CHAPTER-II MATERIALS AND METHODS

The aim of the present study was to estimate net primary productivity (NPP) of tropical deciduous forests in Kanha National Park (KNP), Bandhavgadh National Park (BNP) and Madhav National Park (MNP) and to determine its relation with different weather parameters for the period 2010-2014. The locations of the study areas are presented in **Figure 3**. Detailed description of the study areas is given in the following sections including vegetation types and climatic patterns.

2.1 Study area

2.1.1 Kanha National Park

Physical characteristics: Kanha National Park (KNP) is located in Mandla and Balaghat districts of the state Madhya Pradesh India across the latitude of 22°7' to 22°27'N; longitude of 80°26' to 81°3'E. KNP was declared as a national park in the year of 1955, and came under the "Project Tiger" as a Tiger reserves in 1973-74. The total geographical area of the park is 1945 sq.km with a core area of 940 sq.km which is surrounded by buffer zone of 1,005 sq.km. Madhya Pradesh Forest Department has further divided the park into 6 ranges (Kisli, Kanha, Sarhi and Mukki in the western block; and Bhaisanghat and Supkhar) for better management of precious flora and fauna in the park.

Soils properties: In Kanha, Kisli and Mukki ranges soil is sandy. In the lower pockets, soil is finely textured and rich in humus. It tends to be somewhat clayey and is locally called Kanhar. Perhaps the name Kanha, the village after which the park is named, comes from this soil. The main Maikal range forms the watershed between the rivers Narmada and Mahanadi. Within the park, it continues west as Bhaisanghat ridge which devides the Narmada catchment between Banjar to the west and Halon to the east. Banjar and Halon form the two main rivers in the park. From Maikal and Bhaisanghat ridges, a number of spurs branch off to the north and divide the headwaters of Halon in to its tributaries. At 850m from Bamhnidadar, the Bhaisanghat ridge splits and the spur running west divides the Banjar catchment in to Bajar and its tributary, the Sulkum.

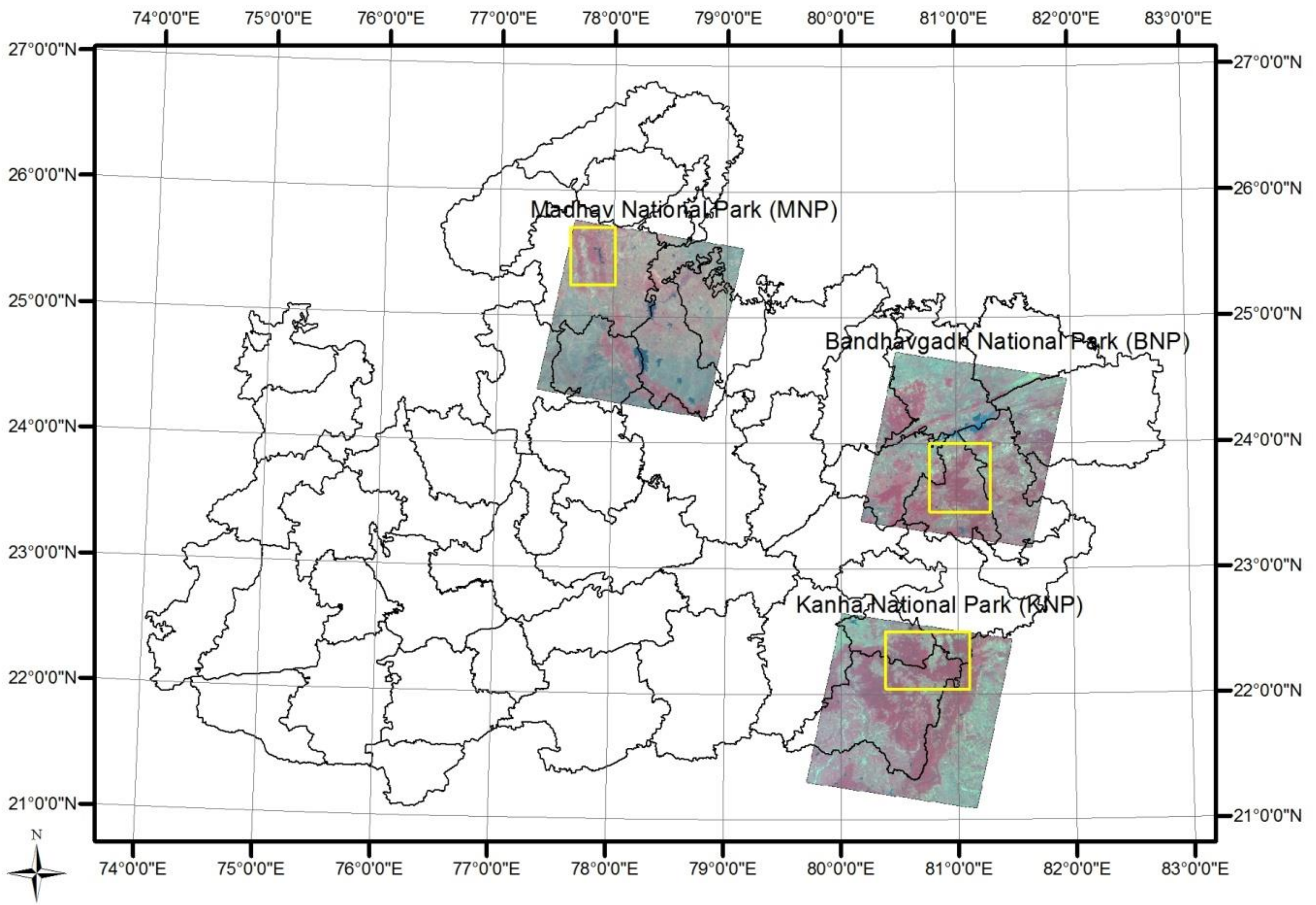

Figure 3: *Location of the study regions in Madhya Pradesh state, Central India.*

Climate: The park experiences tropical climate with three distinct seasons: winter (November-February), summer (March-June), and monsoon (July-October). Seasonal profiles of different weather parameters in KNP for the study period (2010-2014) is presented in **Figure 4**. Rainy season in the park starts with pre-monsoon showers usually received in the second or third week of June, and regular onset takes place by the first week of July. The wettest months are July and August, when around 90% of the total annual rainfall is received in this season, which is around 1325mm. On an average there are 84 rainy days (i. e. days with rainfall of 2.5 mm or more) in a year in the park. Maximum temperature (Tmax) and minimum temperature (Tmin) increases gradually from February and attains peak in May. May is the hottest month with mean monthly maximum and minimum temperature at about 41°C and 26°C. Due to onset of monsoon in June, the temperature falls significantly. During mid- September there is a little rise in the day temperature while the night's turnout to be cooler. Both day and night temperatures fall rapidly from November and lasts till February. January is generally the coldest month with the mean monthly maximum and minimum temperature at about 25 °C and 9°C.

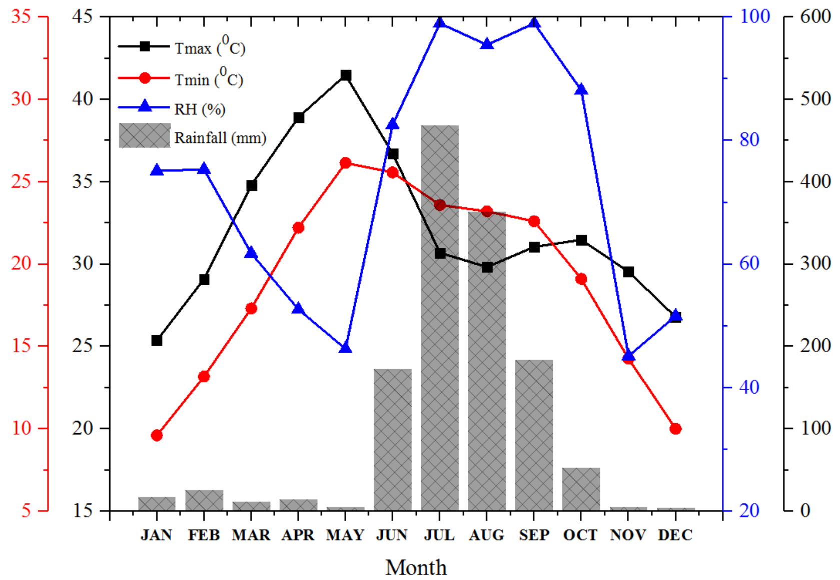

Figure 4: *Seasonal variation of different weather parameters in KNP (2010-2014).*

Relative humidity (%) rises progressively during the end of May and attains maximum in monsoon and after the season, it falls considerably. In mid-November there is little increase followed by significant drop after February and reaches its lowest value in May (46%).

The vegetation and cover type: Largely due to the combination of land forms, soil types and humidity variability of the region, KNP is very rich in flora. It has been estimated that KNP has around 800 species of flowering plants, and 18 of them were categorised as rare plants in the Kanha Management Plan of 1988-89 (Kotwal and Parihar, 1988). Some of the important tree species and animals found in the park are given in **Appendix 1** and **Appendix 2**. After (Champion and Seth, 1968), the following forest types have been identified in the KNP.

1) Moist Peninsular Sal Forests (3C/C2)

   a) High level sal (3C/C2ci)

   b) Low level sal (3C/C2cii)

   c) Valley sal (3C/C2ciii)

2) A) Southern Tropical Moist Mixed Deciduous Forest (3A/C 2a)

   B) Southern Tropical Dry Mixed Deciduous Forest (5A/C-3)

The highland forests are tropical moist dry deciduous type and of a completely different nature with bamboo (*Dendrocalamus strictus*) on slopes. However, a working classification in the field suggests that the forests are mainly of two types: Sal *(Shorea robusta*) and mixed deciduous forests interspersed with meadows. The streams are fringed with thick bamboo breaks and tall mango trees. The upper slopes carry mixed forest with numerous Mahul climbers which are often in flowering phase which make the tree tops look white in summer. In middle slopes, bamboo grows abundantly under the trees and in the lower slopes, pure stands of sal replace the mixed woodlands. The valleys are covered with dense stands of sal alternating with grassy meadows. Grass growth is not thick in Kanha and it turns dry and coarse, and becomes very prone to fire in the summer. The grasslands that occur in winding strips along rivers and streams have a very high water - table during the monsoon. These flat, silted beds are locally called Bahra. Tall grasses that grow in the Bahra provide well - sheltered fawning sites, much favoured by the Barsingha.

2.1.2 Bandhavgadh National Park

Physical characteristics: Bandhavgadh National Park (BNP) is located in Umaria district of the state Madhya Pradesh India across the latitude of 23°30′ to 23°46′ N; and longitude of 80°47′ to 81°11′ E (**Figure 3**). The altitude of the park varies between 410m and 810m. The park was declared as a national park in the year of 1968, and came under the Project Tiger" as a Tiger reserves in 1993-94. The total geographical area of the park is 448.84 km^2 with a core area of 105 km^2.

Soil properties: Geology of the park is soft feldspathic sandstone with quartzite. Soil type varies from sandy to sandy-loam. Because of this, rain water percolates through the ground, forming a number of perennial streams and springs. More than 20 streams flows through the forest. Among them, Umrar river forms the western boundary and is the largest.

Climate: The park experiences tropical climate with well-defined winter, summer and monsoon seasons. Winters set in around mid-November and last till the end of February. Summer last from the end of March until the end of June. By mid-June the rains can start with very little prior warning. Seasonal patterns of different weather parameters in BNP for the study period (2010-2014) are shown in **Figure 5**. The arrival of rainy season starts with pre-monsoon showers usually receives around 15^{th} of June, and the regular monsoon starts in the first week of July. Around 90% of the total annual rainfall is received in this season, which is around 1050 mm. On an average there are 68 rainy days in a year in the park. Maximum temperature (Tamx) and minimum temperature (Tmin) increases gradually from February and attains peak in May. May is the hottest month with mean monthly maximum and minimum temperature at about 40°C and 25°C. Due to rainfall in June, the temperature goes below significantly. By mid-September there is a little increase in the day temperature while the night's turnout to be cooler. Both day and night temperatures fall rapidly from November and lasts till February. January is generally the coldest month with the mean monthly maximum and minimum temperature at about 22°C and 8°C. In the monsoon season the relative humidity goes above 80%. In the post monsoon and winter seasons the humidity is ranges between 50 to 65% while in the summer, humidity is usually below 30%.

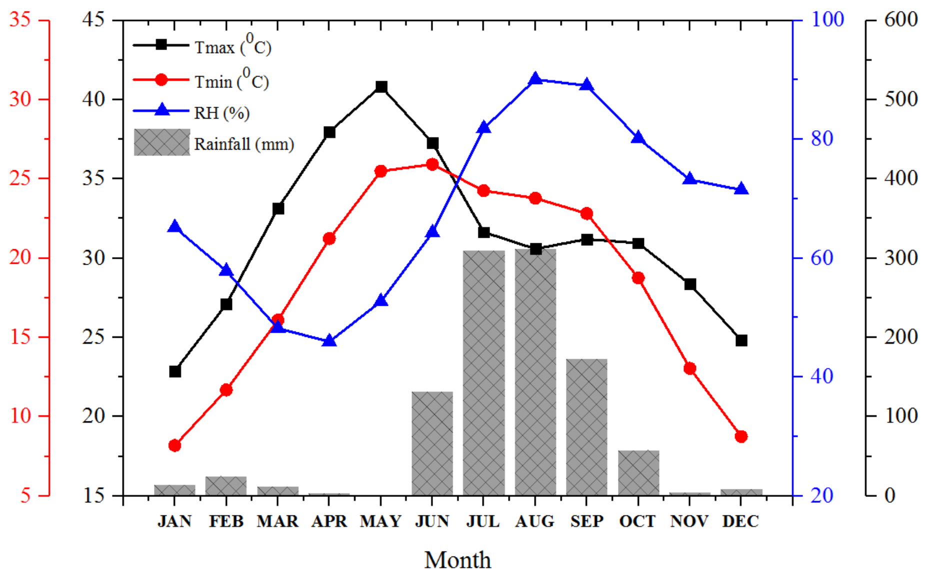

Figure 5: *Seasonal variation of weather parameters in BNP (2010-2014).*

The vegetation and cover type: The foliage in BNP is mostly of dry deciduous type and is the only region which is quite rich in flora and fauna. The area brings relatively moderate climate and favourable topography that uniquely supports the growth of a rich and varied flora in the park. The park has over 500 species of flowering plants. Some of the important tree species and animals found in the park is presented in **Appendix 6** and **Appendix 7**. Forests of BNP are broadly classified in to the following types in accordance with the revised forest types of India (Champion and Seth, 1968).

1) Moist Peninsular Low-level Sal forest (3C/C2a)
2) West Gangetic Moist Mixed Deciduous Forest (3C/C3a)
3) Moist Peninsular Low-level Sal forest (3C/C2a)
4) Northern Dry Mixed Deciduous forest (5B/C2)
5) Dry Deciduous Scrub Forest (DS1)

For general management purposes, the forests of the BNP has been be divided in to sal forest, mixed forest, and grasslands. In the park, sal (*Shorea robusta*) is the predominant species with the associate miscellaneous species and grasslands. Bamboo (*Dendrcalamus strictus*) is found almost throughout the park.

Sal forests: Sal characteristically forms a high forest in which it constitutes about 60 - 80% of the top canopy, which is 25–40 m high. The undergrowth is abundant with the presence of climbers. The predominant associates are *Terminalia tomentosa, Pterocarpus marsupium*, *Anogeissus latifolia*, *Madhuca indica*, *Phyllanthus emblica,* *Buchanania lanzan, Diospyros melanoxylan, Terminalia Chebula, Kydia calycina, Ougeinia oojeinensis, Bridelia retusa, Bauhinia retusa and Phoenix acaulis.* Around 60% of the park area comprises of sal forests and its associates (Dwivedi, 1987). Generally, these species cover low undulating and plain tracts and degenerates in growth and quality as they ascend hill slopes, giving place to mixed forests on upper slopes due to edaphic factors.

Mixed forest: Occurs on upper hill slopes and hilltops containing shallow soil and rocky outcrops and on Southern and Western aspects. They also occur interspersed with sal forests on lower slopes mainly due to edaphic factors. Few patches of mixed forests are met with on nala banks, containing alluvial or black clayey soils where the moisture tends to accumulate and create bad soil aeration.

Grass lands: Grassy patches or meadows occur all along the park. Important grasslands are Chakradhara, Bathan, Sehra, Rajbehra, Bhitri Bah, Jobi Bah, Kudra Keruvah, Kerawaha, etc. Some of these patches are reported to have been cultivated in the past and some of the old park grasslands along the nalas are marshy in nature abounding in aquatic plants. Rare species such as insectivorous plant (*Drocera peltata*), medicinal plant such Buch (*Acorus calamus*) are found in isolated patches of the park.

2.1.3 Madhav National Park

Physical characteristics: Madhav National Park (MNP) is situated in Shivapuri district of the state Madhya Pradesh between 25°20′ to 25°38′ latitudes and 77°38′ to 77°56′ longitude (**Figure 3**). The highest point in the national park is near George Castle at 1597 feet (484 mts). MNP got status of national park in 1958. Total geographical area of the park is 375 km^2.

Soil properties: In Vindhyan hills, generally, the soil is shallow, sandy loam and well drained. Lateritic zone is covered by red soil with stony concretions. The texture is coarse as most of the soils contain an appreciable proportion of incompletely weathered pebbles and boulders. On the ‘Pathars’ of plateaus and steep slopes, the depth of soil is generally shallow, hardly exceeding 30 cms. At places the soil is absent and the underlying rock practically comes to the surface.

Climate: Climate of the park is characterized as tropical climate with three distinct seasons: winter (November-February) summer (March-June), and monsoon (July-October). Seasonal profiles of different weather parameters in MNP for the study period (2010-2014) is presented in **Figure 6**. The park generally receives rainfall in the month of June. Average annual rainfall in the park is 725mm. About 92% of the annual rainfall in the park receives during monsoon months (June to September). On an average there are 45 rainy days (i. e. days with rainfall of 2.5 mm or more) in a year in the park. Maximum temperature (Tmax) and minimum temperature (Tmin) rise progressively from February and attains peak in May. May is the hottest month with mean monthly maximum and minimum temperature at about 42°C and 26°C. With the onset of monsoon in second week of June, the temperature drops considerably. After the withdrawal of the monsoon by about the end of September, there is a slight increase in the day temperature while the nights become progressively cooler. From November, both day and night temperatures decrease rapidly. January is generally the coldest month with the mean monthly maximum and minimum temperature at about 22°C and 6°C. In the monsoon season, the relative humidity goes above 80%. In the post monsoon and winter seasons the humidity is usually between 50 and 65% while in the summer, the daytime humidity is usually below 20%.

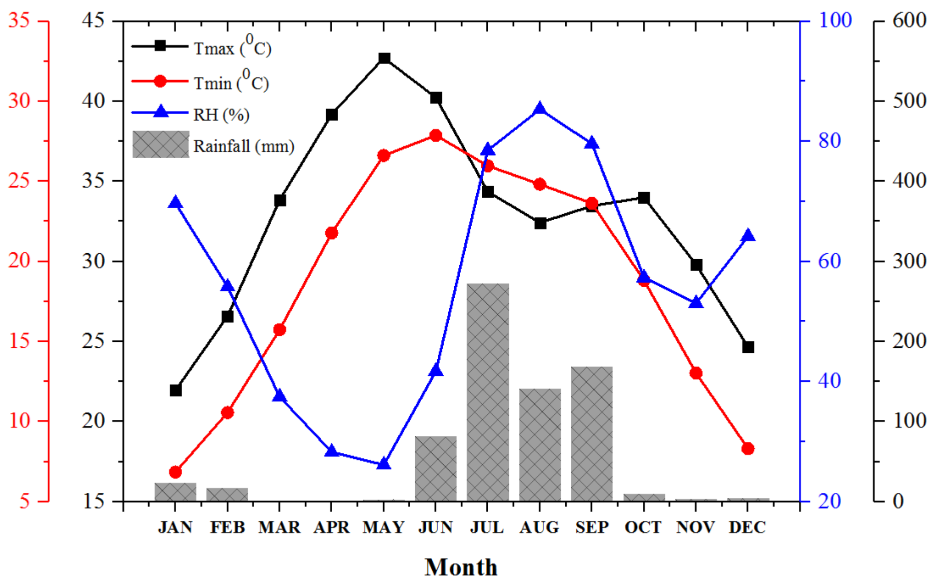

***Figure 6:** Seasonal variation of weather parameters in MNP (2010-2014).*

The vegetation and cover type: Forests at MNP fall in the category of Northern tropical dry deciduous mixed forest. Some of the important tree species and animals found in the park are given in **Appendix 11** and **Appendix 12**. According to the

Champion and Seth classification scheme, they are classified under 5B/C2. Predominant species in the park comprised Kardhai, Salai, Dhaora and Khair. The understory includes mostly Ber, Makor and Karonda.

Kardhai forests: It is found throughout the park in varying proportions. Pure kardhai patches are found in Mamoni, Chironji and Satanwada blocks between elevations of 330 mts to 440 mts. It is also found in pure patches along nullas at low elevations.

Salai forests: It occurs in almost all the reserved forest blocks in the park except Ludhauli. Salai is generally found to occur on the higher plateau and slopes on the warmer aspects and on hilltops. It occurs in soils with poor moisture conditions and hard shallow soils. Salai is generally found associated with Dhaora while its other associates are Jhingan, Tendu, Khair, Saja, etc.

Khair forests: It occupies open areas along the foothills of the park. The forests are almost pure with open patches. The quality is generally poor. The main Khair areas are in compartment nos. N/52, N/70, N/42 and N/44. Main associated forests are of Dhaora, Kardhai and Tendu.

Mixed forest: These are limited in the original park area, but are widely distributed in the extension area. These forest occurs on flat, relatively good well drained soils. The species composition includes Bahera, Chichwa, Kasai, Jamun, Mitragyna, Ficus, safed Siris, Kusum, etc.

2.2 Data and Methods

The present study has made an attempt to estimate NPP of tropical deciduous forests and to determine its relation with regional meteorological parameters in KNP, BNP and MNP for the period 2010-2014. A gist of overall methodology followed in this anlsysis is depicted in the flow chart (**Figure 7**). In general, the methodology can be grouped in two parts, first part covers extensive ground data collection and the second one focuses on the remote sensing parameters and meteorological data. Geographic Information System (GIS) and statistical tools were employed to integrate both the parts to achive research objectives of the present study.

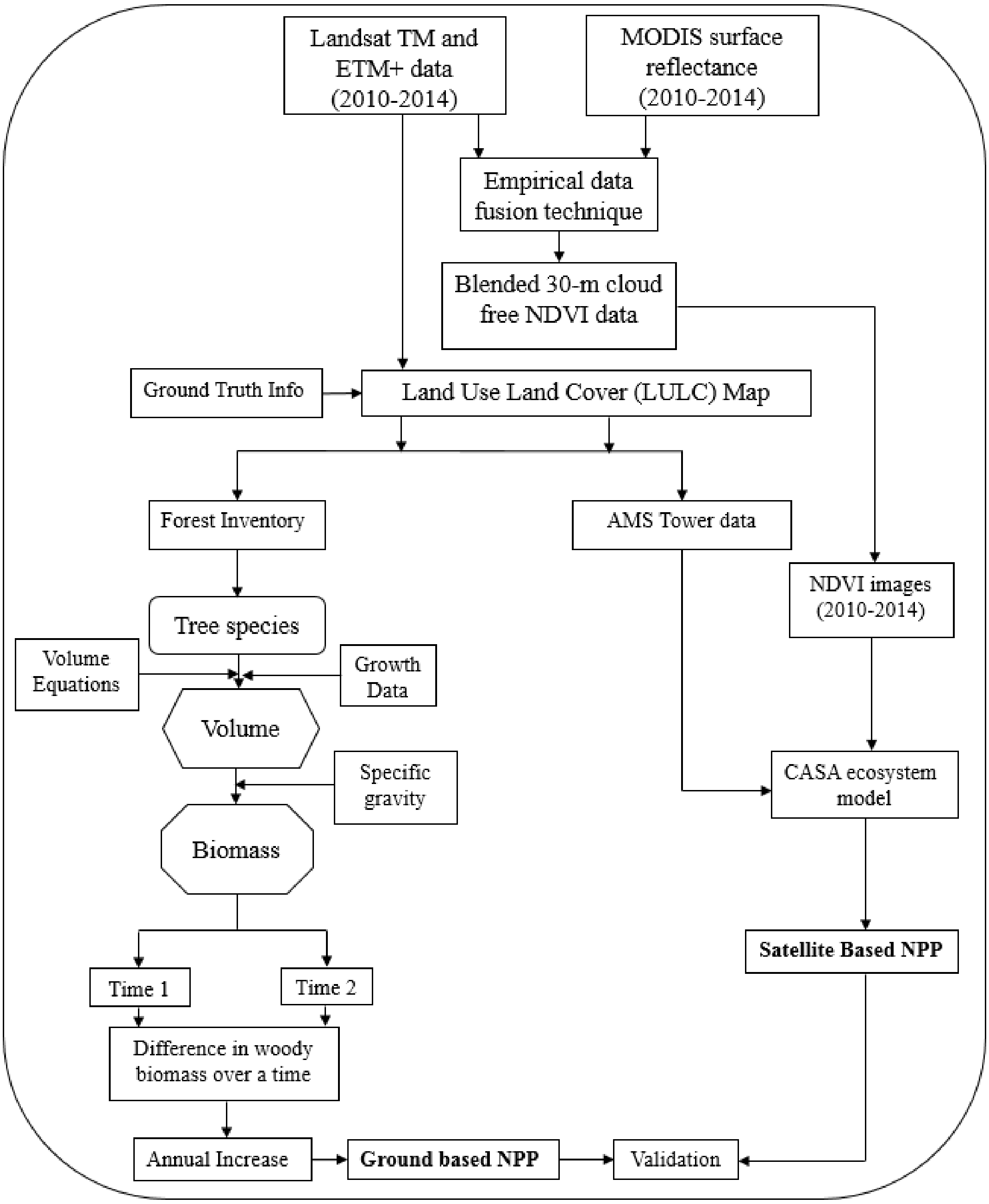

Figure 7: Methodology followed in the present study.

2.2.1 Field inventory

The sampling techniques to be adopted in forest invenroty varies with the study objectives, forest type, stand density and topography. A sampling plan basically entails determining the size of the sampling units across the study area and statistical procedure to be employed for analysing the data. In the present study, sample plots of size 0.1 ha were laid out in KNP, BNP and MNP based on standard procedure suggested by working plan wing of M.P, Forest Department (MPFD). The same size of sampling unit is being followed by Forest Survey of India (FSI, 2010, 2013), State Forest Departments (Tripathi et al., n.d.) and in several national projects like National Vegetation Carbon Pool Assessment project, ISRO Geosphere Biosphere project (Devagiri et al., 2013). Further, 0.1 ha sample size is justified from the fact that pixel size of Landsat sensor is 30 m which can be up-scaled to 31.61 m for better analysis. The size and shape of the sample plots were as shown in **Figure 8**. Stratified random sampling technique was adopted to lay the sample plots on the ground. For the purpose of this study about 10 plots of 0.1 ha each were laid out across different forest types in KNP and BNP, and MNP.

Forest invenory work was carried out at every three month duration from 2010 to 2014. Botanical name and local name of all the tree species lying within the sampling plots were noted. Trees standing in the sample plot and having GBH more than 10 cm were numbered and band mark was put at breast height (1.37m). Species wise height and DBH of all standing trees was recorded using electroninc clinometer and vernier callipers (**Figure 10a-b**). Height of only those trees which were standing in North-West quadrant of the plots were recorded. The trees standing on North–West and South–West boundaries of the plots were taken into consideration for enumeration and growth measurement while the trees standing on North-East and South-East boundaries were not taken into account. The condition (sound, half sound, unsound) of the trees was also recorded. The global position of each sample plot was recorded in terms of latitude and longitude. Location of sample plots laid out in KNP, BNP and MNP are depicted in **Figure 9a-c**. and their geographical location are presented in **Table 1-3**.

Aboveground biomass calculation: A non-destructive allometric equation approach (Eq. 1) was adopted in this study for estimating aboveground biomass, which requires tree measurements (height and DBH), volume equations and species specific gravity of each tree. Diameter at breast height (DBH) was calculated by dividing GBH values with 3.14 (value of π).

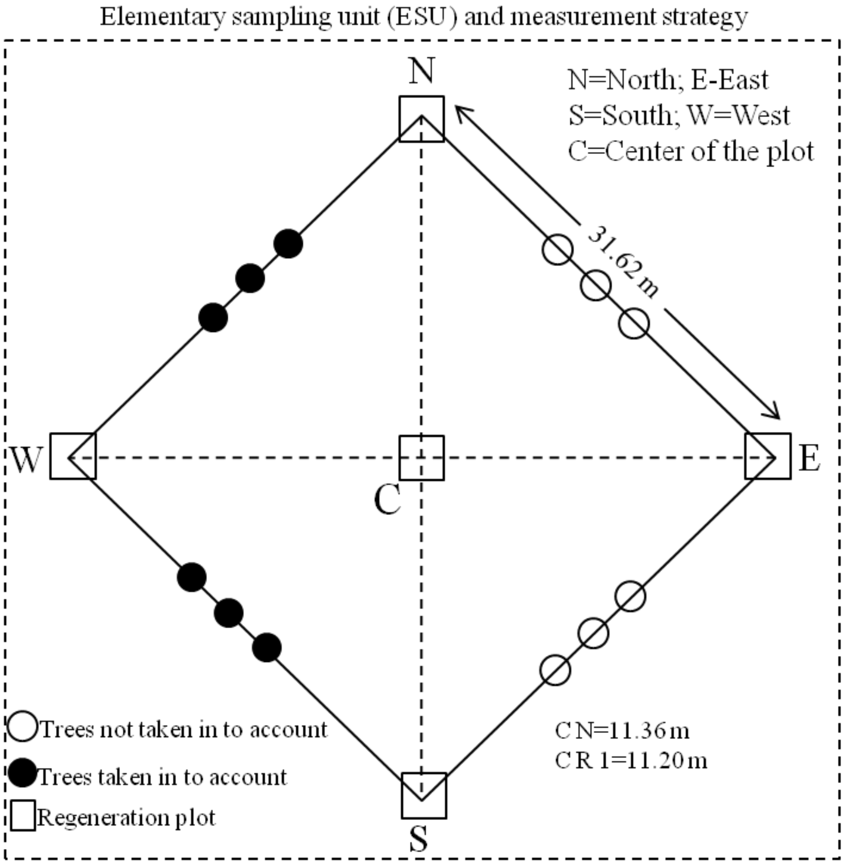

Figure 8: *An elementary sample unit is delineated as a 31.62mx31.62m.*

Tree volume was calculated by using the site or region specific (phytogeographic/physiographic) volume equations, which were procured from the Forest Survey of India. (1996). Generic volume equation of same region was used for trees whose volume equations were not available. Species volume equation of recorded tree species are summarized in **Appendix 16**.

Aboveground biomass (Mg ha^{-1}) = Volume of tree x species specific gravity (1)

The volume equations provided in FSI. (1996) calculates tree volume based on tree height and tree diameter at breast height (DBH). Volume of each tree obtained from the equation was multiplied with species specific gravity (wood density, g cm^{-3}) to ascertain biomss of each tree. Species specific garvity was obtained from Indian Woods, volume (I-VI); this book lists the specific gravity of tree species (organised family wise) based on the area and eco-climatic zone (**Appendix 17**). The biomass values of all the trees lying in the sample plots were summed up to achive the total plot wise biomass. After calculating the AGB (kg/0.1ha), the total biomass was calculated in megagrams per hectare (Mg ha^{-1}), and this valus was extrapolated to the hectare, as follows:

$$AGB = \left(\sum AU/1000\right) \times (10/\text{plot area}), \qquad (2)$$

where AGB = Aboveground tree biomass (Mg ha^{-1}); $\sum$AU = Sum of the tree biomass of all trees in the plot (kg /plot area); Factor 1000 = Conversion of sample units of kg to Mg; Factor 10= Conversion of the area (0.1ha) to hectare.

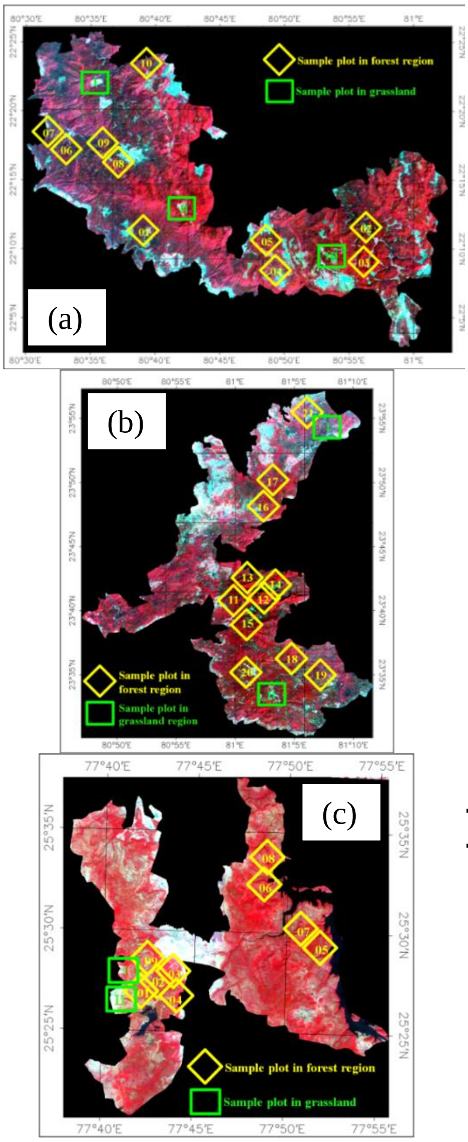

Table 1: *Geographical locations of the forest biomass sample plots (yellow box) in KNP.*

P.No	Range	Latitude	Longitude
1	Mukki	22^{0} 11' 30.8"	80^{0} 39' 12.4"
2	Supkhar	22^{0} 10' 31.2"	80^{0} 56' 23.8"
3	Supkhar	22^{0} 09' 32.8"	80^{0} 56' 23"
4	Bhaisanghat	22^{0} 09' 00.1"	80^{0} 49' 21.3"
5	Bhaisanghat	22^{0} 11' 02.7"	80^{0} 48' 46.9"
6	Kisli	22^{0} 17' 41.5"	80^{0} 32' 43.2"
7	Kisli	22^{0} 18' 51.1"	80^{0} 31' 37.4"
8	Kanha	22^{0} 16' 46.5"	80^{0} 36' 58"
9	Kanha	22^{0} 17' 38.4"	80^{0} 36 ' 24.6"
10	Sarhi	22^{0} 23' 30.8"	80^{0} 39' 09.6"

Table 2: *Geographical locations of the forest biomass sample plots (yellow box) in BNP.*

P.No*	Range	Latitude	Longitude
1	Tala-I	23^{0}40′58.3″	81^{0}02′11.7″
2	Tala-II	23^{0}41′06.1″	81^{0}02′28.3″
3	Tala-III	23^{0}41′31.6″	81^{0}02′16.7″
4	Tala-IV	23^{0}41′55.2″	81^{0}02′43.9″
5	Tala-V	23^{0}39′37.6″	81^{0}01′44.0″
6	Patur	23^{0}48′49.3″	81^{0}02′30.5″
7	Pathure	23^{0}49′11.0″	81^{0}02′34.9″
8	Kallwa	23^{0}36′32.3″	81^{0}04′56.8″
9	Kalwaha	23^{0}34′51.3″	81^{0}07′0.5″
10	Magdhi	23^{0}35′24.5″	81^{0}01′9.6″

Table 3: *Geographical locations of the forest biomass sample plots (yellow box) in MNP.*

P.No	Range	Latitude	Longitude
1	South Range (Ammakunj Beet)	25^{0} 26' 54.6"	77^{0} 42' 20.0"
2	South Range (Ammakunj Beet)	25^{0} 27' 00.2"	77^{0} 42' 50.0"
3	South Range (Ammakunj Beet)	25^{0} 27' 26.9"	77^{0} 43' 07.8"
4	South Range (Ammakunj Beet)	25^{0} 26' 46.0"	77^{0} 44' 17.5"
5	East Range (Babanaua Beat)	25^{0} 29' 13.0"	77^{0} 52' 00.3"
6	Central Range (Dhamkan Beat)	25^{0} 32' 22.5"	77^{0} 48' 45.0"
7	Central Range (Dhamkan Beat)	25^{0} 32' 17"	77^{0} 49' 09.1"
8	Central Range (Eravan Beat)	25^{0} 33' 46.4"	77^{0} 49' 10.2"
9	Norht Range (Bhurakha)	25^{0} 28' 51.3"	77^{0} 42' 31.2"
10	South Range (Kota beat)	25^{0} 00' 00"	77^{0} 54' 2.5"

Figure 9: *Sample plots and their geographic locations in a) Kanha National Park, b) Bandhavgadh National Park, and c) Madhav National Park.*

Figure 10: *(a) Tree girth at breast height (GBH) being measured using Vernier callipers and (b) tree height being measured using electronic clinometer at one of the sample plots in KNP.*

Net Primary Productivity Estimation: Schematic overview of the procedure for estimating deciduous forest NPP using field measurements is shown in **Figure 7**. Aboveground biomass for each plot computed for the period 2010-2014 using ground based apparoch and the net increment/decrement in biomass (biomass value in 2010 was substracted from biomass estimated for the subsequent years i.e 2011, 2012, 2013 and 2014) was noted for each plot for a given area and time (Eq.3). The unit for NPP is (Mg ha^{-1} $year^{-1}$).

$$NPP = \Delta y/\Delta t \quad (3)$$

Δy is annual increment in aboveground biomass between tree measurements carried out in 2010 and subsequent years. Δt is time difference between initial biomass measurement (2010) and biomass measurement carried out in subsequent years. Thus unit of the NPP obtained from this equation is Mg ha^{-1} $year^{-1}$.

2.2.2 Meteorological Station data

Space Applications Centre had recently established a network of INSAT-linked Agro-Met Station (AMS) and Automated Weather Station (AWS) located in different land use categories in the country (Vyas et al., 2016; Kumar et al., 2014; Bhattacharya., 2009). Primary objective of this network is to model the radiative and convective fluxes and water exchange behaviour of different vegetative systems using *in-situ* measurements, satellite observations and simulation models. The AMS towers are usually 10 m tall and it had sensors capable of measuring radiation, energy and soil water balance components continuously at half-an-hour interval (**Table 4**). Whereas, AWSs are about 3m tall and record the automated measurements of air temperature, wind speed, relative humidity, and sunshine hours at single height at half-an-hour interval. A prototype model of AMS and AWS defined and designed for natural vegetation are depicted in **Figure 11**. The observations recorded by AMS and AWS are transmitted through Yagi antenna to INSAT 3A Data-Relay Transponders (DRT) which then retransmit to Bopal Earth Station (BES) at Ahmedabad, India. The data are available in user friendly format at MOSDAC site (http://www.mosdac.gov.in/).

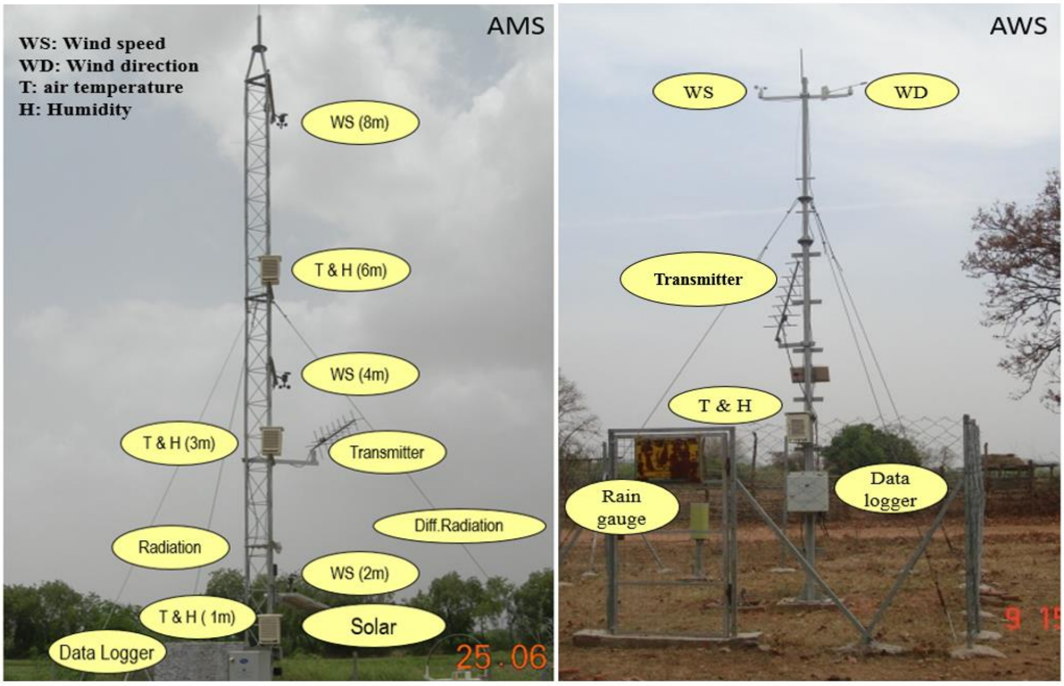

Figure 11: *Agro-Meteorological Station (AMS) and Automatic Weather Station (AWS) with different instruments mounted at different heights.*

The AMS network included about 24 stations, out of which 10 stations are deployed in natural ecosystems across the country. Due to large forest area and high species diversity at deciduous forests in KNP, BNP and MNP, one AMS and one AWS station in each park was installed during the year 2010-11. AMS stations those installed at KNP and BNP recorded all the weather parameters until Dec. 2011. Due to some technical issues, pyranometers in both the stations were stopped recording incoming solar radiation after Dec. 2011. In case of AMS in MNP, all the weather parameters were recorded until Oct. 2010. In the first week of Nov. 2010, all the instruments mounted on the AMS were stolen/damaged by miscreants. However, any of the weather parameters were not recorded at AMS in MNP after Oct. 2010. The AWS located in KNP, BNP and MNP recorded air temperature, wind speed, relative humidity, and sunshine hours regularly for the entire study period. Solar radiation, temperature and rainfall are the key input parameters in Carnegie Ames Stanford Approach (CASA) biosphere model. The experiment was initially designed to estimate deciduous forests NPP in KNP, BNP and MNP using AMS observations. Due to poor management and technical issues, we could not get radiation data from AMS in KNP and BNP and any of the observations from AMS in MNP. In order to overcome this problem, following approach was used to estimate and validate solar radiation from air temperature using various statistical tools.

Estimation of insolation: Several studies across the world reported that there is a strong linear relationship between incoming solar radiation and air temperature (Gilani et al., 2011; Bajpai and Singh, 2009; Bristow and Campbell, 1984). Therefore, in the present study an effort was made to develop a relation between incoming solar radiation and air temperature to obtain radiation data for the estimation of NPP. In order to facilitate radiation modelling, only daytime (sunrise to sunset) incoming solar radiation readings were considered. The entire radiation dataset recorded till Dec. 2011 (KNP and BNP) and Oct. 2010 (MNP) was divided into a training set with 75% of the samples; and a test set with the remaining 25% of the samples. The training radiation data set was used to develop model with air temperature (Eq.3) and the test set was used to validate the predicted radiation data. Further air temperature recorded after Dec.2011 in AMS (KNP and BNP) and after Oct.2010 in AWS (MNP) was used to estimate radiation at half-an-hour interval and the same was used in CASA ecosystem

$$y = a * x + b \tag{4}$$

Where y represents modelled radiation (Wm^{-2}) and x represents the air temperature (^{o}C) recorded from the AMS station, a and b are the intercept and slope.

Table 4: *Details of the instruments mounted on the Agro-Meteorological Station (AMS)*

S. No.	Basic observational parameters	Sensor type	Accuracy	Nos.	Heights (m)
1	Air temperature	Fine wire thermocouple	±0.05 ^{0}C range: -20 to 60 ^{0}C	3	1.25, 2.5, 5
2	Actual vapor pressure	Dew point cooled mirror hygrometer	0.1kP	3	1.25, 2.5, 5
3	Wind speed	Anemometer	±2% of FSQ (range : 0.2-60ms^{-1})	3	2, 4, 8
4	Atmospheric pressure	Transducer	±2% of FSQ	1	2
5	Rainfall	Tipping bucket	±1 mm	1	1
6	Net radiation	Four component net radiometer	±5 -10Wm^{-2} (range: 0-1000Wm^{-2})	1	4
7	Diffuse radiation	Shaded pyranometer	±5 -10Wm^{-2} (range: 0-1000Wm^{-2})		4
8	Ground heat flux	a) Heat flux plate b) Soil thermometer	±3% of FSQ ±0.1 ^{0}C	2 3	- 0.1, - 0.2 -0.05, -0.1, -0.2
9	Soil moisture	TDR	± 5% FSQ, range 0- 0.45cm^3 cm^{-3}	3	-0.05, -0.1, -0.2

model to estimate NPP and to determine its relation with different weather parameters in the study regions during the period 2010-2014. A commonly used statistical approach (RMSE) to test for an agreement between the estimated radiation dataset (e) and the station data (s). According to Quansah et al. (2014), Khalil and Shaffie. (2013), the Root Mean Square Error (RMSE) is given in Eq. 5:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(G_e - G_s)^2} \quad (5)$$

where G_e and G_s are the estimated and station radiation values (measured) respectively (W m^{-2}), for n number of observations. The value of RMSE is always positive, representing zero in the ideal case. The smaller the value, the better is the model's performance (Khalil and Shaffie, 2013).

2.2.3 Satellite data and fusion

The National Aeronautics and Space Administration (NASA) has launched multiple satellites in to the orbit to address diverse issues. One of the primary objectives of those missions was to support remote sensing data for land and water resources management with improved spectral and spatial coverage. This data also supports many scientific and operational projects in diversified fields of applications. Time series data from two NASA's major missions'(Landsat and MODIS) was used in this study for modelling NPP over tropical deciduous forest in Central India from 2010-2014. Details of the satellite data used in this analysis are given below.

Landsat TM and ETM+ data: Landsat is a joint effort of the U.S. Geological Survey (USGS) and the National Aeronautics and Space Administration (NASA). Since 1972, Landsat satellites have continuously acquired spacebased images of the Earth's land surface. Landsat TM and ETM+ data were acquired in this study from January 2010 to December 2014. All data sets had high data quality and were cloud free (<10%). The Landsat TM and ETM+ sensors onboard the Landsat 5 and 7 platform have a spatial resolution of 30 m and a spatial extent of 183×170 km per with a 16-day revisit, which are well suited for high spatial resolution forest cover mapping and deciduous forest NPP estimation in this study. Major obstacle of using Landsat data over the present study regions was the availability of cloud-free scenes in monsoon months (June-

September), which was crucial growth period for deciduous forests in the study regions (Parihar et al., 2013; Kale and Roy, 2012). Generally, deciduous forests in India attains their annual peak NPP in September (Goroshi et al., 2014; Nayak et al., 2010). Therefore it was very necessary to include those data sets in the time series to estimate annual NPP accurately. Another important issue with Landsat data is that ETM+ land scenes are globally on average about 35% cloud covered (Ju and Roy, 2008), and failure of the scan line corrector (SLC) in May 2003, reducing the usable data in each SLC-off scene by about 22% (Maxwell et al., 2007; Scaramuzza and Barsi, 2005).

MODIS09 Surface reflectance: Another important data sets from NASA (Surface reflectance, MOD09Q1-V006) was acquired for the same period of 2010 to 2014. The data was download from the Earthdata Search data gateway distributed archive (https://search.earthdata.nasa.gov/). Moderate Resolution Imaging Spectroradiometer (MODIS) sensor onboard NASA’s Terra and Aqua satellites provides similar spectral information as Landsat, but with more frequent 8-day composite global observations of surface conditions at 250m spatial resolution. Besides that, both the systems are in the same polar orbit, with Landsat ETM+ observations occurring about 15 min before MODIS Terra nadir observations. Bands 1-6 of Landsat TM and ETM+ and bands 1-7 of MODIS images were designed primarily for remote sensing of land surface. Surface reflectance values from the red and the near-infrared (NIR) bands were used to compute NDVI. To match the bandwidths with the MODIS sensor, a comparison of bandwidth between the Landsat TM and ETM+ sensor and the MODIS sensor is shown below in **Table 5**.

Table 5: *Landsat TM, ETM+ and MODIS bandwidth*

Landsat TM and ETM+ band	TM and ETM+ Bandwidth (nm)	MODIS Band	MODIS Bandwidth (nm)
1	450-520	3	459-479
2	530-610	4	545-565
3	630-690	1	620-670
4	780-900	2	841-876
5	1550-1750	6	1648-1652
6	2090 - 2350	7	2105 - 2155

Landsat and MODS data fusion: Satellite data driven Carnegie-Ames-Stanford Approach (CASA) ecosystem model simulates annual NPP based on continuous satellite measurements. Landsat had lack of quality data in monsoon months due to extensive cloud cover. Therefore to address this issue of data unviability of Landsat TM and ETM+ in the monsoon months, the present study had adopted empirical relation (Landast NDVI=0.87*MODIS NDVI-0.03, R^2=0.87; Bindhu et al., 2013) based data fusion approach for blending 30-m Landsat 5 and Landsat 7 NDVI with 250m eight day MODIS NDVI observations. An empirical fusion technique (spatial and temporal adaptive reflectance fusion model or STARFM) for combining 30 m Landsat ETM+ data with daily 500 m MODIS reflectance data was developed by earlier researchers (Yang et al., 2015; and Gao et al., 2006) to address the issue of unavailability of quality data for time series analysis. He et al. (2018) used combined data set for estimating Gross Primary Productivity (GPP) and yield in United States. For the period of January 2014 to December 2014, 30m Landsat and 250m MODIS NDVI (8 days interval) were used for data fusion to produce harmonized 30m NDVI data record for all the study areas. Later this time series 30-m NDVI data set was used in CASA model as a primary input to estimate NPP at 30-m resolution and monthly interval for the different deciduous forest types in KNP, BNP and MNP.

Atmospheric correction: Atmospheric correction is a prerequisite to most optical sensor data analysis. Several empirical and model-based atmospheric correction methods are available to compensate for the atmospheric effects of each channel in optical satellite imageries. Fast Line-of-sight Atmospheric Analysis of Spectral Hyper cubes (FLAASH) based on MODTRAN4 radiative transfer model (Felde et al., 2003) is one of the extensively used atmospheric correction methods at present. It is basically designed to eliminate atmospheric effects caused by molecular and particulate scattering and absorption from the radiance at the sensor and to obtain reflectance at the surface. It provides significantly accurate, physics-based derivation of apparent surface reflectance through derivation of atmospheric properties such as surface albedo, surface altitude, water vapour column, aerosol and cloud optical depths, surface and atmospheric temperatures from HSI data. In this study, atmospheric correction was performed to the multi-date Landsat TM and ETM+ scenes using inbuilt FLAASH module available with ENVI image processing software v5.5. The model key input parameters like scene sensor type and altitude, satellite overpass time, ground elevation, pixel size etc. were obtained from the metadata file available with the satellite data. Secondary data information like, near real time atmospheric characteristics such as aerosol optical thickness at 550nm, columnar water vapour content (g cm^{-2}) were acquired from the MODIS, whereas total ozone content (Dobson unit) was obtained from Total Ozone Monitoring Spectrometer (TOMS). After obtaining the required parameter, the true surface reflectance of the whole image was calculated pixel by pixel using the Eq. 6 and Eq. 7.

$$L' = \left(\frac{A\rho}{1-\rho_{\varepsilon}S}\right) + \left(\frac{B\rho_{\varepsilon}}{1-\rho_{\varepsilon}S}\right) + L'_a \tag{6}$$

$$L_e \approx \left(\frac{(A+B)\rho_e}{1-\rho_e S}\right) + L_a \tag{7}$$

where, L': radiance for the single pixel received by the sensor (μw cm^{-2} nm^{-1} sr^{-1})

ρ: surface reflectance for the pixel

ρ_e: average surface reflectance for this pixel and surrounding pixel

S: spherical albedo for the atmosphere

L'_a: radiance when atmosphere radiation enters into the sensor

A, B: coefficient determined by the atmospheric conditions and the geometric conditions of underlying surface with nothing to do with surface albedo

L_e: spatial average radiation image generated by convolution with the radiation image and spatial weighting function

Forest type map: In this analysis most widely used unsupervised method of classification was performed on multi date LANDSAT images acquired at three key phenological stages of deciduous forest such as onset of greenness, full growth phase and leafless phase. In unsupervised classification method, computer searches for natural groupings of similar pixels called clusters (Jensen, 1996). There are numerous clustering algorithms that can be used to perform unsupervised classification mainly: a) ISODATA clustering (Iterative Self–Organizing Data Analysis Technique) b) K-Mean clustering and c) Maximum minimum classifier. In this study, ISODATA clustering approach was adopted for carrying out the forest classification. ISODATA is considered to be one of best approaches and is based on the minimum of a performance index, which is the squared distance from all points in a cluster domain to the cluster center. For this algorithm, the analyst assigns the number of clusters desired and a confidence threshold as well. The computer will then build clusters iteratively. Thus with each new iteration the clusters become more and more refined. The iterations stop when the confidence level (or a maximum number of iterations specified by the user) is reached (Jensen, 1996). In the following study, 80 clusters were initially assigned in order to obtain landuse/landcover (LULC) classes to fully utilize the spectral variability. Maximum numbers of iterations were set at 10 to reach up to 95% confidence level. After the classification was over, total numbers of 80 clusters were clubbed, resulting into eight number of LULC. Subsequently, masking out all the classified LULC classes and for the better illustration of the classified output, desired colour scheme along with the attributes were assigned to generate resultant output i.e. LULC map, obtained from the unsupervised classification. Steps followed in generating forest type map for KNP, BNP and MNP is depicted in **Figure 12**.

Accuracy Assessment of the classified forest map: Accuracy assessments determine the quality of the information derived from remotely sensed data. In this study accuracy assessment of LULC generated for KNP, BNP and MNP was performed using ERDAS IMAGINE 9.1. Total 100 random points in each study region were taken for performing accuracy assessment. Direct field observation was used to determine the true land use land cover classes represented by each random pixel. Kappa statistics of the classification was performed to achieve the measure of agreement or accuracy between the classified map and the reference data. The Kappa statistic ranges from 0 to 1. A value close to 1 indicates a high agreement between the two datasets (Congalton and Green, 2008).

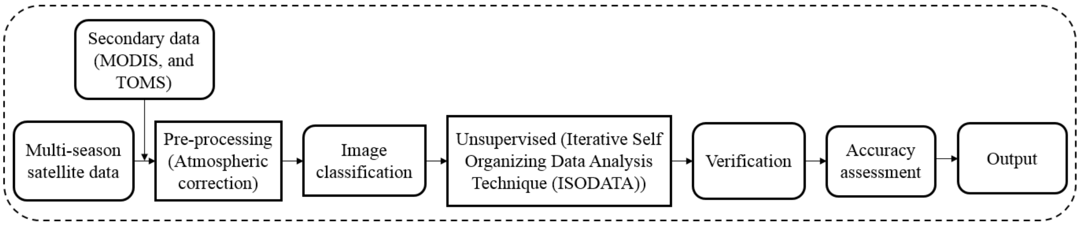

Figure 12: *Steps followed in satellite data based forest type classification.*

Modelling NPP: Satellite data driven Carnegie-Ames-Stanford Approach (CASA) ecosystem model was used in this analysis to derive NPP of deciduous forests in KNP, BNP and MNP for the period 2011-2014. This model simulates NPP on a monthly time scale as a product of Absorbed Photosynthetically Active Radiation (APAR) and maximum LUE, which is corrected for spatio-temporally varying stress constraints resulting from the temperature and water. All the following equations (8-19) were used to derive deciduous forest NPP in the study regions. The CASA model can be expressed as (eq. 8).

$$NPP(x, t) = APAR(x, t) \times \varepsilon(x, t) \quad (8)$$

Where NPP (x ,t) is Net Primary Productivity (NPP) at a location (x) and time (t) (gC m^{-2} $month^{-1}$), APAR (x,t) is Absorbed Photosynthetically Active Radiation at a location (x) and time (t) (MJ m^{-2} $month^{-1}$) and Ɛ(x, t) is Light Use Efficiency (LUE) (gC $(MJ)^{-1}$) of the vegetation.

Absorbed Photosynthetically Active Radiation (APAR): It can be estimated by employing Eq. (9) by (Yun and Hua, 2001) as a product of fraction of PAR by the green vegetation (fPAR), incident solar radiation at photosynthetic wavelength (0.38-0.71 µm) S, and a factor 0.5 (F) which corresponds to ratio of incident solar radiation, which can be used by vegetation for their physiological processes.

$$APAR(x, t) = F \times fPAR(x, t) \times S(x, t) \quad (9)$$

In remote sensing analysis, fPAR is generally derived as a linear function of NDVI (Sellers, 1985; Huemmrich and Goward, 1992; Potter et al., 1993; Ruimy., 1994). fPAR can be derived using NDVI as eq. 10

$$fPAR_{NDVI}(x, t) = \frac{[(NDVI)(x, t) - (NDVI)_{i,min}] \times (fPAR_{max} - fPAR_{min})}{NDVI_{i,max} - NDVI_{i,min}} + fPAR_{min} \quad (10)$$

$NDVI_{i,max}$, $NDVI_{i,min}$, $fPAR_{i,max}$, $fPAR_{i,min}$, correspond respectively to the 98^{th} and 5^{th} percentile of the NDVI, and fPAR data population for type *i* vegetation (Sellers et al., 1996). The value of 98^{th} percentile from NDVI is assumed to represent vegetation at full cover and maximum photosynthetic activity with fPAR obtained at 98^{th} percentile close to unity, while the 5^{th} percentile value is assumed to represent no photosynthetic activity with an fPAR computed at 5^{th} percentile close to agreement. Values of $NDVI_{i,max}$, $NDVI_{i,min}$, $fPAR_{i,max}$ and $fPAR_{i,min}$ for deciduous forest was obtained in this analysis by Goroshi et al. (2014).

Light Use Efficiency (LUE): Light use efficiency varies widely with different vegetation (Field et al., 1995; Ruimy et al., 1994; Prince and Goward, 1995) due to their maintenance respiration costs and suboptimal climatic conditions. Algorithm for LUE can be expressed as Eq. (11):

$$\varepsilon(x,t) = W\varepsilon(x,t) \times T\varepsilon_1(x,t) \times T\varepsilon_2(x,t) \times \varepsilon_{max} \tag{11}$$

where, ε (x, t) is light use efficiency, W_ε(x, t) is moisture stress coefficient, $T_{\varepsilon 1}$(x, t) x$T_{\varepsilon 2}$(x, t) are temperature stress coefficients and ε_{max} is maximum light use efficiency of vegetation in optimal condition. In this analysis ε_{max} term was set to a constant 0.461 gC MJ^{-1} PAR, this value was determined by using predicted annual NPP and observed NPP (Yu et al., 2009). Previous studies over deciduous forests in India have found this value produce reasonably accurate NPP for deciduous forest when initializing CASA model with satellite derived vegetation indices (Goroshi et al., 2014).

Moisture stress coefficient: Moisture stress coefficient is an indicator used to signify reduction in maximum LUE owing to soil moisture stress. This can be determined at a varying spatio-temporal scale by evaporative efficiency (Yun and Hua, 2001) approach, Eq. (12). The coefficient ranges from 0.5 to 1, low values indicate regions in which ET rates are extremely water-limited (dry regions) whereas, high values indicate regions in which ET rates are very high (wet regions).

$$W\varepsilon(x,t) = 0.5 + 0.5 \times [ET(x,t)/PET(x,t)] \tag{12}$$

where, ET (x, t) is the estimated actual evapotranspiration and PET (x, t) is the potential evapotranspiration. When accumulated monthly precipitation (P) is greater than monthly PET (x, t), then ET(x,t)= PET (x, t) and W_ε(x, t) =1, whereas when P is less than or equal to PET (x, t), then ET (x, t)/PET (x, t) is characterized as regional moisture index to indicate soil moisture status, at this circumstances ET (x, t) can be determined by employing regional evapotranspiration model (Zhou and Zhang, 1995) shown in Eq. (13):

$$ET(x,t) = \{PET \times Rn(x,t) \times [PET^2 + (Rn(x,t))^2 + PET \times Rn(x,t)]\} / \{[PET + Rn(x,t)] \times [PET^2 + Rn(x,t)^2]\} \tag{13}$$

where, Rn (x,t) is net solar radiation (MJ m^{-2} $month^{-1}$), PET (x, t) can be estimated using Eq. (14) (Thornthwaite, 1948; Zhou and Zhang, 1995);

$$\text{PET}(x, t) = [\text{ET}(x, t) + \text{ET}_0(x, t)]/2 \quad (14)$$

where, ET_0 (x, t) is monthly potential evapotranspiration (mm month^{-1}) and this can be computed using Thornthwaite water balance method as Eq. (15)

$$\text{ET}_0(x, t) = 16 \times [10 \times T(x, t)/I(x)]^{\alpha(x)}. \quad (15)$$

where, T is mean monthly (t) temperature (°C) of location (x), I is a heat index for a given location (x) which is the sum of 12 monthly index values i. i is derived from mean monthly temperatures using the following Eq. (16)

$$I(x) = \sum_{i=1}^{12} [T(x, t)/5]^{1.514} \quad (16)$$

where, α (x) is an empirically derived exponent, which is a function of I and it can be derived as Eq. (17)

$$\alpha(x) = (0.675I^3 - 771I^2 + 17920I + 492390) \times 10^{-6} \quad (17)$$

where, sum heat index in a year for a location x, this condition is applicable only when the air temperature for the location ranges between 0°C and 26.5°C. T(x, t) is the air temperature. When the air temperature reaches below 0°C, (Thornthwaite, 1948) set P (x, t) to zero, whereas when it goes above 26.5°C, P(x, t) increases with temperature and thus is not affected by the value of I(x).

Temperature stress coefficient: Temperature significantly affects light use efficiency when it reaches at extreme low and high, it can be determined by Eq. (18) (Potter et al., 1993):

$$T1(x, t) = 0.8 + 0.02\text{Topt}(x) - 0.0005(\text{Topt}(x))^2 \quad (18)$$

where, T1 (x, t) is the stress coefficient resulting from an extreme low and high temperature. Temperature also affects LUE when it changes from optimal condition; the algorithm of the coefficient can be expressed by Eq. (19) (Potter et al., 1993):

$$T2(x, t) = 1.1814 / \{1 + e^{\{0.2(\text{Topt}(x) - 10 - T(x,t))\}}\} / \{1 + e^{\{0.3(-\text{Topt}(x) - 10 + T(x,t))\}}\} \quad (19)$$

where, T_{opt} is air temperature in the month when the NDVI attains its maximum for the year. T2 (x, t) is decreasing trend of LUE of vegetation when environmental conditions changes from the optimal temperature.

Validation of CASA simulated NPP: Deciduous forests NPP simulated from the CASA ecosystem model was validated using field based NPP obtained from 10 sample plots in KNP, BNP, and MNP for the period 2011-2014. Coefficient of determination (R^2), and root mean square error (RMSE) were used to validate CASA simulated NPP from the measured NPP.

2.2.4 Influence of Climate on NPP

One more important objectives of the study was to understand how deciduous forest NPP in KNP, BNP and MNP was influenced by different weather parameters (rainfall, temperature and radiation) during the study period 2010-2014. To achieve this objective, different weather parameters recorded at AMS and AWS stations in the study regions was processed and computed mean annual temperature, solar radiation and cumulated annual rainfall for the study period. Relationship between NPP and weather parameters was determined using simple linear relationship between NPP obtained from all the sample plots and different weather parameters recorded at AMS and AWS stations at KNP, BNP and MNP. One-way ANOVA was employed to assess significance of relation between both the datasets.

2.2.5 Statistical analysis

One-way ANOVA had been performed to check whether the differences seen in the measured parameters (stand density, DBH, AGB, NPP, weather parameters) across the sample plots and study regions are significant or not. Simple linear regression was performed to develop a radiation model from radiation and temperature data recorded at AMS towers. Root Mean Square Error and Pearson's Correlation Coefficient were used to test an agreement between modelled radiation and station measured radiation data. An empirical relation based data fusion approach was used for blending 30-m Landsat TM and ETM+ NDVI with 250m eight day MODIS NDVI observations. Coefficient of determination (R^2), and root mean square error was employed to validate CASA simulated NPP from field measurements based NPP. Linear regression analysis was performed between CASA NPP and different weather parameters (rainfall, radiation and temperature) recorded at AMS towers to understand influence of weather parameters on variability of NPP in KNP, BNP and MNP.