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Spatio-temporal variability of net ecosystem productivity over India and its relationship to climatic variables

R. K. Nayak · N. R. Patel · V. K. Dadhwal

Abstract 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. The present study examined the spatial and temporal variability of NEP over India during 1981–2006 in relation to the climatic variables using the Carnegie–Ames–Stanford Approach (CASA) terrestrial ecosystem model and regional databases on the land surface-vegetation characteristics and the climatic parameters. At 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 year^{-1}. It had undergone substantial inter-annual change in response to the climate variability. In the early 1980s, 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.

Introduction

Terrestrial ecosystem plays a crucial role in regulating variability of the atmospheric CO_2 in different time scales. Studies revealed that global terrestrial biosphere acted as a net C sink over past two and half decades. The annual uptake capacity of the global ecosystem was highly variable ranging from 0.3 to 5.0 PgC year^{-1} and these values were very significant as compared to the emission of about 7 PgC year^{-1} from fossil fuel burning (Prentice et al. 2001; Schimel et al. 2001; Sabine et al. 2004). Understanding of the global terrestrial C cycle has been improved over the past few decades owing to the rapid establishment of atmospheric CO_2 measurement networks and vegetation inventories; the development in remote sensing based monitoring of land surface properties; and the improvement on the ecosystem modeling procedure. Large diversity of biome types and their functioning across the world causes uncertainties in C source and sink properties of terrestrial ecosystems at regional and continental scales. 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 (Potter et al. 2003; Tian et al. 2003; Piao et al. 2009). 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 (21 %) and agricultural land (55 %).

India's terrestrial biosphere may have distinct pattern of C sink/source over space and time owing to the monsoonal

R. K. Nayak (✉) · V. K. Dadhwal
National Remote Sensing Centre (ISRO),
Hyderabad 500625, India
e-mail: rabindrakumar_nayak@nrsc.gov.in

N. R. Patel
Indian Institute of Remote Sensing (ISRO),
Dehradun 248001, India

climate, the diverse land cover distribution, the rainfed-irrigated agricultural practices and the seasonality of vegetation phenology. The climate over India has undergone significant change during the past two decades with the clear warming trend under the background of global warming (Dash and Hunt 2007). The land use change during the past few decades is very significant. The rate of afforestation in India is 2 Mha per annum and stands as the highest among the tropical countries (Ravindranath and Hall 1994). Recent report of the Forest Survey of India 2009 suggests that the forest cover of India has increased by 5 % in the present decade (http://www.moef.nic.in/downloads/public-information). Earlier studies on carbon cycle for India were mainly based on the forest inventory data sets and they were focused to assess biomass (Haripriya 2000), growing stocks (Chhabra et al. 2002), primary productivity (Hingane 1991), carbon sequestration in forest (Lal and Singh 2000) and net C flux from land use changes (Ravindranath et al. 1997; Haripriya 2003). The net C flux over the Indian forest as estimated by different studies ranges from an emission of 0.4 Tg year^{-1} to a sink value of 5.0 Tg year^{-1} (Ravindranath et al. 1997). Recently Kaul et al. (2009) reported that the Indian forest has sequestered 1.09 TgC year^{-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 and its link with the global carbon cycle. Development and improvement in the global terrestrial ecosystem models (Potter et al. 1999; McGuire et al. 2001) in last two decades have opened a scope for gearing up carbon cycle research at global and regional scales. These models are perhaps the best tools for estimating variability in carbon cycle processes at different scales ranging from local to the regional and global scales, because they allow integration of data from a variety of sources and sensitivity analysis to prescribe important biome-specific parameters. The Carnegie–Ames–Stanford Approach (CASA; Potter et al. 2003) is one such model popularly used for the analysis of carbon cycling parameters at local to regional to continental scales. Nayak et al. (2010, 2013) have implemented this model over the Indian subcontinent to study seasonal and inter-annual variability of the net primary productivity (NPP) over India. The NPP only accounts vegetation component of CO_2 exchange between the ecosystem and the atmosphere. On the other hand, the heterotrophic respiration (Rh) is an important component of the net CO_2 exchange which was not investigated in the earlier studies. Difference between NPP and Rh is termed as the net ecosystem productivity (NEP) which describes the net exchange of atmospheric CO_2 by the undisturbed ecosystem. The CASA model has a mechanism that can link seasonal pattern of NPP to soil heterotrophic respiration (Rh). Therefore, the aim of the present research is to simulate long-term pattern of net ecosystem productivity (NEP) over different vegetation covers in India and study its spatial and temporal variability.

Materials and methods

The CASA is a terrestrial biosphere model based on the light-use efficiency (LUE) that simulates net primary productivity (NPP) by estimating optimal metabolic rates of carbon fixation under the limiting effect of temperature and water stress scales (Potter et al. 2003). The model has mechanism that can link seasonal patterns of the NPP to the soil heterotrophic respiration (Rh). 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. The model is used in this study to simulate long-term (1981–2006) monthly carbon cycling parameters (NPP, Rh, NEP, etc.) over India at 8 km spatial resolution. The model is driven by spatially explicit data of the climate parameter, normalized differential vegetation index (NDVI) and stationary maps of soil and vegetation attributes. The monthly NDVI data at 8-km spatial resolution are obtained from archives of Global Inventory Modeling and Mapping Studies (GIMMS) (Tucker et al. 2005). The high-resolution (0.5°) long-term monthly climate databases of Climate Research Unit (CRU), University of East Anglia (UEA) (http://www.cru.uea.ac.uk/cru/data/hrg) form the source of input climatic parameters: air-temperature (T_{air}), precipitation (ppt), cloud fraction/solar radiation. The land use and land cover (LULC) map for India is obtained from the digitally classified land cover map of Southeast Asia at 1 km spatial resolution (Agrawal et al. 2003). The soil attributes map is taken from the UNESCO world soil map (Reynolds et al. 1999). These data are projected into the model grid at GIS (Geographic Information System) environment using appropriate transformation function (further details are given in Nayak et al. 2013). Analysis of inter-annual variability of simulated monthly NEP is carried out for the agricultural year (June–May) instead of a calendar year to highlights the effect of the southwest (SW) monsoon on vegetation activity and enables comparison of carbon fluxes against those from ground based on crop statistics (Pandya et al. 2004). Thus the monthly time series of NEP is converted to annual NEP by adding monthly data for the agricultural years. Annual mean and standard deviation are estimated to describe variability of NEP across

different land cover types of the country. Long-term linear growth rates of NEP and associated parameters were estimated by fitting linear trend line with respect to time (years) using the least square procedure.

Results and discussion

Spatial patterns of annual NEP

Spatial patterns of the annual NEP climatology over India and associated coefficient of variation (CV) during the 26-year study period are presented in Fig. 1. Statistics on long-term mean of the simulated NEP and associated NPP and Rh over the major land cover types in India are presented in Tables 1 and 2, respectively. The region with

Fig. 1 Spatial distribution of mean annual NEP and associated coefficient of variability over India during 1981–2006

positive NEP represents a C sink regime and the region with negative NEP represents a C source regime. It is observed that high (small) productivity (NPP) areas are the locations of high (small) Rh; however, their relative magnitudes determine whether the region being a source or a sink of C (Table 2). As shown in the figure, the NEP climatology exhibits large 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 the mixed shrub and grassland over deserted tracts of northwestern and interior peninsular India. 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 2). These high values are mainly due to relatively smaller value of Rh, 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 observed over the forest region in the southeastern parts of the northeast states and the Western Ghats and the southwestern coastal plains. At the national scale, the Indian terrestrial ecosystem acts as a net sink of the atmospheric CO_2 with a mean annual uptake of 9.85 TgC (equivalently 2.57 gC $m^{-2}year^{-1}$). Out of the total annual NEP, the cropland contributed 9.1 TgC, the mixed shrub and grassland contributed 1.32 TgC and the forestland contributed −0.54 TgC (Table 1). The negative NEP budget over the forest cover is a result of the effect of the climatic stress on the NEP during early 1980s. This uptake strength is significantly larger (19.2 TgC $year^{-1}$) during the later 15-year period (1991–2006) owing to the enhanced contributions from the agricultural lands (Table 1). The Indian ecosystems contribute almost 2.5 % (20 TgC) of the global annual NEP budget (730 TgC) corresponding to 1981–1998 period as reported by Cao et al. (2005).

Seasonality of NEP

Temporal evolution of the monthly NEP over India during the climatological year (1981–2006) undergoes a semi-annual cycle with primary positive values (up to 80 TgC $month^{-1}$) during August–December and secondary positive values (up to 15 TgC $month^{-1}$) during January–March (Fig. 2a). These two periods represent the net sink of the atmospheric CO_2 by the Indian terrestrial ecosystem. Negative values (up to −70 TgC $month^{-1}$), representing C sources are observed during April–July. It can be noted that during the dry periods, January to May and September–December, NEP mostly parallels the variability of NPP. On the other hand, enhanced negative estimates of NEP observed during the wet summer period
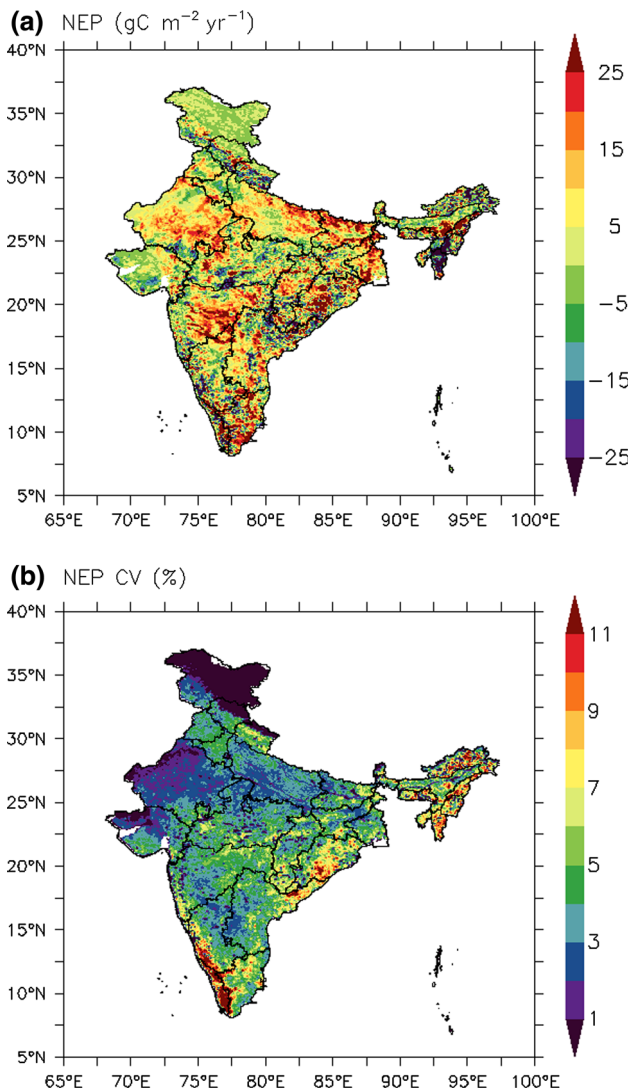
Table 1 Statistics of annual NEP climatology and long-term linear growth rate of total NEP over major land cover types in India

Land use/land cover (% land coverage of the country)	Statistics during 1981–2006			During 1991–2006		
	Mean NEP and σ (gC m^{-2} year^{-1})	Total NEP and σ (TgC year^{-1})	Trend (TgC year^{-2})	Mean NEP and σ (gC m^{-2} year^{-1})	Total NEP and σ (TgC year^{-1})	Trend (TgC year^{-2})
Mixed dry land and irrigated crop land (37)	4.5 (17.6)	5.44 (15.4)	0.72	7.1(18)	3.8 (7.4)	0.08
Irrigated cropland and pasture (16.5)	6.8 (16.5)	3.65 (7.1)	0.13	7.8 (19)	9.3 (15.5)	0.76
Broadleaf deciduous forest (14.5)	−0.12 (34.6)	−0.41 (8.5)	0.23	1.8 (37)	1.0 (9.6)	0.68
Mixed shrub and grass land (11)	3.77 (18.2)	1.32 (4.9)	0.15	8.0 (20)	2.82 (4.9)	0.29
Broadleaf evergreen tree (5)	−1.15 (60.8)	−0.13 (2.9)	−0.06	−3.78 (62)	−0.6 (3.2)	−0.1
Grassland (4)	−0.06 (9.3)	−0.01 (0.6)	0.02	1.2 (9)	0.15 (0.39)	−0.01
All LU/LC (100)	3.01 (25.2)	9.85 (36.9)	1.79	5 (26)	16.4 (38)	1.45

Table 2 Statistics of annual NPP and Rh during 1981–2006 for major land cover types in India

| Land use/land cover	Statistics of NPP			Statistics of Rh		
	Mean NPP and (σ) (gC m^{-2} year^{-1})	Total NPP and (σ) (TgC year^{-1})	Trend (TgC year^{-2})	Mean Rh and (σ) (gC m^{-2} year^{-1})	Total Rh and (σ) (TgC year^{-1})	Trend (TgC year^{-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 LULC	463 (339)	1415 (55)	4.5	459 (340)	1406 (34)	2.76

(June–August) against the increasing trend of NPP, which could be due to soil-moisture-induced enhancement of Rh. Variation of NEP for the cropland (irrigated cropland and pasture plus mixed dry irrigated cropland) exhibits the similar semi-annual cycle that dominates the seasonality of the national NEP budget (Fig. 2b). NEP over the forest and the shrub–grass lands exhibit annual cycles with positive values during August–December and negative values during March–July (Fig. 2b). Indian forest, primarily dominated by the broadleaf deciduous trees, usually shades leave during the dry seasons (March–June). Consequently, 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 for the shrub–grass land are almost one-third and two-thirds of the amplitude of the semi-annual cycle as observed for the agricultural lands. This dominance of the cropland NEP on the national NEP budget is because of the larger area (55 %) occupied by the cropland followed by 21 % by the forest and 11 % by the shrub-grass land.

Inter-annual variability of NEP

Inter-annual variability of NEP holds prime importance in the analysis of sink capacity of the atmospheric CO_2 by the terrestrial ecosystems. Bar plot of NEP budgets for the agricultural years is presented in Fig. 3 and the cumulative NEP budgets for the major land-cover types are presented in Fig. 4. As shown, NEP budgets remain positive during the 26-year study period except the years 1982, 1984, 1991, 1999, and 2003 when the NEP budgets are negative. The Indian ecosystems all together sequestered around 300 TgC during the 26-year study period where the cropland contributed 225 TgC followed by the shrub–grassland with 25

Fig. 2 Temporal evolution of monthly NEP (*continuous line*) and NPP (*dash line*) over India during the climatological years (1981–2006) is shown in the *upper panel*. The *lower panel* shows the evolution of NEP and NPP for the agriculture, the shrub–grass and the forest land-cover types in the country
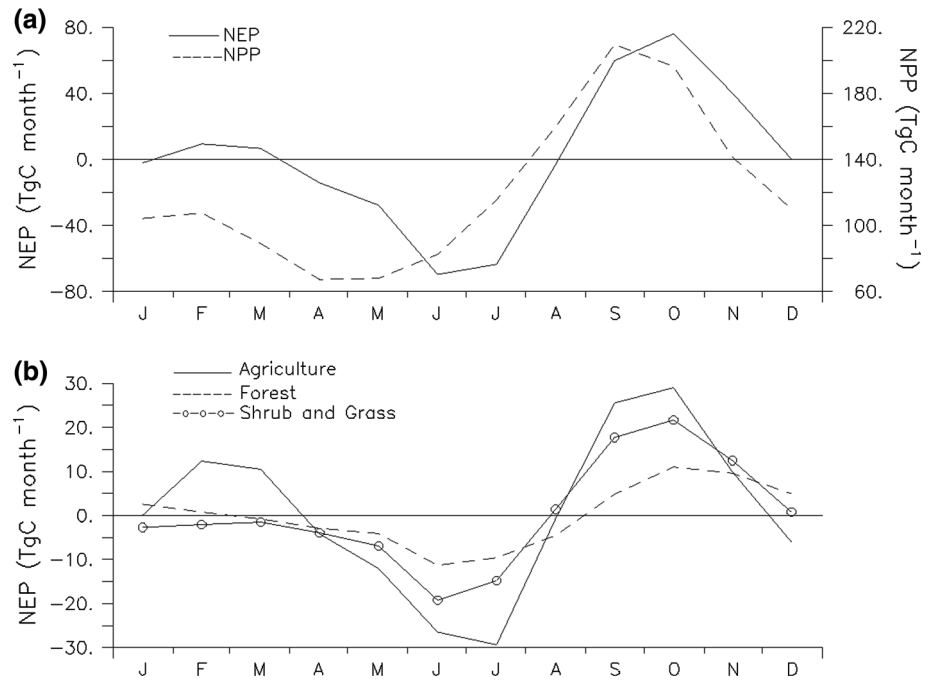
**Fig. 3** Bar plot of NEP budgets of India during 1981–2006 agricultural years
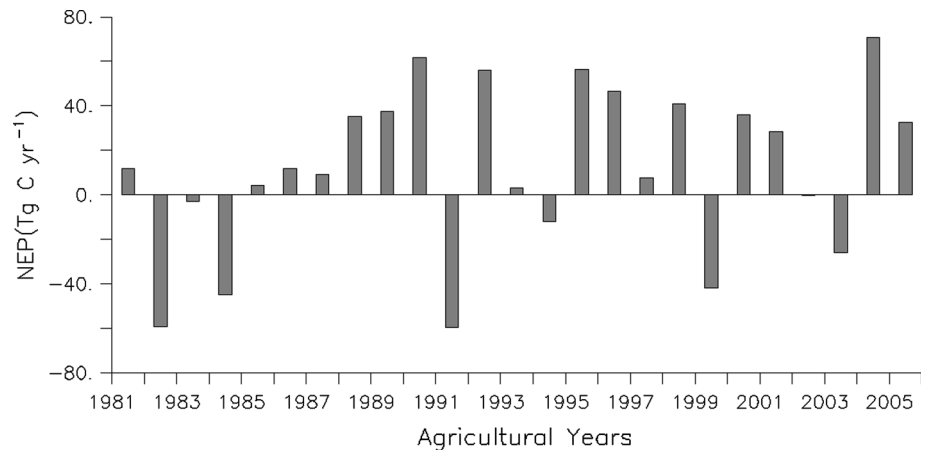
TgC. The forest remained the source with small negative NEP budget (Fig. 4). These estimates of NEP budget for India is associated with 1.8 TgC year^{-1} long-term linear growth rate, which is largely contributed by the cropland ecosystem (0.85 TgC year^{-1}) followed by the shrub–grassland (0.36 TgC year^{-1}) and the forest (0.18 TgC year^{-1}). The Indian terrestrial NEP budgets varied coherently with the global terrestrial NEP estimates and contributed substantially to the global budgets. Potter et al. (2003) reported that the global NEP budget varied between highest negative value (−900 TgC year^{-1}) in 1982 and highest positive value (2100 TgC year^{-1}) in 1998. Indian ecosystems also exhibited characteristic negative (−32 TgC in 1982) and positive budget (35 TgC

in 1998) in the respective years. These estimates, respectively, are 3 and 1.5 % of the global NEP budgets.

In order to analyze the inter-annual variability of the NEP in greater detail, estimates of the NEP budgets together with NPP and Rh budgets for the country and for the regions dominated by the cropland and the forest corresponding to the agricultural years (June of the given year to May of the next year) are shown in Fig. 5. At the national scale, the NEP exhibits large inter-annual variability together with the NPP and the Rh budgets. The national NEP budgets remained mostly negative during the early 5 years period (1981–1985) owing to the large decline of NPP with relatively less reduction in Rh in 1982 and in 1984. Most parts of India had negative NEP during this pentad except

Fig. 4 Cumulative annual NEP budgets for India and for the major land-cover types in the country during 1981–2006
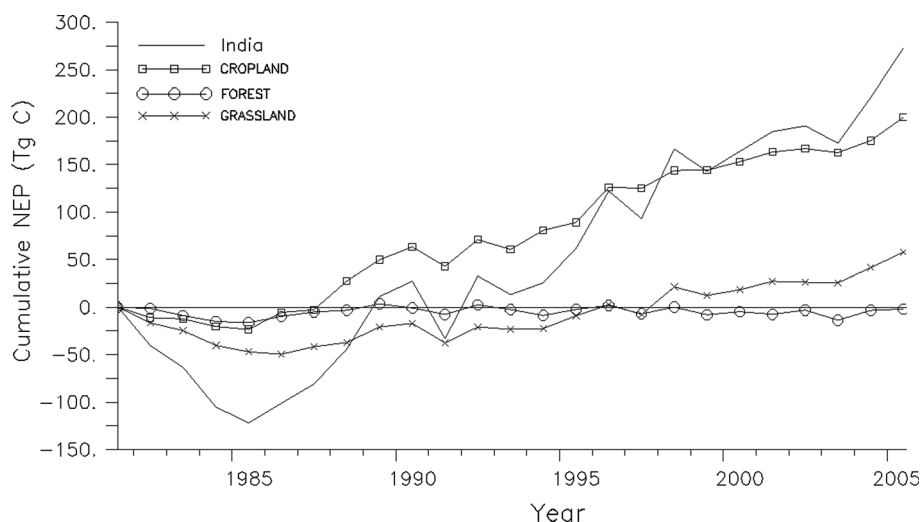

eastern parts of the Indo-Gangetic plains, dry-land tracts (mostly shrub-grassland) in the western India and some areas on the northeast states, the Western Ghats and eastern and southern coastal peninsular India (Fig. 6). The Indian ecosystem released, cumulatively 120 TgC CO_2 (at the rate of 24 TgC year^{-1}) to the atmosphere with a contribution of 60 TgC release from the shrub-grassland followed by 25 TgC from the cropland and 20 TgC from the forestland. This result is in agreement with a continental-scale study by Tian et al. (2003) where it has been reported that the south Asian region (comprised 75 % land covered by India) released 21 TgC year^{-1} in early 1980s.

The national NEP budget increased continuously from neutral value in 1985 to 61 TgC year^{-1} in 1990 (Fig. 5). Both NPP and Rh have undergone slow decline during 1986–1987 and rapid enhancement during 1988–1990 with NPP remaining larger than Rh resulting in net positive NEP budgets in this period. Spatial map of mean annual NEP during this pentad suggests that the major parts of India turned into C sink regions except very dry-land tracts (mostly shrub–grassland) in the western India (Fig. 5). The Indian ecosystems absorbed 130 TgC (at a rate of 26 TgC year^{-1}) during this 5-year period, which is associated with 85 TgC uptakes by the forestland followed by 20 TgC by the shrub-grassland and 15 TgC by the cropland (Fig. 4). Very intense negative NEP budget (−70 TgC) is observed in 1991 which is associated with −40 TgC over the cropland and −17 TgC over the forest. Since then national NEP budgets remained mostly positive for the remaining 14-year period except the years 1999 and 2003. The large negative budget in 1999 is associated with enhanced estimate of Rh and small decline of NPP budgets while the negative NEP in 2003 is associated with the increased estimates in both the budgets of NPP and Rh. During the pentad years: 1991–1995, net C sink by the Indian ecosystem is about 20 TgC (4 TgC year^{-1}), which is

6 times less than the previous pentad. In this period, major parts of the central and the eastern peninsular India (dominated by forest) turned into C source area with negative NEP (Fig. 6). Large decline of NPP and relatively small decrease of Rh budgets during 1991 and 1994 over the forest region could cause large negative estimates of the NEP budgets in respective years that led substantial reduction of the C sink capacity of India during this pentad. During 1996–2000, most parts of the Indian ecosystem remained as C sink regions except forest-dominated region on the central India and the northeast sates (Fig. 6). In this period, cumulative C uptake by the Indian ecosystems enhanced to 115 TgC (at the rate of 23 TgC year^{-1}) which is associated with 75 TgC uptakes by the cropland 18 TgC by the shrub-grassland and 5 TgC by the forest. During 2001–2005, the C uptake by the Indian ecosystem is about 85 TgC (equivalently 17 TgC year^{-1}), which is associated with 50 TgC from the cropland, 30 TgC from the shrub–grass-land and 5 TgC by the forest. Much of the reduction on C uptake over the cropland, in particular over the Indo-Gangetic plains, led to significant reduction of C uptake (by 25 TgC) by the Indian ecosystem during this pentad-period. It is worth noting that there is large decline of NPP budgets which occurred over the forest-dominated region together with enhance Rh during 2002–2003, which led to large negative NEP budget in 2003 (Fig. 4).

Climate variability and anthropogenic activities such as land cover change and improved methods in agricultural practices (irrigation and fertilization inputs) have strong influence on inter-annual variability of the NEP and its associated parameters NPP and Rh. As the land cover is assumed to be stationary in this modeling study, we cannot quantify the change of NEP due to the land cover change although India had a good afforestation program after 1990. However, the continuous increasing value of

Fig. 5 Inter-annual variation of NEP, NPP, and Rh budgets for India and for the agricultural land, and the forestland in the country during 1981–2006 agricultural years
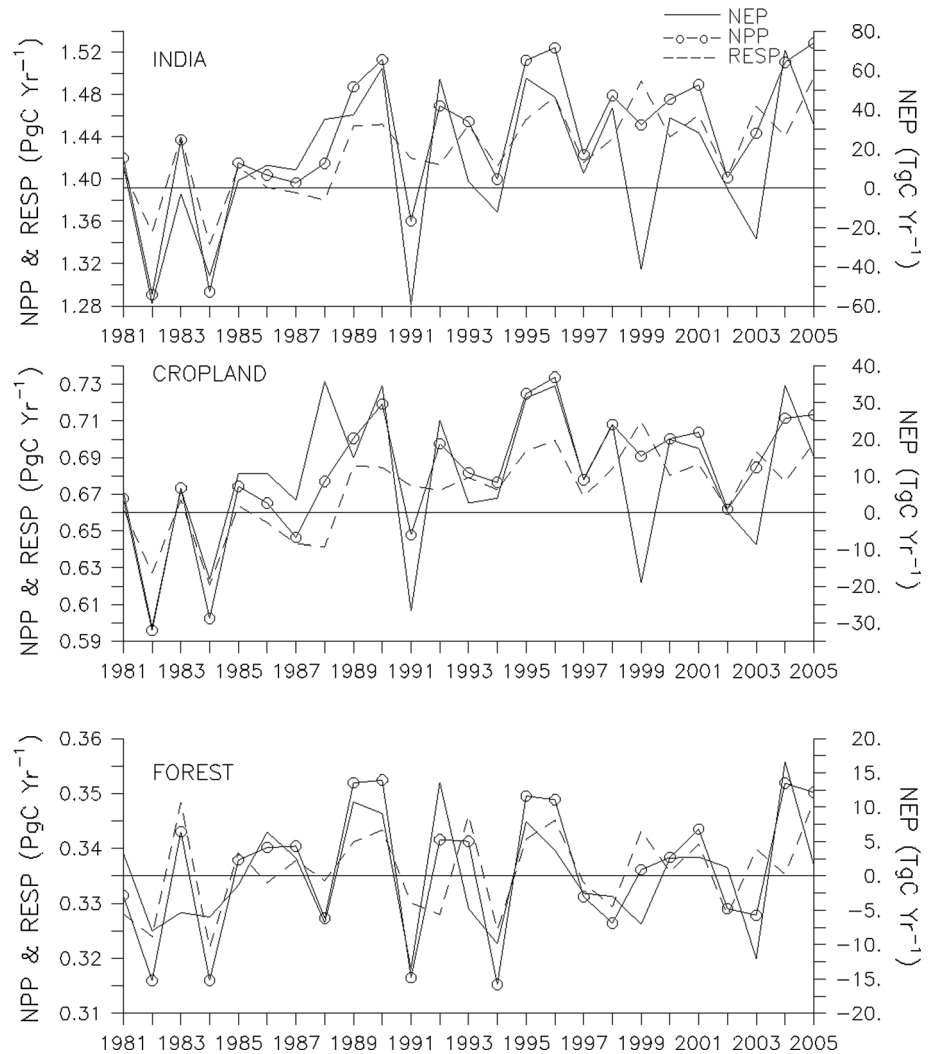
cropland NEP (that has dominating role on the Indian total NEP) after 1990 in the model result is primarily due to enhanced vegetation activity (NPP) resulted partly from climatic effect and partly from improved agricultural practices. The role of climatic on the control of NEP variability over the Indian ecosystem is described in the following section.

Inter-annual variability of NEP in relation to climate

NEP is the difference between NPP and Rh. Thus, the relationship between NEP and climate is dependent on the NPP–climate and the Rh–climate relationships. Terrestrial ecosystem models such as the CASA, estimates NPP based on light-use efficiency under the limiting effect of temperature and water stress scalars (Potter et al. 2003). Moisture limitation can suppress microbial activity and reduce sensitivity of Rh to temperature. Thus most of the ecosystem models, including

CASA, simulate Rh using the temperature response function (Q_{10}) along with soil moisture as a stress scalar. Nayak et al. (2013) have shown that the annual NPP variance across the country strongly related with the variance of precipitation and weakly with the variances of air-temperature and solar radiation. The region of large (small) variance of precipitation has the large (small) variance of NPP. We also found the similar relationship between the Rh and the precipitation: region of large variance of precipitation is also the region of large Rh variance (figures are not provided).

Further investigation is carried out to evaluate the relationship between the ecosystem responses (NEP, NPP, and Rh) and the climatic parameters (precipitation and air-temperature) for three major land-cover types: cropland, forest and grassland through correlation coefficients. Correlation analysis reveals that the negative NEP response of various ecosystems to precipitation is evident from strong and positive association of precipitation with Rh as

Fig. 6 Spatial patterns of annual NEP over India for different pentad periods during 1981 and 2006
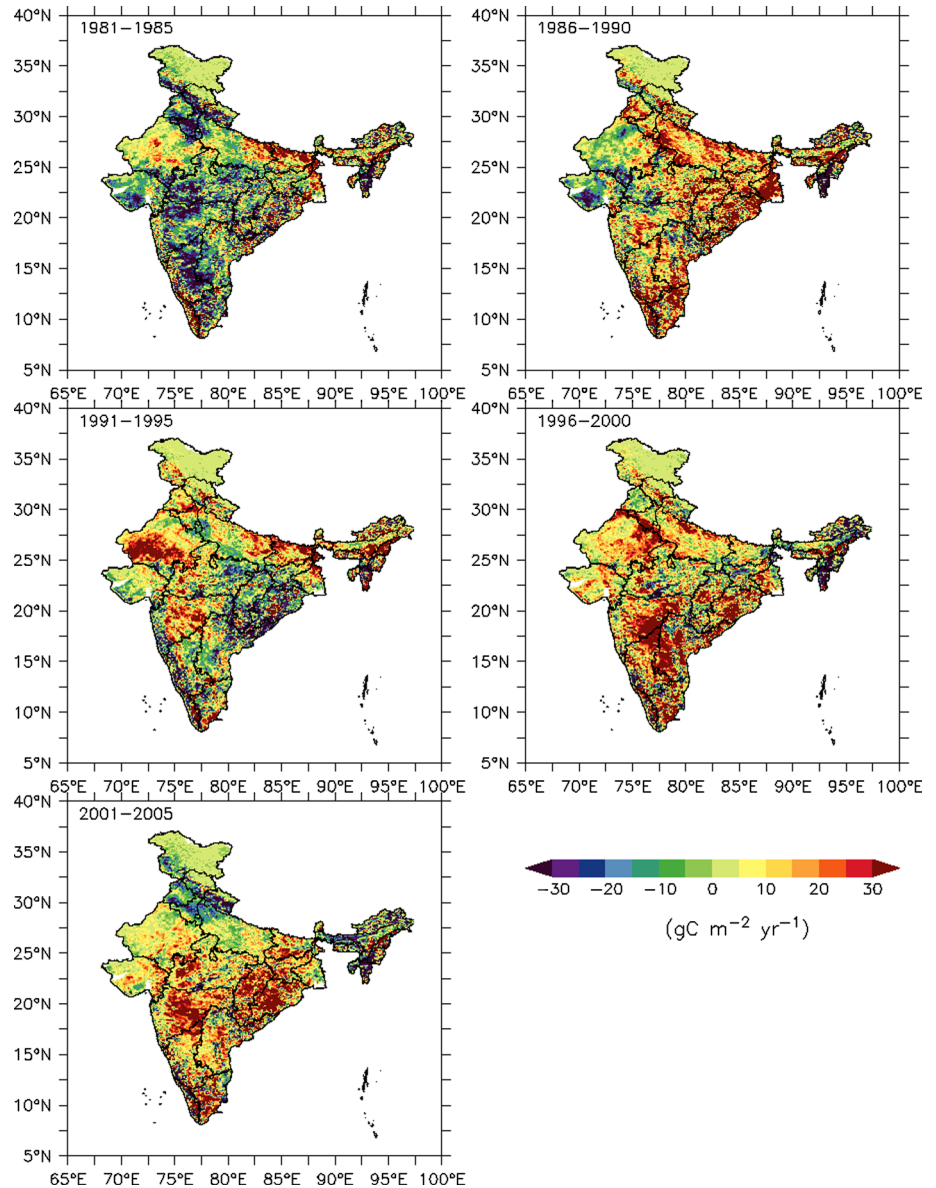
compared to that of the NPP (Table 3). Variability of air-temperature has insignificant coherence with the NPP and moderate to weak coherence with the Rh; however, it has moderate coherence with the NEP. It is difficult to conclude temperature control on NPP, Rh and NEP while it is very clear that precipitation has dominant control on ecosystem exchanges. Previous study on global simulations using SIB2 model also indicates a predominant influence of precipitation on NPP and Rh (Schaefer et al. 2002). This unique response of NPP and Rh to precipitation is manifested by predominance of arid and semi-arid land mass (68 %) in India, which is subject to moisture limitation during major part of year. As the vegetation growth in tropical environment is mainly controlled by wet and dry regimes, NPP primarily controls NEP with a

Pearson's correlation coefficient, r, ranging from 0.65 to 0.75. However, when moisture availability goes beyond the optimum threshold in good monsoon years, Rh dominates the NEP variability. In subtropical environment, Jung et al. (2011) also observed strong linkage of inter-annual variability of photosynthesis/respiration with inter-annual variations in precipitation.

Although both NPP and Rh exhibit large coherences with precipitation, the national NEP budgets during different years are highly variable between large positive and negative values and having no specific relation with precipitation budgets in the country. This could be due to other indirect and anthropogenic effects such as drought, flood and irrigation management, which may have significant control on the ecosystem responses. Large-scale flood can

Table 3 Pearson correlation coefficients (r) between ecosystem carbon exchange components (NEP, NPP and Rh) and environmental variables (PPT and T_{air}) for major land cover types

Land cover class	NEP and PPT	NEP and T_{air}	NPP and PPT	NPP and T_{air}	Rh and PPT	Rh and T_{air}
Cropland	−0.33	−0.31	0.33	−0.17	0.88	0.19
Forest	−0.54	−0.53	0.24	−0.09[×]	0.92	0.52
Grassland	−0.22	−0.24	0.37	0.02[×]	0.86	0.35
Whole country	−0.32	−0.33	0.35	−0.07[×]	0.90	0.32

PPT precipitation, T_{air} near surface air temperature

[×] Non-significant correlation ($P < 0.01$, $N = 312$)

damage the cropland ecosystem, resulting in reduction of NPP and enhancement of Rh leading to the negative NEP budgets. In subsequent period, after the flood, fertility of the land could be enhanced that may lead to enhancement of the NPP. On the other hand, drought condition leads to significant reduction on both NPP and Rh. Efficient irrigation systems improve the productivity of cropland at the severe climatic/drought condition. The flood years in India, with all India Summer Monsoon Rainfall (ISMR) in excess of one standard deviation above the mean or anomaly exceeding 10 %, occurred in 1983, 1988 and 1994, and drought years, with ISMR less than one standard deviation below the mean or anomaly below −10 %, are 1982, 1985, 1986, 1987, 2002 and 2004. It is interesting to note that positive NEP budgets are estimated for all the flood years and for most of the drought years except the year 1982. NEP budgets could be positive or negative for the normal years. Negative NEP budgets for the country are observed in 1982, 1984, 1991, 1999, and 2003. These negative and positive NEP values are not only caused by decline or increase in NPP associated with reduction in precipitation, but also due to moisture-induced triggering of soil respiration (Rh) and reduction of NPP owing to reduction in solar radiation by more cloudy/rainy days during good monsoon years. For example, El Nino events in 1987, 1997 and 2002 may have caused decline in rainfall below the normal, but did not affect the NEP much. El Nino events in 1987 and 2002 caused about 20 % decline in rainfall but induced increase in solar radiation for photosynthetic activity. The intensity of solar radiation during June–September month of 2002 was above 18 MJ m^{-2} day^{-1}. The slightly positive levels of NEP during 1987 and 2002 might be attributed to the strong decline of Rh (Rh < NPP) over the natural vegetations (forest, grassland) and over the cropland owing to predominate control of moisture limitation on microbial soil respiration. On the other hand, NEP is negative in good monsoon year 2003 due to reduction of NPP caused by low level of solar radiation during cloudy conditions and positive effect of precipitation on heterotrophic respiration. Over India and tropics, cloud cover holds strong negative relationship with solar radiation received at the earth surface (Biggs et al. 2007). The India Meteorological Department (IMD) observations of sunshine hours during June–September months over India in 2002 and 2003 were found be in the range of 3.5–5.0 and 5.0–7.0 h, respectively. As a result, the intensity of radiation observed in 2003 was also low (15–17 MJ m^{-2} day^{-1}). The low and high cloud cover in 2002 and 2003 over India was also noticed in terms of small and large values of MODIS-derived cloud optical thickness, respectively (Patra et al. 2005). However, seasonal precipitation during June–September of the year 2003 was 15 % above the long-term average and hence it has caused non-limiting moisture conditions for the microbial decomposition of substrate. Similar response of NEP to climatic variables is also observed over the East Asia and China terrestrial ecosystem during 2002 and 2003 (Saigusa et al. 2010). Large-scale negative anomaly of precipitation caused by EL Nino effects on 1982 and 1984 appeared to be a main cause for the Indian biosphere to act as a carbon source in early 1980s.

Conclusions

Annual climatology of the simulated NEP exhibits large spatial variation across the country. The regions dominated by the agriculture, and the shrub and grassland by land cover types are the regions of positive NEP with less inter-annual variation and hence the regions are constant sink of the atmospheric CO_2. On the other hand, small negative NEP values with large variance are present over the forestlands. On an average, India is the region of net sink of the atmospheric CO_2 with a total annual uptake of 9.85 TgC year^{-1}. This annual uptake comprised 85 % contribution from the agricultural lands, 10 % from the mixed shrub and grassland, and less than 1 % contribution from the forestlands. The country is primarily a sink of atmospheric CO_2 during peak periods of both the growing seasons (August–November and February–March) and is a source during the remaining periods of a year. It exhibits large inter-annual changes. In early 1980s (1981–1985),

major parts of the Indian ecosystem behave as a major source of the atmospheric CO_2 owing to a significant reduction of precipitation influenced by EL Nino events. After 1986, India remained the sink of atmospheric CO_2 during most of the years, except during the years 1991, 1994, 1999, and 2003. Inter-annual variability of the cropland NEP budgets has dominant control on the national NEP budgets inter-annual variability. The Indian ecosystems as a whole behave as a sink of the atmospheric CO_2 during major flood or major draught years, except 1982. It may act either source or sink during the normal years. Estimated long-term linear growth rate of NEP over the country is 1.8 TgC year^{-2} (8.5 %) which is small but significant. This increasing rate is primarily due to enhancement of productivity over the agricultural lands and the mixed shrub and grassland of the country.

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