecting future forest growth and their response to climate dynamics.

1.1 Tropical forests' cover

Tropical and subtropical forests occur in regions where the annual mean precipitation ranges from 250 mm to 2500 mm, mean annual temperature is above 17 °C, and potential evaporation is more than precipitation for a significant part of the year

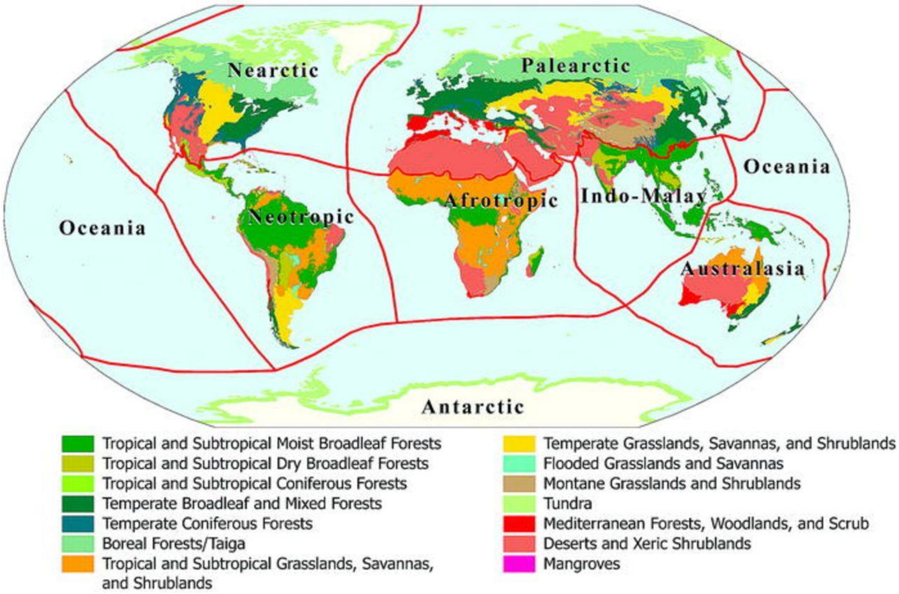

Figure 1: *Eight biogeographic realms and 14 biomes according to terrestrial ecoregions of the world: a New Map of Earth (Olson et al., 2001).*

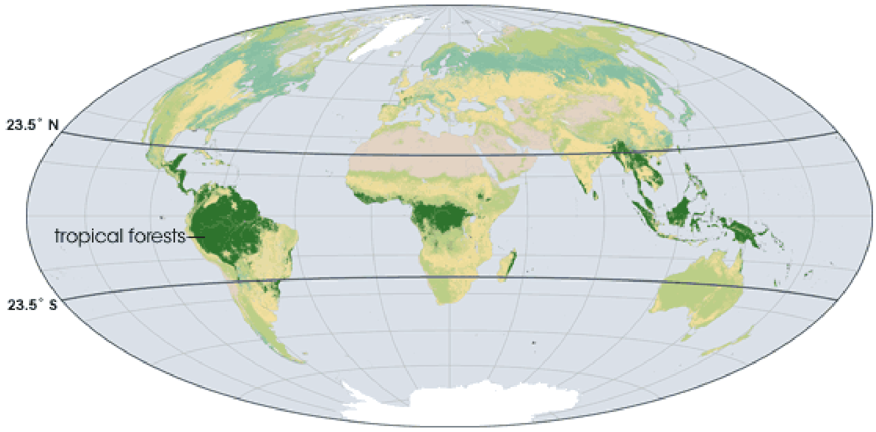

Figure 2: *Tropical forests are shown in dark green colour. The occurrence between the tropic of Cancer and tropic of Capricorn. Source: http://earthobservatory.nasa.gov/.*

(Holdridge, 1967; Murphy and Lugo, 1986). Tropical forests occupy about 7% of the terrestrial surface and cover more than 50 per cent of all plant and animal species (Tucker and Townshend, 2000). Tropical forests spread all over the world (**Figure 1** and **Figure 2**) and play important role in global exchanges of energy, in biogeochemical cycling and as reservoirs of biodiversity. As a consequence, they have been a major focus of investigations of global change (Chowdhury, 2006; Lambin et al., 2003; Laurance et al., 1998). Tropical forests are among the most productive ecosystems on the Earth, estimated to account for about 20 per cent of global terrestrial carbon stock. These forests affect the global climatic conditions by acting as pollution filters /

"carbon sinks" / "lungs of the earth" (Malhi and Grace, 2000; Foley et al., 2007). The rapid loss of tropical forests, due to competing land uses and forms of exploitation that often prove to be unsustainable, is a major contemporary environmental issue. The main concern, globally, is with tropical forests that are disappearing at a rate that threatens the economic and ecological functions that they perform. Deforestation in developing countries is more recent, with tropical forests having declined by nearly one-fifth so far, in these countries. Till date very few studies have been conducted in these regions to assess forest dynamics and biophysical characteristics. There is an urgent need for regular monitoring of tropical forest and understanding their response to climate change.

India is one of the ten most forest-rich countries in the world and one of the 17 mega bio-diverse regions of the world (Venkataraman, 2012). Forests are the second largest land use in India next to agriculture. These forests play vital role in harbouring a unique high level biodiversity with more than 45,500 floral and 91,307 faunal species, of which, 5150 floral and 1837 faunal species are endemic (Venkataraman, 2012). The forest cover of India is assessed as 70.68 Mha, which constitute 22 per cent of the country's geographical area ranging from the Himalayan Temperate to Dry Zone forests (*Global Forest Resources Assessment*, 2017). India contains great wealth of biological diversity in its forests due to wide physiography and climatic conditions. Due to wide variation in vegetation and climate, India has been delineated in to two realms (Palaearctic and Indo-Malayan) and three biomes (tropical humid forests, tropical dry deciduous forests and warm and semi deserts) which comprises 12 biogeographical regions (*Global Forest Resources Assessment*, 2017). During the last few decades, due to an increase in human population, livestock population, urbanisation and industrialization, intensity of altering existing forest has increased immensely (Christian and Krishnayya, 2009). Indian forest cover is in a critical phase due to serious anthropogenic stress. The depleting tropical forest cover in India calls for the urgent possible care in planning a strategy to reassess the climate change mitigation opportunities in the context of sustainable and commercial forestry strategies. An accurate and continuously updated resource data is a prerequisite for the present day forest ecosystem management in India. Moreover, assessing the health and function of forest ecosystems requires a long-term inventory and monitoring effort. Among different tropical forest types, most extensive forest biomes in India are the tropical deciduous forests. Out of total forests area in India, more than 50 per cent area is under deciduous forests. These forests are found in a range of landscapes from the plains to the hills. Apart from the extensive space that they cover, the deciduous forests are important by the fact that they are home to some of the most endangered wildlife in the country. The largest remaining populations of species such as the tiger, Asian elephant and Gaur in the country occur in these forests. As with all other ecosystems in India, deciduous forests also are under extensive pressures from human resource-use. Several studies have been conducted to assess spatial variability of evergreen broadleaf forests, grasslands, mixed forests but very little is known about deciduous forests in the country. Therefore, it is critical to know about the deciduous forests and their response various local stresses.

1.1.1 Tropical deciduous forests

Deciduous forests are the most widely-represented forests among all the forests types in India. These forests are popularly called as the monsoon forests. They grow over a wide range of rainfall ranging from 700 mm to 2000 mm. These forests are so called because trees of these forests shed their leaves during dry season for about six to eight weeks, in order to prevent loss of moisture through the process of transpiration. Every species has its own time of shedding leaves. Therefore, the entire forest does not appear leafless at any time of the year. These forests are found in a wide range of landscapes from the plains to the hills. Deciduous forests have predominantly broad-leaved trees. These forests occur as Sal dominated forests in the Bhabhar tract of the Himalayan foothills and Central India, and continue as teak-dominated forests across the Deccan Plateau. Apart from largest space that they occupy in the country's geographical area, these forests are considered to be vital by the fact that they provide shelter to some of the most endangered wildlife in the country. The deciduous forests usually cover a wide range of rainfall regimes and they can be classified into two divisions, namely the moist deciduous forests and the dry deciduous forests.

1.1.2 Moist deciduous forest

Tropical moist deciduous forest covers an extensive forest area of the country. These forests constitute about 19.73% (State of Forest Report, 2011) of the total forest's area in the country. These forests are commonly found in the regions where annual rainfall ranging from 1000 mm to 2000 mm, mean annual temperature of about 27 ºC and the average annual relative humidity of 60 to 70%. Owing to scarcity of soil moisture during dry season, trees of these forests shed their leaves for about six to eight weeks, generally during the months from March to May, in order to prevent the loss of moisture through the process of transpiration. The general appearance is burnt up and bare in extreme summers (April-May). New leaves sprout just before onset of the southwest monsoon (Yadav and Yadav, 2008). These forests have broad trunk, uneven top storey (25 to 60 m high), heavily buttressed trees and there is a layer of undergrowth with shorter trees, patches of bamboo, climbers, canes and evergreen shrub. These forests are found throughout India except in the western and the North-Western regions. Particularly, these forests are seen along the wet western side of the Deccan plateau, i.e. Mumbai, North-East Andhra Pradesh, Gangetic plains and in some parts of the Himalayan tracts continuing from Panjab in west to Assam valley in the east. These forests have several commercial values due to timber and several other forest products. Predominant species found in south India are by Teak (*Tectona grandis*), *Terminalia paniculata, T. bellerica, Grewia tilliaefolia, Dalbergia latifolia, Lagerstroemia parviflora,* Roxb.*, Adina cordifolia, etc.* are the other major species in forests of South India. In north India, they are dominantly covered by Sal *(Shorea robusta).*

1.1.3 Dry deciduous forest

These forests are similar to the moist deciduous forests. The major difference is that the species of this forests can grow in regions of comparatively less rainfall 700 mm to 1000 mm per annum. These forests cover vast area of the country with 41.87% (State of Forest Report, 2011) of the total forests area in in the country. These forests are found in the rainier parts of the peninsular plateau and the plains of Bihar and Uttar Pradesh. In the dry season, trees of these forests shed their leaves for six to eight weeks. These forests have a more open and dwarfish composition, the trees being more stunted and widely spaced. The tree height ranges from 10 m to 15 m, and undergrowth is abundant during monsoon. These forests occupy large areas between the Thar Desert, the Himalayas and the Sahyadris. In north, the forests are dominated by sal and in south by teak (*Tectona grandis*). The common constituents of these forests in South are *Dalbergia, Terminalia, Dillenia, Acacia, Pterospermum, Diospyros, Anogeissus, Boswellia, Chloroxylon, Bauhinia, Hardwickia, Gymnosporia, Zizyphus, Moringa, Dendrocalamus*, and so on. The other species of trees and shrubs of Sal dominated forests of northern region are *Terminalia, Semicarpus, Buchnania, Carissa, Madhuca, Acacia, Sterculia, Launea, Salmalia Adina, Bauhinia, Aegle, Grewia, Phyllanthus*, etc.

Common animals of these forests are lion, tiger, pig, deer, and elephants, huge variety of birds, lizards, snakes, tortoise, insects and worms.

1.2 Net Primary Productivity

Terrestrial Net Primary Productivity (NPP) is the net amount of carbon captured by green plants through photosynthesis per unit area per unit time (expressed in weight or energy units, e.g. g m^{-2} yr^{-1} or kJ m^{-2} yr^{-1}) (Melillo et al., 1993; Cao and Woodward, 1998). Field et al. (1995) defined NPP as the time integral of the positive increments to plant biomass. It is the central carbon related variable summarizing the interface between plant and other processes. As a key component of the global carbon cycle, NPP provides a measure of the uptake of atmospheric CO_2 by plants via photosynthesis (Beer et al., 2010). It is one of the most studied ecological variables, not only because it determines the allocation of energy to the biosphere and terrestrial carbon dioxide assimilation, but also because of its importance in indicating the conditions of the land (Field et al., 1995b; Scholes and Biggs, 2004; Kremen and Ostfeld, 2005) and status of a wide range of ecological processes (Piacentini and Rosina, 2012). NPP is a central process in the terrestrial ecosystem and nexus of the climate, energy and water cycles. Actually, it is important to note that most of the life on the earth is directly or indirectly depended on NPP (Pachavo, 2013). Estimation of NPP has been an important and major objective of several basic and applied ecological studies all over the world for projecting the future. Efforts have been also made for understanding global carbon balance, missing C links and its response to climate change.

Terrestrial ecosystem is considered to be more efficient in terms of productivity and C sequestration. Several researchers made efforts to estimate global terrestrial NPP using various approaches. Field. (1998) estimated the global terrestrial NPP as about 56.4 PgC yr^{-1} which is 53.8% of the total NPP of the earth (104.9 Gt C yr^{-1}). Running et al. (2004) analysed inter-annual variation of the global terrestrial NPP and reported that the global annual NPP ranged from 57.7 PgC (2001) and 55.5 PgC NPP (2002). Pan et al. (2014) provided an estimate of global terrestrial NPP induced by multiple environmental factors using an improved process-based terrestrial ecosystem model (DLEM, Dynamic Land Ecosystem Model). The model simulation estimates an average global terrestrial NPP of 54.6 PgC yr^{-1} during 2000–2009, varying from 52.8 PgC yr^{-1} in the dry year of 2002 to 56.4 PgC yr^{-1} in the wet year of 2008. Rafique et al. (2016)

reported mean global NPP about 63 PgC yr^{-1} based on estimates of five process-based models. The wide variation among these estimates is due to different model formulation, different number of input variables, model resolution and calibration, and the quality of input data. Recently, understanding the spatial and temporal variations of global NPP has attracted considerable attention for obtaining true estimates of terrestrial NPP capacity to act as a major source of carbon. Spatial variation of global terrestrial NPP is basically governed by various factors including climate conditions, soil, topographic conditions, disturbance regime and anthropogenic impacts, vegetation types and their spatial distribution, and factors that contribute to change these distributions such as land use practices (Cao et al., 2004). Likewise, the temporal variations of NPP are largely governed by the seasonal phenology of vegetation, and climatic conditions (Running et al., 2004). Therefore, it is critical to characterize the spatial and temporal dynamics of terrestrial NPP as a result of various driving forces (Potter et al., 2012).

The variation of NPP determined by global change has been one of the key aspects in climate-vegetation studies. Understanding the suit of factors influencing NPP is one of the important objectives that has elicited substantial interest across the world. This will allow development of different approaches that will predict variation of NPP with dynamic climate conditions. Several researchers across the world made an effort to investigate trends and variability in global terrestrial NPP. Nemani et al. (2003) estimated an increase in global net primary production with 6.17% or 3.42 PgC, over the 18 years between 1982 and 1999. A recent study using five process based models estimated an increasing trend in global NPP about 0.214 PgC yr^{-1} between 1982 and 2012 (Rafique et al., 2016). A simulation study using multi-model ensemble (MME) reported an increasing trend in global NPP about 3.647 PgC during historical period, which shows an increasing temporal trend of 3.9 $gCm^{-2}\cdot 100\ yr^{-2}$ in the past 150 years (Li et al., 2015). Many scientists have examined terrestrial productivity trends in Asia. (Fang et al., 2003) have looked at the whole of China, documenting that it's terrestrial NPP increased by 18.7% between 1982 and 1999. In a similar study, (Piao et al., 2005) reported that terrestrial NPP in China increased at a rate of 0.015 PgC yr^{-1} over the period 1982-1999, corresponding to a total increase of 18.5%, or 1.03% annually. (Singh et al., 2011a) used National Oceanic and Atmospheric Administration (NOAA) satellite-derived Advanced Very High Resolution Radiometer (AVHRR) data together with the Global Production Efficiency Model (GloPEM) developed by (Goward and Prince, 1995) to calculate annual NPP over all of India for the period 1981-2000. According to their analysis about 20 year NPP values indicated a significant increase in temporal trend of NPP over India ($r=0.7$, $p<0.001$), with the mean rate of increase being 10.43 gC m^{-2} yr^{-1}, which yields a mean rate-of-increase in carbon fixation of 34.3 TgC yr^{-1} for the entire country. In another long-term study from India, (Nayak et al., 2013) using NOAA derived NDVI together with climate data from other sources in a terrestrial biosphere model, inter-annual variability of NPP over India during 1981–2006 was studied. This work revealed that over the period 1981-2006, NPP linearly increased with a growth rate 0.005 PgC yr^{-1}, which is equivalent to 8.5% increase over the country during past 25 years. Like Asia, a significant amount of terrestrial NPP research has been conducted for locations in North America. Hicke et al. (2002) conducted an independent study, simulating NPP over North America for the years 1982-1998 using the Carnegie-Ames-Stanford-Approach (CASA) ecosystem model, driven by satellite NDVI data. This effort revealed that NPP increases of 30% or more occurred all over the continent between 1982 and 1998.

Despite various limitations, NPP is considered to be one of the important descriptors of the global carbon storage. More specifically, terrestrial NPP varies significantly among ecosystems in response to variation in type and conditions of the ecosystems-that is, its species composition, structure, and (in the case of forests) age distribution. In addition, important influencing factors are site conditions, including, climate, and soils, natural disturbances, and management. Understanding spatial distribution of NPP among ecosystems and assessing its sensitivity to changes in the global environment is an important step in estimating terrestrial ecosystem feedbacks to such changes. Research on NPP of different ecosystems is and will continue to be important, as solutions are sought for issues such as global change, sustainable indirect management, and conservation of biodiversity. The spatial distribution of NPP within biomes and the factors that control that distribution have become the new focus of research. In earlier study, (Melillo et al., 1993) used a process based terrestrial ecosystem model (TEM) to estimate global pattern of NPP for contemporary climate condition and current atmospheric CO_2. Potter et al. (1993) used a satellite data driven CASA ecosystem model to estimate spatial variability of NPP in different ecosystem. This seven researchers' effort revealed that annual NPP varied significantly between the ecosystems with low NPP in bare soils and desert (28 gC m^{-2} yr^{-1}) and high NPP in broad evergreen trees (1027 gC m^{-2} yr^{-1}). Yu et al. (2009) by using a land cover map, NDVI data sets, monthly meteorological data and observed NPP data, they improved the method of estimating light use efficiency (LUE) for different biomes and soil moisture coefficients in the Carnegie–Ames–Stanford Approach (CASA) ecosystem model over East Asia for 1999. Based on this improved carbon cycle model, mean NPP of evergreen broadleaf forest (1215.82 gC m^{-2}) was estimate to be the largest, followed by that of deciduous broadleaf forest (567.90 gC m^{-2}), cropland (524.66 gC m^{-2}), wooded grassland (445.94 gC m^{-2}), woodland (409.38 gC m^{-2}), mixed forest (407.0 gC m^{-2}), evergreen needleleaf forest (330.38 gC m^{-2}), deciduous needleleaf forest (298.25 gC m^{-2}), closed shrubland (266.39 gC m^{-2}), tundra vegetation (243.39 gC m^{-2}), grassland (228.12 gC m^{-2}), open shrubland (144.14 gC m^{-2}) and mean NPP of sparse vegetation (26.2 gC m^{-2}) was found to be the smallest. Fang et al. (2003) conducted an independed simulation study, exploring the trends and spatial patterns of NPP in China between 1982 and 1999 using a CASA carbon cycle model, which was based on satellite NDVI recorded at 8 km spatial resolution together with a number of surface observations. Results of this study indicated that annual mean NPP over different ecosystem in China ranged from 18.7 gC m^{-2} yr^{-1} in desert and 418.3 gC m^{-2} yr^{-1} in evergreen broadleaf forests. Recently Goroshi et al. (2014) estimated NPP using improved CASA ecosystem model driven by Indian National Satellite System (INSAT-3A) derived NDVI data together with surface meteorological data obtained from various national and international agencies over India for 2009. The study showed that mean annual NPP among different ecosystem in the country varied between <100 gC m^{-2} in desert of Rajasthan and >1200 gC m^{-2} in evergreen broadleaf forest of North-East and Western-Ghats regions.

Many researchers across the world showed that NPP varies significantly among and within the species due to variation in age, climate, and soil. Christian et al. (2015) reported seasonal variations in gross primary productivity (GPP) of a predominant tropical dry deciduous forests (teak, bamboo and mixed species) in Shoolpaneshwar Wildlife Sanctuary using satellite data (MODIS and Hyperion data) driven vegetation photosynthesis model (VPM). Seasonal variations of average GPP values were ranging from 3.71 g C m^{-2} day^{-1} (88 DOY (day of the year)) to 29.84 g C m^{-2} day^{-1} (294 DOY) for teak, 4.13 g C m^{-2} day^{-1} (88 DOY) to 33.37 g C m^{-2} day^{-1} (294 DOY) for mixed species and 5.23 g C m^{-2} day^{-1} (88 DOY) to 34.62 g C m^{-2} day^{-1} (294 DOY) for bamboo. Tripathi and Singh. (1994) reported an annual productivity of bamboo (*Dendrocalamus strictus*) in the range of 1.8 to 7.7 Mg ha^{-1} yr^{-1}; (Lodhiyal et al., 2002) determined NPP in different age groups Shisham (*Dalbergia sissoo*) forest planted after clearing up of Sal (*Shorea robusta*) tree species in Bhabbar (a nutrient poor and low water table site) adjacent to the foothills in Kumaun of Central Himalayas. The total NPP ranged from 11.4 Mg ha^{-1} yr^{-1} for 5 years to 14.8 Mg ha^{-1} yr^{-1} for 15 years. Kumar et al. (2011) estimated NPP of different age grouped (5, 10 and 15-year-old) *Butea monosperma* forests in Rajasthan. It was found that the trees NPP increased with increasing age of the forest stand, whereas the herb NPP decreased significantly ($P<0.01$) with increase in the forest age. The total herbaceous and woody NPP varied between 11.9 and 19.1 Mg ha^{-1} yr^{-1}. Garkoti. (2008) reported that the NPP of Maple (*Acer cappadocium*) forest occurring at an altitude of 2750 m in the West Central Himalayas was estimated to be 19.5 Mg ha^{-1} yr^{-1}. Kale and Roy. (2012) estimated NPP of different tropical dry deciduous forests species in Shivpuri districts of Madhya Pradesh, Central India. It was found that NPP in dry deciduous forests varied between 0.58–275.78 gCm^{-2} yr^{-1} during growth phase and 0.43–74.34 gCm^{-2} yr^{-1} during senescence phase. Pande and Patra (2010) estimated biomass and productivity in Sal and miscellaneous forests of Satpura plateau, Madhya Pradesh. NPP in the region ranged from 38.1 Mg ha^{-1}yr^{-1} to 9.73 Mg ha^{-1} yr^{-1}. George et al. (1990) reported NPP in some of the tropical forests of Coimbatore as 2.47 Mg ha^{-1} yr^{-1}. Karmacharya and Singh. (1992) reported NPP between 12.93 to 25.59 Mg ha^{-1} yr^{-1} in some of the tropical teak plantation. Negi et al. (1990) reported NPP in the range of 6.42 to 11.3 Mg ha^{-1} yr^{-1} in some of the teak plantations of Haldwani (UP).

1.3 Meteorology; Meteorology-NPP

Terrestrial Net Primary Productivity is influenced by various climatic factors. Precipitation and temperature will have direct effects on NPP because half of the world's ecosystems are limited by the availability of water (Heimann and Reichstein, 2008) and several species vulnerable to extreme temperatures (Allen et al., 2015; Hatfield and Prueger, 2015). There is an increasing effort in documenting the influence of climatic variation on NPP (Nemani et al., 2003; Zhang et al., 2009; White et al., 1999). These climatic dynamics effect ecosystem biogeochemical cycles through changing energy and nutrient flow as varied by changing precipitation and temperature patterns (Breshears et al., 2005). One of the best descriptor of the ecosystems response to climate change is variations in NPP. Changes in seasonal and inter-annual NPP pattern may be among the easier ways to determine species response to changing ecosystem conditions. Precipitation and temperature are the major climatic drivers of tropical deciduous forest NPP. These climatic parameters influence vegetation biophysical processes such as tree phenology, growth rate, biomass accumulation etc. Temperatures during spring season have been found to be more critical influencing tree phenophases at all other times of growing season (Walther et al., 2002). For instance, variations in spring temperature affect the onset date of greenness that can change tree productivity (Yadav and Yadav, 2008). Robinson et al. (2013) described that tree phenological patterns could be influenced by water budgets that are significantly changed by climatic variations in temperature and precipitation. If precipitation and temperature put strong control on forest total NPP and C allocation patterns, then variation in annual and seasonal precipitation potentially drives inter-annual variability in NPP and C allocation. Such climatic patterns are expected to have adverse effect on deciduous forests NPP. Given the role played by deciduous forests in hydrological cycle, carbon cycle and biodiversity, it is important to quantify these effects to ensure adequate monitoring and management of these forest ecosystems. In the past several decades, earth has experienced significant climate change, such as increased temperature and changed pattern of precipitation (Pachauri et al., 2014) influencing NPP of forest covers.

Rainfall and temperature variability have been historically being key causes of seasonal and inter-annual variability of NPP in tropical deciduous forests. Even though their variability is not a new phenomenon, their variability has reportedly increased during the past few decades and created huge water stresses in many countries across the world. Understanding the impact of precipitation and temperature on deciduous forest NPP is very important for determining accurate carbon budget and projecting how these forests' NPP will be affected by changing precipitation pattern and increasing temperature. Tropical deciduous forests show higher seasonal and inter-annual variations in NPP, and have been considered very sensitive to changes in precipitation and temperature. Variations in precipitation and temperature are not only linked to total NPP, but also strongly associated to different temporal dimensions (Peng et al., 2008). In short time scales, precipitation and temperature directly affect the key physiological process like stomatal conductance, plant photosynthesis and respiration (Field et al., 1995). These may lead to variation of NPP with different levels of inter-annual variation of magnitude. Several studies across tropical countries shown that seasonal and inter-annual variation in deciduous forest NPP is strongly correlated with precipitation and temperature (Singh et al., 2011; Nayak et al., 2013; Bala et al., 2013; Fabricante et al., 2009). Given the rapid rise of temperature and likely average increase in rainfall of about 3.4 per cent globally per 1°C temperature rise that is seen (Allen and Ingram, 2002), it is important to consider the dynamics of rainfall and temperature in the assessment of NPP, particularly in areas where climatic change is likely to reduce forest NPP. The role played by tropical deciduous forests in India seems to be threatened by changing precipitation patterns and rising temperature. Changes in precipitation and temperature include predictions of increased frequency of extreme weather events such as drought and heat waves (Whetton and Suppiah, 2003). Some studies in the country (Nayak et al., 2013) reported that extreme droughts, usually associated with El Niño Southern Oscillation (ENSO), causes higher rates of tree mortality and increased forest flammability (Nepstad et al., 2004). However, contrasting measurements have been made where extreme greening has been linked with drought in the Amazon forests (Saleska et al., 2007). It is clearly indicating that the sensitivity of tropical forests to extreme weather events is poorly understood. Consequently, more studies on seasonal, inter-annual patterns of NPP and its relationship to precipitation and temperature is very important for strengthening the understanding of NPP-climate relationships.

The impact of seasonal and inter-annual dynamics of precipitation and temperature on NPP was delayed and persisted for some time (Peng et al., 2008), yet the relative importance of these climatic factors and NPP is that they are the geographical variables (Running et al., 2004). Hence, it is indispensable to study the spatial variability of the relationship between seasonal and inter-annual variability of NPP with precipitation, and temperature. Unevenly distributed annual precipitation is the major factor for spatial and temporal variation of NPP in deciduous forests in India. With nearly 70 per cent of the annual precipitation occurs from July to the end of September, drought in the late spring and early summer always affect deciduous forest growth and productivity. In such regions, an increase of temperature under climate change might enhance evapotranspiration and decrease soil moisture, further limiting plant growth (Yang et al., 2003, 2006) and decreasing forest productivity. Singh et al. (2011); Nayak et al. (2013); and Bala et al. (2013) analysed time series NPP data for different vegetation types in India and determined its correlation with precipitation and temperature for the past three decades. They found significant positive correlation between NPP and precipitation, whereas they found negative correlation between NPP and temperature. It has been argued that measuring and quantifying deciduous forests NPP is one of the several approaches to assess response of deciduous forests to the climatic dynamics and recurring extreme weather events. So far in India no studies have been conducted to understand spatio-temporal variability of moist deciduous forest NPP and dry deciduous forests NPP and its relation with precipitation and temperature at national parks, more specifically in Madhya Pradesh. Although some short term studies have documented (Kale and Roy, 2012) spatial variability of NPP in Madhav NP, but they have not demonstrated its relation with precipitation and temperature. Little is known about spatio-temporal variability of deciduous forest in NP in Madhya Pradesh and its relation with climatic parameters. Therefore, it is extremely important to carry out more studies on NPP dynamics and its relation with climatic parameters in NP in Madhya Pradesh which are predominantly covered moist deciduous and dry deciduous forests.

1.4 Importance of NPP estimation in national parks

Madhya Pradesh is the second largest state in India with the geographical area about 308,144 km^2 which is 9.38% of the total land area of the country. The state has the highest forests area of the country of about 95,221 km^2 constituting 31% of the geographical area of the state and 12.44% of the forest area of the country. Forests in the state have been classified into reserved forest, protected forest and unclassified forest, which comprise 61.7%, 37.4% and 0.9% of the forest area respectively. Per capita forest area in the state is 2,400 m^2 as against the national average of 700 m^2. In terms of forest types, 88.65% of area is under dry deciduous forest followed by 8.97% of area as moist deciduous forest and 0.26% of area as thorny forest. These forest covers support rich wildlife and biodiversity. The Government of India has declared nine national parks in the state between 1955 and 1983. Among all those parks, Kanha national park (KNP), Madhav national park (MNP) and Bandhavgadh national park (BNP) are the oldest national parks, which have been declared in 1955, 1959 and 1968, respectively. KNP, BNP and MNP together cover about 49% of the total forest area. According to the Gazette of Government of India, “National park” is defined as an area which is strictly reserved for the betterment of the wildlife and biodiversity, and where activities like developmental, poaching, hunting and grazing or cultivation are not permitted. In these parks, even private ownership rights are not allowed. Their boundaries are well marked and circumscribed. They are usually small reserves spreading in an area of 100 km^2 to 500 km^2.

Rainfall and temperature variability have historically been key causes of significant difference in various biophysical parameters of the vegetation in the state. Even though their variability is not new phenomenon in the state, their variability has reportedly increased during the past few decades and created huge water stress across the state. More recent study by Mishra et al., (2016) revealed that most of the districts in Madhya Pradesh are projected to experience 1-1.2 ºC increase in mean annual air temperature in near term while 2-2.5 ºC warming in the mid-term (2046-2075) climate. A significant increase in the number of hot days, hot nights, droughts, and extreme precipitation is likely under the future climate, which may pose enormous pressure on various sectors. Some of the studies in Madhya Pradesh state action plan on climate change (2014) reported that projections of rainfall in MP for the period 2021 to 2050 are likely to exhibit a decrease in winter rainfall from eastern part of the state to western part of the state. In pre-monsoon period, the rainfall is increasing only in the Southern part of the state, with decrease in rainfall in all other parts. In the Monsoon period, there is a slight increase in rainfall all over MP (the increase being 1.25 times the rainfall observed currently). During the recent past, tropical deciduous forests of different bio-geographic provinces of India have witnessed severe climatic pressure due to change in precipitation pattern and increase in temperature. Till date no studies have been conducted in KNP, BNP and MNP to understand spatial variability of forests biophysical parameters and their response to climate variability. Although some studies have documented spatial variability of NPP in dry deciduous forest of MNP (Kale and Roy, 2012), but they have not demonstrated the influence of precipitation and temperature on NPP. Therefore, it is very important to investigate spatial and temporal variability of deciduous forests NPP and its relation with precipitation and temperature in KNP, BNP and MNP.

1.5 NPP through Remote Sensing

In studies of ecosystem specific processes and their regular monitoring, accurate net primary productivity (NPP) measurements are crucial as it provides fundamental understanding of ecology and it plays important role in global carbon cycle (Cramer and Field 1999). Conventionally, it has been measured using sample surveys and field measurements (Bo et al., 2003). Although these traditional field based measurements have been used successfully with accurate NPP output for small scale observations (Gier, 2003; Li et al., 2005), they are often time intensive and laborious (Lu, 2006). The methods are also difficult to extend to larger spatial scales due to spatial variability of environmental conditions and limitations of allometric equations used to estimate carbon gain from different ecosystems (Goetz et al., 1999). Besides, destructive sampling of trees at target research sites, for biomass/NPP estimates may lead to loss of habitat and biodiversity as well as carbon sequestration potential (Wang et al., 2007). Therefore, it is necessary to employ alternative methods of NPP estimation to replace or complement traditional methods. The development of remote sensing has enhanced the ability to study ecosystems at landscape and regional scales with improved accuracy (Lu, 2006) . It allows scaling and monitoring large areas with minimum field work. It provides an unique opportunity for improving the estimation of NPP at large scales in a cost effective, efficient and accurate manner (Running et al., 1999; Running et al., 2000) at high temporal and spatial scales (Myneni et al., 1998; Zhou et al., 2001). Early applications of remote sensing have seen the use of the normalized difference vegetation index (NDVI), as a surrogate measure for NPP (Townshend and Justice 1986). NDVI has been proven to provide an effective measure of photosynthetically active biomass and has been correlated to NPP at extensive spatial scales (Oindo and Skidmore, 2002). However, NDVI is just an indicator so it does not give an estimate of the real quantity of biomass per unit area per unit time unless it is linked to ground measurements. Recent developments in remote sensing are now focusing on estimating NPP quantities usually in grams of carbon per square meter per year (gC m^{-2} yr^{-1}) or tons of carbon per hectare per year (ton C ha^{-1} yr^{-1}). As a result, various NPP models that use remote sensing data have been developed (Potter et al., 1993; Goetz et al., 2000). Several researchers made an effort to provide a consistent, continuous estimate of NPP using various production efficiency models (PEM) like C-fix model (Veroustraete, 1994; Veroustraete et al., 1996; Veroustraete et al., 2002), Global production efficiency model (Goward and Prince, 1995), Vegetation photosynthesis model (Xiao et al., 2004), Carnegie-Ames-Stanford Approach (CASA) by Potter et al. (1993), MOD17 (Running et al., 2004). In general, all PEMs employ a similar basic methodology to calculate NPP. Typically, these models estimate NPP as a product of light-use efficiency (LUE) and absorbed photosynthetically active radiation (APAR). However, limitations of these models have been their demand for densely measured shortwave radiation (SWR) flux for APAR estimation, as well as LUE values. The LUE and SWR flux measurements have mainly been obtained from coarse resolution satellite-based weather data, making biome specific NPP studies difficult in cases where intensively measured LUE and SWR information is required (Rahman et al. 2004). Scientists have therefore depended on calibrated LUE and SWR values for most of the vegetation types in India (Nayak et al., 2010) whose accuracy is still largely unknown. Thus, the development of efficient and accurate methods for determining moist deciduous and dry deciduous forests NPP using biome specific LUE value and SWR obtained from the weather station located at/near to targeted site is critical.

1.6 Missing links

The study regions (KNP, BNP and MNP) are the oldest national parks in Madhya Pradesh. They cover about 49% of total forest area. Tropical moist deciduous and dry deciduous forests are the predominant forests in these parks. Recent studies in Central India revealed that tropical deciduous forests in Madhya Pradesh have experienced significant environmental changes in past decades due to extreme weather events. In response to these environmental challenges, forest ecosystems in KNP, BNP and MNP may have experienced changes in their NPP. To date, scientific understanding of the responses of forest ecosystems in these parks to environmental changes is still incomplete and so an improved understanding of current spatial variation of NPP and its relation with climatic parameters is critically needed. Because of large seasonal and inter annual variability of NPP between deciduous forests and atmosphere, forests are likely to influence regional/global carbon balance in response to projected change in climate. Determining sensitivity of deciduous forests' NPP in these parks to climate may give some clue for understanding the potential for carbon cycling in these forests to respond to changes in climatic parameters like temperature, precipitation, incoming solar radiation etc.

In general estimating or modelling deciduous forests NPP and its interaction with climatic parameters is seriously inhibited in KNP, BNP and MNP due to lack of adequate observational data or due to significant uncertainties in model parameterisation and validation, such as NPP from field measurements. The challenge to forest researchers who are inquisitive to know the spatial variability of NPP in these parks and to know its relation with climate parameters, are need to carry out extensive regular forest growth measurements and weather data recording and their analyses in a consistent manner. A limitation to our knowledge about the moist deciduous and dry deciduous forests productivity patterns in these national parks is that relatively few studies are longer than a single year. Some of the studies (Kale and Roy, 2012; Christian et al., 2015) showed spatial distribution of NPP in dry deciduous forests of MNP, but not documented its relation with climate parameters. If climatic parameters exert strong control on deciduous forests NPP, then variation in annual and seasonal precipitation potentially drives inter-annual variability in NPP of these forests. The long-term implications for this variability relate to the ability of forest stands to respond to changing climatic conditions. Therefore, it is extremely important to monitor deciduous forests as important natural resources in developing countries like India. An accurate and regularly updated biome specific resource data is a prerequisite for the present-day forest ecosystem management to understand their quantitative contribution to the regional/global carbon budgets and for projecting how these forests will be responding to changing climate. Assessing the health and function of deciduous forest ecosystems essentially requires a long-term inventory and monitoring effort. By means of different potential sources (field inventory, remote sensing and ecosystem models) one can easily achieve requirements of continuously updated resource data and long-term inventory and monitoring. In order to characterise NPP accurately and understand its relationship with different meteorological parameters the study region should be protected and least disturbed. By considering all these missing links in deciduous forests, the present study was aimed at three national parks (KNP, BNP and MNP) in Madhya Pradesh, Central India with the following research objectives:

1) To study spatial variability in the NPP of tropical deciduous forests of KNP, BNP and MNP using field measurements from 2010 to 2014.

2) To obtain NPP of tropical deciduous forests of KNP, BNP and MNP using satellite data from 2010 to 2014.

3) Validation of satellite derived NPP using field data based NPP.

4) Assessment of relation between measured NPP and meteorological parameters (precipitation and temperature) during the study period, for these forest covers.