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Estimating Trends and Variation of Net Biome Productivity in India for 1980–2012 Using a Land Surface Model

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Key Points:

- Net carbon sink represented by net biome productivity (NBP) has decreased for terrestrial Indian region in the last three decades
- Land cover change and climate change drive the decrease in NBP from 1980s to 1990s and 1990s to 2000s, respectively
- Rise in average temperatures has led to significant loses of carbon from ecosystems in the form of respiration

Supporting Information:

- Supporting Information S1

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Abstract In this paper we explore the trend in net biome productivity (NBP) over India for the period 1980–2012 and quantify the impact of different environmental factors, including atmospheric CO_2 concentrations ([CO_2]), land use and land cover change, climate, and nitrogen deposition on carbon fluxes using a land surface model, Integrated Science Assessment Model. Results show that terrestrial ecosystems of India have been a carbon sink for this period. Driven by a strong CO_2 fertilization effect, magnitude of NBP increased from 27.17 TgC/yr in the 1980s to 34.39 TgC/yr in the 1990s but decreased to 23.70 TgC/yr in the 2000s due to change in climate. Adoption of forest conservation, management, and reforestation policies in the past decade has promoted carbon sequestration in the ecosystems, but this effect has been offset by loss of carbon from ecosystems due to rising temperatures and decrease in precipitation.

Plain Language Summary Our study presents the results for net biome productivity (NBP) for India on a country scale, which are estimated using a state-of-the-art land surface model. Environmental factors, such as elevated atmospheric CO_2, climate change, nitrogen deposition, and land cover changes, have been identified as the major factors responsible for changes in terrestrial carbon fluxes. Broadly, the manuscript presents the relative contribution of these environmental factors to changes in NBP in India for the last three decades. Most of the published studies on this topic have focused on the NBP estimates at regional or global scale. To the best of our knowledge, this is the first attempt to quantify NBP at country scale. The results presented are timely because this manuscript adds to the knowledge of the carbon budget on a country level, identifies uncertainties in our understanding that can motivate further experiments, and aides in quantifying the regional and global carbon budget. These original research results presented in this study have implications for the ongoing international debate on climate treaty which calls for countries to apply the carbon stored in its forests and other ecosystems toward its budgeted reduction in carbon dioxide and other greenhouse gases.

1. Introduction

Quantification of the exchange of carbon between the atmosphere and terrestrial biosphere is central to monitoring the influence of anthropogenic disturbances on the terrestrial ecosystems. This exchange is well represented by the net biome productivity (NBP = GPP − Ra − Rh − E_luc) which considers gross carbon assimilation or gross primary productivity (GPP), total ecosystem respiration including both autotrophic (Ra) and heterotrophic (Rh) respirations, and anthropogenic carbon fluxes, such as net emissions due to land use and land cover change (E_luc) for a given ecosystem and for a region or globe. The ecosystem acts as a net carbon source or carbon sink, if the NBP flux values are negative or positive, respectively. There are numerous global-scale carbon flux studies (Beer et al., 2010; Le Quéré et al., 2015), but very few have focused on India. Most of the studies on India (Bala et al., 2013; Banger et al., 2015; Goroshi et al., 2014; Nayak et al., 2010) estimate the net primary productivity (NPP) by vegetation, (NPP = GPP − Ra) and do not account for soil carbon fluxes (e.g., soil heterotrophic respiration Rh), and anthropogenic disturbances, for example, E_luc. Majority of the studies that calculate NPP have used empirical models, like Carnegie-Ames-Stanford Approach (CASA) (Dadhwal et al., 2011; Goroshi et al., 2014; Nayak et al., 2015) and light use efficiency model implemented for the MODIS sensor (Bala et al., 2013). Only Banger et al. (2015) have used a process-based model, Dynamic Land Ecosystem Model, to study the role of environmental factors on NPP in India. Empirical models typically need a wide range of remote sensing data and hence are confined to the recent decades. In contrast, process-based models can be used to study the presatellite era as well as the future.

More importantly, process-based models can be used to conduct numerical experiments to derive insights into the processes and interactive feedback mechanisms that are responsible for variation in carbon fluxes with time.

Nayak et al. (2015) and Nayak et al. (2016) have studied net ecosystem production (NEP = NPP − Rh) that does not account for anthropogenic flux. Using CASA model, Nayak et al. (2015) found India to be a net carbon sink with a total annual averaged uptake of 9.9 TgC/yr over the time period 1981–2006. Nayak et al. (2016) reported 42 TgC/yr and 18 TgC/yr as average NEP values for India from 2001 to 2006 from MODIS-based and AVHRR-based estimates, respectively. By taking ensemble average of many approaches, Cervarich et al. (2016) found NEP and NBP values for India to be in the 200.6 ± 137.7 TgC/yr and 185.9 ± 145.6 TgC/yr range, respectively, for the 2000–2013 period. It is evident from this literature review that information on long-term variability and drivers of NBP over India is lacking, thereby limiting our understanding of the dynamics of the terrestrial carbon cycle, which is overall objective of the study.

In specific, this study has two main objectives: (1) to estimate the trend of NBP for the last three decades (1980–2012) and (2) to quantify the influence of major environmental and anthropogenic factors on carbon fluxes. We accomplish these objectives using a process-based land surface model, Integrated Science Assessment Model (ISAM), that is driven by forcings of [CO_2], land use and land cover change (LULCC), climate change, and nitrogen deposition to simulate terrestrial carbon dynamics for India from 1801 to 2012.

2. Methods

2.1. Model Description

The carbon fluxes for this study are generated using ISAM that is a state-of-the-art land surface model that simulates carbon, water and energy fluxes at 0.5° × 0.5° spatial resolution, and multiple temporal resolutions ranging from half hour to yearly time steps. ISAM simulates carbon fluxes through the processes of photosynthesis, carbon allocation to different plant parts, and autotrophic and heterotrophic respirations. Effects of different environmental factors like [CO_2], climate (e.g., temperature and precipitation), and photosynthetically active radiation are considered in flux estimation. Availability and effect of nitrogen is taken into account by fully coupling the carbon and nitrogen cycles in the model. The model accounts for dynamic phenology, root distribution, and depth parameterizations for different ecosystems. Stress factors of light, water, and nutrient limitation are considered while allocating the assimilated carbon to different plant parts (El-Masri et al., 2015; Song et al., 2016, 2013). The structure, parameterization and performance of ISAM have been extensively tested and verified in various studies (Barman et al., 2014a, 2014b; El-Masri et al., 2013, 2015; Jain et al., 2009, 2013).

2.2. Input Data

The ISAM model requires [CO_2], climate, nitrogen deposition, and LULCC data as input. We use [CO_2] data from Global Carbon Project Budget 2015 (Le Quéré et al., 2015). Gridded estimates of airborne nitrogen deposition are from Lamarque et al. (2011). The source of climate data is Climate Research Unit-National Centers for Environmental Prediction reanalysis (Harris et al., 2014). LULCC data (Jain et al., 2013) used have been reconstructed from Historical Database of the Global Environment (HYDE 3.1) (Klein et al., 2011) for cropland and pastureland transitions (Figure S1 in the supporting information). HYDE land cover data set used for driving the model has been compared with land cover data set based on updated version of Ramankutty and Foley (1999) (hereafter referred as SAGE) for India in Table S1. HYDE and SAGE data sets show slightly different levels of cropland and forest cover, the two main vegetation types for India. HYDE data estimated cropland areas over the last three decades are consistently higher than SAGE data, whereas HYDE-based estimated forest areas is lower. As discussed in Meiyappan and Jain (2012), the differences between the cropland and forest areas are a result of adoption of different methods and agricultural inventory data sets by both global landcover data sets. Where HYDE inventory data is based on FAO (2008), SAGE estimates have relied more on national-level census statistics and FAO estimates for recent years.

2.3. Experiment Design and Analysis

As a first step to start the model simulations, we spin-up ISAM to allow the carbon and nitrogen pools to reach a steady state at approximately 1800 levels. [CO_2], LULCC, and nitrogen deposition data are fixed at 1800 levels for the spin-up. Since climate data are available only from 1900 onward, climate data from years

Table 1
Description of Model Simulations Conducted With ISAM for India From 1801 to 2012

	Model simulation				
Environment factor	S_{CON}	S_{CO2}	S_{LUC}	S_{CLI}	S_{N_DEP}
Variable CO_2	✓	✗	✓	✓	✓
Variable LCLUC	✓	✓	✗	✓	✓
Variable climate	✓	✓	✓	✗	✓
Variable N deposition	✓	✓	✓	✓	✗

Note. Tick mark (✓) indicates the environmental factor was varied with time. Cross mark (✗) indicates the factor was held static at initial (assumed zero for nitrogen deposition and LCLUC) value. S_{CON}, S_{CO2}, S_{LUC}, S_{CLI} and S_{N_DEP} are model simulations with respective input environmental factors. For example, S_{CON} is the model simulation where all environment factors were accounted for.

1900 to 1930 are recycled to represent stable background climate. The details of this spin-up process are explained in El-Masri et al. (2013, 2015). Next, we conduct a control simulation (S_{CON}) by running ISAM from 1801 to 2012 with all four environmental and anthropogenic forcings, [CO_2], climate, LULCC, and nitrogen deposition, varying with time. Four additional simulations are conducted by turning off one of the four forcings at a time (Table 1). For the S_{CLI} run, [CO_2], LULCC, and nitrogen deposition are assumed to be the same as for the S_{CON} and the climate data are allowed to vary as used for spin-up experiment. The results of each additional simulation are compared with the S_{CON} simulation to estimate the impact of each forcing on the carbon fluxes. Since NEP does not account for LULCC effect, the NBP for S_{LUC} is equal to the NEP. E_luc is calculated by subtracting the NBP for S_{LUC}, which is without land use change, from the NBP for S_{CON}, which includes land use change. The temporal variability of the forcings (Table S2 and Figure S1) and their impacts on the carbon fluxes (Table 2) are averaged over three approximate decades, 1980s (1980–1989), 1990s (1990–1999), and 2000s (2000–2012), for further analysis.

To test the performance of the model specific for India region, we compare the simulated GPP with the spatially explicit FLUXNET-Multi-Tree Ensemble (MTE) data derived from empirical upscaling of eddy covariance measurements (Jung et al., 2009) and the MOD17A2 GPP data products from MODIS observations (Zhao & Running, 2010). For comparing the satellite-based observation data with ISAM model results both of these observed data sets are spatially aggregated to match the 0.5° × 0.5° resolution of ISAM. In addition, model-estimated NPP, NEP, and NBP have been compared and validated with other studies following multiple approaches for different study periods.

3. Results

3.1. Model Evaluation

The magnitude and overall spatial patterns of ISAM-simulated GPP broadly match the observed values from the FLUXNET-MTE and MODIS data sets (Figure S2). ISAM is able to capture important features such as the low productive Himalayan tundra ecosystem in the north, arid ecosystems in the northwest, and high productive regions like the Himalayan foothills and agricultural lands in the eastern and central parts of India. However, GPP is overestimated in the natural forest ecosystems in the northeast and Western Ghats but is underestimated in the grasslands and croplands in the northwest region as compared to FLUXNET-MTE. Average ISAM estimated GPP for the period 2001–2008 is 2.9 PgC/yr, which lies between MODIS and FLUXNET-MTE estimates of 2.8 PgC/yr and 3.3 PgC/yr, respectively. Simulated NPP (including the effect of LULCC) and NEP at country scale for different time periods have also been compared with other studies in Tables S3a and S3b. Our estimates of NPP and NEP are lower than most studies that have used remote sensing data with LUE models because the measurement of vegetation indices using remote sensing is prone to overestimation caused by lack of downregulating mechanisms due to limiting factors (Nayak et al., 2010). ISAM-simulated NBP for India has also been compared with results from bottom-up and top-down modeling approaches (Figure S3 and Table 3). NBP for India from other modelling studies was calculated by extracting the spatial grids for India from global NBP estimates. The yearly variations (Figure S3) and the ensemble of decadal averages of NBP from eight TRENDY version 4.0 models and five top-down models have been calculated for India to represent interannual variations and decadal average NBP from bottom-up models and top-down (or atmospheric-inversion) models, respectively. It is worth mentioning here that the top-down model estimated results for NBP are only available for the 1996–2012 (Thompson et al., 2016). Prior to 1996 the top-down model, results are not available, because this region is largely missing

Table 2
Variation in Model Estimated Impact of Environmental Factors, Including CO_2, LULCC and Climate, on the Rate of Change of Decadal Average for NBP from 1980s to 2000s

Decadal Transition	Impact of CO_2 (TgC/yr^2)	Impact of LCLUC (TgC/yr^2)	Impact of Climate (TgC/yr^2)
1980s to 1990s[a]	0.44	-1.29	-0.16
1990s to 2000s[a]	0.61	-0.25	-1.28
Net Impact (1980s to 2000s)[a]	0.52	-0.77	-0.72

[a]1980s, 1990s and 2000s are the averages for the periods 1980-1989, 1990-1999 and 2000-2012. The ecosystem acts as a net carbon source or carbon sink, if the NBP flux value is negative or positive.

Table 3
Comparison of ISAM Estimated Decadal Average NBP (TgC/yr) for India With Bottom-Up and Top-Down Models

DECADE	1980s[a]	1990s[a]	2000s[a]
Bottom-up models[b]	1.04 ± 46.75	34.65 ± 54.16	18.50 ± 48.40
Top-down models[c]	-	45.22 ± 69.53[d]	42.12 ± 67.40[e]
ISAM	27.17	34.39	23.70

[a]The 1980s, 1990s, and 2000s are the averages for the periods 1980–1989, 1990–1999, and 2000–2012. The ecosystem acts as a net carbon source or carbon sink, if the NBP flux value is negative or positive. [b]Based on TRENDY model intercomparison version 4.0 results (Sitch et al., 2015). In this study we used eight bottom-up model results: CLM4.5 (Oleson et al., 2013), JULES (Clark et al., 2011), LPJ (Sitch et al., 2003), LPJ_GUESS(Ahlström et al., 2012), LPX (Stocker et al., 2014), ORCHIDEE (Krinner et al., 2005), VEGAS (Zeng et al., 2005), and VISIT (Ito & Inatomi, 2012). Uncertainties have been calculated as 1σ (standard deviation) and represent differences between estimates from different models. [c]Top-down model results for the period 1996–2012 are based on Thompson et al. (2016). [d]The averaged value is for the period 1996–1999, which are calculated based on three top-down model results: ACTM (Patra et al., 2011), CCAM (Rayner et al., 2008), and JMA_CDTM (Sasaki et al., 2003). Uncertainties have been calculated as 1σ (standard deviation) and represent differences between estimates from different models. [e]The results are based on five top-down model results: ACTM (Patra et al., 2011), CCAM (Rayner et al., 2008), GELCA (Ganshin et al., 2011), JMA_CDTM (Sasaki et al., 2003), and Carbon Tracker-Europe (Peters et al., 2007). Uncertainties have been calculated as 1σ (standard deviation) and represent differences between estimates from different models.

atmospheric CO_2 measurement data prior to 1996 (Patra et al., 2016; Thompson et al., 2016).This comparison shows that ISAM estimates of NBP for India are well within the range of NBP estimates from other approaches and follow the same trend as decadal mean NBP from bottom-up models. However, the estimates of NBP from top-down models for India are many times larger than the estimates from bottom-up models. This large uncertainty in NBP estimates indicates the complexity and sensitivity of the terrestrial ecosystems to changes in environmental factors, which is the major objective of this study. The differences between flux estimates from bottom-up and top-down models can also be attributed to incomplete accounting of all relevant fluxes in each of these modeling approaches. Top-down models have a coarser spatial resolution (>1.8° × 1.8°) which adds to the large uncertainties in the model estimates. Despite the large differences between top-down and bottom-up model results, it is worth noting that the NBP estimates from top-down models lie within one standard deviation of that from bottom-up models.

3.2. Carbon Fluxes From 1980 to 2012

Over the last three decades, carbon fluxes for India including GPP, Ra, NPP, and Rh have increased at the rates of 6.00 TgC/yr^2, 4.50 TgC/yr^2, 1.55 TgC/yr^2, and 1.85 TgC/yr^2, respectively (Figure S4). In contrast, NBP does not show any definite trend for the study period. Magnitude of NBP has increased from 27.17 TgC/yr in the 1980s to 34.39 TgC/yr in the 1990s and then decreased to 23.70 TgC/yr in 2000s (Figure 1). The increase in NBP from 1980s to 1990s can be attributed to CO_2 fertilization impact that has led to positive trend for NPP and NEP promoting carbon sequestration potential of terrestrial ecosystems. However, because of higher rate of increase in loses of carbon from the ecosystems in the form of respiration than net carbon sequestered by the plants from 1990s to 2000s, NBP has shown a negative trend for this period. Positive NBP values estimated by ISAM from 1980s to 2000s indicate that terrestrial ecosystems of India are a net carbon sink due to enhanced CO_2 fertilization effect, but the reducing trend in NBP of 1.07 TgC/yr^2 from 1990s to 2000s points to a declining carbon assimilation rate in recent years mainly due to rise in average temperatures and decreased precipitation, resulting an increase in loss of carbon from ecosystems in the form of respiration, and partly due to loss of forest cover in the 1980s and 1990s.

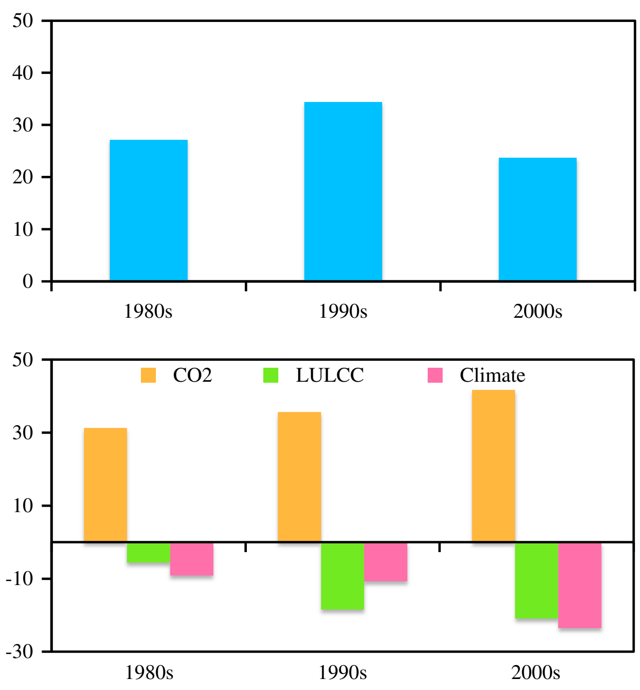

Figure 1. Model estimated decadal average (1980s, 1990s, and 2000s) of (top) net biome productivity and (bottom) contribution of different factors to it.

ISAM simulations indicate that majority of changes in carbon fluxes over India are driven by increasing [CO_2], LULCC, and climate change (Figure 1). CO_2 fertilization effect, on one hand, is promoting higher NBP at the rate of 0.52 TgC/yr^2 (Table 2), but LULCC and climate change contribute to the increasing tendency of the ecosystems to act as carbon sources for the study period 1980s to 2000s at the rates of -0.77 TgC/yr^2 and -0.72 TgC/yr^2, respectively (Table 2). However, the overall impact of environmental and anthropogenic factors of [CO_2], LULCC, and climate on carbon fluxes of terrestrial ecosystems of India has not been uniform throughout the last three decades.

CO_2 fertilization effect is evident in our results as increase in NPP over time with a net positive influence on NEP and NBP. With rise in [CO_2], the CO_2 fertilization effect on NBP is much more pronounced from 1990s to 2000s at 0.60 TgC/yr^2 than from 1980s to 1990s at 0.44 TgC/yr^2 (Table 2).

Deforestation in natural forestland and conversion of forests to croplands has led carbon flux related to LULCC to act as a major source of carbon for India for most part of the 20th century (Figure S1). LULCC is found to be the most dominant driver of negative NBP trend from 1980s to 1990s, resulting in the carbon loss at the rate of 1.29 TgC/yr^2 (Fig 1). But recent attempts of forest restoration and conservation have led to steady decrease in rates of deforestation and increase in secondary forest cover for India in the last three decades (Figure S1). This has led to reduction in carbon loss from terrestrial ecosystems due to LULCC from 1.29 TgC/yr^2 from 1980s to 1990s to 0.25 TgC/yr^2 from 1990s to 2000s (Table 2). This positive impact of increase in forest cover and reduction in deforestation activites on carbon uptake of ecosystems in recent years has also been mentioned in previous studies (Bala et al., 2013; Banger et al., 2015; Kaul et al., 2009; Nayak et al., 2015, 2016; Patra et al., 2013).

The impact of climate change on carbon cycle remains one of the most uncertain components in carbon studies. Increase in decadal average temperature for the study period is expected to negatively affect plant photosynthetic rates and hence total carbon assimilated by terrestrial Indian region. Warmer temperatures have also led to loss of carbon from the ecosystems due to increase in respiration rates. Decadal average temperature has seen much larger increase from 1990s to 2000s than in the decade prior (Table S2). Decadal average of annual precipitation has been found to increase by 2.44% from 1980s to 1990s but has decreased by 4.77% from 1990s to 2000s, causing a net decrease of 2.45% over the study period. The large increase in temperature and subsequent decrease in precipitation have collectively led to climate change acting as an overall major and most dominant source of declining NBP (Figure 1) from 1990s to 2000s impacting NBP at the rate of -1.28 TgC/yr^2 (Table 2). Such strong influence of climate on carbon uptake of ecosystems calls for our attention and need for more such studies focused on climate change trends and its effects on the terrestrial ecosystems of India specific to different vegetation types and at finer spatial resolution.

The role of nitrogen deposition is found to be negligible for fluxes over India (Figure S5), which indicates that India, being a tropical country, is not nitrogen limited. Hence, results for the case of nitrogen deposition are not discussed in this paper.

NBP in India varies a lot along the spatial expanse of the country (Figure S6). More than 50% of Indian land is covered by croplands (Figure S1) that have a low capacity of carbon sequestration. However, parts of Western Ghats, natural evergreen and deciduous forests in the north-east and regions around the Himalayan foothills are seen to be large carbon sinks with higher NBP.

4. Discussions and Conclusions

This study explores the variability of NBP over India from 1980 to 2012 and how this variability is influenced by environmental and anthropogenic factors like [CO_2], LULCC, climate, and N deposition by conducting numerical experiments with the ISAM model. Results show that terrestrial ecosystems of India have been a carbon sink for the entire study period with positive NBP, but with a negative trend in NBP in the recent decades (1990s to 2000s), suggesting that carbon sequestration potential of the ecosystems is decreasing overtime. Even though CO_2 fertilization continues to increase carbon sequestration in the terrestrial ecosystems, this increase is offset majorly by climate change and to some extent by deforestation activities. Of all the factors studied as a part of this research, climate change is the most uncertain and significant factor that is likely to impact carbon fluxes the most in future, because under climate change the terrestrial ecosystems are found to lose carbon in the form of ecosystem respiration proportionally. Induced warming patterns and water limitation due to less precipitation are found to be the most dominant and significant sources driving negative trend of NBP from 1990s to 2000s.

It is important to note that the uncertainties in magnitudes of NEP and NBP in different studies are large (Patra et al., 2013) reflecting the complexity of the system and the sensitivity to the processes involved. Interactions amongst different environmental and anthropogenic forcings and their effect on ecosystems are nonlinear as reflected in our runs. For instance, impact of increasing [CO_2] with changing LULCC is different from summing the impacts of changing [CO_2] and LULCC separately. This nonlinear effect adds to the uncertainty in the estimated carbon fluxes. These uncertainties and disagreements between different studies point toward the need of more extensive research in this area focusing on individual environmental and anthropogenic factors and their impacts at finer spatial resolutions.

To contextualize our estimates of carbon fluxes, it is essential to include other major sources of carbon emission. Figure S7 depicts the carbon budget for India with fluxes of NEP, LULCC (E_luc), NBP, fire (E_fire) (van der Werf et al., 2010, but with updated burned area from Giglio et al., 2013), and fossil fuel (FF) emissions (Le Quéré et al., 2015) averaged for 2000–2012. These estimates show that the large magnitude of fossil fuel emissions clearly makes India a carbon source despite the fact that its terrestrial natural ecosystems are currently acting as a net sink for [CO_2]. Such comprehensive analysis is essential to develop more effective policies for environmental management.

It is to note that while net terrestrial CO_2 sink on a global scale has been reported to increase in recent years by global scale studies (Le Quéré et al., 2015), our study has shown opposite trend for India, mainly driven by increasing temperatures and decreasing precipitation. While greening in high latitudes has been reported due to warmer temperatures that have led to an increase in terrestrial CO_2 sink for these places, for a tropical country like India, increase in respiration has reversed the trend on a country scale. It can be inferred that with the current trend of increasing temperatures, tropical countries might be on a higher risk of losing carbon from their terrestrial ecosystems.

Most of the existing studies on global or regional scales have used multiple approaches to estimate the carbon fluxes on regional and global scales. This study, however, goes beyond flux estimation and focuses on understanding the sensitivity of net carbon fluxes for India to various environmental and anthropogenic factors, such as elevated CO_2 levels in the atmosphere, climate change, land cover and land use change, and nitrogen deposition. This is necessary to improve our understanding of processes responsible for sources and sink of carbon in terrestrial ecosystems. Country-level estimates are particularly relevant, for example, in the context of the 2015 Paris Climate agreement (UNFCCC, 2015), which requires quantifiable biosphere sources and sinks of carbon dioxide (CO_2) and other greenhouse gases at country level in order to enable successful implementation of climate policy.

Acknowledgments
The four sets of gridded terrestrial carbon fluxes outputs (GPP, NPP, NBP, Ra, Rh, and land use emission) simulated using ISAM for India under four different experimental discussed in the paper can be downloaded from the ISAM model website: http://climate.atmos.uiuc.edu/Gahlot_etal_GRL_Data.tar.gz. These runs were conducted from 1801 to 2012, and here we provide the results from 1980 to 2012, which is the period the paper mainly focusing on. Part of the research was carried out under a visiting fellowship offered to Shilpa Gahlot by the University of Illinois under NASA grant (NNX414AD94G). Atul K Jain and Shijie Shu were supported by the NSF (NSF AGS 12-43071) and the US DOE (DOE DE-SC0016323). We thank Prabir Patra from JAMSTEC Japan for providing us the top-down model-estimated NBP results presented in Table 3.

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