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LETTER

The terrestrial carbon budget of South and Southeast Asia

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Abstract

Accomplishing the objective of the current climate policies will require establishing carbon budget and flux estimates in each region and county of the globe by comparing and reconciling multiple estimates including the observations and the results of top-down atmospheric carbon dioxide (CO_2) inversions and bottom-up dynamic global vegetation models. With this in view, this study synthesizes the carbon source/sink due to net ecosystem productivity (NEP), land cover land use change (E_{LUC}), fires and fossil burning (E_{FIRE}) for the South Asia (SA), Southeast Asia (SEA) and South and Southeast Asia (SSEA = SA + SEA) and each country in these regions using the multiple top-down and bottom-up modeling results. The terrestrial net biome productivity (NBP = NEP − E_{LUC} − E_{FIRE}) calculated based on bottom-up models in combination with E_{FIRE} based on GFED4s data show net carbon sinks of 217 ± 147, 10 ± 55, and 227 ± 279 TgC yr^{-1} for SA, SEA, and SSEA. The top-down models estimated NBP net carbon sinks were 20 ± 170, 4 ± 90 and 24 ± 180 TgC yr^{-1}. In comparison, regional emissions from the combustion of fossil fuels were 495, 275, and 770 TgC yr^{-1}, which are many times higher than the NBP sink estimates, suggesting that the contribution of the fossil fuel emissions to the carbon budget of SSEA results in a significant net carbon source during the 2000s. When considering both NBP and fossil fuel emissions for the individual countries within the regions, Bhutan and Laos were net carbon sinks and rest of the countries were net carbon source during the 2000s. The relative contributions of each of the fluxes (NBP, NEP, E_{LUC}, and E_{FIRE}, fossil fuel emissions) to a nation's net carbon flux varied greatly from country to country, suggesting a heterogeneous dominant carbon fluxes on the country-level throughout SSEA.

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1. Introduction

South and Southeast Asia (SSEA) is characterized by a faster than global average population growth and is increasing its food and energy production for the growing population by expanding agricultural land and burning more fossil fuels. A carbon budget, the net gain or loss of carbon, for this region will enable the constraining of other neighboring regional fluxes and act as an overall constraint on the global carbon budget. A full carbon budget, as the one presented here is also important to support the development of climate mitigation policies, and project future climate change.

Geographically, SSEA occupies one of the largest areas of tropical forests. These forests account for about 20% of the potential global terrestrial net primary productivity (NPP) and play an important role in regulating the Earth's carbon cycle and climate (Tian *et al* 2003). Studies suggest tropical land carbon fluxes exhibit, on average, a larger variability than temperate carbon fluxes (Tian *et al* 1998, Foley *et al* 2002, Peylin *et al* 2005, Zeng *et al* 2005, Ahlström *et al* 2015), due to the influence of climatic events, such of El Niño and La Niña events on ecosystem processes, and the subsequent ecosystem disturbance such as large scale forest fires (Patra *et al* 2005). Specifically, studies suggest that enhanced sources occur during El Niño episodes and abnormal sinks during La Niña (Gérard *et al* 1999, Jones *et al* 2001). The large variability in land source and sink fluxes makes it difficult to determine long-term trends in the net terrestrial carbon flux. Therefore, a better understanding of how the SSEA ecosystems respond to natural variability will reduce uncertainties in understanding the long-term trends and the magnitude and sign of the carbon-climate feedbacks.

The region has a history of land use land cover change (LULCC) activity such as intensive cultivation and overgrazing of pasturelands (Canadell 2002) and transitioning forestland to agricultural land. Globally, SEA had the highest deforestation rate (FAO 2010) between 1990 and 2010 with the forests of SEA contracting in size by just less than 33 million hectares (FAO 2010). A great deal of concern has been raised regarding to what extent such rapid changes in LULCC and management practices have affected the amount of carbon in vegetation, soil organic matter, and litter pools, thereby impacting the net land-atmosphere carbon flux, which is essential to ecosystem sustainability in SSEA.

Forest fires also contribute to the carbon budget by rapidly releasing carbon from vegetation. van der Werf *et al* (2010) estimated global biomass burning emitted 2.0 PgC yr^{-1} with substantial interannual variability from 1997 to 2009. Fires caused by both natural and human sources impact biomass emission, sometimes in tandem. For example, in SEA it is economically advantageous to clear land via fire (Dennis *et al* 2005). Transitioning of land from tropical forest or peatland to agricultural or other commercial uses is driving SEA to have the highest deforestation rate worldwide (Langner and Siegert 2009). Langner and Siegert (2009) showed fire events are three times more frequent during El Niño years than non-El Niño.

Fossil fuel burning is another important source of carbon emissions. Globally, fossil fuels have emitted 9.0 PgC yr^{-1} during 2000s and are the greatest source of carbon (Le Quéré *et al* 2015). SSEA is also likely to have a large source of carbon emissions from the combustion of fossil fuels due to the rapidly expanding population and gross domestic product growth, both of which are closely related to fossil fuel emissions (Raupach *et al* 2007).

Carbon budgets for the globe (Le Quéré *et al* 2015), South Asia (Patra *et al* 2013, Thompson *et al* 2016), and SEA (Thompson *et al* 2016) have been established. Additionally, Pan *et al* (2011) and Adachi *et al* (2011) evaluated the carbon budget of tropical forests in SEA and Tao *et al* (2013) estimated the carbon exchange due to changes in cropland coverage and management in SSEA. This study builds upon and extends the previous budget studies by further investigating the terrestrial carbon budget and its components for SSEA region and each country of SSEA region. By quantifying the country-specific terrestrial carbon budget and related carbon fluxes, this study will help to determine how much carbon is being stored or released in its forests and other ecosystems toward its budgeted reduction in carbon dioxide. Country-level estimates are particularly relevant e.g., 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. Further division of the sectorial carbon budget for large countries like India is desired for preparing efficient emission mitigation policy.

The specific objectives of this study are: (1) to estimate the terrestrial carbon budget components; net ecosystem productivity (NEP), LULCC emission (E_{LUC}), and fire emissions due to non-land use change activities (E_{FIRE}); of South Asia (SA) and Southeast Asia (SEA), the two sub-regions of SSEA, and that of each contributing country of SA (Bangladesh, Bhutan, India, Nepal, PakistanSri Lanka,) and SEA (Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Vietnam) regions for the period 2000–2013; (2) estimate NEP and its interannual variability for the period 1980–2013; (3) compare the terrestrial carbon budget, in terms of net biome production (NBP $=$ NEP $-$ E_{LUC} $-$ E_{FIRE}) of SA and SEA and the countries within these two regions to the fossil fuel emissions. We use multiple data products; including fossil fuel inventory data and remote sensing data products for E_{FIRE}; the results of dynamic global vegetation models (DGVMs) (or bottom-up models), atmospheric inversion models (or top-down models) and a book-keeping model to estimate the carbon fluxes and terrestrial carbon budget.

2. Data and methods

The study region is SSEA. We report here carbon fluxes for SA, SEA and entire SSEA and for those countries whose areas occupy twelve or more $0.5° \times 0.5°$ pixels, which is the standard resolution for the bottom-up models being used in this study. Singapore and Brunei are the only two countries whose areas do not satisfy our criteria; therefore we do not report carbon emissions for these two countries, but account for their carbon fluxes in regional total estimates. In the following we describe the methods and the data we used to estimate the terrestrial carbon budget (carbon sink and source terms), and the fossil fuel emissions for comparison purpose.

2.1. Net ecosystem production (NEP) and LULCC emissions estimated based on TRENDY models (or bottom-up models)

We use an ensemble of nine dynamic global vegetation models (DGVMs: CLM4.5 Oleson *et al* 2013, ISAM Jain *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 and Inatomi 2012) results for carbon fluxes over for SSEA region. Model simulations follow the protocol as described by the carbon cycle model intercomparison project (TRENDY) (Sitch *et al* 2015), where each model was run from its pre-industrial equilibrium (assumed at the beginning of the 1860) to 2013. Here we use the TRENDY model results for NEP (=NPP (net primary productivity)—Rh (heterotrophic respiration)) based on two different simulation scenarios, S2 (S2 NEP) and S3 (S3 NEP). For S2 simulations, the models were forced with changing CO_2 (Dlugokencky and Tans 2014), CRU-NCEP reanalysis climate forcing (Harris *et al* 2014) and time-invariant pre-industrial (year 1860) HYDE land use (Klein Goldewijk *et al* 2011) data sets over the period 1860–2013. The S3 simulations assume the same input for CO_2 and climate as for S2 case, but the land use varies with time based on HYDE land use data set (figure 1). All models account for nitrogen deposition. Model parameterizations are summarized in table S1. For each simulation NPP and Rh are spatially integrated at the regional and country level for further analysis. Land use change emissions (E_{LUC}) are estimated by subtracting S2 NEP from S3 NEP (S3 NEP – S2 NEP).

2.2. Fire emissions due to non-LULCC activities

The E_{LUC} term already accounts for fire emission due to LULCC activities, such as deforestation. In order to account for fire emissions due to non-LULCC activities (E_{FIRE}), such as lightning induced fires, we obtained carbon emissions from fires from the Global Fire Emissions Database version 4.1, which includes small fire burned area (GFED4s) as described in van der Werf *et al* (2010) but with updated burned area (Giglio *et al* 2013). The burned area information is used as input data in a modified version of the satellite-driven Carnegie–Ames–Stanford Approach (CASA) biogeochemical model to estimate carbon emissions associated with fires, both LULCC- and non-LULCC related (see van der Werf *et al* 2010). To calculate E_{FIRE}, we subtract GFED4s-estimated fire emissions due to land use change from the fire emissions due to all fire activities (land use change and non-land use related fire activities). In this way, E_{FIRE} also accounts for emissions from peat land, which has also not been accounted for in TRENDY model results. We analyze E_{FIRE} emission data from 1997 to 2013 in this study.

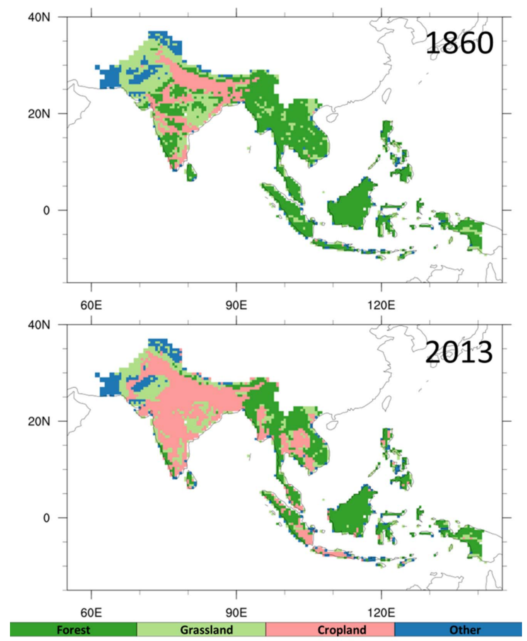

Figure 1. South and Southeast Asia (SSEA) with HYDE land cover data (Klein Goldewijk *et al* 2011) in 1860 and 2013.

2.3. Net biome production (NBP) calculated based on bottom-up modeling approach

We estimate NBP after accounting for disturbances due to LULCC and forest fire (excluding fire emissions due to deforestation) such that NBP = S2 NEP – E_{LUC} – E_{FIRE}. The E_{LUC} and E_{FIRE} terms are described in sections 2.1 and 2.2.

The variables are averaged for the 1980s, 1990s, and 2000–2013 (hereafter, referred to as the 2000s) to evaluate the change in the NEP and NBP over the past three decades. To study the impact of climate variability on NEP anomalies we detrended the NEP and climate data (temperature and precipitation) by removing the linear trend. Negative NBP values represent net C release to the atmosphere and positive values represent net C sequestered by the terrestrial biosphere.

2.4. Estimates of NBP based on atmospheric CO_2 inverse models (or top-down models)

In order to compare TRENDY models estimated NBP for the 2000–2013 period, which uses bottom-up modeling approach, we used NBP estimates based on the following 5 atmospheric inversion or top-down models: ACTM (Patra *et al* 2011), CCAM (Rayner *et al* 2008), GELCA (Ganshin *et al* 2011), JMA_CDTM (Sasaki *et al* 2003), and CarbonTracker-Europe (Peters *et al* 2007). Atmospheric inversion models used here inferred NBP by applying Bayesian statistics to observed atmospheric CO_2 concentrations, the carbon flux due to fossil fuels and simulated atmospheric transport. Fossil fuel fluxes were based on data from CDIAC and PBL. The inversion models are forced with atmospheric data from JCDAS, ECMWF, NCEP2, NCEP, or JRA-25. The inverse models are run at a relatively coarse resolution (>1.8° × 1.8° spatial resolution only have 11 divisions of global land) and therefore cannot be applied at the country level.

2.5. Estimates of LULCC emissions based on the bookkeeping model

Additionally, country specific LULCC emissions estimated based on TRENDY models are compared with a bookkeeping method (Houghton 2003 and 2010), which uses the following two data types to calculate annual sources and sinks of carbon from LULCC: first, rates of land use (e.g., wood harvest) and land-cover change (e.g., conversion of forest to cropland) and, second, carbon densities (MgC ha^{-1}) in four pools of carbon: living biomass, above- and below-ground; dead biomass, including coarse woody debris; harvested wood products; and soil organic carbon. The effects of environmental change (e.g., the concentration of CO_2 in the atmosphere, changes in climate, and N deposition) were not included in the defined changes. Rates of forest growth and rates of decay varied with type of ecosystem, type of land use, and region, but they did not vary through time in response to changing environmental conditions. Changes in the areas of croplands and pastures used in bookkeeping model calculation were obtained from FAOSTAT (2015) from 1961 to 2013. After 1990, rates of deforestation and reforestation were obtained from the FRA 2015 (FAO 2015). Earlier changes were compiled from data and assumptions similar to those used in previous analyses (Houghton 1999, 2003, 2010). The bookkeeping model results for SA, SEA and SSEA presented in this study are part of a new global estimate (Houghton and Nassikas 2016). Although bookkeeping model results are available from period 1850 to 2015, we are using the results for the period

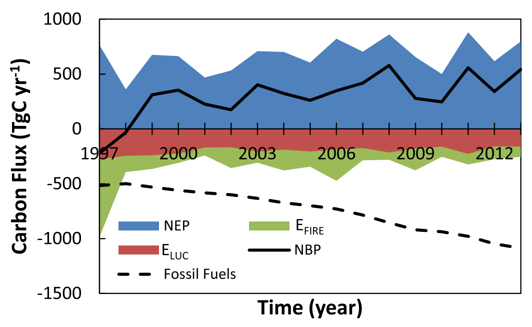

Figure 2. Cumulative components of the terrestrial carbon budget (NEP, E_{LUC}, E_{FIRE}) NBP, and fossil fuels for the period 1997–2013. Positive values are a land sink of carbon and negative values are emissions to the atmosphere. Net ecosystem productivity (NEP; dark blue) and land use change emissions (E_{LUC}; red) are the average of TRENDY models estimates. Fire emission estimates due to non-land use change activities (E_{FIRE}; green) are from the Global Fire Emissions Database version 4 (van der Werf *et al* 2010). Net biome productivity (NBP; solid line) is the difference between emissions from the land sink, NEP, and the land sources, E_{LUC}, and E_{FIRE}. Fossil fuel emission (dashed line) is sourced from the Carbon Dioxide Information Analyses Center (CDIAC) database.

1980–2013 for comparing two modeling approaches (DGVMs and bookkeeping).

2.6. Emissions from fossil fuel consumption and cement production

We also compare country specific NBP estimates with the emissions from fossil fuel burning and cement production. Carbon emissions from fossil fuel consumption were retrieved from Le Quéré *et al* (2015), which were compiled from many sources, including the Carbon Dioxide Information Analysis Center (CDIAC) (Boden *et al* 2015), BP statistical review of world energy the International Energy Agency (IEA), the United Nations (UN) (2014), the United States Department of Energy (DOE), Energy Information Administration (EIA), and more recently also the Planbureau voor de Leefomgeving (PBL) Netherlands Environmental Assessment Agency. Here the fossil fuel emissions at national and regional levels include emissions from gas flaring and cement production (US Geological Survey 2013). Data is available at a country level from 1959 to 2013. In this study we analyze data from 1980 to 2013.

3. Results

3.1. NEP

The TRENDY model results based on the S2 experiment, which does not consider land use change over time, suggests that NEP for SSEA increased from a sink of 414 TgC yr^{-1} in the 1980s to 489 TgC yr^{-1} and 542 TgC yr^{-1} in the 1990s, and the 2000s, respectively, and had a 1980–2013 absolute C sink growth rate of 5.8 TgC yr^{-1} (figures 2 and 3(a), table S2). The increase in NEP over the period 1980–2013 has mainly been

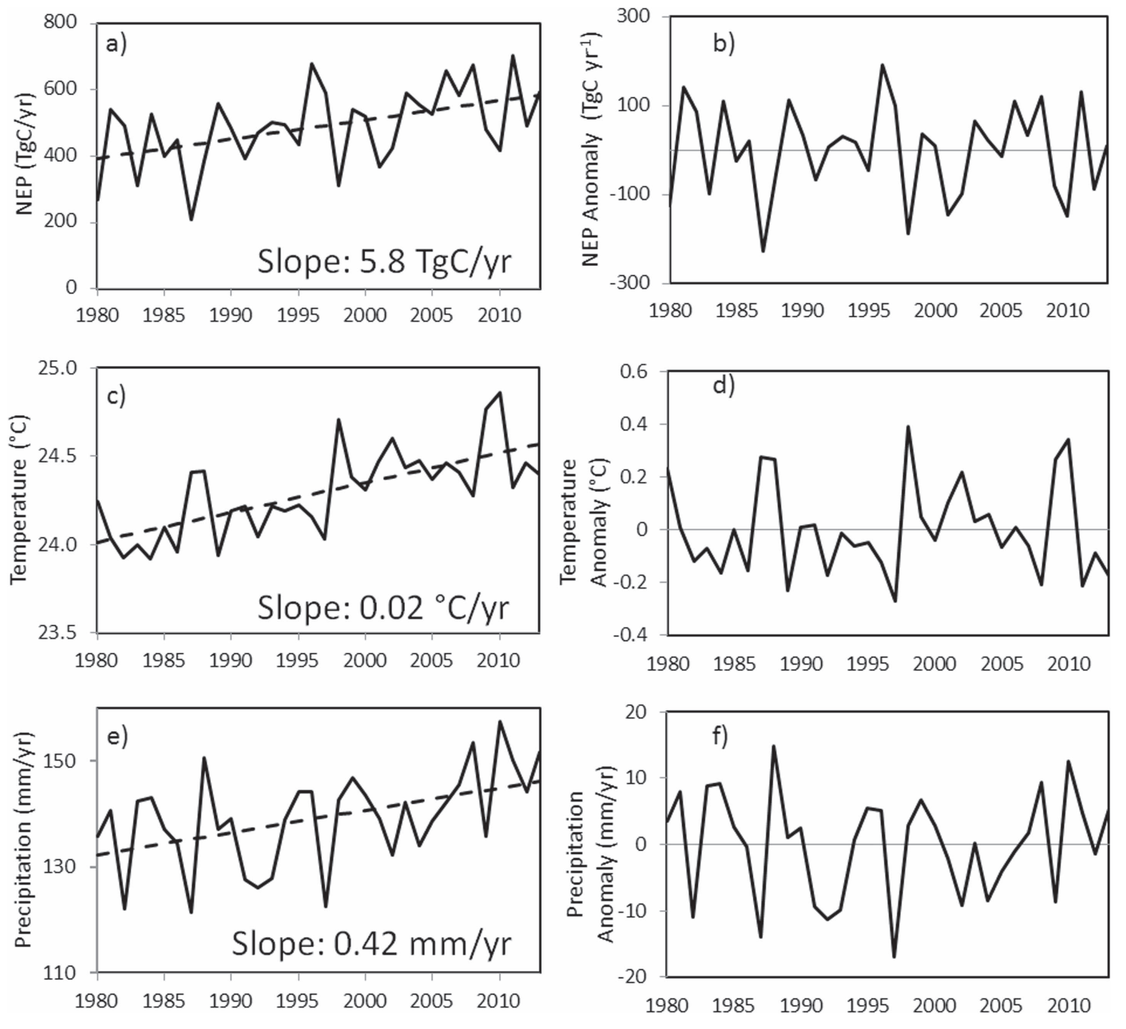

Figure 3. Interannual variation in net ecosystem productivity (NEP) (a), temperature (c), precipitation (e). Dashed lines represent least squared linear fit with slope shown in text. Detrended interannual variation in NEP (b), temperature (d), and precipitation (f).

attributed to the carbon dioxide fertilization effect due to the incremental increase in atmospheric carbon dioxide concentrations (Sun *et al* 2014). For the 1980–2013 period, SSEA coefficient of variation (CV), the standard deviation divided by the mean, is relatively large (25%) compared to the growth rate (115 TgC yr^{-1}) (table S2), suggesting there is substantial interannual variability.

All countries had positive absolute growth rates (increasing sink; decreasing source) except Bangladesh, Bhutan, and Nepal. Bangladesh had the least absolute growth rate (−0.04 TgC yr^{-1}) and the Indonesia had the greatest normalized growth rate (3 TgC yr^{-1}) (table S2). Sri Lanka had a highest variation relative to the mean as shown by a CV greater than 100% (112%), while Bangladesh had the lowest (CV = 24%) (table S2). The growth rates, which are increasing due to CO_2 fertilization, describe the trend in NEP, but the relatively high CVs suggest there is considerable year-to-year variability in every country.

To investigate model response to internal climate variability we first removed the linear trend from NEP model estimates time series (figure 3(b)), which is influenced by non-internal climate factors, such as CO_2 fertilization. We also de-trend the temperature and precipitation to remove the confounding climate change effects (figures 3(d) and (f)). The first order trend for temperature and precipitation was 0.02 °C yr^{-1} and 0.42 mm yr^{-1} (figures 3(c) and (e)). Detrended SSEA NEP had statistically significant correlation with detrended temperature ($r = -0.71$, $P < 0.5$) (table S3) and a statistically significant correlation with detrended precipitation ($r = -0.15$, $P > 0.5$) (table S3) suggesting the year to year variability in NEP was driven mainly by changes in temperature. The strong negative correlation of temperature to NEP suggests NEP in the region decreases carbon uptake or increases carbon emissions in warmer years due to the increase in heterotrophic respiration in warmer environments (Moncrieff and Fang 1999). Although the relationship of CO_2 emission and sink change with climate variability is well accepted, the relative effects of rainfall and temperature are debated (Wang *et al* 2014). The DGVM simulated interannual variations are often much weaker than those estimated by the inverse models (e.g., Patra *et al* 2005), suggesting

Table 1. Terrestrial carbon fluxes for the countries in South Asia (SA), Southeast Asia (SEA) and South and Southeast Asia (SSEA = SA + SEA) (listed in alphabetic order) for the 2000–2013 period based on the average of the nine TRENDY models. NBP for SSEA for 2000–2013 Positive values are sink of carbon and negative values are source of carbon. Uncertainty is estimated with the 1-σ standard deviation from the terrestrial ecosystem models. Fossil fuel emissions are from the Carbon Dioxide Information Analysis Center (CDIAC) database and averaged over the 2000–2013 period.

Country	NEP (TgC yr^{-1})	LULCC (TgC yr^{-1})	FIRE (TgC yr^{-1})	NBP (TgC yr^{-1})	Fossil Fuels (TgC yr^{-1})
Bangladesh	10.6 ± 8.8	−1.4 ± 4.6	−0.0 ± 0.0	9.3 ± 9.2	−12.2
Bhutan	2.2 ± 1.9	−0.4 ± 1.1	−0.5 ± 0.0	1.2 ± 2.3	−0.1
India	200.6 ± 137.7	−6.2 ± 44.4	−8.5 ± 0.6	185.9 ± 145.6	−439.9
Nepal	9.2 ± 7.6	−0.2 ± 2.8	−1.0 ± 0.1	8.0 ± 8.4	−0.9
Pakistan	14.2 ± 7.7	−1.1 ± 2.8	−0.4 ± 0.0	12.7 ± 10.9	−38.2
Sri Lanka	3.6 ± 1.6	−3.1 ± 2.2	−0.2 ± 0.0	0.4 ± 3.2	−3.3
SA	**240.6 ± 138.4**	**−12.4 ± 44.8**	**−10.6 ± 0.6**	**217.5 ± 146.6**	**−494.6**
Cambodia	11.5 ± 3.61	−5.8 ± 6.6	−8.1 ± 0.5	−2.3 ± 7.4	−0.9
Indonesia	106.3 ± 48.9	−94.9 ± 76.5	−49.6 ± 49.2	−38.2 ± 17.8	−101.4
Laos	24.8 ± 11.1	−6.8 ± 8.0	−10.3 ± 0.7	7.7 ± 16.0	−0.4
Malaysia	22.2 ± 11.9	−14.6 ± 16.6	−4.5 ± 0.4	3.1 ± 26.4	−49.4
Myanmar	53.1 ± 18.7	−10.9 ± 12.4	−17.3 ± 1.9	24.9 ± 25.9	−2.9
Philippines	16.2 ± 5.3	−13.2 ± 9.4	−1.3 ± 1.1	1.8 ± 13.4	−20.5
Thailand	37.4 ± 13.3	−10.1 ± 16.5	−11.2 ± 0.8	16.1 ± 24.2	−70.0
Vietnam	34.7 ± 16.6	−19.1 ± 14.1	−18.6 ± 1.3	−3.0 ± 17.5	−29.5
SEA	**306.2 ± 59.2**	**−175.4 ± 83.4**	**−120.9 ± 49.3**	**9.8 ± 55.4**	**−274.9**
SSEA	**546.6 ± 200.6**	**−187.7 ± 192.2**	**−131.6 ± 3.5**	**227.3 ± 278.9**	**−769.5**

that either the DGVM NEP estimates are relatively less sensitive to environmental conditions or the variability of upper tropospheric CO_2, which is used to drive the top-down models, is not representative variability of the boundary layer CO_2 which is interacting with the vegetation.

3.2. LULCC emissions

The TRENDY models estimated E_{LUC} for SSEA were a net source in the 1980s, 1990s, and 2000s with mean annual emissions of 199 TgC yr^{-1}, 304 TgC yr^{-1}, and 244 TgC yr^{-1}, respectively. Every country, except Indonesia and Sri Lanka, had lower carbon emissions in the 2000s than in the 1990s (figure S1). In all three decade, Indonesia had the highest E_{LUC} with increasing trend (figure S1) and the emissions contributed to 32%, 30%, and 39% of the total SSEA emissions for the 1980s, 1990s, and 2000s, respectively. Malaysia had the second largest E_{LUC} in the 1980s (24 TgC yr^{-1}, 12%) and 2000s (14 TgC yr^{-1}, 6%) (table 1). In the 1990s, India had the second highest E_{LUC} (32 PgC yr^{-1}, 10%). However, India experienced the greatest decrease in E_{LUC} (26 TgC yr^{-1}, 80%), whereas Indonesia experienced greatest increase in E_{LUC} (3 TgC yr^{-1}, 4%) between the 1990s and 2000s. Indonesian and Malaysian deforestation is primarily due to logging and the expansion of oil palm plantations (Wicke *et al* 2011, FAO 2010). From 1980 to 2013, 11 Mha or 6% of Indonesia's total land area had been converted from forest to cropland (Klein Goldewijk *et al* 2011). In contrast, in India reforestation/afforestation policies practiced by India's Ministry of the Environment and Forests in the 2000s have decelerated the rate of deforestation (Reddy *et al* 2015). On the regional scale, deforestation (due to conversion of forest to cropland and pasturelands) was

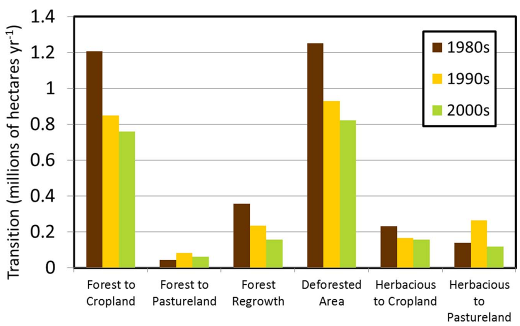

Figure 4. Decadal average rate of conversions of land in South and Southeast Asia (SSEA).

the major driving factor of LULCC emission over the last three decades. The deforestation rates for SSEA region in the 1980s, 1990s, and 2000s were 1.25, 0.93, and 0.82 Mha^{-1}. Part of the deforestation effect is compensated by the forest regrowth in the regions which were the greatest in the 1980s (0.36 Mha yr^{-1}) (figure 4) mitigating part of the carbon emissions associated deforestation. Likewise, the 2000s had a forest regrowth of 0.16 Mha yr^{-1} with a majority (81%) of regrowth due to the abandonment of cropland.

The E_{LUC} from the bookkeeping model for the 2000s are within the uncertainty range of the bottom-up models for SSEA region and for 11 of 14 countries (figure S1). Additionally, the bookkeeping model is consistent with bottom-up models with respect to the decadal trend for SSEA—an increase from the 1980s to the 1990s followed by a decrease from the 1990s to the 2000s. Differences may be due to different LULCC inputs and different modeling approaches to estimate emissions due to land use changes.

3.3. Fire emissions

The estimated average SSEA E_{FIRE} for 1997–2013 were 132 ± 4TgC yr^{-1}. Forest fires from Indonesia accounted for 50 ± 49 TgC yr^{-1}. Indonesia employs peatland fires as a land clearing technique before the planting of crops. Cambodia, Laos, Thailand, Myanmar, and Vietnam collectively contribute to 31% of the region total with rates of 8 ± 1 TgC yr^{-1}, 10 ± 1 TgC yr^{-1}, 11 ± 1 TgC yr^{-1}, 17 ± 1 TgC yr^{-1}, and 18 ± 1 TgC yr^{-1}, respectively. These countries are the region's maxima for lightning activity (Christian *et al* 2003) and, in conjunction with periods of low precipitation, may be one of the causes of forest fires. Additionally, man-made fires have extensively been used to clear land for agricultural and other economic purposes (Fox 2000) and may have a higher tendency to spread during dry conditions. On the regional scale, rates of are decelerating at 12 TgC yr^{-2} (7.3% yr^{-1}) with substantial country to country variation (figure S2). Indonesia's emissions are estimated to be decreasing 14 TgC yr^{-2} (11.2% yr^{-1}), whereas India's are increasing by 1.4 TgC yr^{-2} (0.12% yr^{-1}). Bangladesh, Cambodia, Myanmar, Pakistan, and Sri Lanka all have rates of change of less than 1 TgC yr^{-1}. Additionally, there is substantial year to year variability. The CV was 86% for SSEA. The large interannual variability suggests that fire emissions are impacted by the variables that have high interannual variations, such as precipitation. During El Nino years, a descending branch of the Walker circulation is established over the western pacific and suppresses convection in Southeast Asia (Julian and Chervin 1978), resulting in a low precipitation that leads to drying of the biomass and increases the potential to ignite a fire due to lightening. Other countries also experience fire emission variability due to changes in precipitation, but the countries that experience the greatest variability have greater forest area (figure 1), and therefore emit carbon during fire events and have larger amplitudes in fire emissions.

3.4. NBP emissions

Figures 5 and S3 and table 1 show the bottom-up models estimated mean NBP for the period 2000-2013 and its components, including S2 NEP, E_{LUC} and E_{FIRE} for SA, SEA and SSEA regions and individual countries within SA and SEA, respectively. The bottom-up models estimated NBP for SA, SEA and SSEA (SA + SEA) were 217 ± 147 TgC yr^{-1}, 10 ± 55 TgC yr^{-1}, and 227 ± 279 TgC yr^{-1} (1-σ standard deviation of the 9 DGVM models (table 1), compared to the top-down estimated NBP of 20 ± 170 TgC yr^{-1}, 4 ± 190 TgC yr^{-1} and 24 ± 180 TgC yr^{-1} (1-σ standard deviation of the five inverse models). Clearly, the bottom-up models and top-down models both suggest the terrestrial biosphere for SA and SEA regions acted as a net sink for the period 2000–2013, but the sink estimated with the bottom-up models is about many

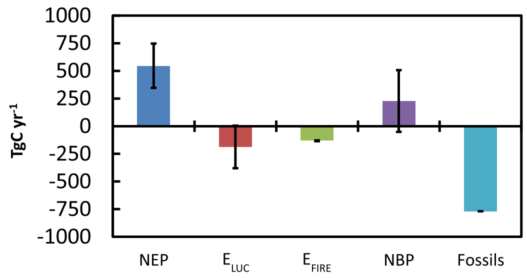

Figure 5. Mean carbon fluxes for the period 2000–2013. Error bars represent the first standard deviation of the model results. Fire emissions due to non-LUC related fire activities, E_{FIRE}, are from Global Fire Emissions Database version 4 s (van der Werf *et al* 2010) and fossil fuel emissions are from the Carbon Dioxide Information Analysis Center (CDIAC) database. NEP, E_{LUC}, and NBP are estimated from the TRENDY models. Positive values are a land sink of carbon and negative values are emissions to the atmosphere.

times the estimate from the atmospheric inversion models for both regions. However, the atmospheric inversion models estimate was within one standard deviation of the bottom-up models. Multi-model syntheses suggest large uncertainties in the estimated CO_2 fluxes by both the top-down and bottom-up approaches. Contributing to the found discrepancy is the incomplete accounting of all relevant carbon fluxes inherent in these modeling approaches. For example, the budget estimated by top-down models for the Asian regions is only weakly constrained by atmospheric observations and may be reflected as weak or no increase in uptake over SSEA, as this region is largely missing atmospheric CO_2 measurement data (Patra *et al* 2016). Another possible reason for the lower estimates of carbon uptake may be the underestimate of the increase in fossil fuel emissions in this region, which is assumed *a posteriori* and is subtracted from the total optimized CO_2 flux (Thompson *et al* 2016). At the same time bottom-up models may have overestimated the CO_2 sink amount due to overestimation of the CO_2 fertilization effect, as most models do not include nitrogen and phosphorous-limitation on gross primary production, and/or the LULCC database may have underestimated rates of deforestation. Uncertainties from initial/boundary conditions such as climate variability (monsoons, droughts), model parameters and land use cover data can increase the inter-model variability. A recent study analyzing TRENDY project model outputs on global scale supports the large variability of the estimated land-atmosphere carbon exchange in tropical regions (figure 3, Zhao *et al* 2016).

The estimated E_{FIRE} for SA, SEA and SEA are 11 ± 1, 121 ± 49 and 132 ± 4 TgC yr^{-1}, which are approximately the same as the estimated E_{LUC} emissions for SA, but about 50 TgC yr^{-1} lower than E_{LUC} emissions for SEA and SSEA regions (table 1), suggesting that E_{LUC} emissions influence the terrestrial carbon budget of SEA and SSEA more than E_{FIRE} emissions.

For the 2000s period, the estimates of the carbon sink due to S2 NEP SA, SEA and SSEA are 240 ± 45 (CV = 18%), 306 ± 83 (27%) and 547 ± 201 TgC yr^{-1} (CV = 37%). The estimates of E_{LUC} for three regions are 12 ± 45 (CV = 375%), 175 ± 83 (CV = 47%) 188 ± 192 TgC yr^{-1} (CV = 88%) (table 1). The relatively high CV values in E_{LUC}, particularly for SA, suggest uncertainty in estimates of NBP based on bottom-up models is, in part, caused by representation of LULCC and varying parameterizations of plant function types across the numerical models.

With regard to the individual country's terrestrial carbon fluxes, the terrestrial ecosystems of acted as a sink for atmospheric CO_2 with India had the greatest sink (NBP = 185 ± 146 TgC yr^{-1}) with relatively higher estimates of NEP (201 ± 138 TgC yr^{-1}) and lower estimates of E_{LUC} (−6 ± 44 TgC yr^{-1}) and E_{FIRE} (−9 TgC yr^{-1}) (figure S3). On the other hand, terrestrial ecosystems of three countries in SEA acted as source. Indonesia, Cambodia and Vietnam had estimated NBPs that were a source of carbon (table 1 and figure S3), primarily due to large emissions due to fires.

Uncertainty in NBP arises from the 9 TRENDY models representing LULCC activities and NEP differently. Major differences among the models are the inclusion/exclusion of carbon-nitrogen interactions, fire simulations, cropland harvest, shifting cultivation, and wood harvest and forest degradation (table S1). It is difficult to tease out relative contribution of each of the processes to the total uncertainty because controlled sensitivity simulations with each model are not available.

3.5. Comparison of NBP flux with fossil fuel emissions

Carbon emissions due to fossil fuel burning increased in every country within SA and SEA (figure S4). Overall, the total regional emissions (SA, SEA and SSEA) increased from the 1980s (179, 72 and 221 TgC yr^{-1}) to the 1990s (278, 153 and 431 TgC yr^{-1}), and from the 1990s to the 2000s (2000–2013) (493, 275 and 768 TgC yr^{-1}). Fossil fuel emissions are largely connected to economic activity. India had the fastest absolute growth rates and Bhutan had the slowest absolute growth rates at 16 TgC yr^{-2}, and 0.005 TgC yr^{-2}, respectively. India, which contributed greater than half of the regions fossil fuel emissions, has expanded its gross domestic product 10-fold from 1980 to 2013 (World Bank 2015). SSEA fossil fuel emissions increased every year except for in 1998 when the regions GDP decreased by 32% during the East Asian Financial crisis (World Bank 2015).

While the SA and SEA terrestrial biosphere during the 2000s acted as the net carbon sink for atmospheric CO_2, the magnitudes of the NBP sinks for both regions are less than the magnitude of the source due to fossil fuels (table 1).

India was a net source of carbon, when fossil fuel emissions (441 TgC yr^{-1}) are also considered. In Cambodia, Laos, Myanmar, Thailand, and Vietnam (collectively called Mainland Southeast Asia (MSEA)), non-deforestation fire emissions were of similar magnitude or of greater magnitude than fossil fuel emissions. This suggests the net land to atmosphere carbon emissions in MSEA is equally or more-so driven by emissions due to fires than fossil fuels. Bhutan, Laos, Myanmar, and Nepal were net sink of carbon when considering NBP and fossil fuels. NBP estimates for Myanmar are 25 ± 26 TgC yr^{-1} and fossil fuel emissions estimates are 3 TgC yr^{-1} (table 1, figure S3). The SSEA region has emissions due fossil fuel burning which are more than 4 times higher than the region's NBP. In contrast, the varying magnitudes of carbon sources in the countries of SSEA are different from each other and different from SSEA. This suggests the carbon budget of each country is determined by factors unique to the given country, possibly including land cover type, economic activity, climate, forest fire frequency, and management.

Our analysis suggests that the distribution of carbon emissions is not homogenous for the countries that make up SA and SEA (table 1). This suggests carbon emission reduction strategies should consider the sources at the country level.

4. Discussion and summary

Our assessment of the terrestrial carbon budget and fossil fuel emissions for SSEA and its countries provides insight into the trends and fluxes of NBP and its components. Additionally, our use of fossil fuel emissions data allows us to make quantitative comparisons between the NBP and the emission from fossil fuel burning. NBP of SSEA region was a net sink of carbon in the 2000s.

The NBP determined from the average of the nine TRENDY models' estimates, was 227 TgC yr^{-1} and based on average of atmospheric inverse models is 24 TgC yr^{-1}. In comparison, fossil fuel emissions were 700 TgC yr^{-1}. Fossil fuel emissions grew at 27 TgC yr^{-2}, whereas the growth of NBP sink was 9 TgC yr^{-2}, indicating that fossil fuel emissions grew about three times faster than the growth of the NBP sink. The NBP sink is increasing steadily due to higher atmospheric CO_2 and its effect on plant growth (CO_2 fertilization effect), while atmospheric CO_2 source is increasing due to E_{LUC}, E_{FIRE} and fossil fuel emissions.

NEP, the largest component of the terrestrial carbon budget, had an average sink of 545 TgC yr^{-1} and grew at 12 TgC yr^{-2} in the 2000s. Unlike fossil fuel emissions, NEP has a large interannual variation negatively correlated with temperature suggesting that increased heterotrophic respiration in warm years increases carbon emissions or decreases carbon sink.

On yearly timescales, the land sink was sensitive to changes in fire emissions and variations in the local temperature. Warm and dry anomalies, typically associated with El Niño events, triggered less NEP and hence weaker carbon sink. Countries in MSEA had the greatest correlation with temperature (table S2). The interannual variability of NEP is consistent with the warming of MSEA during El Niño events and associated decrease in NEP via an increase in Rh, which is particularly sensitive to temperature increases in MSEA (Zhou *et al* 2009).

The interannual variability of NEP is greater in DGVM than in top-down models. Top-down models are driven by tropospheric CO_2 sampled from aircraft in the upper atmosphere. Stephens *et al* (2007) showed the seasonal variability of upper tropospheric CO_2 is less than the seasonal variability of boundary layer CO_2. Further investigation is needed into interannual variability of the vertical distribution of CO_2 to better constrain the top-down models.

E_{LUC} increased from the 1980s to 1990s then reversed the trend from the 1990s to the 2000s. The reversing of the trend is attributed to human and policy factors such as the afforestation efforts in India. E_{LUC} was 244 TgC yr^{-1} and decreased at 1.6 TgC yr^{-2} in the 2000s, with relatively low interannual variability suggesting the E_{LUC} is seldom influenced by environmental factors. Furthermore, E_{LUC} decreased in nearly every country, with the exception of Laos and Indonesia, from the 1990s to the 2000s (figure S1). Land use change practices in Indonesia have been well-documented and attributed to the expansion of palm oil plantations at the expense of tropical forests (FAO 2010, Wicke *et al* 2011), and in Laos due to the expansion of agriculture, deforestation for timber, and expansion of cities (Fox and Vogler 2005).

Fire emissions due to non-LULCC fire activities, E_{FIRE} in SSEA are primarily from Indonesia and MSEA. In MSEA, there is a local maxima of lightening that triggers fires in vegetated areas, including forest fires.

Considering both NBP and fossil fuels, both for SA and SEA were net sources of atmospheric CO_2 (276 and 265 TgC yr^{-1}) in the 2000s. Fossil fuel emissions increased at an exponential rate throughout the 2000s, simultaneously the NBP sink also increased, but at a slower rate. If the trends continue the NBP sink will further increase, but many factors may complicate future projections. For example, increased temperatures may further weaken the carbon sink, in terms of NEP, in the region due to the lager enhancement of ecosystem respiration comparing to the increment of carbon assimilation, which is expected to be water-limited under the drier future climate. LULCC has been a source over the 2000s, but this source term is shrinking in magnitude since the 1990s and therefore is helping to increase the NBP sink through the legacy effect of slower rate of deforestation. The E_{FIRE} emissions are approximately constant over the last three decades (figure S2), but the emission rates may grow in the future, as the environmental conditions grow drier and hotter due to climate change.

This study presents the terrestrial carbon budget estimates, in terms of NBP, at regional and country levels. While fine scale carbon budget information can be used to inform decision-makers regarding carbon management or policy-related activities, the uncertainty in estimated regional and country specific NBP based on top-down and bottom-up modeling approaches are large, represented here as the 1 σ standard deviation of the model derived estimates (figures 5 and S3, and tables 1 and S2). The magnitude of the terrestrial carbon source terms, including deforestation and other disturbances, for countries within SSEA are probably less reliable than that of the CO_2 emissions from fossil-fuel burning. Additional uncertainty in the carbon budget estimates arises from sinks associated with post disturbance recovery and interannual variations due to climate anomalies. Clearly, the current approaches to model carbon dynamics need improvements to account for subgrid scale level processes and feedbacks. Future carbon budget analyses will require data for environmental variables, such as LULCC activities, at higher resolutions accounting for detailed decisions on land management at a sub-national scale, given that most countries have different land classes, different commodities and multiple options for managing commodities (West *et al* 2013). This can be accomplished by using satellite-based land products to improve spatial representation, and supported by highly accurate ground-based estimates. Higher resolution data in combination with extending the DGVMs to account for carbon and other nutrient dynamics at higher resolutions will be useful for informing policy decisions, because of their ability to connect carbon and other nutrient stocks and flows to ground-based physical processes.

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