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Terrestrial Net Primary Productivity and Net Ecosystem Productivity over India

Ocean Sciences Group
Earth and Climate Science Area
NATIONAL REMOTE SENSING CENTRE
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Contents

1. Abstract

The Carnegie-Ames-Stanford Approach (CASA) terrestrial ecosystem model is implemented for simulating long-term monthly Net Primary Productivity (NPP), Net Ecosystem Productivity (NEP), Soil Respiration, Soil Organic Carbon Content and associated CO_2 exchange parameters between Indian terrestrial ecosystem and atmosphere at 5 km grids during 1981-2006. This model is driven by time varying normalized difference vegetation index (NDVI), climate parameters (air-temperature, precipitation, solar radiation) and land cover and soil attribute maps. Besides that a number of biome-specific parameters (such as Light Use Efficiency, C/N ratio) in the model are tuned to the values for accounting regional heterogeneity of the ecosystem response accurately. NPP and NEP products were analyzed for understanding seasonal, inter-annual and climatic variability of these parameters over India and published.

2. Introduction

Terrestrial ecosystem plays a dominant role in regulating variability of the atmospheric CO_2 in different time scales. Understanding the carbon (C) sink or source potential of terrestrial ecosystems and their variability in relation to climatic drivers are critical to elucidate and quantify climate-carbon feedbacks. Over the past few decades, understanding of the global terrestrial C cycle has been improved owing to several reasons: rapid establishment of in situ networks of atmospheric CO_2 observations and inventory of vegetation types and their attributes; development in remote sensing based monitoring of land surface properties; and enhanced ecosystem modeling. For regions such as USA, Europe and China carbon budgets and associated causes of variability in C sources and sinks are more or less understood. However, regional scale C budget for India is not yet accurately assessed or understood despite the country has occupied large land mass (3.28 million km^2) with sizeable forest cover (23%) of high biomass potential.

In the past, studies on carbon cycle for India were mainly based on forest inventory data sets and were focused to assess biomass, growing stocks, primary productivity, carbon sequestration in forest, and net carbon flux from land use changes. The inventory estimate of the net carbon flux over Indian forest from diverse methodology and data sources had large uncertainty. The net carbon balance estimates over Indian forests range from emissions of 0.4 Tg y^{-1} to a sink value of 5.0 Tg y^{-1}. Estimates based on IPCC report shows that Indian forests act as a sink with CO_2 uptake of 1.09 Tg C y^{-1} in 1990s.

Accurate and long-term monitoring of carbon exchanges and its inter-annual variability over India is essential for better understanding of the regional carbon budget for India and its link with global carbon cycle. Development and improvement in global terrestrial ecosystem models in the last two decades have opened a scope for gearing up carbon cycle research at global and regional scales. In our study, we have used remote sensing driven CASA (Carnegie Ames Stanford Approach) model to simulate long-term pattern of net ecosystem productivity (NEP) over diverse terrestrial ecosystems in India and studied its spatial and temporal variability.

3. Model Description

The CASA is a simple terrestrial biosphere model based on light-use efficiency (LUE) that simulates terrestrial Net Primary Productivity (NPP) by estimating optimal metabolic rates of carbon fixation under the limiting effect of temperature and water stress scalars. The model mechanism can link seasonal pattern of NPP to soil heterotrophic respiration (Rh) worldwide. First order decay equations simulate exchanges of decomposing plant residue (metabolic and structural fraction) at the soil surface. The model also simulates surface soil organic matter (SOM) fraction that presumably vary in age and chemical composition. Turnover of active (microbial biomass and labile substrates), slow (chemically protected), and passive (physically protected) fraction of the SOM are represented in the model. Figure 1 shows how the soil module and biomass allocations are defined within the model. The model has been implemented by several organizations to estimate regional or continental patterns of NPP and the CO2 sink over North America, Eurasia, South America, Africa, and recently, it has also been implemented for the Indian subcontinent (Nayak et al., 2010).

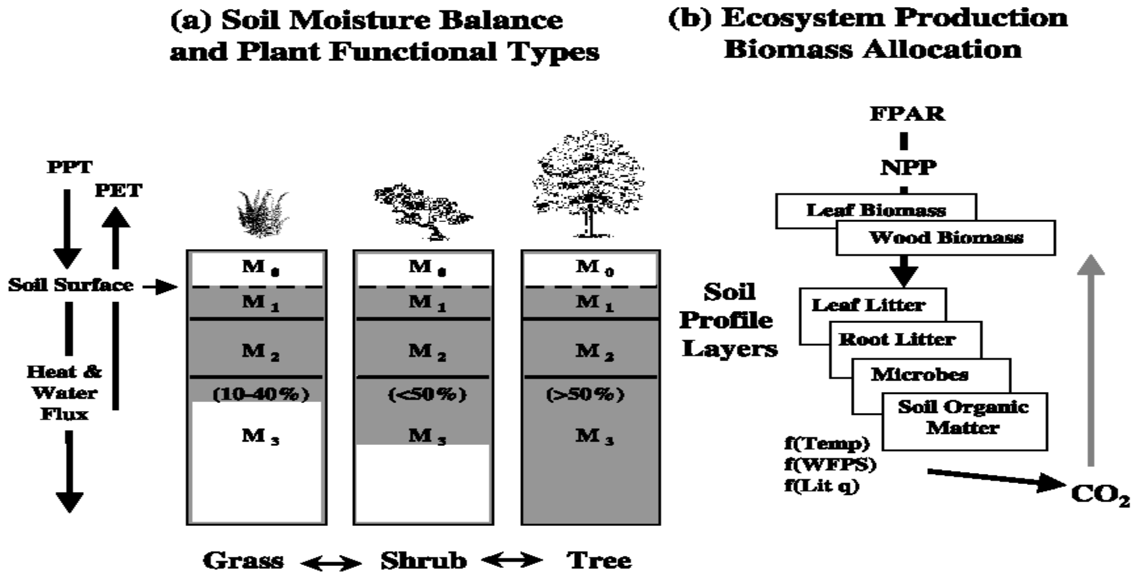

Figure 1: Schematics of simplified soil module and ecosystem production biomass allocation inside the CASA model.

4. Model Data Sets and Methodology

4.1 Forcing Fields: NDVI and Climatic Parameters

We employed CASA model to simulate long-term (1981-2006) monthly carbon cycling parameters (NPP, NEP etc.) at 8 km spatial resolution with spatially explicit input of monthly climate and normalized differential vegetation index (NDVI) and stationary maps of soil and vegetation attributes. Monthly vegetation greenness and climatic elements, and other land surface properties are obtained from variety of sources. The monthly NDVI data at 8-km spatial resolution are obtained from archives of Global Inventory Modeling and Mapping

Studies (GIMMS).The high resolution (0.5 degree) monthly long-term climate databases based on Climate Research Unit (CRU), University of East Anglia (UEA) (www.cru.uea.ac.uk/cru/data/hrg) form the source of input climatic parameters: air-temperature, precipitation and cloud fraction in the model.

4.2 Land Cover Attributes Map

Spatial pattern of natural and agricultural land cover types and their characteristics are among the basic variables that the model needs to specify land cover LUE. This is taken from digitally classified land cover map of Southeast Asia at 1 Km spatial resolution which was originally prepared from multi-date SPOT-VEGETATION data under global land cover-mapping project. The map contains 16 natural forest vegetation and 28 other non-forest classes. These large numbers of categories were grouped into 12 categories as per USGS land cover scheme. The land cover characteristics such as Maximum Leaf Area Index (LAI), maximum NDVI (NDVImax), and minimum NDVI (NDVI min) were based on published studies for each vegetation type so as to represent regional heterogeneity. The land cover attribute data were then resampled at 2minute spatial grids using ENVI pixel aggregate function. The map is presented in Figure 2. As shown, the landmass of India is predominantly covered by croplands (irrigated and rain-fed; 53.5%), followed by natural forest (deciduous and evergreen broadleaf; 20%), and mixed shrub and grassland (11%) categories (Table1).

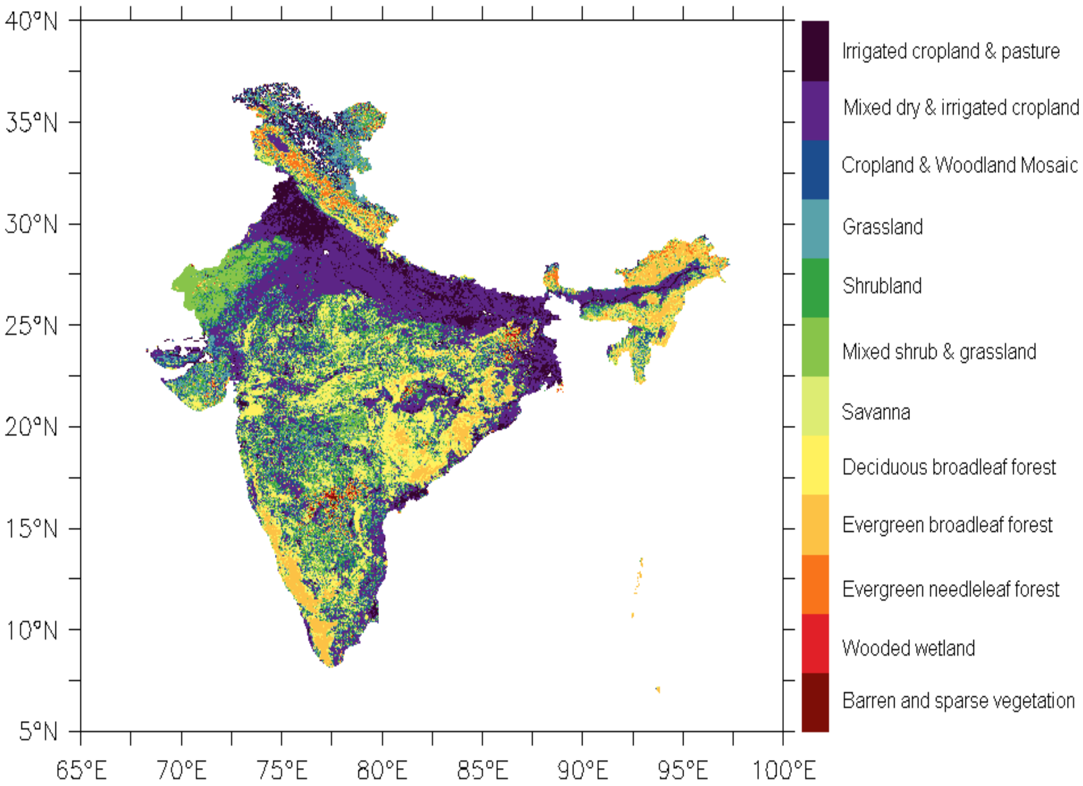

Figure 2: Land Cover Map of India used in CASA Model.

4.3 Soil Attributes Map

Spatial patterns of soil texture map along with temperature and precipitation govern the soil moisture sub-model in the CASA. In this study, the soil attribute map of India at the model resolution was prepared from global datasets of sand, silt, and clay fraction in 0–30 cm depth at 5-min resolution based on the Food and Agriculture Organization (FAO) of UNESCO world soil map. Steps followed to prepare the soil texture map of India include: (i) interpolation of sand, silt, and clay fraction data at the model resolution of 2’ ×2’ and (ii) preparation of soil attribute map as per the seven classes defined in the CASA model.

4.4 Ground Based Cropland NPP Estimates

Annual crop production data at district level were obtained from Department of Agriculture of three States namely Gujarat, Rajasthan and Punjab. Analysis of data was restricted to only those crops grown on more than 10 thousand hectares in each state (Table 1). Steps followed to convert harvestable product into NPP at district level are discussed in detail in Nayak et al.,2010 .The present study assumes that 45% of crop biomass is C and above ground biomass accounts for 80% of total crop biomass. The cropland NPP is thus expressed as gram C per unit area and is calculated as:

$$NPP(gCm^{-2}) = \sum_{i=1}^{N} \frac{Y_i \times MY_i \times (1 - MC_i) \times 0.45 \frac{gC}{g}}{HI_i} / \sum_{i=1}^{N} A_i$$

Where, Y_i is reported production for crop *i*, MY_i is the mass per unit of harvestable product, A_i is the harvest area of crop *i*. The numerator and denominator are summed over N = 16 crops. The values of MC_i and HI_i of different crops were taken from published literature **(**Lobell *et al.* 2002; Bastiaanssen and Ali 2003).

Table1. Maximum leaf area index (LAI) and maximum light use efficiency (ε) across different vegetation cover types used in CASA model in present study.

Vegetation type	**% total land coverage of the country (~329 million hectares)**	**LAI max[a]**	**ε*[b]**
Irrigated cropland and pasture	16.45	6.0	0.770
Mixed dry/ irrigated cropland mosaic	36.83	5.0	0.498
Cropland and wood land mosaic	1.65	5.0	0.452
Grassland	3.73	5.0	0.234
Shrub land	0.98	4.5	0.345
Mixed Shrub and grassland	10.81	4.5	0.300

Savanna	0.11	5.5	0.400
Deciduous broad-leaf forest	14.80	7.5	0.540
Evergreen broadleaf forest	5.15	8.0	0.700
Evergreen needle-leaf forest	1.74	9.0	0.42
Wooded wetland	0.004	7.0	0.41
Barren or Sparse vegetation	1.21	3.0	0.21

[a] Values are compiled from global LAI datasets (Scurlok et al. 2001) and literature

[b] ε* for agricultural land taken from Lobell et al. 2002 and for forest cover categories from Ahl et al. 2004

Table2. Parameter values of major crops used in cropland NPP estimates.

Crop	**Harvest index[a]**	**Moisture content (%)[b]**	**Unit of harvested product**
Paddy	0.425	9	kg/ha
Sorghum	0.35	10	kg/ha
Maize	0.4	11	kg/ha
Millets	0.3	-	kg/ha
Other pulses	0.3	9	kg/ha
Tur	0.3	9	kg/ha
Segamum	0.25	10	kg/ha
Ground nut	0.35	9	kg/ha
Castor	0.3	11	kg/ha
Cotton	0.1	8	Bales/ha

Bajra	0.3	10	kg/ha
Wheat	0.35	11	kg/ha
Gram	0.25	10	kg/ha
Mustard	0.25	9	kg/ha
Sugar cane	0.25	80	Ton/ha
Cumin	0.4	9	kg/ha
Potato	0.6	80	Ton/ha

[a] Harvest index values are taken from Datye et al., 1997, Bastiaanssen and Ali, 2003

[b] Values taken mainly from Lobell et al., 2002

4.5 Setting the Model Parameters and experiments

There are several parameters needed to be specified in the model. In present study, except the two parameters: maximum light use efficiency (ε*), and leaf area index (LAI), the values of other parameters were taken as the same used in global NPP study. ε^* is an important parameter which exhibits large variation within the different vegetation cover type. Generally in the global NPP simulation studies, ε^* is taken as a constant value between the range of 0.39-0.43 gC MJ^{-1}, which might be one of the major causes of exhibiting large uncertainty in the model results. Most of the previous studies carried out over Indian agro ecosystem have used ε^* as constant; however, ε^* exhibits spatial variation across vegetation types. In the present study, we, have used variable ε^* and LAI parameter for various land cover/vegetation types based on published literature (Table 1).

5. Seasonal Variability of NPP

The spatial pattern and country-level mean NPP on a monthly time scale for the climatological year is presented in Figure 3a-b. These figures illustrate that there are two growing seasons: January to March (winter) and July-October (summer and post summer). When dry winter monsoon spell continues in the country, most part of the country exhibits low magnitude of NPP (<100 g C m^{-2} $month^{-1}$) in the month of January. The normalized cumulative frequency plot (Fig. 4) shows that more than 85% pixels in this month have the lower range NPP (< 40 g C m^{-2} $month^{-1}$). The mean NPP over the country during this month is 27.5 ± 24.1 g C m^{-2} $month^{-1}$ (mean ± standard deviation). Low magnitude of mean NPP in January was mainly ascribed to retardation of deciduous forest growth over Western-Ghats and north-eastern region caused by inhibiting low temperatures. In subsequent month (February), NPP increases substantially in the most part of the Indo-Gangetic plain (150 - 200 g C m^{-2} $month^{-1}$) and elsewhere in the agricultural lands of the country. Now the number of pixels showing lower values of NPP (< 40 g C m^{-2} $month^{-1}$) reduced to 65%. High magnitude of NPP in the February mainly results from its coincidence with peak growth stages of major crops grown in India. The drastic increase in NPP over the croplands enhances the mean NPP of the country up to 48.2 ± 47.3 g C m^{-2} $month^{-1}$ in this period. However, towards the end of winter season (March), the levels of NPP over croplands decline due to senescence and maturity of crops which in turn results into reduced mean NPP (42.0 ± 40.0 g C m^{-2} $month^{-1}$) of the country. The magnitude of NPP from April onwards declines more rapidly particularly over Indo-Gangetic plain and attain lower levels of NPP (<15 g C m^{-2} $month^{-1}$) by the end of May. The histogram plot also shows that more than 70% of pixels in country have lower ranges of NPP during these dry months. Although the higher NPP (> 150 g C m^{-2} $month^{-1}$) observed over forested lands of western peninsula and north-eastern States during these dry months, the country-level mean NPP declines drastically and is reached to the yearly lowest value (25.5 ± 23.5 g C m^{-2} $month^{-1}$) in May.

The commencement of southwest monsoon by the end of June leads to an increase of NPP over major parts of the country. The progress of south-west monsoon through July and August further enhances magnitude of NPP over most part of the country. The NPP over the Indo-Gangetic plain increases from 20 - 100 g C m^{-2} $month^{-1}$ in June to large values (> 100 g C m^{-2} $month^{-1}$) in August, whereas the NPP over the eastern peninsular regions (mainly agricultural lands) increases from 10 - 40 g C m^{-2} $month^{-1}$ in June to 100 - 200 g C m^{-2} $month^{-1}$ in August. The histogram plots suggest that more and more number of pixels are shifted to higher range of NPP (>40 g C m^{-2} $month^{-1}$) during this period. These higher levels of NPP over most part of Indian landmass increase the mean NPP to the tune of 44 ± 37.5 g C m^{-2} $month^{-1}$ and 59 ± 40.5 g C m^{-2} $month^{-1}$ in July and August, respectively. During the post-monsoon period (September – October), spatial pattern in NPP over the country remains almost similar to the month of August but the magnitude of NPP is further increased to larger values (above 80 g C m^{-2} $month^{-1}$) in the central and peninsular regions of India. On the contrary, the levels of NPP substantially decline from very large values (>120 g C m^{-2} $month^{-1}$) to moderate values (80 g C m^{-2} $month^{-1}$) over the Indo-Gangetic plain. The normalized histogram plot suggests that more than 40% of pixels are shifted to higher NPP range (> 80 g C m^{-2} $month^{-1}$) in October. The large parts of country with such high magnitude of NPP lead to attainment of the peak in mean NPP (69.3 ± 44.5 g C m^{-2} $month^{-1}$). The NPP towards later months in the year declines all over the country and large number of pixels shift towards the moderate and lower values of NPP during November and December. Magnitude of NPP reaches below 80 g C m^{-2} $month^{-1}$ over most of the regions in the central and peninsular India. The mean NPP over the country declines to 43.4 ± 33.5 g C m^{-2} $month^{-1}$ in November and to 34.5 ± 30.0 g C m^{-2} $month^{-1}$ in December.

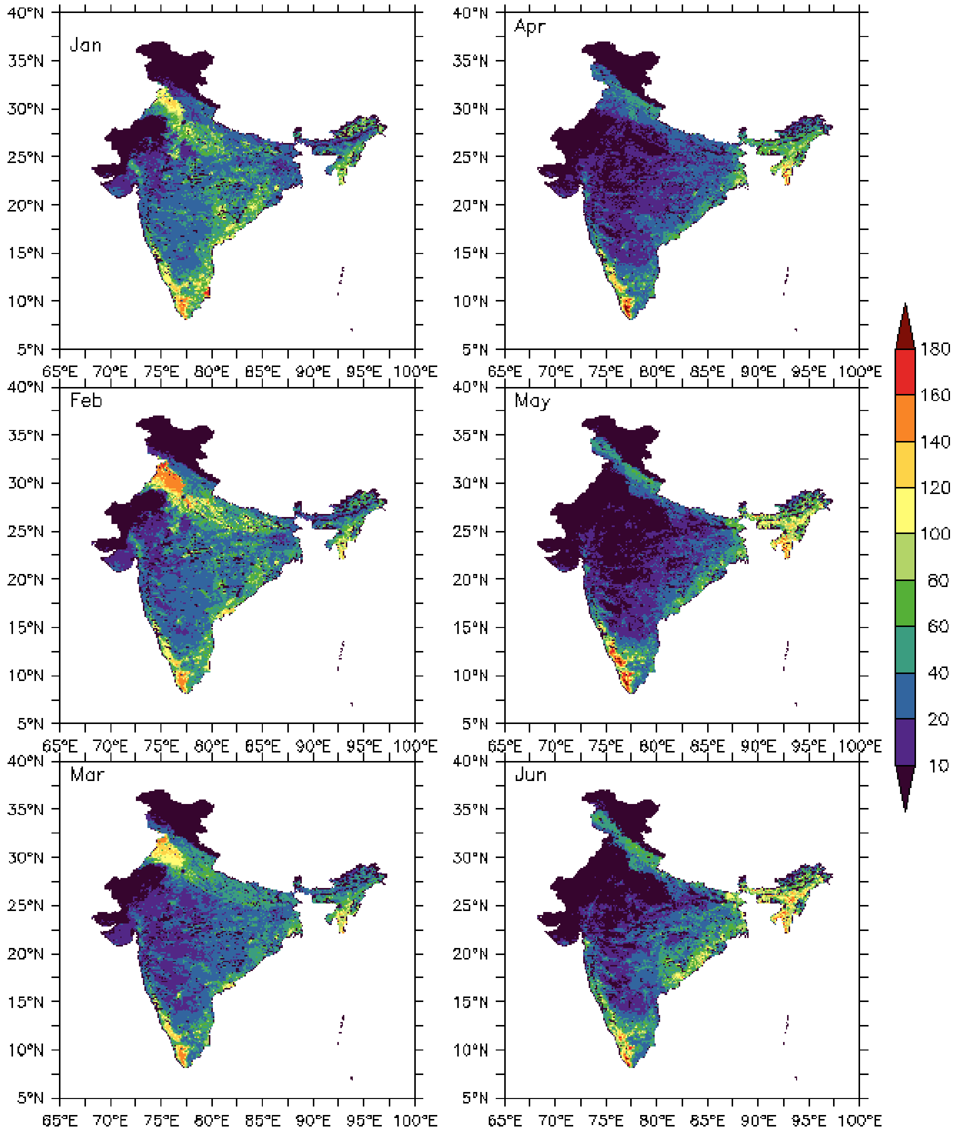

Figure 3a: Spatial pattern of monthly NPP over Indian during the climatological year (1981-2006).

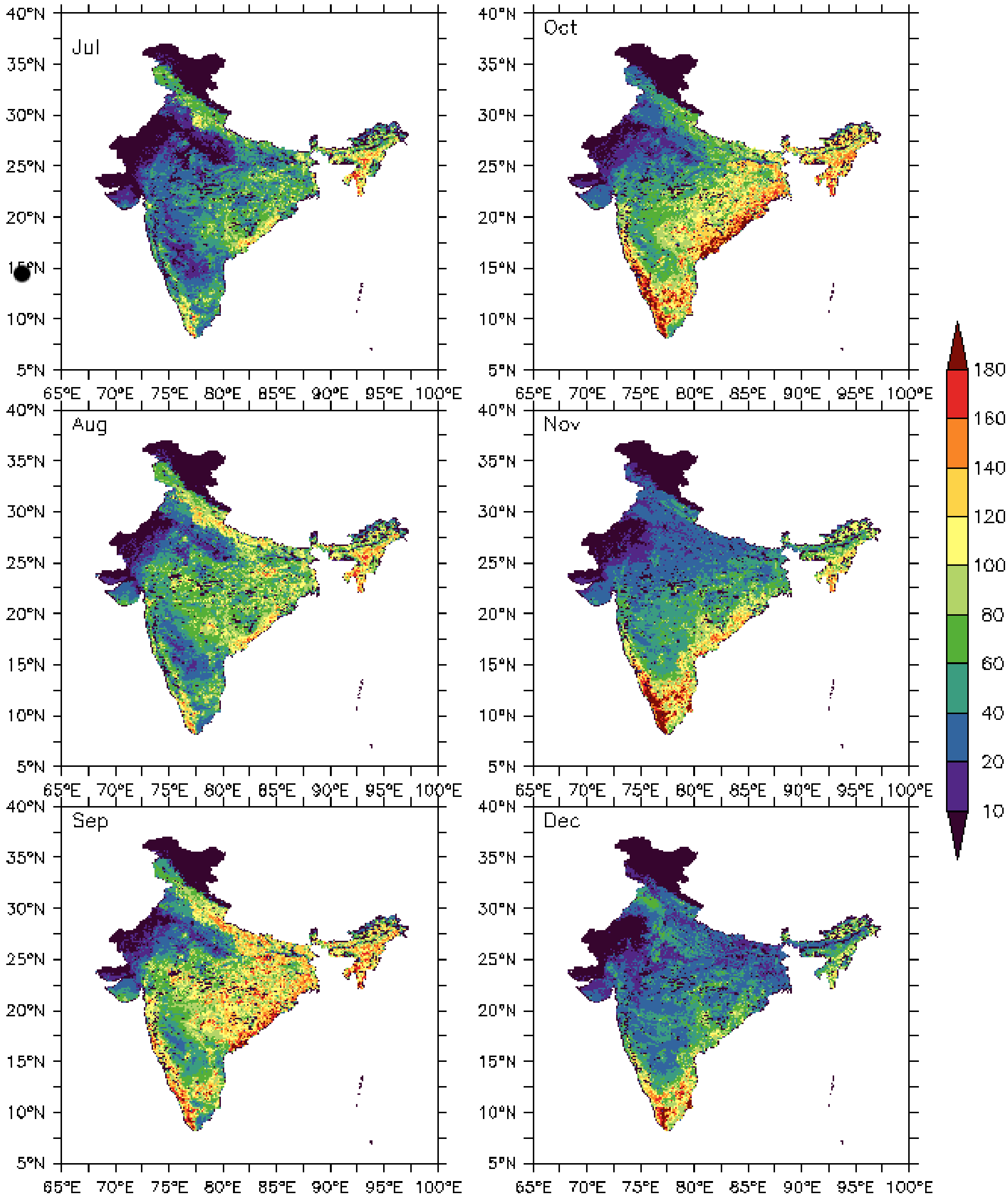

Figure 3b: Spatial pattern of monthly NPP over Indian during the climatological year (1981-2006).

6. Spatial pattern of annual NPP climatology

The spatial pattern of annual NPP climatology and associated coefficient of variation (CV) based on model simulations of past 26 years (1981-2006) over India are presented in Figure 4. As shown in figure, the estimated NPP exhibits large spatial variation across the country. Very large NPP (>900 g C $m^{-2}yr^{-1}$) together with small variance (CV <15%) are estimated over the evergreen and deciduous forest regions of northeast states, eastern and southwestern peninsular region of the country, and partly over the Indo-Gangetic plain. NPP over the Indo-Gangetic plains and over the coastal states in the eastern and south-western India are estimated in the range of 600 - 900 g C $m^{-2}yr^{-1}$ together with small variance (CV <5%).

Moderate values of NPP in the range of 200 - 600 g C $m^{-2}yr^{-1}$ associated with relatively large inter annual variability (CV is in the range of 15-30%) are estimated over the mixed shrub and grassland of central India. Low mean NPP in the range of 100-200 g C $m^{-2}yr^{-1}$ is estimated in the desert tracts of northwestern India and northern portion of Himalaya mountain ranges. The high variability (CV >30%) is also found in desert tracts of western India where rainfall amount are low and erratic. In this area, vegetation signal shows pulse during dry and wet years. Mean total NPP of the country estimated to be 1.42 Pg C at the rate of 520 g C m^{-2}.

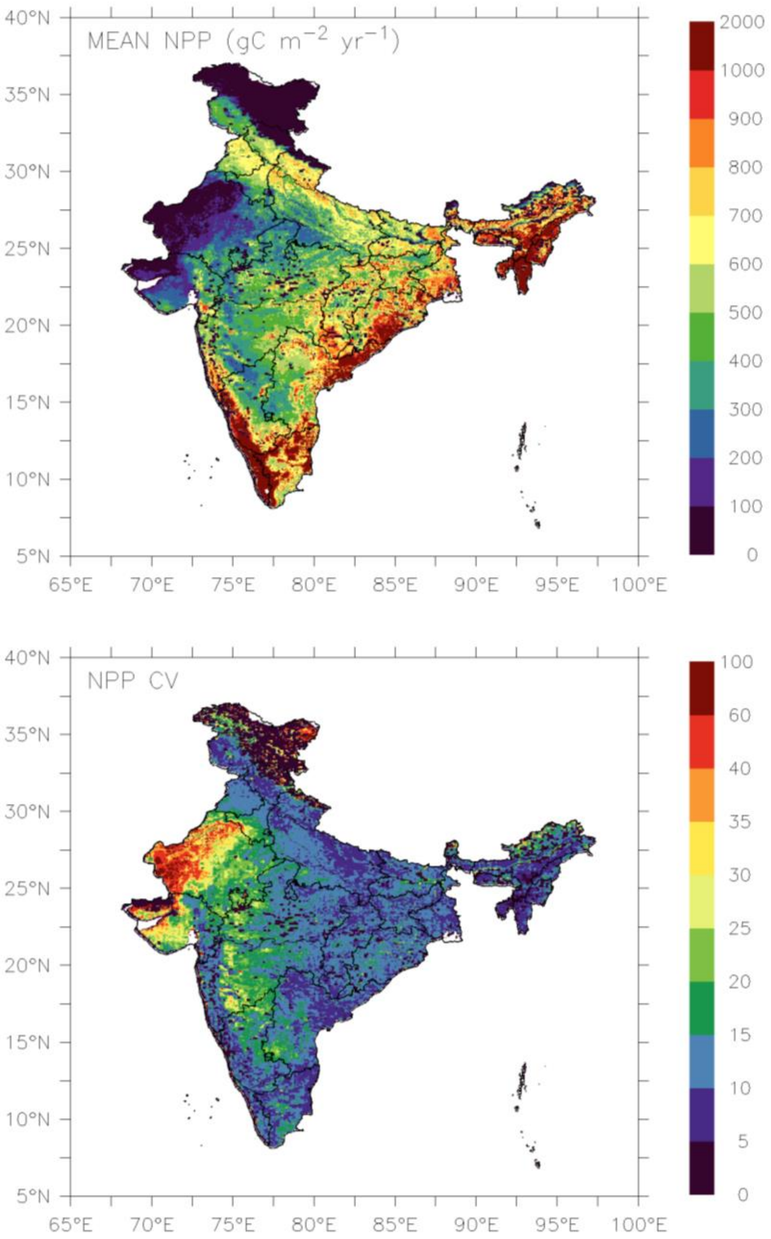

Figure 4: Mean and percentage of variation of annual NPP over India during study period 1981-2006.

7. Validation

The precise evaluation of simulated NPP on regional or global scale needs *in situ* measurements of NPP from network of flux towers which does not exist in India. Alternatively two methods are usually used to validate the simulated NPP: one is to compare with ground based measurements, and the other to compare with the estimates by other models. Thus, in the following subsection, the simulated annual NPP is compared with ground based cropland NPP estimates. In subsequent section, the present estimated NPP is compared against the NPP estimates based on other operational models.

7.1 Inter Comparison with ground based cropland NPP estimates

Scatter plot between the cropland NPP obtained from district level annual crop statistics of three states and corresponding modeled annual NPP (by CASA) is presented in Figure 5. There is very good agreement between them (R^2 = 0.54; $p < 0.05$). The root-mean square error associated with modeled NPP for crop land is 118 g C $m^{-2}yr^{-1}$, which is 27 per cent of the mean observed crop NPP for the selected region. Overall, mean NPP estimates of croplands by CASA (414 g C $m^{-2}yr^{-1}$) are relatively lower than observed crop NPP (433 g C $m^{-2}yr^{-1}$). This difference may be due to the fact that pixels labeled as cropland in the satellite land cover map at 1 km resolution often include both crops and other nonproductive cover types, such as roads and water bodies.

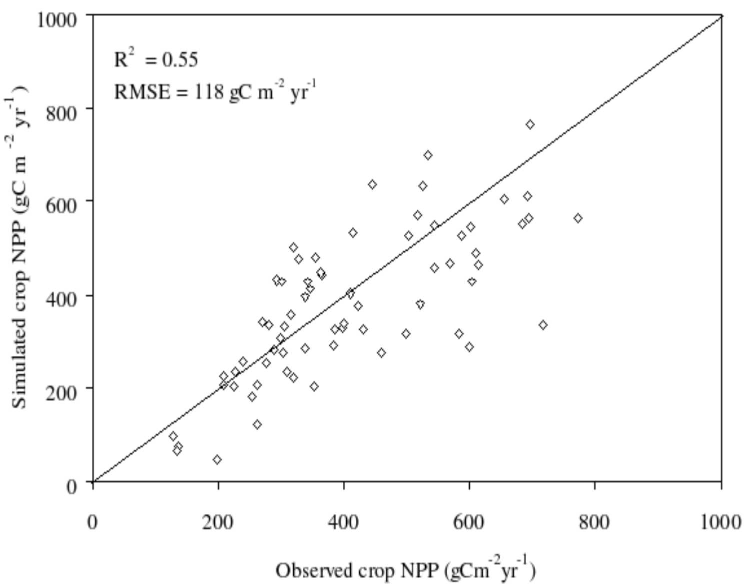

Figure 5: Comparison of simulated annual NPP using the CASA model vis-à-vis ground-based NPP estimates from crop statistics in the western India (Rajasthan, Gujarat, and Punjab).

7.2 Comparison with the C-Fix and MODIS NPP

In order to compare CASA based annual NPP estimates with the similar estimates from operational MODIS and C-Fix algorithms ,data of MODIS and C-Fix NPP were transformed in to the same grid where CASA NPP modeling were performed (i.e. at 2’ grid). Comparison of these figures with the spatial patterns of the CASA estimated NPP suggests that CASA exhibits larger NPP than the MODIS based estimates, and MODIS exhibits larger NPP than the C-Fix estimates over the regions of evergreen forest of northeastern states and southwestern peninsula and agricultural lands of Indo-Gangetic plain and eastern peninsular India. On the contrary, the C-Fix exhibits relatively larger NPP than the CASA estimates over the regions of central India which is mainly dominated by mixed shrub and grassland by vegetation type. MODIS NPP is almost comparable to CASA based estimates over these regions. The cumulative histogram plots between the number of pixels and ranges of NPP of these products (shown in Figure 8) suggest that very large number of pixels of C-Fix (75%) are in the moderate range (300 - 800 g C m^{-2} yr^{-1}) followed by 20% in the lower (<300 g C m^{-2} yr^{-1}) and 5% in the upper ranges (> 800 g C m^{-2} yr^{-1}) of NPP. In contrast MODIS and CASA both have relatively less number of pixels (52%) in the moderate range and relatively larger number of pixels (i.e. 45% and 33% respectively) in lower range of NPP than that of C-Fix estimates. Furthermore, the CASA estimate has relatively larger number of pixels (15%) in the higher range (> 800 g C m^{-2} yr^{-1}) than that of MODIS (5%) and C-Fix (5%).

Regarding the national annual NPP budget of the country, the C-Fix has estimated 1.45 Pg C and MODIS has estimated 1.30 Pg C. These estimates are relatively smaller than the CASA based estimates (1.57 Pg C). While comparing the percentage contribution of major land cover types in respective estimated national NPP budgets of the country (table c1), C-Fix has estimated 58% of its national budget coming from the agricultural land which is almost comparable to CASA based estimates (57%) and larger than the MODIS base estimate (52%). Over the deciduous broadleaf forest, C-Fix and MODIS estimated 15% and 17 % of their respective national NPP budgets respectively. These contributions are almost comparable to the contribution obtained by CASA model. In contrast, C-Fix has estimated much smaller contribution of its budget (5%) from the evergreen broadleaf forest as compared to MODIS and CASA based contributions (12% and 10% respectively). The contributions of mixed shrub and grassland in respective national budgets are almost comparable (8% in case of CASA and MODIS and 9% in case of C-Fix). One important difference is noticed in case of C-Fix model estimates, i.e. grassland has contributed 10% of its national NPP budget whereas CASA and MODIS based estimates provided negligible contributions in their national budgets.

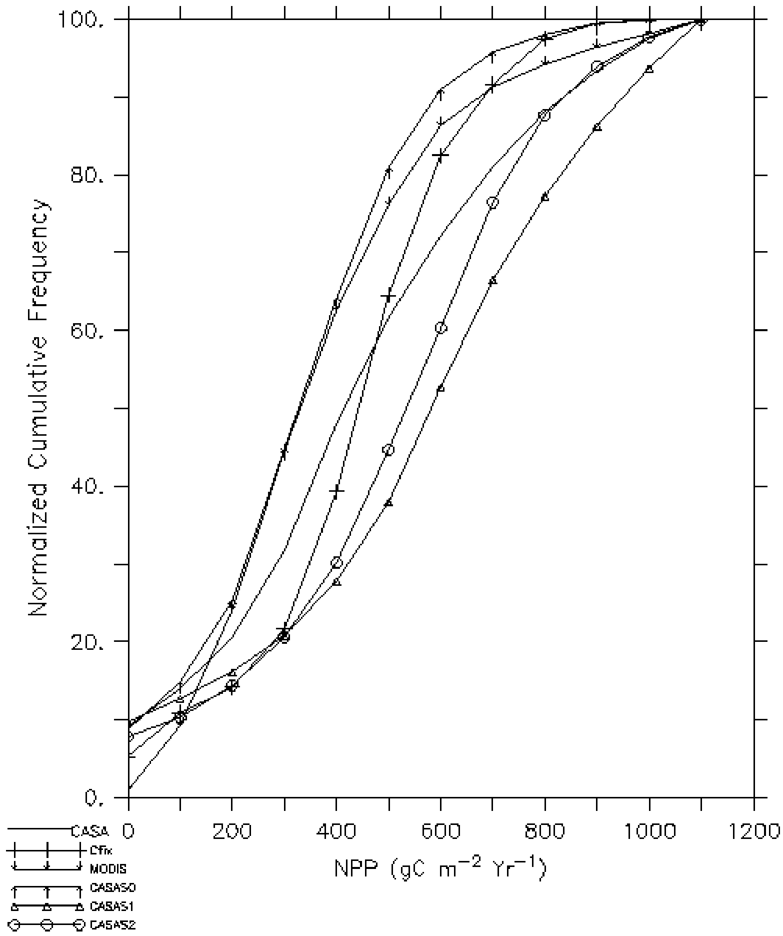

Figure 6: Normalized cumulative histogram plots for annual NPP based on CASA main run and for sensitivity experiments: CASAS0, CASAS1, and CASAS2. Same are for C-Fix and MODIS estimated NPP over the country.

The scatter plots between the CASA and MODIS based annual NPP estimates over 5 major land cover types of the country (irrigated cropland and pasture; mixed dry/irrigated cropland and pasture; mixed shrub and grassland; deciduous broadleaf forest; and evergreen broadleaf forest) are presented in the left panels of the Figure C1. The similar scatter plots between CASA and C-Fix modeled NPP are presented in the right panels of Figure C2. Over the irrigated cropland of the country, the R^2 (square of co-relation coefficient) and RMSE (root mean square error) values estimated between the CASA-NPP and MODIS-NPP are 0.375 and 206 gC m^{-2} yr^{-1} respectively. In contrast the relation between the CASA and C-Fix is relatively weaker (R^2 = 0.124; RMSE = 216 gC m^{-2} yr^{-1}). Over the mixed dry/irrigated cropland and pasture, the relation between CASA and MODIS (R^2 = 0.590 and RMSE = 142 gC m^{-2} yr^{-1}) is much stronger than the relation between CASA and C-Fix estimates (R^2 = 0.175 and RMSE = 185 gC m^{-2} yr^{-1}). The relation between CASA and MODIS based NPP estimates over the mixed shrub and grassland is much stronger (R^2 = 0.674 and RMSE = 124 gC m^{-2} yr^{-1}) than the relation between CASA and C-Fix based estimates (R^2 = 0.674 and RMSE = 163 gC m^{-2} yr^{-1}). Over the broadleaf deciduous forest, the R^2 value between CASA and MODIS product is much larger (0.507) as compared to very small R^2 (0.0562) value between CASA and C-Fix product. The estimated RMSE (170 gC m^{-2} yr^{-1}) between the first pair is relatively smaller than that of second pair (226 gC m^{-2} yr^{-1}). Over the broadleaf evergreen forest, the relation between CASA and MODIS (R^2 = 0.297 and RMSE = 334 gC

m^{-2} yr^{-1}) is stronger than the relation between CASA and C-Fix NPP estimates ($R^2 = 0.138$ and RMSE = 305 gC m^{-2} yr^{-1}).

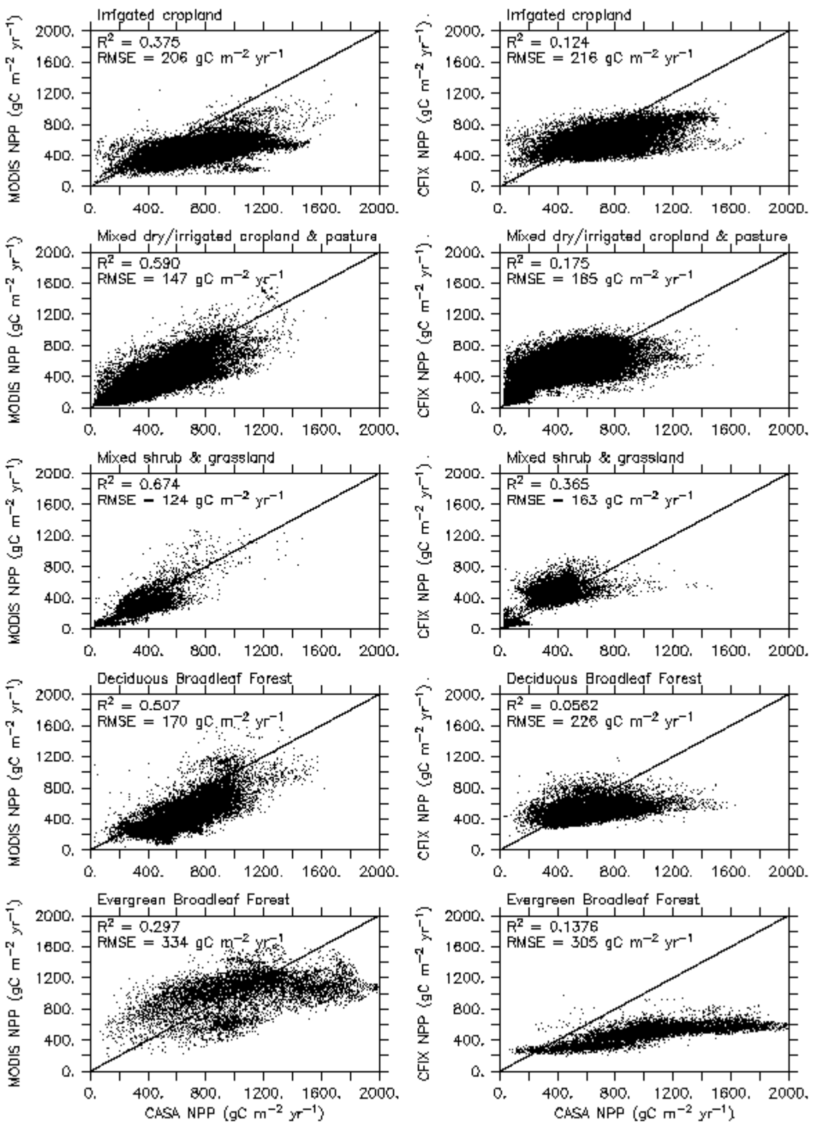

Figure 7: Comparison of CASA based estimates of annual NPP over major land cover of the country with the MODIS based estimates (in the left panels) and with the C-Fix based estimates (in the right panels).

8. Spatial Pattern of Annual NEP Climatology and Variance

Spatial patterns of annual NEP climatology over India and associated coefficient of variation (CV) during the 26-year study period are presented Figure 8. Statistics on long-term mean NEP over major land cover types of the country and associated NPP and Rh statistics are presented in table 3 and table 4 respectively. The region with positive NEP represents a carbon sink regime and the region with negative NEP represents a carbon source regime. As shown in the figure, annual mean NEP exhibits large and distinct spatial variability across the country. Positive NEP with small variance (CV < 5%) are present over most parts of the agricultural lands (lower Indo-Gangetic plains; the coastal states in the eastern and southern peninsular plateau) and mixed-shrub and grassland over deserted tracts of northwestern and interior peninsular India. These regions are the major sinks without significant inter annual variability. Deserts/dry cropland tracts of western as well as interior peninsular India had high and positive NEP values in spite of low levels of NPP in these areas (table 4). These high values are mainly due to relatively smaller value of Rh (soil respiration), which can be attributed to the limited moisture available for decomposition of soil organic matter (SOM) by heterotrophs. Small negative NEP values with large variance (>5%) are estimated over the forest region in the south-eastern region of north-east states and Western-Ghats and south-western coastal plains. At the national scale, Indian terrestrial ecosystem acts as a net sink of atmospheric CO_2 with a mean annual uptake of 9.85 Tg C (equivalently 2.57 gC $m^{-2}y^{-1}$). Out of the total annual NEP, cropland contributed 9.1 Tg C, mixed shrub and grassland contributed 1.32 Tg C and forest land contributed –0.54 Tg C (table 1). The negative NEP budget over the forest areas is mainly a result of the effect of climatic stress on NEP during early 80s (that will be clarified later in section 3.4). This uptake strength is significantly larger (19.2 Tg C y^{-1}) during the later 15-year period (1991-2006), owing to the enhanced contributions coming from the agricultural lands (table 1). When compared to global NEP climatology, Indian ecosystems contributed 2.5% (20 TgC) of the global annual NEP budget (730 TgC) corresponding to 1981-1998 period (Cao *et al.*, 2005).

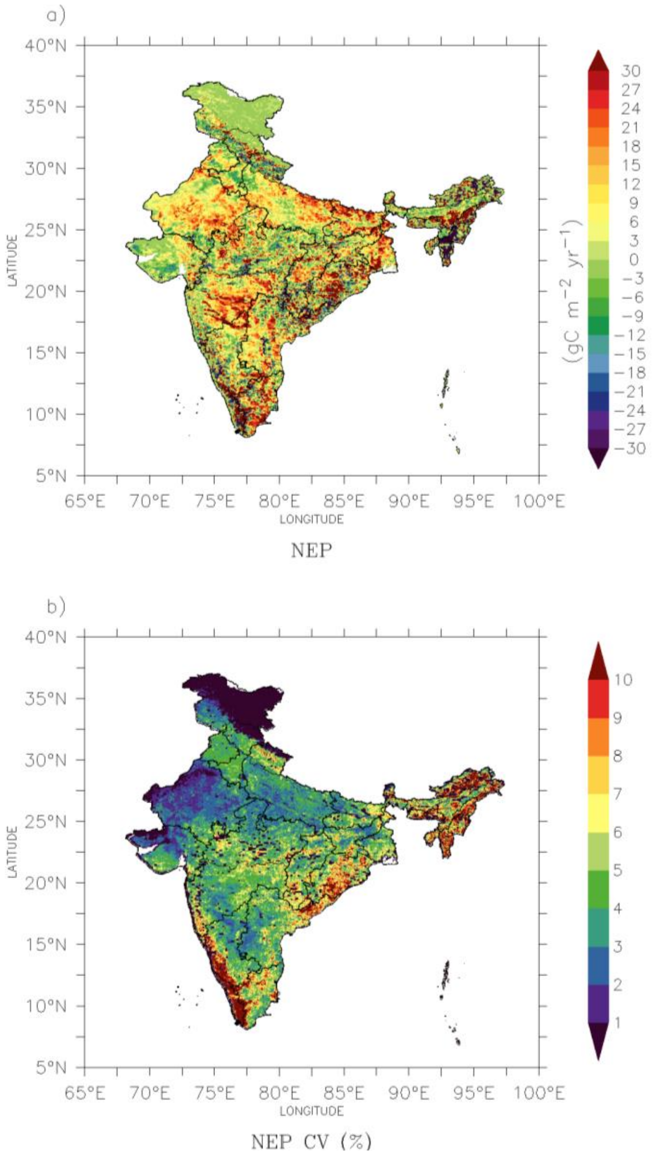

Figure 8: Distribution of annual mean (a) and coefficient of variability (b) of NEP over India during 1981-2006.

Table 3: Statistics of annual NEP climatology and long-term linear growth rate of total NEP over major land cover types in India.

Statistics During 1981-2006				*During 1991-2006*		
Land use/land cover (% land coverage of the country)	*Mean NEP and (σ) (gC m^{-2} y^{-1})*	*Total NEP and (σ) (Tg C y^{-1})*	*Trend (Tg C y^{-2})*	*Mean NEP and (σ) (gC m^{-2} y^{-1})*	*Total NEP and (σ) (Tg C y^{-1})*	*Trend (Tg C y^{-2})*
Mixed dry land and irrigated crop land	4.5 (17.6)	5.44 (15.4)	0.72	7.1(18)	3.8 (7.4)	0.08
Irrigated cropland and pasture	6.8 (16.5)	3.65 (7.1)	0.13	7.8 (19)	9.3 (15.5)	0.76
Broadleaf deciduous forest	-0.12 (34.6)	-0.41 (8.5)	0.23	1.8 (37)	1.0 (9.6)	0.68
Mixed shrub and grass land	3.77 (18.2)	1.32 (4.9)	0.15	8.0 (20)	2.82 (4.9)	0.29
Broadleaf evergreen tree	-1.15 (60.8)	-0.13 (2.9)	-0.06	-3.78 (62)	-0.6 (3.2)	-0.1
Grassland	-0.06(9.3)	-0.01 (0.6)	0.02	1.2 (9)	0.15 (0.4)	-0.01
All LU/LC (100)	3.01 (25.2)	9.85 (37)	1.79	5 (26)	16.4(38)	1.45

Table 4: Statistics of annual NPP and Rh during 1981-2006 for major land cover types in India.

Statistics of NPP				*Statistics of Rh*		
Land use/land cover	*Mean NPP and (σ) (gC m^{-2} yr^{-1})*	*Total NPP and (σ) (Tg C yr^{-1})*	*Trend (Tg C yr^{-2})*	*Mean Rh and(σ) (gC m^{-2} yr^{-1})*	*Total Rh and (σ) (Tg C yr^{-1})*	*Trend (Tg C yr^{-2})*
Mixed dry land and irrigated crop land	411 (267)	497 (25)	2.35	406 (268)	492 (15)	1.44
Irrigated cropland and pasture	538 (290)	290 (12)	0.76	531 (289)	286 (9)	0.60
Broadleaf deciduous forest	586 (337)	274 (11)	0.60	586 (338)	271 (7)	0.24
Mixed shrub and grass land	371 (263)	132 (7)	0.74	366 (265)	131 (5)	0.42
Broadleaf evergreen tree	817 (555)	135 (3)	-0.08	818 (556)	136 (2)	-0.01
Grassland	80(158)	10 (1)	0.05	79 (158)	10 (0.5)	0.02
All LU/LC	463 (339)	1415 (55)	4.5	459 (340)	1406(34)	2.76

9. Seasonality of NEP

The long-term (1981-2006) mean of monthly NEP budget for India undergoes a semi-annual cycle with primary positive values (up to 80 Tg C month^{-1}) during August-December and secondary positive values (up to 15 Tg C month^{-1}) during January-March (Figure 2a). These two periods represent the net carbon sink of atmospheric CO_2 by the Indian terrestrial ecosystem. Negative values (up to -70 Tg C month^{-1}), representing carbon sources are present during April-July. This temporal variation of monthly NEP budget over the country has a seasonal cycle following that of NPP with one month lag. Variation of NEP over the dominant land covers as shown in Figure 2b shows that the agricultural land exhibits a similar semi-annual cycle as observed for the entire country. On the other hand, NEP over the forest and shrub-grass lands exhibit annual cycles with positive values during August-December and negative values during March-July. Indian forest is mainly dominated by broadleaf deciduous forest that usually shades leave during the dry seasons (March-June). As a consequence, NPP decreases and Rh increases leading to negative NEP during the dry seasons. The amplitudes associated with the annual cycle of NEP for the Forest and shrub-grass lands are almost one third and one fifth of the amplitude of the semi-annual cycle as observed for the agricultural lands. This large dominance of agricultural NEP on the annual cycle of Indian NEP is because of the larger area (48%) occupied by agricultural lands followed by 20% by forests and 11% by shrub-grass lands.

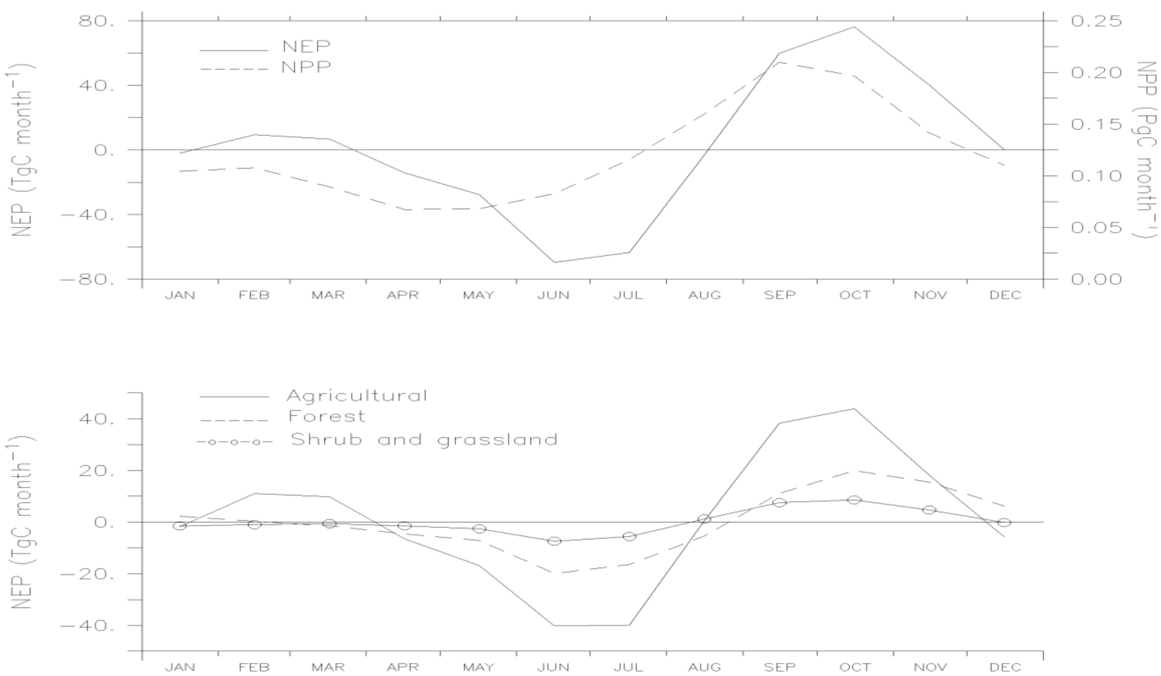

Figure 9: Annual cycle of total NEP (continuous line) and NPP (dash line) for the country during the period 1981-2006 are presented in the upper panel. The lower panel shows annual cycle of total NEP for dominant land cover types in the country.

10. Spatio-Temporal Variability of Net Ecosystem Productivity over India

The net ecosystem productivity (NEP) represents net carbon exchange between the terrestrial ecosystem and the atmosphere that plays a crucial role on the control of the atmospheric CO_2 in different time scales. Here we examined the spatial and temporal variability of NEP over India during 1981-2006 in relation to the climatic parameter. At the national scale the NEP exhibits semi-annual cycle with primary positive values up to 80 TgC month^{-1} during August-December, secondary positive values up to 15 TgC month^{-1} during January-March and negative values up to -70 TgC month^{-1} during April-July. The estimated long-term NEP budget for the country is 10 TgC y^{-1}. It had undergone substantial inter-annual change in response to climate variability (Figure 3). In the early eighties, the Indian terrestrial biosphere remained a source and later became a sink of carbon during four pentad periods. The NEP budgets are positive for all the extreme years with severe flood and drought conditions except 1982. The normal years have either positive or negative NEP budgets. The precipitation-induced reduction of the net primary production (NPP) dominates the NEP variability in dry years, whereas in good monsoon years the precipitation-induced enhancement of the soil respiration (Rh) dominates the NEP variability.

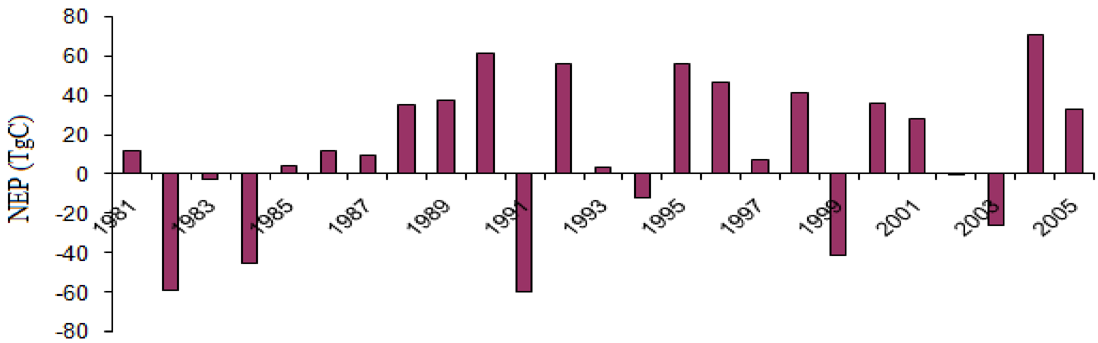

Figure 10: Barplot of NEP budgets of India during 1981-2006 agricultural years (adopted from Nayak et al. 2015).

11. Conclusions

CASA model is implemented to simulate terrestrial NPP and NEP over India at monthly scale for the period of past 26 years during 1981-2006. At the annual scale the total NPP budget for India is estimated as 1.42 Pg C and the NEP budget is about 20 Tg C. These simulated NPP and NEP budgets exhibit strong seasonal and Inter annual variability in response to the climatic variability.

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