

CHAPETER-IV

DISCUSSION

4.1 Kanha National Park

4.1.1 Forest biophysical parameters

Tree species: A total number of 54 tree species were recorded from ten moist deciduous sample plots (0.1 ha) in Kanha National Park (KNP). The number of species recorded in the present study were comparable to the total number of species of other tropical forests such as that reported (26-56spp.) for semi-evergreen forests in Kollihills (Chittibabu and Parthasarathy, 2000), 33-50spp. at Shervarayan hills (Kadavul and Parthasarathy, 1999), 57spp. ha⁻¹ in Mylodai and Courtallam reserve forest (Parthasarathy and Karthikeyan, 1997), 16-54 spp. at tropical wet evergreen forest in Arunachal Pradesh, Eastern Himalayas (Bhuyan et al., 2003), 48-74spp. ha⁻¹ at the humid tropical forest in Tamil Nadu (Swamy et al., 2000), 52-79spp ha⁻¹ at tropical evergreen forest in Varagaliar, Anamalis (Ayyappan and Parthasarathy, 1999). The number of species recorded in this study were higher than those reported (14-23spp. ha⁻¹) for three sacred groves in Kerala (Chandrashekara and Sankar, 1998), 38spp. ha⁻¹ Thirumanikuzhi sacred grove (Parthasarathy and Karthikeyan, 1997). The number was also higher than those reported for various sites in the Western Ghats ranging from 30spp. ha⁻¹ at Nelliampathy (Chandrashekara and Ramakrishnan, 1994) to 3-20spp. in Corbett National Park (Singh et al., 1995). The total number of tree species recorded in the current study was much lowered when compared to those reported (129spp. ha⁻¹) for deciduous forest at the Eastern Ghats in Andhra Pradesh (Naidu and Kumar, 2016), 126spp. ha⁻¹ at deciduous forests in Singhori Wildlife Sanctuary, Madhya Pradesh (Vipin and Madhuri, 2014), 64-82spp. ha⁻¹ at evergreen forest in Kalakad (Parthasarathy, 1999), 90spp. at a 3.82 ha⁻¹ area in Kalakad Mundanthurai Tiger Reserve (Ganesh et al., 1996), 87spp. ha⁻¹ at Sal forest in the Eastern Himalayas (Shankar, 2001), 123spp. ha⁻¹ at Jaintia hills in Meghalaya, North East (Upadhaya et al., 2003), 11-150spp. ha⁻¹ in the Tansa valley (Veach et al., 2003), 132-192spp. ha⁻¹ at sacred grove in Meghalaya, North East India (Mishra et al., 2004), 208spp. ha⁻¹ in the forest of Gorakupur (Pandey and Shukla, 2003). This large difference in the total number of tree species reported across the regions could be due to variation in biogeography, habitat, and disturbance (Neumann and Starlinger, 2001; Padalia et al., 2004). Out of 54 tree species, Sal (*Shorea robusta*) was found to be maximum with the

presence of 381 trees, which was estimated to be 49.64% of the total tree density (767 trees) in KNP. The findings were coherent with the results reported in Atlas Forest Types of India (FSI, 2011) as well as values those reported in Management Plan for Kanha National Park (2007-08 to 2016-17).

Stand Density: Stand density in tropical forest generally varies from 245 to 859 trees ha⁻¹ (Ashton, 1964; Campbell et al., 1992). Stand density in the present study varied between 180-1570 trees ha⁻¹ with an average of 767 trees ha⁻¹. The mean stand density and range measured in this study was within the range of 276 – 905 trees ha⁻¹ reported in the tropics (Reddy et al., 2007; Sundarapandian and Swamy, 2000; Utkarsh et al., 1998), 735 trees ha⁻¹ at deciduous forests in the Eastern Ghats of Southern Andhra Pradesh (Reddy, Babar, et al., 2008), 735 trees ha⁻¹ at deciduous forests in the Niyamgiri hills in the South-Eastern parts of Orissa, India (Dash et al., 2009), 640-986 trees ha⁻¹ in Kalrayan hills of Eastern Ghats (Kadavul and Parthasarathy, 1999), 639–713 trees ha⁻¹ in Central Amazonia (Ferreira and Prance, 1998), and 420-777 trees ha⁻¹ at tropical forest sites in Brazil (Campbell et al., 1992). On the otherhand the mean stand density and range observed in this study was relatively higher than those reported for tropical forests in the Indian subcontinent varies from 298 trees ha⁻¹ at Mudumalai Forest Reserve, India to 689 trees ha⁻¹ at Sinharaja, Sri Lanka (Condit et al., 2000), 649 trees ha⁻¹ in moist deciduous forest ecosystems of North India (Majumdar et al., 2014), 655 trees ha⁻¹ at tropical deciduous forests in the Eastern Ghats (Mahapatra et al., 2013), 266-632 trees ha⁻¹ in Koli Hills of Western Ghats of India (Chittibabu and Parthasarathy, 2000), and 270-673 trees ha⁻¹ in the Anamalais (Ayyappan and Parthasarathy, 1999), 448–617 trees ha⁻¹ at tropical forests in Costa Rica (Heaney and Proctor, 1990). This wide variation in stand density could be due to variation in local climatic condition, soil properties, availability of water sources and anthropogenic disturbances. The stand density as reported in the present study was modest when compared to those reported for other deciduous forest regions in the country. Among 10 sample plots, maximum stand density was found to be with Plot-9 (1570 trees ha⁻¹), whereas minimum stand density was recorded at Plot-8 (180 trees ha⁻¹). Plots those covered short trees with poor girth size had higher stand density; whereas plots those covered tallest trees with larger girth size had poor stand density. These findings were in agreement with other reports (Brokaw et al., 1997; Campbell et al., 1992; Chandrashekara and Ramakrishnan 1994; Hara, 1997; Ho et al., 1987; Kadavul and

Parthasarathy, 1999; Lieberman and Lieberman, 1987; Sahoo et al., 2017; Sundarapandian and Karoor, 2013; Sundarapandian and Swamy, 2000; Swaine et al., 1987).

Tree Height: Tree height at moist deciduous forest in KNP varied significantly among the sample plots from 8.14m (Plot-4) to 25.17m (Plot-6) with an average of 15.76m. Average tree height measured in the present study was consistent with that of an average tree height reported (14.77m) at *Shorea robusta* dominated forest region in Chitwan district, Nepal (Asmare, 2013), 14.5m at tropical rain forest in Royal Belum State Park, Parek, Northern Peninsular Malaysia (Sium, 2015), 17.9m at a multi-tiered mixed deciduous stand in southern Ontario (Hopkinson et al., 2004), 3-19.88m at Kolli forests in Eastern Ghats (Mohanraj et al., 2011), 3.5-26m in mixed/moist evergreen forest of Omo Forest Reserves, Southwest of Nigeria (Dauda et al., 2004), 7.13-28.68m at forests of Kalkkinen, Helsinki, in Southern Finland (Yu et al., 2004), 3-35.5cm at mixed forest in Koli National Park, North Karelia, Eastern Finland (Villikka et al., 2007), 2.1-33.93m at Lama forest reserve, a semi-deciduous forest (Nagel et al., 2004) located in southern Benin (Goussanou et al., 2016), 11-47.5m in forests of the companies Klabin Riocell (Guaíba), Todeschini (Cachoeira do Sul), the Federal University of Santa Maria and Aracruz Company, located in Rio Grande do Sul, Espirito Santo and Bahia, Brazil (Nutto et al., 2006), 3-24.3m at moist deciduous forest in Mae Nam Phachi Wildlife Sanctuary, Baan Beung, Suan Pheung District, Ratchaburi province, Western Thailand (Chaiyo et al., 2011), 3.3-27.9m at mixed deciduous forest in Kratie, Cambodia (Monda et al., 2016), 2.5-23.5m, 3.8-23.5m, and 4.4-14.1m at mixed species, *Dipterocarpus genus* and *Shorea genus*, respectively in two eco-regions of Vietnam (Huy et al., 2016), 13.2m mean tree height reported for dry hill/evergreen forest in Popa Mountain Park, Myanmar (Aye et al., 2014). The tallest trees were observed in Plot-6, whereas shortest trees were observed in Plot-4. Several studies also reported significant variations in tree architectural properties, both within and across sites (Nogueira et al., 2008; Brien et al., 1995; Osunkoya et al., 2007; Poorter, Bongers et al., 2006; Poorter et al., 2003; Sterck and Bongers, 2001). This variations between the plots within the same region may attributed to spatial variability in soil moisture, nutrients, and microclimatic conditions induced due to the topographic variations.

Diameter at Breast Height (DBH): DBH of moist deciduous tree spp. in KNP varied significantly among the sample plots from 12.5cm (Plot-10) to 49cm (Plot-8) with an

average of 23.36cm. Average DBH in the present study was consistent with that of an average DBH reported (25.46cm) at deciduous forest at Nooksack River Basin, Northwestern Washington (Capuana, 2013), 27.77cm at *Shorea robusta* dominated forest region in Chitwan district, Nepal (Asmare, 2013), 22.87cm at tropical rain forest in Royal Belum State Park, Perak, Northern Peninsular Malaysia (Sium, 2015), 17.18cm at deciduous forests in the Piedmont physiographic province of Virginia (Sorin et al., 2004), 25cm at a multi-tiered mixed deciduous stand in southern Ontario (Hopkinson et al., 2004), 7-58.3cm in mixed/moist evergreen forest of Omo Forest Reserves, Southwest of Nigeria (Dauda et al., 2004), 5-53.8m at mixed forest in Koli National Park, North Karelia, Eastern Finland (Villikka et al., 2007), 1.3-67.7cm at Lama forest reserve, a semi-deciduous forest (Nagel et al., 2004) located in southern Benin (Goussanou et al., 2016), 9.1-49.4cm in forests of the companies Klabin Riocell (Guaíba), Todeschini (Cachoeira do Sul), the Federal University of Santa Maria and Aracruz Company, located in Rio Grande do Sul, Espírito Santo and Bahia, Brazil (Nutto et al., 2006), The Dinghushan Biosphere Reserve, a subtropical monsoon evergreen broad-leaved forest, 4.62-67.48cm at moist deciduous forest in Mae Nam Phachi Wildlife Sanctuary, Baan Beung, Suan Pheung District, Ratchaburi province, Western Thailand (Chaiyo et al., 2011), 5.5-57.3cm at mixed deciduous forest in Kratie, Cambodia (Monda et al., 2016), 3.4-48.8cm, 4.9-48.8cm, and 5.6-23cm at mixed species, *Dipterocarpus* genus and *Shorea* genus, respectively in two eco-regions of Vietnam (Huy et al., 2016), 24.03cm mean DBH reported for dry hill/evergreen forest in Popa Mountain Park, Myanmar (Aye et al., 2014). DBH decreased with increase in stand density observed in the present study was in agreement with other reports (Brokaw et al., 1997; Campbell et al., 1992; Chandrashekara and Ramakrishnan, 1994; Hara, 1997; Ho et al., 1987; Kadavul and Parthasarathy, 1999; Lieberman and Lieberman, 1987; Sahoo et al., 2017; Sundarapandian and Karoor, 2013; Sundarapandian and Swamy, 2000; Swaine et al., 1987). DBH growth in tropical trees is usually around 1–10 mm year⁻¹ (Worbes, 1999). In the present study, DBH growth rates varied among the tree species, despite the fact that they were close together in stem size and their habitat was similar. The different tree species exhibited different behaviors under similar conditions. Even for the same species, DBH growth rates vary according to tree age or stem size.

Aboveground biomass (AGB): Average AGB obtained across the study period varied from 189-471 Mg ha⁻¹ with an average of 332 Mg ha⁻¹. The biomass estimates obtained in the present study was well within the range reported for moist deciduous forests in India as well for other countries (Bijalwan, 2010; Brown and Lugo, 1982; Chave et al., 2005; Giri, Hergoualc'h and Verchot, 2011; Kumar et al., 2011; Mani and Parthasarathy 2007; Pande, 2005; Patra et al., 2013). The biomass estimates in the present study were similar to the African average (395.7 Mg ha⁻¹; Lewis et al., 2013), higher than the Amazonian average (288.6 Mg ha⁻¹; Malhi et al., 2006), but lower than the Bornean average (457.1 Mg ha⁻¹; Slik et al., 2010). The values observed in the present study were within the range of biomass reported by Mohanraj et al. (2011), Becknell et al. (2012), Becknell and Powers (2014) and Sahu et al. (2016) and comparable with several reports from the world tropical forests (Bhat and Ravindranath, 2011; Shahid and Joshi, 2015; Berta et al., 2015; Gandhi and Sundarapandian, 2017; Mensah et al., 2016). The values were higher than those reported by Khun et al. (2012), Anup et al. (2013), Borah et al. (2013), Sundarapandian et al. (2013), Pawar et al. (2014), Nagler et al. (2015), Devisscher et al. (2016), Majumdar et al. (2016) and Zaragoza et al. (2016), but lower than Yam and Tripathi (2015). It is known that the biomass is a function of stand density, height, diameter at breast height (DBH), stand age and species composition at any given location. These parameters contribute significantly to the aboveground biomass which differs with site, habitat, forest successional stage, composition of forest, species variability and varying tree density etc. (Joshi and Ghose, 2014). Mehta et al. (2014) revealed that variation in biomass across the region could be attributed to some internal and external factors, such as forest composition, site disturbances, rainfall and geographical location of the forests. Findings in this study clearly suggested that though Plot-2 had relatively less stand density (93 trees/0.1 ha), but the plot hold maximum biomass (average biomass, 471.4 Mg ha⁻¹) among all the plots. This could be due presence of sized trees of *Shorea robusta* with an average height of 19m and mean DBH of 21.6cm. Estimates of biomass for *Shorea robusta* dominated plots (422-471 Mg ha⁻¹) were comparable with earlier studies carried out in similar forest types. (Misra 1970) reported total biomass of 407 Mg ha⁻¹ for *Shorea robusta* forests in Chakia, Varanashi (India). Baishya et al. (2009) have reported 406 Mg ha⁻¹ aboveground biomass for *Shorea robusta* forest at a Nongkhylllem wildlife sanctuary in Meghalaya of North-Eastern India. Tiwari. (1994) has reported 371.08 Mg ha⁻¹ in *Shorea robusta* forest of Rajaji National Park, Dehra Dun, India. Shahid and Joshi

(2015) had reported an average moist deciduous forest biomass of 347.75 Mg ha⁻¹ in Lachchiwala Range, Dehra Dun. Least biomass storage was accounted throughout the study period in Plot-10 with an average biomass of 189.2±12.19 Mg ha⁻¹. Higher stand density with lower girth class was not observed in the plot to contribute to higher biomass, at the same time the number of old tree species with higher DBH was not observed much in this plot. Poor girth increment was also one of the major reasons for holding low biomass in the plot. Poor soil structure and scarcity of sources of ground water availability also key reason to this condition.

Field based NPP: Field based aboveground NPP estimated in the present varied across the plots between 5.65 and 10.08 Mg ha⁻¹ year⁻¹ with an average of 8.2 Mg ha⁻¹ year⁻¹. The NPP estimated in this study were consistent with those reported (6.42–25.39 Mg ha⁻¹ year⁻¹) for tropical forests (Karmacharya and Singh, 1992; Negi et al., 1995), 8.9 Mg ha⁻¹ year⁻¹ at tropical dry forest in Mexico, Chamela lower plot (Clark et al., 2001), 10.2 Mg ha⁻¹ year⁻¹ at tropical deciduous forest in Uttar Pradesh (Singh and Singh, 1991), 14.7 Mg ha⁻¹ year⁻¹ at deciduous forest in Vindhyan highlands of India (Kumar, PhD thesis, 2011), 6-16 Mg ha⁻¹ year⁻¹ global pattern of aboveground NPP at dry tropical forest (Murphy and Lugo, 1986), 10 Mg ha⁻¹ year⁻¹ at Subtropical forest sites in Puerto Rico, Guanica (Clark et al., 2001), 7-10 Mg ha⁻¹ year⁻¹ at Conifer forest in USSR (Rodin and Bazilevich, 1967), 10 Mg ha⁻¹ year⁻¹ for *Gmelina arborea* forest in India (Pacholi, 1997), 10.4 Mg ha⁻¹ year⁻¹ at tropical forest in SE Peru (Girardin et al., 2010), 10.9 Mg ha⁻¹ year⁻¹ for *Camelia japonica* forest in Japan (Tadaki, 1965), 11.4 Mg ha⁻¹ year⁻¹ at tropical moist forest (Golley, 1975), 11 Mg ha⁻¹ year⁻¹ at Pine forest in USA (Whittaker, 1966), 13-20 Mg ha⁻¹ year⁻¹ for Shisham forests (Lodhiyal et al., 2002). On the otherhand, NPP estimated in this study was lower than those reported (19.2 Mg ha⁻¹ year⁻¹) at tropical rain forest in Malaysia (Reichle, 1981), 15.5 Mg ha⁻¹ year⁻¹ at Rianj dominated forest in India (Rana et al., 1989), 16-18.9 Mg ha⁻¹ year⁻¹ (Singh and Singh, 1989), 17.3 Mg ha⁻¹ year⁻¹ at Chir-pine forest in India (Rana et al., 1989), 18.7 Mg ha⁻¹ year⁻¹ for *Cassia siamea* forest in India (Pacholi, 1997). The estimates in the current study was higher than the NPP reported (6.9 Mg ha⁻¹ year⁻¹) for other deciduous forest types such as at tropical dry forest in Mexico (Martinez et al., 1996), 7.3 Mg ha⁻¹ year⁻¹ at tropical dry forest in Mexico, Chamela middle plot (Clark et al., 2001), 6.4 Mg ha⁻¹ year⁻¹ at tropical dry forest in Puerto Rico, Pico del Este (Clark et al., 2001), 7.7 Mg ha⁻¹ year⁻¹ at 24 year old Sissoo plantation (Sharma et al., 1988).

This wide variation in field based NPP may be partly due to variations in climate, especially the length of the growing season when both thermal and moisture conditions were favorable. This could be also attributed to differences in the availability of soil water and nutrients. Chaturvedi et al. (2011) and Kumar, Phd thesis. (2011) had observed a significant effect of soil moisture on growth of tropical deciduous forests at Vindhyan highlands in India. In several other studies also nitrogen availability was shown to be constrain the productivity of tropical forests (Tanner et al., 1998; Vitousek et al., 1986). In the present study, high NPP was observed in Plot-10, which was due to presence of large sized trees with high growth rate (increment in DBH, cm tree⁻¹ year⁻¹) as well as adequate soil moisture and consequently less frequent fires and higher biomass increment. Poor NPP in Plot-7 was probably caused by presence of younger trees with poor height and girth and its increment.

4.1.2 Temperature-based Radiation model

Due to lack of radiation data between 2011 and 2014, a temperature based radiation model was developed in this study using temperature and radiation data recorded at all the Agro-Meteorological Stations (AMS) during 2010. A simple linear regression model was developed between the data sets of temperature and radiation of 2010 using 75% of their total data points recorded. The model showed itself to be a simple, robust and reasonably accurate for estimating daily solar radiation by explaining 87% of radiation variability in the regions (**Figure 13a**). Validation of the modelled radiation with remaining 25% of the observed radiation data showed good agreement with $R^2=0.85$ (**Figure 13b**). Several researchers had also developed temperature based radiation model worldwide for different locations and ecosystems (Dlamini et al., 2017; Gilani et al., 2011; Krishna et al., 2014; J. Liu et al., 2012; Salisu, 2017; Yang and Koike, 2005). Seasonal and inter-annual analysis of modelled radiation showed that the temperature based model's behavior may be influenced by site-specific characteristics. Comparatively high radiation was observed at dry deciduous forests in MNP compared to moist deciduous forests in KNP. It is reported that, apart from forest composition, cloudiness, atmospheric heterogeneities and topography (variability in slope angle and slope orientation) also influence the distribution of temperature and radiation (Dozier, 1980; Dubayah, 1992; Dubayah and Van Katwijk, 1992). Similar inference can be drawn here. These changes have a corresponding influence on the energy-mass balance of the vegetation (Dubayah, 1994). Uncertainty between observed and modelled daily

solar radiation was expressed as RMSE (58 Wm^{-2}), which was 14% of the mean observed radiation. This error may probably be due to climatic influences on temperature other than those associated with daily radiation forcing, such as large-scale advection or persistent cloud cover. Besides, forcing factors that were not included here may have also a role in the type of model developed in this study. Such as seasonal burning, grassland fires, and pollution from fires having significant influence on radiation (Thornton and Running, 1999). Generally meteorological station records often consist only of rainfall and temperature data. This developed model is useful in having radiation data estimates of locations sans recorded radiation data. This enables complete meteorological data set creation for ecosystem models.

4.1.3 Climate variability

Many studies have shown that temperature, precipitation and radiation were among the major controlling factors of NPP at a region scale (Churkina and Running, 1998; Whendee, 1998). Conducive environmental conditions allow all forest type species to survive and flourish and also result in lower stress due to competition for sunlight and nutrients. Forest types in KNP experience the optimum climate conditions as compared to forests in Western Madhya Pradesh, where sites experience large variability in rainfall, temperature and radiation. KNP also hold high number of trees species and stand density as compared to forests in Western Madhya Pradesh, thus indicating a strong influence of local climatic conditions on forest growth and their composition. Net Primary Productivity of deciduous forests in KNP varied significantly with rainfall, temperature and radiation. The results were comparable with another study conducted in an India tropical ecosystem (Chitale et al., 2012). Temperature plays critical role in metabolism through its effects on rates of biochemical reactions (Gillooly et al., 2001), thus optimum temperatures in combination with adequate soil moisture enhance photosynthetic activities of trees resulting increase in their productivity. KNP experiences optimum climatic conditions and also indicated higher productivity as compared to productivity at deciduous forest sites in Western Madhya Pradesh (Kale and Roy, 2012). Inter-annual pattern of productivity in relation with climatic parameters in KNP indicated that increase in temperature, radiation and decrease in rainfall was unfavorable for most of areas in the park. A study by Melillo et al. (1993) showed that elevated temperatures have resulted in decrease in productivity by decreasing soil moisture or enhancing plant respiration. Our findings suggest that seasonal and inter-

annual variation in climatic parameters are strongly associated to the spatial distribution of forest NPP in KNP. CASA modelling using these climate factors suggest that all the sample plots located in the same park may experience the same climate but differ in their productivity. It reveals that at the macro-scale, deciduous forest NPP is mainly governed by climate. At landscape to regional scales, climate factors were not the only components that affect productivity patterns; other environmental components like topography, fire, soil as well as disturbances also play an important role in productivity distribution.

4.3.4 Forest mapping

Multi-date Landsat images representing three key phenological stages (start of senescence and leafless phase and full growth phase) of moist deciduous forests in KNP were used to generate Landuse/Landcover (LULC) of the region. Rationale behind using multi-date images was, every plant species respond to biological processes such as pigmentation and senescence in distinctive ways and at different rates. These multi-date images acquired in key phenological phases capture changes in foliar presentation and facilitate for separating forest classes that may be spectrally similar in any one single acquisition image (Chuine and Beaubien, 2001; Dymond et al., 2002). (Singh et al., 2011a) had also followed the similar approach for forest type mapping in Kanha National Park, Madhya Pradesh. The study area was initially classified with a 80 cluster using unsupervised ISODATA classifier, of which eight LULC have been identified. Among those eight classes, Sal forest (30.2%) followed by Mixed forest (23.2%) were found to be dominant forest types in the region. This finding was consistent with the results obtained in previous studies conducted at KNP (Kale et al., 2002; Roy and Ravan, 1996). Total forest area estimated in the present study was (947 Km²) very close to that of an area reported (940 Km²) in Management Plan for Kanha National Park (2007-08 to 2016-17). Accuracy assessment is crucial for satellite-derived products before using them in to any ecosystem model. Accuracy assessment for the forest map generated in this study was performed using ground survey data as well as information gathered at biomass sample plots. Comparison of both the data sets yielded an overall accuracy of 90%, showing good agreement between both the data sets. This 10% error between both the data sets was attributed to misclassification of grassland to the cropland, fact that grassland and cropland have a similar growth pattern and therefore can easily be misclassified each other. Error could be also due to several other factors

such as challenges in extracting training area statistics, the classification decision model, spectral limitations of the satellite sensor, accuracy assessment constraints, and the reference data itself.

4.3.5 CASA modelling

Carnegie–Ames–Stanford Approach (CASA, Potter et al., 1993) is one of the widely used ecosystem models, which offers an inimitable opportunity for simulating forest NPP at regional and global scale with less input data (Bala et al., 2013; Goroshi et al., 2014; Z. Liu et al., 2018; Nayak et al., 2013; Potter et al., 2013; Potter et al., 2012; Yu et al. 2009). Present study estimates moist deciduous forest NPP at KNP using CASA ecosystem model driven by multi-date Landsat images for the period 2011-2014. Spatial distribution of annual NPP was found to be higher in Eastern region due to presence of large size *Shorea robusta* forest and mixed forest with Sal and Bamboo. This could be also due to presence of perennial water sources, which provide favorable microclimate conditions for tree growth. Due to lack of water sources and poor soil properties, NPP was appeared to be very low in Western parts of the region. This spatial distribution pattern was in accordance with that of Bala et al. (2013); Goroshi et al. (2014); Nayak et al. (2013) who estimated NPP for different biomes in India. NPP varied significantly among different forest types due to their structure, composition, growth rate and their age. Four year average NPP of the three dominant forest types varied as value of Sal forest ($8.94 \text{ Mg ha}^{-1} \text{ year}^{-1}$) > Sal mixed with bamboo ($8.32 \text{ Mg ha}^{-1} \text{ year}^{-1}$) > mixed forest ($7.48 \text{ Mg ha}^{-1} \text{ year}^{-1}$). These finding were well within those reported ($6.17\text{-}12.06 \text{ Mg ha}^{-1} \text{ year}^{-1}$) for deciduous forest in Southern Haryana (Singh et al., 2017), $6.7\text{-}15.8 \text{ Mg ha}^{-1} \text{ year}^{-1}$ tropical forest in Santa Rosa national Park, Costa Rica (Cao et al., 2016) and comparatively higher than those reported ($4.76\text{-}6.39 \text{ Mg ha}^{-1} \text{ year}^{-1}$) for deciduous forest at Chhindwara forest division, Madhya Pradesh (Pande, 2005). Average NPP obtained across the study year varied from $10.06 \text{ Mg ha}^{-1} \text{ year}^{-1}$ (Plot-10) to $6.45 \text{ Mg ha}^{-1} \text{ year}^{-1}$ (Plot-7) with an average of $8.4 \text{ Mg ha}^{-1} \text{ year}^{-1}$. Mean NPP simulated in the present study was much lower than that of an average NPP reported for deciduous broad leaf forest in East Asia using CASA model (Goroshi et al., 2014; Nayak et al., 2010; Yu et al., 2009). Difference between the estimates was due to difference in scales when comparing 30m Landsat NPP simulated in the present study with those reported using MODIS NPP (1km), SPOT VGT (1km) and INSAT NPP (8km) estimates. The difference could be also due to various inputs

like rainfall, temperature and light use efficiency used for simulating NPP. Inter-annual variability of NPP across the sample plot varied from 9.88 Mg ha⁻¹ year⁻¹ (2012) to 6.71 Mg ha⁻¹ year⁻¹ (2014) with an average of 8.4 Mg ha⁻¹ year⁻¹. This inter-annual variability of deciduous forest NPP in KNP was attributed to both extrinsic (e.g., climate) and intrinsic (e.g., stand structure and composition, small-scale disturbance, microclimatic variation created by stand structure, and species competition) drivers. Several studies have showed climate strongly governs stand growth and site productivity patterns (Cook, 1990; Fritts and Swetnam, 1989; Gedalof and Smith, 2001; Peterson et al., 2002), while others have reported stand density including disturbances, mortality, and competition to be key drivers of tree growth as well (Bormann et al., 1995; Cook, 1990; Lutz and Halpern, 2006; Piutti and Cescatti, 1997). Recent studies in Southeast Asia (Fang et al., 2001; Ichii et al., 2013; Wang et al., 2016; Yoneda et al., 2016; Zhang et al., 2012) have point out that inter-annual variations in rainfall was responsible for fluctuation in NPP, but the authors also showed that the sign of a given ecosystem response could differ, and that further investigation of the causes of variations in NPP were warranted.

4.3.6 Validation of CASA NPP

CASA simulated NPP for moist deciduous forest in KNP was validated using field measured NPP obtained across 10 sample plots in the region for the period 2011-2014. Good agreement was observed between both the data sets with coefficient of determination (R^2) 0.93, explaining 93% variability at 95% confidence level. The mean values of ground and CASA simulated NPP were 8.19 Mg ha⁻¹ year⁻¹ and 8.40 Mg ha⁻¹ year⁻¹, respectively. Mean NPP estimated by the CASA model was relatively higher than the field measured NPP with the root-mean square error of 0.76 Mg ha⁻¹ year⁻¹, which is 9.43% of the mean observed NPP over the region. This strong agreement between both the data sets justifies the model's utility for estimating tropical moist deciduous forest NPP in KNP. This model integrates not only with station measured climatic data, but in this study also was parameterized with high spatial resolution forest cover data. The 10% error in the model estimates may be due to CASA NPP estimates were based on land areas represented by the gridded input data sets (Landsat NDVI) used by the model, whereas field based NPP estimates were based on the quadrat areas actually sampled at each site. This was very crucial because the model simulated the average NPP of all vegetation types over a grid square, and because

the issue of scaling-up of NPP from the sampling area to a grid cell should be taken carefully into account. The difference could be also due to several factors, the model as it was used in this study does not, however, simulate the effects of soil variability within the regions, soil moisture at different depths, anthropogenic disturbances and other factors on forest NPP. This may explain why the modeled forest NPP values were higher than those calculated from the field measured data. The strong correlation between inter-annual NPP and rainfall during the study period indicates the need to collect more accurate and spatially explicit rainfall data in the CASA model, despite that only one meteorological station was available to represent rainfall over 947 Km² area in the region. It was also important to determine influence of forest cover type on spatial variability of NPP in the model. This model relies heavily on forest cover inputs and also assumes that forest cover was consistent year to year, which was not what was happening in reality. The fixed forest cover restricts the ability of the model to capture forest cover changes and adjust NPP estimates consequently. Although the model results might relatively overestimate, the CASA model was a powerful ecosystem model for simulating moist deciduous forest NPP at larger spatial scale with less input data. While the application of the CASA model may be reasonable at species scales, the model NPP estimates can be improved through (1) finer forest type classifications, and (2) accurate quantification of the effects of soil water condition on forest NPP. Each ecosystem model has its limitations and CASA is no exception. Owing to these reasons, it is always better to perform and learn from model inter-comparison with respect to various key variables, using common input data sets at global and regional scales.

4.2 Bandhavgad National Park

4.2.1 Forest biophysical parameters

Tree species: A total number of 45 tree species were recorded from ten deciduous sample plots in Bandhavgad National Park (BNP). The number of tree species recorded in this study was similar to those reported (46 spp.) at tropical evergreen forest on the Coromandel coast (Venkateswaran and Parthasarathy, 2003), 42 spp. at tropical deciduous forests in Orchha Sanctuary, Bundelkhand, Madhya Pradesh (Shrivastava et al., 2017), 26-56 spp. at semi-evergreen forests in Kollihills (Chittibabu and Parthasarathy, 2000), 33-50 spp. at Shervarayan hills (Kadavul and Parthasarathy, 1999), 57 spp. ha⁻¹ in Mylodai and Courtallam reserve forest (Parthasarathy and Karthikeyan, 1997), 16-54 spp. at tropical wet evergreen forest in Arunachal Pradesh, Eastern Himalayas (Bhuyan et al., 2003), 56 spp. at tropical dry evergreen forests on the Coromandel coast of southern India (Anbarashan and Parthasarathy, 2013), 59 spp. at tropical deciduous forest in Uttar Pradesh, India (Verma et al., 2015), 57 spp. were recorded from 2.4 ha sampling area in Malyagiri hill range, Eastern Ghats (Sahu et al., 2012). The number of species recorded in this study was lower than those reported (77 spp.) at tropical evergreen forests in South India (Mani and Parthasarathy, 2006), 65-71 spp. at tropical forests of East Godavari, Andhra Pradesh (Premavani et al., 2017), 97 spp. at 4 ha area of tropical deciduous forest in Boudh district, Orissa (Sahu et al., 2007), 92 spp. at tropical deciduous forest in West Godavari, Andhra Pradesh (Premavani et al., 2014), 128 spp. at 7.9 ha area of tropical deciduous forest of the Bannerghatta National Park, a part of the Eastern Ghats (Gopalakrishna et al., 2015). On the otherhand, number of species recorded in this study was much higher than those reported (11 spp.) at tropical deciduous forest in Sri Lankamalla Wildlife Sanctuary, Southern Eastern Ghats, India (Mastan et al., 2016), 10-20 spp. at Boramdeo Wildlife Sanctuary in Kabirdham, Chhattisgarh (Jhariya et al., 2012), 24 spp. at deciduous forest in Hathinala, Sonbhadra district of Uttar Pradesh (Kushwaha et al., 2010). 2-36 spp. in peninsular Indian forests (Parthasarathy et al., 2004). This marked variation in the total number of tree species reported across the country could be due to variation in biogeography, habitat, and disturbance (Neumann and Starlinger, 2001; Padalia et al., 2004). Out of 45 spp. *Shorea robusta* (Sal) was found to be dominant species and found almost everywhere in the region. It indicates a wide range of growth and adoptability of *Shorea robusta* throughout the park. The forest type information obtained in this

study was compared well with the forest type survey and mapping reported in Management Plan for Bandhavgad National Park (2007-08 to 2016-17).

Stand density: As evident from analysis of ten sample plots of deciduous forests in Bandhavgad National Park (BNP), stand density varied in the region from 150-1010 trees ha⁻¹ with an average of 466 trees ha⁻¹. The stand density recorded in this study was comparable with those reported (443 trees ha⁻¹) at deciduous forest in Malyagiri hill ranges, Eastern Ghats, India (Sahu et al., 2012), 492-642 trees ha⁻¹ for *Ailanthus excelsa* dominated deciduous forest in Gurgaon district, Southern Haryana, India (Singh et al., 2017), 11-406 trees ha⁻¹ for tropical forest of Mudumalai wild life sanctuary, Western Ghats, India (Reddy, Ugle, et al., 2008), 448–617 trees ha⁻¹ at tropical forests in Costa Rica (Heaney and Proctor, 1990) and 420-777 trees ha⁻¹ at tropical forest sites in Brazil (Campbell et al., 1992), 276-905 trees ha⁻¹ at Malyagiri hills (Sahu et al., 2012), 268-655 trees ha⁻¹ at the Eastern Ghats region of Odisha (Panda et al., 2013), and 352-1173 trees ha⁻¹ at Kodayar (Sundarapandian and Swamy, 2000). On the otherside, stand density in BNP was lower than those reported for the tropical deciduous forest at Nicaragua (519 trees ha⁻¹) by Marín et al. (2005), 674-794 trees ha⁻¹ at Nallamalais, Seshachalam and Nigidi hill ranges (Reddy, Ugle, et al., 2008), 674-796 trees ha⁻¹ at Niyamgiri hills (Dash et al., 2009), 574-915 trees ha⁻¹ at tropical evergreen forests of Southern Western Ghats Kalakkadu region (Parthasarathy et al., 1992), 635 stems ha⁻¹ at Uppangala (Pascal and Pelisser, 1996). These estimates were higher than those reported by Devagiri et al. (2013) for deciduous forest of Western part in Karnataka (17-362 trees ha⁻¹). Jha and Singh (1990) reported stand density 294-559 trees ha⁻¹ in tropical deciduous forests of Vindhya region. Of the 10 plots, Plot-9 had the highest stand density, whereas Plot-5 had the lowest stand density. The stand structure measurements in this study indicated that, plots those covered tallest trees with large girth size had lowest stand density, whereas plots those covered short trees with poor girth size had highest stand density. These findings were in agreement with other reports (Brokaw et al., 1997; Campbell et al., 1992; Chandrashekara and Ramakrishnan, 1994; Hara, 1997; Ho, Newbery et al., 1987; Kadavul and Parthasarathy, 1999; Lieberman and Lieberman, 1987; Sahoo et al., 2017; Sundarapandian and Karoor, 2013; Sundarapandian and Swamy, 2000; Swaine et al., 1987). This wide variation in stand density could be due to variation in local climatic condition, soil properties, availability of water sources and anthropogenic disturbances.

Tree height: In this study, tree height ranged from 7.5m to 25.13m with an average of 12.18m. The tree height range observed in the present study was similar to that reported (11m-17m) at forests in Mt. Gyeongbansan, Gangwon-do (Province), South Korea (Jung et al., 2011), 14.77m at *Shorea robusta* dominated forest in Chitwan district, Nepal (Asmare, 2013), 13.2m at evergreen forest in Popa Mountain Park, Myanmar (Aye et al., 2014), 14.5m for tropical rain forest in Royal Belum State Park, Perak, Northern Peninsular Malaysia (Sium, 2015), 6.69m and 13.80m, mean tree height reported for dipterocarp forest and mixed deciduous forest in Popa Mountain Park, Myanmar (Aye et al., 2014), 17.9m at a multi-tiered mixed deciduous stand in southern Ontario (Hopkinson et al., 2004), 2.5-23.5m, 3.8-23.5m, and 4.4-14.1m at mixed species, *Dipterocarpus* genus and *Shorea* genus, respectively in two eco-regions of Vietnam (Huy et al., 2016). The tree height measured in this study was lower than those reported (2.5m-20.5m) for deciduous forest in Mae Nam Phachi Wildlife Sanctuary, Ratchaburi province, Western Thailand (Chaiyo et al., 2011), 3.5m-26m at mixed/moist evergreen forest in Omo Forest Reserves, Southwest of Nigeria (Dauda et al., 2004), 7.13m-28.68m at forests of Kalkkinen, Helsinki, in Southern Finland (Yu et al. 2004), 3m-35.5m at mixed forest in Koli National Park, North Karelia, Eastern Finland (Villikka et al., 2007), 2.1m-33.93m at semi-deciduous forest in Lama forest reserve (Nagel et al., 2004), 11m-47.5m at forests in Rio Grande do Sul, Espirito Santo and Bahia, Brazil (Nutto et al., 2006), 3.3-27.9m at mixed deciduous forest in Kratie, Cambodia (Monda et al., 2016), 1.81m-35.77m, range of mean height measured at 500 deciduous tree species at Katarnia Ghat Wildlife Sanctuary (KGWS) in Bahraich District, Uttar Pradesh, and Eda in Ekiti State, Nigeria, The tallest trees were observed in Plot-5 with a mean height of 25.13 ± 3.33 m, whereas shortest trees were observed in Plot-2 with an average height of 7.48 ± 0.76 m. Several studies also recorded significant variations in tree architectural properties, both within and across sites (Nogueira et al., 2008; Brien et al., 1995; Osunkoya et al., 2007; Poorter et al., 2006; Poorter et al., 2003; Sterck and Bongers, 2001). This variations between the plots within the same region may attributed to spatial variability in soil moisture, nutrients, and microclimatic conditions induced due to the topographic variations.

Diameter at breast height (DBH): Among 10 plots studied in BNP, DBH varied significantly between plots from 9cm to 46.95cm. The range of DBH observed in this study was in agreement with those reported (27.14-79.57cm) for deciduous forest at

Chikaldhara hill station, Amaravati district of Maharashtra (Maan et al., 2015), 4.77-43.29cm at deciduous forest in Mae Nam Phachi Wildlife Sanctuary, Western Thailand (Chaiyo et al., 2011), 9.1-49.4cm at different deciduous forest types in Brazil (Nutto et al., 2006), 3.4-48.8cm, 4.9-48.8cm, and 5.6-23cm at mixed species, *Dipterocarpus* genus and *Shorea* genus, respectively in two eco-regions of Vietnam (Huy et al., 2016), 7-58.3cm in mixed/moist evergreen forest of Omo Forest Reserves, Southwest of Nigeria (Dauda et al., 2004), 5-53.8m at mixed forest in Koli National Park, North Karelia, Eastern Finland (Villikka et al., 2007), 5.5-57.3cm at mixed deciduous forest in Kratie, Cambodia (Monda et al., 2016). On the otherhand, DBH measured in this study was much lower than those reported (12-29cm) for deciduous forest in central Cambodia (Kenzo et al., 2017), 17.3-27.35cm at deciduous forest of Latvia in Jelgava District, Riga (Priedītis et al., 2012), 16.7-19.3cm at mixed forest in Universidad Austral de Chile (Moreno et al., 2017), 8.42-28.8cm at deciduous forest in Virginia, Southeastern United States (Sorin, 2002), 11cm and 17.5cm, mean DBH reported for dipterocarp forest and mixed deciduous forest in Popa Mountain Park, Myanmar (Aye et al., 2014). Decrease in DBH with increase in stand density observed in the present study was in agreement with other reports (Brokaw et al. 1997; Campbell et al., 1992; Chandrashekara and Ramakrishnan, 1994; Hara, 1997; Ho et al., 1987; Kadavul and Parthasarathy, 1999; Lieberman and Lieberman, 1987; Sahoo et al., 2017; Sundarapandian and Karoor, 2013; Sundarapandian and Swamy, 2000; Swaine et al., 1987). DBH growth rate in tropical trees is generally varied between around 1 and 10 mm year⁻¹ (Worbes, 1999). In the present study, DBH growth rates varied among the native tree species in BNP, despite the fact that they were close together in stem size and their habitat was similar. Different tree species showed different behaviors under similar conditions. Even for the same species, DBH growth rates vary according to stem size. Average tree growth rate (cm year⁻¹) across the study plots in BNP varied from 0.27-0.85cm year⁻¹ with an average of 0.45 cm year⁻¹. These values compared well with the girth increment observed by (Alder et al., 2002; Silva et al., 2002; Kale and Roy, 2012; Lewis et al., 2004; Murphy and Lugo, 1986; Nebel et al., 2001). While several factors may be responsible for this variation in growth rates, this study considered climatic and edaphic factors had a crucial role in explaining this variation.

Aboveground biomass (AGB): Average AGB across the study plots in BNP varied from 76.16-371.9 Mg ha⁻¹ with an average of 187 Mg ha⁻¹. The biomass estimates

obtained in this study were within the range of values reported worldwide as well as deciduous forests in India (Bijalwan, 2010; Chave et al., 2005; Hergoualc'h and Verchot, 2011; Kumar et al., 2011; Mani and Parthasarathy, 2007; Pande, 2005; Patra et al., 2013). AGB values estimated in the study were higher as compared to the reported values of 187.25 to 263.34 Mg ha⁻¹ (Bhat and Ravindranath, 2011), 32.47-261.64 Mg ha⁻¹ at tropical forest in Cachar district of Assam, in Northeast India (Bora et al., 2013), 238-341 Mg ha⁻¹ in tropical rain forests of Cameroon (Brown and Lugo, 1982), 332-353 Mg ha⁻¹ in evergreen forests of Andaman and Nicobar islands in India (Rajkumar and Parthasarathy, 2008), 153-221 Mg ha⁻¹ in Sri Lankan tropical rain forests (Brown and Lugo, 1992), 170-330 Mg ha⁻¹ in lowland rainforest of Colombia (Folster et al., 1976), 96.28-275.46 Mg ha⁻¹ in tropical rain forests in Thailand (Terakunpisut et al., 2007). However, AGB values of the present study were within the reported values of 225-446 Mg ha⁻¹ in the tropical rain forests in Malaysia (Brown and Lugo, 1992). This wide variation in AGB stockpile of tropical forest could be attributed to variation in stand density, species richness, wood density of trees, forest types, elevation of forest site, species composition and climatic conditions (Udayakumar and Parthasarathy, 2010). However, high biomass at Plot-5 in the present study could be due to high stand density and presence of large diameter class trees such as *Shorea robusta* contributed for the increase in biomass. Several researchers have also confirmed that trees with high diameter class account more biomass in forests (Brown, 1996; Brown and Lugo, 1982; Clark and Clark, 1996; Slik et al., 2013). Though stand age was not recorded in the present study, number of studies showed that biomass and carbon storage varies significantly with stand age, old-growth forests generally hold more biomass than younger forests (Aide et al., 2000; Baker et al., 2004; Brearley et al., 2004; Brown and Lugo, 1990; China and Helmer, 2003; Gehring et al., 2005; Guariguata and Ostertag, 2001; Kennard, 2002; Kumar et al., 2006; Lewis et al., 2009; Lugo and Helmer, 2004; Muniz et al., 2006; Phillips et al., 1998; Turner et al., 1997). However, stand age could be one of the possible reasons why trees in Plot-5 hold more biomass as compared to trees in the other plots. Plot-1 was witnessed with least biomass stock, which was mainly due to presence of young trees with lower girth classes. Soil properties (lower soil depth, soil structure etc) and scarcity of ground water sources can be also responsible for low AGB (Pande, 2005). An effort was made in this analysis to determine relative change (RD%) in biomass stock across the study period. The analysis showed wide variation in RD between the plots. Though stand density and biomass

stock was very less in Plot-1, but RD (%) was very high in this plot. Average RD in this plot was about 30.5%. This was mainly attributed to the growth of intermediate size trees, indicating that trees in this plot could yet to reach their mature stage. It has been consistently shown that biomass of regenerating trees increases over time with particularly high rates of storage in the first 20 years post- abandonment (Bonner et al., 2013; Marín et al., 2008; Silver et al., 2000). Despite of stand age, RD in biomass is also a function of several tree structural parameters like stand density, height, and DBH at given location and time. Minimum RD was observed in Plot-5 with 3.44%. This could be due to static growth rate of forests in this plot. RD across the plot was found to be highest in 2014 with an average of 17.6%, whereas the lowest RD was observed in 2011 with a mean of 4.36%. This inter-annual variation in RD was strongly associated with the meteorological variables especially rainfall, temperature and radiation.

Field based NPP: Aboveground NPP estimated in the present study using field measurements varied across the plots from 4.99-8.45 Mg ha⁻¹ year⁻¹ with an average of 6.69 Mg ha⁻¹ year⁻¹. Average NPP estimated in the present study was similar to those reported (1.1-11.03 Mg ha⁻¹ year⁻¹) for deciduous forest in Shivpuri district of Madhya Pradesh (Kale and Roy, 2012), 6.4 Mg ha⁻¹ year⁻¹ at tropical forest in Puerto Rico, Pico del Este (Clark et al., 2001), 6.9 Mg ha⁻¹ year⁻¹ at tropical forest in Mexico (Martinez et al., 1996), 7-10 Mg ha⁻¹ year⁻¹ at Conifer forest in USSR (Rodin and Bazilevich, 1967), 7.3 Mg ha⁻¹ year⁻¹ at tropical forest in Mexico, Chamela middle plot (Clark et al., 2001), 7.7 Mg ha⁻¹ year⁻¹ at 24 year old Sissoo plantation (Sharma et al., 1988), 8.9 Mg ha⁻¹ year⁻¹ at tropical forest in Mexico, Chamela lower plot (Clark et al., 2001), 10 Mg ha⁻¹ year⁻¹ for *Gmelina arborea* forest in India (Pacholi, 1997), 10 Mg ha⁻¹ year⁻¹ at Subtropical forest in Puerto Rico, Guanica (Clark et al., 2001), 10.2 Mg ha⁻¹ year⁻¹ at tropical deciduous forest in Uttar Pradesh (Singh and Singh, 1991), 10.4 Mg ha⁻¹ year⁻¹ at tropical forest in SE Peru (Girardin et al., 2010), 10.9 Mg ha⁻¹ year⁻¹ for *Camelia japonica* forest in Japan (Tadaki, 1965), 11.4 Mg ha⁻¹ year⁻¹ at tropical moist forest (Golley, 1975), 11.4-14.8 Mg ha⁻¹ year⁻¹ at 5-,10- and 15 years old Bhabar Shisham forests in Uttaranchal (Lodhiyal and Lodhiyal, 2003), 11 Mg ha⁻¹ year⁻¹ at Pine forest in USA (Whittaker, 1966). The NPP range obtained in this study was within those reported NPP (6.42–25.39 Mg ha⁻¹ year⁻¹) for tropical forests (Karmacharya and Singh, 1992; Negi et al., 1995) in India. The values were also within the global pattern of

aboveground NPP (6-16 Mg ha⁻¹ year⁻¹) for dry tropical forest (Murphy and Lugo, 1986). On the otherhand NPP estimated in the present study were lower than those reported (13-20 Mg ha⁻¹ year⁻¹) for other forest types like Shisham forests (Lodhiyal et al., 2002), 14.6-15.7 Mg ha⁻¹ year⁻¹ (Singh, 1979), 19.2 Mg ha⁻¹ year⁻¹ at tropical rain forest in Malaysia (Reichle, 1981), 15.5 Mg ha⁻¹ year⁻¹ at Rianj dominated forest in India (Rana et al., 1989), 16-18.9 Mg ha⁻¹ year⁻¹ (Singh and Singh, 1989), 17.3 Mg ha⁻¹ year⁻¹ at Chir-pine forest in India (Rana et al., 1989), 28.6 Mg ha⁻¹ year⁻¹ at tropical rain forest in Thailand (Kira, 1967), 29.4 Mg ha⁻¹ year⁻¹ at *Camelia japonica* in Japan (Kan et al., 1965), 24.3 Mg ha⁻¹ year⁻¹ at tropical rain forest (Wanner, 1970), 22.3 Mg ha⁻¹ year⁻¹ at *D.sissoo* forest in Bihar (Pacholi, 1997), 12.6-20.3 Mg ha⁻¹ year⁻¹ at 5-15 years old Tarai Shisham forests in central Himalaya (Lodhiyal et al., 2002). This wide variation in NPP may be partly due to variations in climate, especially the length of the growing season when both thermal and moisture conditions were favorable. This could be also attributed to differences in the availability of soil water and nutrients. Chaturvedi et al. (2011) and Manoj, Phd thesis. (2011) had observed a significant effect of soil moisture on growth of tropical deciduous forests at Vindhyan highlands in India. In several other studies also nitrogen availability was shown to be constrain the productivity of tropical forests (Tanner et al., 1998; Vitousek and Sanford, 1986). In the present study, high NPP was observed in Plot-3, which was due to presence of large sized trees with high growth rate (increment in DBH, cm tree⁻¹ year⁻¹) as well as adequate soil moisture and consequently less frequent fires and higher biomass increment. Poor NPP in Plot-4 was probably caused by sparse stand density with poor DBH increment rate and lack of soil moisture.

4.2.2 Climate variability

Many studies have shown that temperature, precipitation and radiation were among the major climatic controlling factors of NPP at a region scale (Churkina and Running, 1998; Whendee, 1998). Favorable environmental conditions allow all forest type species to survive and flourish and also result in lower stress due to competition for sunlight and nutrients. Forest types in BNP experiences the optimum climate conditions as compared to forests in Western Madhya Pradesh, where sites experience large variability in rainfall, temperature and radiation. BNP hold high number of trees species and stand density as compared to forests in Western Madhya Pradesh, whereas BNP had less number of trees species and stand density when compared to forests in

Northeastern regions of Madhya Pradesh. Thus indicating a strong influence of local climatic conditions on forest growth and their composition. Net Primary Productivity of deciduous forests in BNP varied significantly with rainfall, temperature and radiation. The results were comparable with another study conducted in an India tropical ecosystem (Chitale et al., 2012). Temperature plays critical role in metabolism through its effects on rates of biochemical reactions (Gillooly et al., 2001), thus optimum temperatures in combination with adequate soil moisture enhance photosynthetic activities of trees resulting increase in their productivity. BNP experiences optimum climatic conditions and also indicated higher productivity as compared to productivity at deciduous forest sites in Western Madhya Pradesh (Kale and Roy, 2012). Inter-annual pattern of productivity in relation with climatic parameters in BNP indicated that increase in temperature, radiation and decrease in rainfall was unfavorable for most of areas in the park. A study by Melillo et al. (1993) showed the elevated temperatures have resulted in decrease in productivity by decreasing soil moisture or enhancing plant respiration. Our findings suggest that seasonal and inter-annual variation in climatic parameters strongly associated to the spatial distribution of forest NPP in BNP. CASA modelling using these climate factors suggest that all the sample plots located in the same park may experience the same climate but differ in their productivity. It reveals that at the macro-scale deciduous forest NPP is mainly governed by climate, at landscape to regional scales, climate factors were not the only components that affect productivity patterns; other environmental components like topography, fire, soil as well as disturbances also play important role in productivity distribution.

4.2.3 Forest mapping

Multi-temporal Landsat imageries representing three key phenological stages (start of senescence and leafless phase and full growth phase) of deciduous forests species in BNP were used to generate forest cover map of the region. Rationale behind using multi-temporal imageries was, every plant species respond to biological processes such as pigmentation and senescence in distinctive ways and at different rates. These multi-temporal imageries acquired at key phenological phases capture changes in their foliar presentation and facilitate for separating forest classes (Chuine and Beaubien, 2001; Dymond et al., 2002). Singh et al., (2011a) had also followed the similar approach for forest type mapping moist deciduous forest types in Kanha National Park, Madhya

Pradesh. The study area was initially classified with a 80 cluster using unsupervised ISODATA classifier, of which eight landuse/land covers have been identified. Among those eight classes, Mixed forest dominated by Sal was found to be a predominant forest species and found everywhere in the region followed by Mixed forest. Forest types and their area in the park was in agreement with those reported in Management Plan for Bandhavgadh National Park (2007-08 to 2016-17). Total forest area estimated in the present study was (697.3 Km²) very close to that of an area reported (716 Km²) in Management Plan for Bandhavgadh National Park (2007-08 to 2016-17). Accuracy assessment is crucial for satellite derived products before using them in to ecosystem model. The forest map generated in the present study was evaluated using ground survey data collected across the region as well as ground truth information collected at biomass sample plots. Comparison of both the data sets yielded an overall accuracy of 87%, showing very high agreement between both the data sets. This 13% error between both the data sets was attributed to misclassification of grassland to the cropland, fact that grassland and cropland have a similar growth profile and therefore can easily be misclassified each other. Error could be also due to several other factors such as challenges in extracting training area statistics, the classification decision model, spectral limitations of the satellite sensor, accuracy assessment constraints, and the reference data itself.

4.2.4 CASA modelling

Carnegie–Ames–Stanford Approach (CASA, Potter et al., 1993) is one of the widely used ecosystem models, which offers an unique opportunity for estimating forest NPP at regional and global scale with less input data (Bala et al., 2013; Goroshi et al., 2014; Z. Liu et al., 2018; Nayak et al., 2013; Potter et al., 2013; Potter et al., 2012; Yu et al. 2009). Present study estimates deciduous forest NPP in BNP using CASA ecosystem model driven by multi-date Landsat images for the period 2011-2014. Spatial distribution of annual NPP showed higher NPP in Central and Sothern parts of the region, where Sal mixed forest and Lendia mixed forest were the predominant forest types. Adequate soil moisture due to presence of presence of river and favorable microclimate conditions induced due to the topographic variations could have also played a key role in attaining maximum NPP. NPP was appeared to be lower in Northern regions due to (i) their artificial/managed behavior of ecosystem with lesser ground resulting in decrease in soil moisture content affecting the optimum and

complementary nature (Melillo et al. 1993; Pandey and Shukla 2003b), (ii) longer dormancy period to escape excessive water loss due to transpiration, hence lacks the photosynthetic apparatus resulting in decline in NPP (iii) its better survival rate with poor growth rate; (iv) lower average age of the trees in comparison to trees in Central and Southern parts of the region (Chitale et al., 2012). This spatial NPP distribution pattern was in accordance with that of Bala et al. (2013); Goroshi et al. (2014); Nayak et al. (2013), who estimated NPP for different biomes in India. NPP varied significantly among different forest types in the region. Average NPP of the four years of these forest types varied considerably as value of mixed forest dominated by Sal ($9.36 \text{ Mg ha}^{-1} \text{ year}^{-1}$) > mixed forest dominated by Lendia ($7.9 \text{ Mg ha}^{-1} \text{ year}^{-1}$) > mixed forest ($7.0 \text{ Mg ha}^{-1} \text{ year}^{-1}$). These findings were well within the range of other studies conducted in deciduous forests in Central India (Kale and Roy, 2012). These estimates were also in line with those reported for ($4.76\text{-}6.39 \text{ Mg ha}^{-1} \text{ year}^{-1}$) deciduous forest at Chhindwara forest division, Madhya Pradesh (Pande, 2005), $6.17\text{-}12.06 \text{ Mg ha}^{-1} \text{ year}^{-1}$ in Southern Haryana (Singh et al., 2017), $6.7\text{-}15.8 \text{ Mg ha}^{-1} \text{ year}^{-1}$ tropical forest in Santa Rosa national Park, Costa Rica (Cao et al., 2016). Average NPP obtained across the study year varied from $9.6 \text{ Mg ha}^{-1} \text{ year}^{-1}$ (Plot-3) to $6.01 \text{ Mg ha}^{-1} \text{ year}^{-1}$ (Plot-5) with an average of $7.41 \text{ Mg ha}^{-1} \text{ year}^{-1}$. Mean NPP simulated in the present study was lower than those reported for deciduous broad leaf forest in East Asia using CASA model (Goroshi et al., 2014; Nayak et al., 2010; Yu et al., 2009). Uncertainty between the estimates was due to difference in scales when comparing 30m Landsat NPP simulated in the present study with those reported using MODIS NPP (1km), SPOT VGT (1km) and INSAT NPP (8km) estimates. The difference could be also due to various inputs like rainfall, temperature and light use efficiency value used for simulating NPP. NPP averaged across the plots was found to be highest in 2012 ($10.55 \text{ Mg ha}^{-1} \text{ year}^{-1}$), while the lowest NPP ($6.0 \text{ Mg ha}^{-1} \text{ year}^{-1}$) was appeared in 2011 with an average of $7.41 \text{ Mg ha}^{-1} \text{ year}^{-1}$. This inter-annual variability in NPP was due to both extrinsic (e.g., climate) and intrinsic (e.g., stand structure stand structure and composition, small-scale disturbance, microclimatic variation created by stand structure, and species competition) drivers. Several studies have revealed climate in part governs stand growth and site productivity patterns (Cook, 1990; Fritts and Swetnam, 1989; Gedalof and Smith, 2001; Peterson et al., 2002), while others have reported stand density including disturbances, mortality, and competition to be crucial drivers of tree

growth as well (Bormann et al., 1995; Cook, 1990; Lutz and Halpern, 2006; Piutti and Cescatti, 1997). Recent studies in Southeast Asia (Fang et al., 2001; Ichii et al., 2013; Wang et al., 2016; Yoneda et al., 2016; Zhang et al., 2012) have point out that inter-annual variations in rainfall was responsible for fluctuation in NPP, but the authors also showed that the sign of a given ecosystem response could differ, and that further investigation of the causes of variations in NPP were warranted.

4.2.5 Validation of CASA NPP

Deciduous forest NPP simulated from the CASA model was validated using field measured NPP obtained from 10 sample plots for the period 2011-2014. Good agreement was observed between both the data sets with coefficient of determination (R^2) 0.91, explaining 91% variability at 95% confidence level. The mean values of field and simulated NPP were $6.65 \text{ Mg ha}^{-1}\text{year}^{-1}$ and $7.28 \text{ Mg ha}^{-1}\text{year}^{-1}$, respectively. Mean NPP estimated by CASA model was relatively higher than the field measured NPP with the root-mean square error (RMSE) of $0.98 \text{ Mg ha}^{-1}\text{year}^{-1}$, which was 14.5% of the mean field measured NPP. This strong agreement between both the data sets justifies the model's utility for estimating tropical deciduous forest NPP in BNP. This model incorporates not only climatic information, but in this study also was parameterized with high spatial resolution forest cover data. The 14.5% error in the model estimates may be due to CASA NPP estimates were based on land areas represented by the gridded input data sets used by the model, whereas field based NPP estimates were based on the quadrat areas (0.1ha) actually sampled at each site. This is very important because the model simulated the average NPP of all vegetation types over a grid square, and because the issue of scaling-up of NPP from the sampling area to a grid cell should be taken carefully into account. The difference could be also due to several factors, the model as it was used in this study does not, however, simulate the effects of soil variability within the regions, anthropogenic disturbances and other factors on forest NPP. This may explain why the modeled forest NPP values were relatively higher than those calculated from field measured data. The strong correlation between inter-annual NPP and rainfall during the study period highlights the need to collect more accurate and spatially explicit rainfall data in the CASA model, despite that only one meteorological station was available at BNP for our study. It was also important to consider the influence of forest cover type on spatial variability of NPP in the model. This model relies heavily on forest cover inputs and

also assumes that forest cover was consistent year to year, which was not what was happening in reality. The static nature of forest cover limits the ability of the model to capture forest cover changes and adjust NPP estimates accordingly. Although the model results might relatively overestimate, the CASA model was a powerful ecosystem model for simulating dry deciduous forest NPP at larger spatial scale with less input data. While the application of the CASA model may be reasonable at species scales, the model NPP estimates can be improved through (1) finer forest type classifications, and (2) accurate quantification of the effects of soil water condition on forest NPP. Each ecosystem model has its limitations and CASA is no exception. Owing to these reasons, it is always better to perform and learn from model inter-comparison with respect to various key variables, using common input data sets at global and regional scales.

4.3 Madhav National Park

4.3.1 Forest biophysical parameters

Tree species: A total number of 18 tree species were recorded from ten dry deciduous sample plots of size 0.1 ha in Madhav National Park (MNP). The total number of tree species recorded in the present study were similar to those reported (11 spp.) at tropical dry deciduous forest in Sri Lankamalla Wildlife Sanctuary, Southern Eastern Ghats, India (Mastan et al., 2016), 28 spp. at 0.3 ha area in Barnawapara wildlife sanctuary, Raipur, Chhattisgarh (Lal et al., 2015), 10-20 spp. at Boramdeo Wildlife Sanctuary in Kabirdham, Chhattisgarh (Jhariya et al., 2012), 24 spp. at dry deciduous forest in Hathinala, Sonbhadra district of Uttar Pradesh (Kushwaha et al., 2010). Total number of species recorded in the present study was lower when compared to those reported (46 spp.) at tropical dry evergreen forest on the Coromandel coast (Venkateswaran and Parthasarathy, 2003), 56 spp. tropical dry evergreen forests on the Coromandel coast of southern India (Anbarashan and Parthasarathy, 2013), 77 spp. at tropical dry evergreen forests in South India (Mani and Parthasarathy, 2006), 65-71 spp. at tropical forests of East Godavari, Andhra Pradesh (Premavani et al., 2017), 59 spp. at tropical dry deciduous forest in Uttar Pradesh, India (Verma et al., 2015), 57 spp. were reported from 2.4 ha sampling area in Malyagiri hill range, Eastern Ghats (Sahu et al., 2012), 97 spp. at four hectare area of tropical dry deciduous forest in Boudh district, Orissa (Sahu et al., 2007), 128 spp. at 7.9 ha area of tropical dry deciduous forest of the Bannerghatta National Park (BNP), a part of the Eastern Ghats (Gopalakrishna et al., 2015), 42 spp. at tropical dry deciduous forests in Orchha Sanctuary, Bundelkhand, Madhya Pradesh (Shrivastava et al., 2017), 92 spp. at tropical deciduous forest in West Godavari, Andhra Pradesh (Premavani et al., 2014). This wide variation in the total number of tree species reported across the country is attributed to variation in biogeography, habitat, and disturbance (Neumann and Starlinger, 2001; Padalia et al., 2004). Out of 18 spp. recorded in the present study, *Anogeissus pendula* (Kardhai) was found to be dominant and found almost everywhere in the region. The forest type information obtained in the present study was compared well with the forest type survey and mapping in MNP by Kale and Roy. (2012) and Roy and Ravan. (1996).

Stand density: As evident from analysis of ten sample plots of dry deciduous forests in Madhav National Park (MNP), stand density varied from 140-870 trees ha⁻¹ with an

average of 506 trees ha⁻¹. The stand density recorded in the present study was comparable with those reported for other dry deciduous forest in India such as Kalrayan hills (367-667; Kadavul and Parthasarathy, 1999), Nallamalais, Seshachalam and Nigidi hill ranges (average 735 trees ha⁻¹ and range 674-794; (Reddy, Ugle, et al., 2008), Niyamgiri hills (mean 735 trees ha⁻¹ and range of 674-796; (Dash et al., 2009), Malyagiri hills (mean 443 trees ha⁻¹ and ranges 276-905; (Sahu et al., 2012) and Eastern Ghats region of Odisha (mean 353 trees ha⁻¹ ranges from 268-655; (Mahapatra et al., 2013), dry tropical forests of India (Sagar and Singh, 2005), in the tropical evergreen forests of Southern Western Ghats Kalakkadu (574-915 trees ha⁻¹; (Parthasarathy et al., 1992), Kodayar (352-1173 trees ha⁻¹; (Sundarapandian and Swamy, 2000), Uppangala (635 stems ha⁻¹; Pascal and Pelissier, 1996) and other tropical forest of the world such as Costa Rica (448-617 trees ha⁻¹; Heaney and Proctor, 1990). The values of stand density in MNP were closer to those reported for the tropical dry deciduous forest at Nicaragua (519 trees ha⁻¹, Marín et al., 2005). A number of reports appeared recently for those parameters by various researchers. Singh et al. (2017) reported stand density 492-642 trees ha⁻¹ for *Ailanthus excelsa* dominated dry deciduous forest in Gurgaon district, Southern Haryana, India. (Reddy, Ugle, et al., 2008) reported stand density 11-406 trees ha⁻¹ for tropical forest of Mudumalai wild life sanctuary, Western Ghats, India. Bhatt and Khanal. (2010) reported stand density 638 trees ha⁻¹ at Indravati hydropower project areas in Nepal. Devi and Yadava. (2006) reported stand density 685-820 trees ha⁻¹ at tropical evergreen forest of Manipur, North East India. Sahu et al. (2012) reported stand density of 443 trees ha⁻¹ at Malyagiri hill ranges, Eastern Ghats, India. Gandhi and Sundarapandian. (2014) reported stand density of 627 trees ha⁻¹ at tropical dry deciduous forests of Tiruvannamalai district, Tamil Nadu, India. These estimates are higher than those reported by Devagiri et al. (2013) for dry deciduous forest of Western part of Karnataka (17-362 trees ha⁻¹). Jha and Singh (1990) reported stand density 294-559 trees ha⁻¹ in tropical dry deciduous forests of Vindhya region. These stand density records were lower than those reported for tropical dry deciduous forest at Kalakad-Mundanthurai Tiger Reserve in South Western Ghats, India by Giriraj et al. (2008), 890 trees ha⁻¹ at Bhadra Wildlife Sanctuary in Karnataka (Krishnamurthy et al., 2009) and 995 trees ha⁻¹ at dry deciduous forest of Rajasthan, India (Kumar et al., 2011). Joshi. (2012) reported stand density of 500-1700 trees ha⁻¹ at tropical dry deciduous forest of West Bengal. This wide variation in stand density could be due to variation in local climatic condition, tree size, soil properties, availability of water

sources and anthropogenic disturbances. The stand density as reported in the present study was modest when compared to those reported for other dry deciduous forest regions in the country.

Tree height: In this study, tree height ranged from 3.5m to 11.2m with an average of 6.2m. The tree height range observed in the present study was much lower than those reported for (1m-35m) dry deciduous forest in Malyagiri hill ranges, a part of Eastern Ghats of India (Sahu et al., 2012), 2.5m-20.5m at dry deciduous forest in Mae Nam Phachi Wildlife Sanctuary, Ratchaburi province, Western Thailand (Chaiyo et al., 2011), 11m-17m at forests in Mt. Gyebangsan, Gangwon-do (Province), South Korea (Jung et al., 2011), 3.5m-26m in mixed/moist evergreen forest of Omo Forest Reserves, Southwest of Nigeria (Dauda et al., 2004), 7.13m-28.68m at forests of Kalkkinen, Helsinki, in Southern Finland (Yu et al., 2004), 3m-35.5m at mixed forest in Koli National Park, North Karelia, Eastern Finland (Villikka et al., 2007), 2.1m-33.93m at semi-deciduous forest in Lama forest reserve (Nagel et al., 2004), 11m-47.5m at forests in Rio Grande do Sul, Espirito Santo and Bahia, Brazil (Nutto et al., 2006), 3.3-27.9m at mixed deciduous forest in Kratie, Cambodia (Monda et al., 2016), 2.5-23.5m, 3.8-23.5m, and 4.4-14.1m at mixed species, *Dipterocarpus* genus and *Shorea* genus, respectively in two eco-regions of Vietnam (Huy et al., 2016). The average tree height measured in the present study (6.2m) was much lower than those reported (14.5m) for tropical rain forest in Royal Belum State Park, Perak, Northern Peninsular Malaysia (Sium, 2015), 17.9m at a multi-tiered mixed deciduous stand in southern Ontario (Hopkinson et al., 2004), 14.77m at *Shorea robusta* dominated forest in Chitwan district, Nepal (Asmare, 2013), 13.2m at dry hill/evergreen forest in Popa Mountain Park, Myanmar (Aye et al., 2014), 1.81m-35.77m, range of mean height measured at 500 dry deciduous tree species at Katarnia Ghat Wildlife Sanctuary (KGWS) in Bahraich District, Uttar Pradesh, and Eda in Ekiti State, Nigeria, 6.69m and 13.80m, mean tree height reported for dry dipterocarp forest and dry mixed deciduous forest in Popa Mountain Park, Myanmar (Aye et al., 2014). The tallest trees were observed in Plot-10 with a mean height of 11.23 ± 3.29 m, whereas shortest trees were observed in Plot-4 with an average height of 3.5 ± 0.52 m. This variations between the plots within the same region may attributed to spatial variability in soil moisture, nutrients, and microclimatic conditions induced due to the topographic variations. Several studies also recorded significant variations in tree architectural properties, both within and across

sites (Nogueira et al., 2008; Brien et al., 1995; Osunkoya et al., 2007; Poorter et al., 2006; Poorter et al., 2003; Sterck and Bongers, 2001).

Diameter at breast height (DBH): Among 10 plots studied in MNP, DBH varied significantly between plots from 8.87cm to 23.30cm. The range of DBH observed in this study was in agreement with those reported for dry deciduous forest in central Cambodia (Kenzo et al., 2017), 17.3-27.35cm at deciduous forest of Latvia in Jelgava District, Riga (Priedītis et al., 2012), 16.7-19.3cm at mixed forest in Universidad Austral de Chile (Moreno et al., 2017), 8.42-28.8cm at deciduous forest in Virginia, Southeastern United States (Sorin, 2002), 4.77-43.29cm at dry deciduous forest in Mae Nam Phachi Wildlife Sanctuary, Baan Beung, Suan Pheung District, Ratchaburi province, Western Thailand (Chaiyo et al., 2011), 11cm and 17.5cm, mean DBH reported for dry dipterocarp forest and dry mixed deciduous forest in Popa Mountain Park, Myanmar (Aye et al., 2014). DBH range observed in the present study was much lower than those reported (27.14-79.57cm) for different dry deciduous forest spp. at Chikaldhara hill station, Amaravati district of Maharashtra (Maan et al., 2015). DBH decreased with increase in stand density observed in the present study was in agreement with other reports (Brokaw et al., 1997; Campbell et al., 1992; Chandrashekara and Ramakrishnan, 1994; Hara, 1997; Ho et al., 1987; Kadavul and Parthasarathy, 1999; Lieberman and Lieberman, 1987; Sahoo et al., 2017; Sundarapandian and Karoor, 2013; Sundarapandian and Swamy, 2000; Swaine et al., 1987). DBH growth rate in tropical trees is usually around 1–10 mm year⁻¹ (Worbes, 1999). In the present study, DBH growth rates varied significantly among the native tree species in MNP, despite the fact that they were close together in stem size and their habitat was similar. Different tree species presented different behaviors under similar conditions. Even for the same species, DBH growth rates vary according to stem size. Average tree growth rate (cm year⁻¹) across the study plots in MNP varied from 0.28-0.91cm year⁻¹ with an average of 0.46 cm year⁻¹. These values compared well with the girth increment observed by (Alder et al., 2002; Silva et al., 2002; Kale and Roy, 2012; Lewis et al., 2004; Murphy and Lugo, 1986; Nebel et al., 2001). While several factors may be responsible for this variation in growth rates, this study considered climatic and edaphic factors had a crucial role in explaining this variation.

Aboveground biomass (AGB): Average AGB across the study plots in MNP varied from 8.3-177.8 Mg ha⁻¹ with an average of 56 Mg ha⁻¹. The biomass estimates obtained in the present study were well within the range of those reported worldwide as well as dry deciduous forests in India (Bijalwan, 2010; Brown and Lugo, 1982; Chave et al., 2005; Hergoualc'h and Verchot, 2011; Kumar et al., 2011; Mani and Parthasarathy, 2007; Pande, 2005; Patra et al., 2013). However, the estimates of present study are higher than those reported by Ranawat and Vyas. (1975) for deciduous forest of Udaipur, India, (George et al., 1990) (28.2 Mg ha⁻¹), for tropical dry ecosystem of India, 19 Mg ha⁻¹ in Mysore district and 24 Mg ha⁻¹ for Hassan district by Devagiri et al. (2013) for dry deciduous forests of Western part of Karnataka, India and 27.44 Mg ha⁻¹ by Kale et al. (2009) in tropical dry deciduous forests of Shivpuri district of Madhya Pradesh in Central India. Mean biomass reported in the present study were relatively lower than those reported by Singh and Singh. (1981) for dry deciduous forests in Varanashi district of UP., India with 64.3 Mg ha⁻¹, the mean biomass of 78.31 Mg ha⁻¹ in mixed and 66.34 Mg ha⁻¹ in teak mixed forest have been reported by Bijalwan. (2010) at tropical dry deciduous forests of Chattisgarh state in India. These discrepancies in biomass storage among those studies were probably associated to stand age structure and disturbance (Goodale et al., 2002; Keith et al., 2009; Pregitzer and Euskirchen, 2004). Biomass in tropical forest vary on a landscape scale because of the spatial heterogeneity in species composition, successional states, stand age, slope, geography, climate, rainfall pattern etc as stated by (Slik et al., 2010), Lewis et al. (2013) and Berenguer et al. (2014). However, high biomass at Plot-10 in the present study could due to high stand density and presence of large diameter class trees such as *Syzygium cumini* contributed for the increase in biomass. Several researchers have also confirmed that trees with high diameter class account more biomass in forests (Brown, 1996; Brown and Lugo, 1982; Clark and Clark, 1996; Slik et al., 2013). Though stand age was not recorded in the present study, number of studies showed that biomass and carbon storage varies significantly with stand age, old-growth forests generally hold more biomass than land with younger forests (Aide et al., 2000; Baker et al., 2004; Brearley et al., 2004; Brown and Lugo, 1990; Chinea and Helmer, 2003; Gehring et al., 2005; Guariguata and Ostertag, 2001; Kennard, 2002; Kumar et al., 2006; Lewis et al., 2009; Lugo and Helmer, 2004; Muniz et al., 2006; Phillips et al., 1998; Turner et al., 1997). However, stand age could be one of the possible reasons why trees in Plot-10 hold more biomass as compared to trees in the other plots. Plot-4 showed least biomass

stock, which could be due to poor stand density (140 tree ha⁻¹) and many trees with lower girth classes. Soil properties and scarcity of ground water sources were also reason for this situation (Pande, 2005). An effort was made in the present study to determine relative deviation (RD) in biomass stock across the study period. The analysis showed marked variation in RD between the plots. Though stand density and biomass stock was very less in Plot-4, but RD (%) in biomass was very high in this plot. Average biomass change in Plot-4 was about 227% of its biomass in 2010. This was mainly attributed to the growth of intermediate size trees, indicating that trees in this plot could yet to reach their mature stage. It has been consistently show that biomass of regenerating trees increases over time with particularly high rates of storage in the first 20 years of post- abandonment (Bonner et al., 2013; Marín et al., 2008; Silver, et al., 2000). Despite of differences in stand age, RD in biomass is also a function of several tree structural parameters like stand density, height, and DBH at given location and time. Minimum RD in biomass AGB was witnessed in Plot-10 with 4.9%. This could be due to static growth rate of forests in the plot. RD across the plot was found to be highest in 2013 with an average of 83%, whereas the lowest change in AGB was observed in 2011 with a mean of 12%. This inter-annual variation in RD was strongly linked with the seasonality of meteorological variables especially rainfall, temperature and radiation.

Field based NPP: Field based average NPP obtained across the study period from 2.42-3.66 Mg ha⁻¹ year⁻¹ with an average of 3.22 Mg ha⁻¹ year⁻¹. Comparisons with other forests around the world show that the aboveground NPP of the dry deciduous forest in MNP was comparable (1.1-11.03 Mg ha⁻¹ year⁻¹ with an average of 4.9 Mg ha⁻¹ year⁻¹) with another study conducted at MNP (Kale and Roy, 2012). The aboveground NPP values obtained in this study was lower than those reported (6.42–25.39 Mg ha⁻¹ year⁻¹) for tropical forests (Karmacharya and Singh, 1992; Negi et al., 1995), 10.2 Mg ha⁻¹ year⁻¹ at tropical dry deciduous forest in Uttar Pradesh (Singh and Singh, 1991), 14.7 Mg ha⁻¹ year⁻¹ at dry deciduous forest in Vindhyan highlands of India (Kumar, PhD, Thesis), 6-16 Mg ha⁻¹ year⁻¹ global pattern of aboveground NPP at dry tropical forest (Murphy and Lugo, 1986), 6.9 Mg ha⁻¹ year⁻¹ at tropical dry forest in Mexico (Martinez et al., 1996), 10 Mg ha⁻¹ year⁻¹ at Subtropical dry forest in Puerto Rico, Guanica (Clark et al., 2001), 8.9 Mg ha⁻¹ year⁻¹ at tropical dry forest in Mexico, Chamela lower plot (Clark et al., 2001), 7.3 Mg ha⁻¹ year⁻¹ at tropical dry forest in

Mexico, Chamela middle plot (Clark et al., 2001), 6.4 Mg ha⁻¹ year⁻¹ at tropical dry forest in Puerto Rico, Pico del Este (Clark et al., 2001), 10.4 Mg ha⁻¹ year⁻¹ at tropical dry forest in SE Peru (Girardin et al., 2010), 13-20 Mg ha⁻¹ year⁻¹ for Shisham forests (Lodhiyal et al., 2002), 10 Mg ha⁻¹ year⁻¹ for *Gmelina arborea* forest in India (Pacholi, 1997), 14.6-15.7 Mg ha⁻¹ year⁻¹ (Singh, 1979), 7.7 Mg ha⁻¹ year⁻¹ at 24 year old Sissoo plantation (Sharma et al., 1988), 19.2 Mg ha⁻¹ year⁻¹ at tropical rain forest in Malaysia (Reichle, 1981), 11.4 Mg ha⁻¹ year⁻¹ at tropical moist forest (Golley, 1975), 15.5 Mg ha⁻¹ year⁻¹ at Rianj dominated forest in India (Rana et al., 1989), 16-18.9 Mg ha⁻¹ year⁻¹ (Singh and Singh, 1989), 17.3 Mg ha⁻¹ year⁻¹ at Chir-pine forest in India (Rana et al., 1989), 7-10 Mg ha⁻¹ year⁻¹ at Conifer forest in USSR (Rodin and Bazilevich, 1967), 11 Mg ha⁻¹ year⁻¹ at Pine forest in USA (Whittaker, 1966), 18.7 Mg ha⁻¹ year⁻¹ for *Cassia siamea* forest in India (Pacholi, 1997), 10.9 Mg ha⁻¹ year⁻¹ for *Camelia japonica* forest in Japan (Tadaki, 1965), 28.6 Mg ha⁻¹ year⁻¹ at tropical rain forest in Thailand (Kira, 1967), 29.4 Mg ha⁻¹ year⁻¹ at *Camelia japonica* in Japan (Kan et al., 1965), 24.3 Mg ha⁻¹ year⁻¹ at tropical rain forest (Wanner, 1970), 22.3 Mg ha⁻¹ year⁻¹ at *D.sissoo* forest in Bihar (Pacholi, 1997), 12.6-20.3 Mg ha⁻¹ year⁻¹ at 5-15 years old Tarai Shisham forests in central Himalaya (Lodhiyal et al., 2002), 11.4-14.8 Mg ha⁻¹ year⁻¹ at 5-,10- and 15 years old Bhabar Shisham forests in Uttaranchal (Lodhiyal and Lodhiyal, 2003). This wide variation in NPP across different dry tropical forests regions may be partly due to variations in climate, especially the length of the growing season when both thermal and moisture conditions were favorable. This could be also attributed to differences in the availability of soil water and nutrients. Chaturvedi et al. (2011) and Kumar Phd Thesis. (2011) had observed a significant effect of soil moisture on growth of tropical dry deciduous forests at Vindhyan highlands in India. In several other studies also nitrogen availability was shown to be constrain the productivity of tropical forests (Tanner et al., 1998; Vitousek and Sanford, 1986). In the present study, high NPP was observed at Plot-10, which could be attributed to presence of large sized trees with high growth rate (increment in DBH, cm tree⁻¹ year⁻¹) as well as adequate of moisture and consequently less frequent fires and higher biomass increment. Poor NPP in Plot-4 was probably caused by sparse stand density with poor increment in DBH and lack of soil moisture.

4.3.2 Climate variability

Many studies have shown that temperature, precipitation and radiation were among the major climatic controlling factors of NPP at a region scale (Churkina and Running, 1998; Whendee et al., 1998). Optimal climatic conditions allow all forest type species to survive and flourish and also result in lower stress due to competition for sunlight and nutrients. Forest types in MNP experiences large variability in climatic conditions. Therefore MNP hold less number of trees species and stand density as compared to forests at Central and Northeastern regions in Madhya Pradesh. Thus indicating a strong influence of local climatic conditions on forest growth and their composition. Net Primary Productivity of deciduous forests in MNP varied significantly with rainfall, temperature and radiation. The results were comparable with another study conducted in an Indian tropical ecosystem (Chitale et al., 2012). Temperature plays critical role in metabolism through its effects on rates of biochemical reactions (Gillooly et al., 2001), thus optimum temperatures in combination with adequate soil moisture enhance photosynthetic activities of trees resulting increase in their productivity. MNP experiences large variability in local climatic conditions and also indicated poor forest productivity as compared to productivity at deciduous forest sites at Northeastern regions in Madhya Pradesh (Singh et al., 2011a). Inter-annual pattern of productivity in relation with climatic parameters in MNP indicated that increase in temperature, radiation and decrease in rainfall was unfavorable for most of areas in the park. A study by Melillo et al. (1993) showed the elevated temperatures have resulted in decrease in productivity by decreasing soil moisture or enhancing plant respiration. Our findings suggest that seasonal and inter-annual variation in climatic parameters strongly associated to the spatial distribution of forest NPP in MNP. CASA modelling using these climate factors suggest that all the sample plots located in the same park may experience the same climate but differ in their productivity. It reveals that at the macro-scale deciduous forest NPP is mainly governed by climate, at landscape to regional scales, climate factors were not the only components that affect productivity patterns; other environmental components like topography, fire, soil as well as disturbances also play important role in productivity distribution.

4.3.3 Forest mapping

Multi-temporal Landsat imageries representing three key phenological stages (start of senescence and leafless phase and full growth phase) of dry deciduous forests in MNP were used to generate forest cover map of the region. Rationale behind using multi-

temporal imageries was, every plant species respond to biological processes such as pigmentation and senescence in distinctive ways and at different rates. These multi-temporal imageries acquired in key phenological phases capture changes in foliar presentation and facilitate for separating forest classes that may be spectrally similar in any one single acquisition image (Chuine and Beaubien, 2001; Dymond et al., 2002). (Singh et al., 2011) had also followed a similar approach for forest type mapping in Kanha National Park, Madhya Pradesh. The study area was initially classified with a 80 cluster using unsupervised ISODATA classifier, of which eight landuse/landcovers have been identified. Among these eight classes, mixed forest dominated by Kardhai was found to be a major forest type in the region. This finding was consistent with the results obtained in previous studies conducted at MNP (Kale et al., 2002; Roy and Ravan, 1996). Total forest area estimated in the present study was (357.80 Km²) very close to that of an area reported (375.22 Km²) in Forest Management Plan of the region. Accuracy assessment is crucial before using satellite derived products in to any ecosystem model. Accuracy assessment for the forest map generated in the present study was performed using ground survey data. Comparison of both the data sets yielded an overall accuracy of 82%, indicating very high agreement between both the data sets. This 18% error between both the data sets was basically due to misclassification of grassland to the cropland, fact that grassland and cropland have a similar growth profile and therefore can easily be misclassified each other. Error could be also due to several other factors such as challenges in extracting training area statistics, the classification decision model, spectral limitations of the satellite sensor, accuracy assessment constraints, and the reference data itself.

4.3.4 CASA modelling

Carnegie–Ames–Stanford Approach (CASA, Potter et al., 1993) is one of the widely used ecosystem models, which offers an inimitable opportunity for simulating forest NPP at regional and global scale with less input data (Bala et al., 2013; Goroshi et al., 2014; Liu et al., 2018; Nayak et al., 2013; Potter et al., 2013; Potter et al., 2012; Yu et al. 2009). Present study estimates dry deciduous forest NPP in MNP using CASA ecosystem model driven by multi-temporal Landsat imageries for the period 2011-2014. Spatial distribution of annual NPP indicated higher NPP along with Sankya Sagar Lake and Atal Sagar Lake. These high NPP areas were largely covered with Kardhai mixed forest and Salai mixed forest. High NPP along with the water bodies could be

due to favorable microclimate conditions induced due to the topographic variations. NPP appeared to be lower in Northern parts of the region due to sparse stand density. This spatial NPP distribution pattern is in accordance with that of Bala et al. (2013); Goroshi et al. (2014); Nayak et al. (2013), who estimated NPP for different biomes in India. NPP varied significantly among different forest types in the region. Average NPP varied as value by mixed forest ($5.78 \text{ Mg ha}^{-1} \text{ year}^{-1}$) > Kardhai mixed forest ($3.78 \text{ Mg ha}^{-1} \text{ year}^{-1}$) > Salai mixed forest ($3.16 \text{ Mg ha}^{-1} \text{ year}^{-1}$). The findings were well within the range of another study conducted in MNP (Kale and Roy, 2012). These estimates were also in line with those reported ($0.29\text{-}3.81 \text{ Mg ha}^{-1} \text{ year}^{-1}$) for dry deciduous forest species in Panna National Park in Madhya Pradesh (Singh, 2008). The results were relatively lower than those reported for ($4.76\text{-}6.39 \text{ Mg ha}^{-1} \text{ year}^{-1}$) dry deciduous forest NPP at Chhindwara forest division, Madhya Pradesh (Pande, 2005), $6.17\text{-}12.06 \text{ Mg ha}^{-1} \text{ year}^{-1}$ in Southern Haryana (Singh et al., 2017), $6.7\text{-}15.8 \text{ Mg ha}^{-1} \text{ year}^{-1}$ at tropical dry forest in Santa Rosa national Park, Costa Rica (Cao et al., 2016). Average CASA NPP obtained across different sample plots varied from $4.32 \text{ Mg ha}^{-1} \text{ year}^{-1}$ (Plot-6) to $2.72 \text{ Mg ha}^{-1} \text{ year}^{-1}$ (Plot-4) with an average of $3.7 \text{ Mg ha}^{-1} \text{ year}^{-1}$. Mean NPP simulated in the present study was much lower than that of an average NPP reported for deciduous broad leaf forest in East Asia using CASA model (Goroshi et al., 2014; Nayak et al., 2010; Yu et al. 2009). Difference between the estimates was due to difference in scales when comparing 30m Landsat NPP simulated in the present study with those reported using MODIS NPP (1km), SPOT VGT (1km) and INSAT NPP (8km) estimates. The difference could be also due to various inputs like rainfall, temperature and light use efficiency used for simulating NPP. Inter-annual variability of NPP across the sample plot varied from $2.87 \text{ Mg ha}^{-1} \text{ year}^{-1}$ (2014) to $5.5 \text{ Mg ha}^{-1} \text{ year}^{-1}$ (2013) with an average of $3.7 \pm 0.2 \text{ Mg ha}^{-1} \text{ year}^{-1}$. This inter-annual variability of deciduous forest NPP in MNP was due to both extrinsic (e.g., climate) and intrinsic (e.g., stand structure stand structure and composition, small scale disturbance, microclimatic variation created by stand structure, and species competition) drivers. Several studies have revealed that climate in part governs stand growth and site productivity patterns (Cook, 1990; Fritts and Swetnam, 1989; Gedalof and Smith, 2001; Peterson et al., 2002), while others have reported about stand density including disturbances, mortality, and competition to be crucial drivers of tree growth as well (Bormann et al., 1995; Cook, 1990; Lutz and Halpern, 2006; Piutti and Cescatti, 1997).

Several studies in Southeast Asia (Fang et al., 2001; Ichii et al., 2013; Wang et al., 2016; Yoneda et al., 2016; Zhang et al., 2012) have point out that inter-annual variations in rainfall was responsible for fluctuation in NPP, but the authors also showed that the sign of a given ecosystem response could differ, and that further investigation of the causes of variations in NPP were warranted.

4.3.5 Validation of CASA NPP

CASA simulated NPP for dry deciduous forest in MNP was validated using field measured NPP across 10 sample plots in the region for the period 2011-2014. Good agreement was observed between both the data sets with coefficient of determination (R^2) 0.94, explaining 94% variability at 95% confidence level. The mean values of field and CASA simulated NPP were $3.22 \text{ Mg ha}^{-1}\text{year}^{-1}$ and $3.71 \text{ Mg ha}^{-1}\text{year}^{-1}$, respectively. Mean NPP estimated by CASA model was relatively higher than the field measured NPP with the root-mean square error (RMSE) of $0.59 \text{ Mg ha}^{-1}\text{year}^{-1}$, which was 18% of the mean field measured NPP. The agreement between both the data sets justifies the model's utility for estimating tropical dry deciduous forest NPP in MNP. This model incorporates not only climatic information, but also high spatial resolution forest cover data, as parameterized in this study. The 18% error in the model estimates may be due to CASA NPP estimates were based on land areas represented by the gridded input data sets used by the model, whereas field based NPP estimates were based on the quadrat areas (0.1ha) actually sampled at each forest cover site. This is very important because the model simulated the average NPP of all vegetation types over a grid square, and because the issue of scaling-up of NPP from the sampling area to a grid cell should be taken carefully into account. The difference could be also due to several other factors, the model as it was used in this study does not, however, simulate the effects of soil variability within the regions, anthropogenic disturbances and other factors on forest NPP. This may explain why the modeled forest NPP values were relatively higher than those calculated from field measured data. The strong correlation between inter-annual NPP and rainfall during the study period highlights the need to collect more accurate and spatially explicit rainfall data in the CASA model, as there was only one meteorological station was available at MNP for our study. It was also important to consider the influence of forest cover type on spatial variability of NPP in the model. This model relies heavily on forest cover inputs and also assumes that forest cover was consistent year to year, which may not be

happening in reality. The static nature of forest cover limits the ability of the model to capture forest cover changes and adjust NPP estimates accordingly. Although the model results might relatively overestimate, the CASA model was a powerful ecosystem model for simulating dry deciduous forest NPP at larger spatial scale with less input data. While the application of the CASA model may be reasonable at species scales, the model NPP estimates can be improved through (1) finer forest type classifications, and (2) accurate quantification of the effects of soil water condition, meteorological data on forest NPP. Each ecosystem model has its limitations and CASA is no exception. owing to these reasons, it is always better to perform and learn from model inter-comparison with respect to various key variables, using common input data sets at regional and global scales.

4.4 Association between NPP and climatic parameters

4.4.1 Effect of precipitation on NPP: An effort was made in the study to determine correlation between deciduous forest NPP and rainfall at KNP, BNP and MNP for the period 2011-2014. The relation between both the variables provide valuable information to increase our understanding about how deciduous forest respond to variation in rainfall at Central India. Deciduous forest NPP simulated from the CASA ecosystem model and annual rainfall recorded by AMS towers were used in this analysis. Results showed strong correlation between both the variables ($r=0.88$), which implies that rainfall was a major driving force of NPP changes in the study regions. The association between both the parameters perfectly corresponds to the geographic location and forest types. NPP value gradually increases along a gradient from Northwest (MNP, dry deciduous forest) to Southeast (KNP, moist deciduous forest) in the Central India. Noticeably, it appears to be spatially coupled with the characteristic rainfall pattern of Central India. This result was supported by the correlation analysis in the study, which showed significant correlation between NPP and rainfall. Results of this study were consistent with previous studies carried out in India to characterize the relation between terrestrial vegetation NPP and rainfall (Bala et al., 2013; Nayak et al., 2013). On the otherhand, such consistency validated that NPP derived from CASA ecosystem model can represent the real ecosystem production in the current study site, thus providing an effective way to monitor dynamic ecosystem changes on a regional scale in Central India. Results of the present study were also constant with those observed in other regions of the world (Nemani, 2003; Potter et al., 2012; Zhang et al.,

2004; Zhao and Running, 2010). The strong association between NPP and rainfall was well in line with that of the other studies in different biomes (Churkina and Running, 1998; Fang et al., 2001; Garbulsky et al., 2010; Petrie et al., 2016; Thomey et al., 2011; Zhu and Southworth, 2013). This suggests that NPP may be key biophysical variable for determining rainfall effects on deciduous forest growth in the study regions. NPP values remain around their mean NPP unless there was any change in rainfall. As the rainfall surpasses their mean annual rainfall, the NPP values increased rapidly, scattered points were mostly spotted above the linear trend line. For instant, MNP had received 31% more rainfall in 2013 compared to its mean annual rainfall, however forests in the region had shown 48% more NPP ($5.5 \text{ Mg ha}^{-1} \text{ year}^{-1}$) compared to their mean NPP ($3.7 \text{ Mg ha}^{-1} \text{ year}^{-1}$). Contrastingly, KNP had received comparatively less rainfall in 2013 and 2014, where forests in the region had shown considerably low NPP in both the years. The results were in line with those highlighted earlier (Briggs and Knops, 1995; and Jobbagy et al., 2002) as spatial variation in rainfall-NPP relationship caused by topography. These results also confirmed previous findings that rainfall values can be used as a proxy for NPP over a wide geographical scale (Davenport and Nicholson, 1993, Kawabata et al., 2001, Jobbagy et al., 2002). The results obtained from this work also confirms the study by Tucker et al. (1985) and Lasponara. (2006), who found that rainfall patterns were those expected from ecoregion mapping, which were based on a long-term stable climate and topography.

4.4.2 Effect of temperature on NPP: Results from correlation analyses shows the negative effect of temperature on deciduous forest NPP in KNP, BNP and MNP for the study period 2011-2014. Several studies had been also conducted worldwide to understand the relation between NPP and temperature (Bala et al., 2013; Cramer et al., 2001; Nayak et al., 2013; Nemani et al., 2003; Piao et al., 2005). This negative effect of temperature on NPP was possibly due to drier conditions under a warmer climate. Prolonged warming can increase soil moisture deficit and drought conditions. (Zhang et al., 1998) studied about the influence of temperature on vegetation type showed possibility of decrease in wet forest and moist forest area, whereas there was increase of desert shrub area, highlighting a drier condition under higher temperature. (Zhou and Zhang, 1996) evaluated the climate-vegetation relationship and reported that temperature rise will possibly result in a decrease of forest cover in China. A study

using Water Vegetation Energy and Solute modelling (Yang et al., 2003) predicted the possible reduction in plant productivity under warmer conditions due to increased limitation of soil moisture. It has been depicted in **Figure 32** that low NPP in MNP was stringed with low rainfall and high temperature; relatively high NPP in BNP than MNP was due to moderately high rainfall and comparatively low temperature and low radiation, followed by high NPP in KNP was due to high rainfall and high temperature and high radiation. Low temperature may restrict the efficiency of photosynthesis, higher air temperatures in the high rainfall region may get associated with higher NPP. By contrast, forests growing under higher temperature with low rainfall, may have greater respiration rates and if photosynthesis is not higher (or reduced due to higher atmospheric water vapour pressure deficit (Asher et al., 2013; Duveneck and Thompson, 2017; Lloyd et al., 2002) impacting NPP. Although NPP in the present study was not significantly related with mean annual temperature, and in Asia most of the best models relating NPP to climatic conditions do not include temperature, suggesting any NPP-temperature relationship may be relatively weak, or is being masked by other factors. This study made an attempt to look at NPP variability as impacted by temperature change. Relating temperature variability to the NPP dynamics of deciduous forest covers need more attention and exploration.