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Changes in carbon fluxes and pools induced by cropland expansion in South and Southeast Asia in the 20th century

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Abstract

A process-based ecosystem model, the Dynamic Land Ecosystem Model (DLEM), was applied to evaluate the effects of cropland expansion on terrestrial carbon fluxes and pools in South and Southeast Asia in the 20th century. The results indicated that cropland expansion in both regions has resulted in a release of 18.26 Pg C into the atmosphere in the study period. Of this amount, approximately 23 % (4.19 Pg C) was released from South Asia and 77 % (14.07 Pg C) from Southeast Asia. More land area was converted to cropland but less carbon was emitted in South Asia than in Southeast Asia, where forest biomass and soil carbon are significantly higher. Carbon losses in vegetation, soil organic matter, and litter carbon pools accounted for 15.09, 2.01, and 1.60 Pg C, respectively. Significant decreases in vegetation carbon occurred across most regions of Southeast Asia due to continuous cropland expansion and depletion of natural forests. Our study also indicated that it is important to take into account the land use legacy effect when evaluating the contemporary carbon balance in terrestrial ecosystems.

1 Introduction

Cropland expansion, the land conversion from natural vegetation (e.g., forests and grasslands) to cropland, is historically the most dramatic land-use change across the globe (Tilman, 1999; Foley et al., 2005; Chen et al., 2006). Between 1700 and 1992, about 1,135 M ha (22.9 %) of forest and woodland were converted to agricultural use (Lal, 2007). Land-use changes reshape landscapes and may trigger substantial environmental risks, such as carbon and greenhouse gas emissions (Houghton, 1999; Kaye et al., 2004; Foley et al., 2005; Tian et al., 2010a), changes in energy exchange in the land-atmosphere and regional climate (Zhang et al., 1995; Pielke, 2005; Feddema et al., 2005; Snyder, 2010), land degradation (Drake and Vafeidis, 2004; Thornes, 1996), and the loss of biodiversity (Pimm et al., 1995; Sala et al., 2000).

The terrestrial ecosystems in South and Southeast Asia play a crucial role in regional and global carbon cycling (Brown et al., 1991, 1995; Flint and Richard, 1991; Richard and Flint, 1994; Houghton, 2002; Tian et al., 2003). As regions with large populations and growing economies, South and Southeast Asia have witnessed unprecedented rapid land-use change in the 20th century. This is characterized by cropland expansion and natural forest shrinkage, with cropland expansion undertaken to meet growing demands for food, bioenergy and urban development (Richard and Flint, 1994; Houghton, 2002; Tian et al., 2003, 2008, 2010a). Cropland covers about 73 % of the total land area in South Asia today, while it covers about 50 % in Southeast Asia (Wood et al., 2000). For South and Southeast Asia as a whole, cropland has increased by approximately 106 M ha and approximately 81 % of forests and wetlands have been converted during the period 1880–1980 (Flint and Richards, 1991). In India, cultivated area increased by more than 40 % while 40 % of forest area was lost during 1880–1980 (Flint and Richards, 1991). It has been estimated that forest cover in Indonesia decreased by up to 20 million ha in the 1990s as a result of logging, transmigration, spontaneous settlement, and estate crops (Pagiola, 2000). Compared to other regions of the world, major cropland expansion has occurred in South and Southeast Asia over the past 20 years (Millennium Ecosystem Assessment, 2005). Around the globe, the tropical area in Southeast Asia had the highest deforestation rate, followed by Latin America and Africa (Achard et al., 2002). In most of the regions where a high rate of deforestation occurred, forest land was converted to cropland. Tropical forest has the highest biomass and relatively high soil carbon density, so land conversion from tropical forest to other vegetation types will significantly reduce carbon storage in the terrestrial ecosystem (Achard et al., 2002, 2004; Canadell, 2002).

In recent decades, a number of studies have investigated the potential impacts of land-use change on the carbon cycle in South and Southeast Asia using the bookkeeping model, remote sensing data, inventory data, and process-based models at various scales, ranging from site, local, and regional to continental scales (Brown et al., 1991; Houghton and Hackler, 1999; Houghton, 2002; Canadell, 2002; Tian et al., 2003; Suh et al., 2004; Zhao et al., 2006; Adachi et al., 2011). The bookkeeping and inventory methods (e.g. Houghton and Hackler, 1999) are able to calculate changes in carbon storage induced by land area change; however, these approaches lack the capability of providing a quantitative understanding of ecosystem processes that control carbon dynamics; due to the shortage of spatially-explicit, time-series data of biomass and land use/land cover, they rarely provide information on interannual and spatial variations in carbon sources and sinks. In an earlier study, Tian et al. (2003) used a process-based model (the Terrestrial Ecosystem Model, TEM) to estimate changes in carbon fluxes and pools due to land-use change in Asia. Although their study simulated the monthly carbon fluxes induced by land-use change, the TEM model used a generalized crop to represent all types of crops and did not take into account crop-specific information on phenology and cropping systems. To reduce the uncertainty in estimating spatial and temporal patterns of carbon fluxes and pools in association with cropland expansion in South and Southeast Asia, therefore, we have to better understand cropland expansion-driven carbon dynamics by using updated data sets and an improved process-based ecosystem model.

In this study, we applied a process-based Dynamic Land Ecosystem Model (DLEM), which fully couples biogeochemical processes with an agricultural submodel (Tian et al., 2011a; Ren et al., 2011a), to quantify the effects of cropland expansion on carbon fluxes and pools in South and Southeast Asia in the 20th century. The objectives of this study were to: (1) quantify the effects of cropland expansion induced land-use change on temporal and spatial patterns of carbon fluxes and pools in the terrestrial ecosystem of South and Southeast Asia; (2) examine the relative role of different land-use change types on the capacity of terrestrial carbon sequestration; and (3) identify major uncertainties and future research needs.

2 Materials and methods

2.1 Study area

The region of South and Southeast Asia extends from 38° north to 16° south latitude and from 60° to 140° east longitude, encompassing a land area of approximately 5.0×10^6 km^2 and 4.7×10^6 km^2, respectively (Fig. 1). South Asia, which includes the countries of Afghanistan, Bangladesh, Bhutan, India, Nepal and Pakistan in this study, is one of the most populated regions in the world and has a long history of cultivation. Southeast Asia covers the countries of Sri Lanka, Brunei, Burma, Indonesia, Cambodia, Laos, Malaysia, the Philippines, Thailand, and Vietnam. Southeast Asia contains the world's third largest tropical rainforest but this has been heavily deforested over the past decades (UNEP, 2009). Both South Asia and Southeast Asia are influenced by monsoons that bring strong seasonal changes in precipitation, and are subject to climate extremes, particularly floods and droughts.

2.2 Model description

The Dynamic Land Ecosystem Model (DLEM) is a highly integrated process-based ecosystem model which couples biophysical characteristics, plant physiological processes, biogeochemical cycles, and vegetation dynamics and land use to make daily, spatially-explicit estimates of carbon, nitrogen and water fluxes and pool sizes in the terrestrial ecosystems from site and regional to global scales. The DLEM has been documented in previous studies through extensive applications to investigate the impacts of multiple environmental factors, including changes in climate, atmospheric composition (CO_2, O_3, reactive nitrogen), land use and land cover change, and land management (harvest, rotation, fertilization, irrigation etc.), on the structure and functioning of terrestrial ecosystems over China, Monsoon Asia, the conterminous US, and North America (e.g., Tian et al., 2005, 2008, 2010a, b, 2011a, b, c; Chen et al., 2006; Ren et al., 2007, 2011a, b; Zhang et al., 2007, 2010; Liu et al., 2008; Lu et al., 2011; Xu et al., 2010).

The DLEM model has improved process-based simulation to track the effects of land-use change on ecosystem processes that control the terrestrial carbon cycle. An agricultural module is specifically developed to simulate impacts of agricultural activities (such as seeding, planting, irrigation, fertilization, tillage, genetic improvement, and harvest) and environmental factors on carbon, water and nitrogen cycles in agricultural ecosystems (Ren et al., 2011a). Different crop types and rotations are specifically parameterized. Currently, about 20 major crop types (e.g., corn, rice, wheat, barley, soybean, sorghum, cotton, maize, sugarcane) and three cropping systems (i.e., single, double, and triple harvests) are included in DLEM simulations. The main crop categories in each grid were identified according to the global crop geographic distribution map with a spatial resolution of 5 min (Leff et al., 2004), and were then modified with regional agricultural census data derived from FAOSTAT (http://faostat.fao.org/). DLEM simulates crop growth according to prescribed phenology derived from remote sensing methods (i.e., leaf area index, LAI) and large numbers of field observations. Phenological metrics include seeding, germination, development, flowering, fruiting and harvest.

Four general land-use change categories are simulated by DLEM, namely land conversion from natural vegetation types to cropland, land conversion among different natural vegetation types, cropland abandonment, and urbanization (Fig. 2). During land conversions, partial vegetation carbon will be removed as product pools, partial vegetation and soil carbon will be released to the atmosphere through land conversion flux, and the rest will enter the litter carbon pool. Three kinds of product pools are defined in DLEM: 1- (PROD1), 10- (PROD10), and 100- (PROD100) year product pools, which represent 1-, 10- and 100-year turnover time, respectively. Partial vegetation biomass will be burnt (site preparation) immediately after land-use change and then directly enters the atmosphere as land conversion fluxes. The rest of the vegetation biomass will enter different aboveground or belowground litter carbon pools. DLEM separates three litter carbon pools: very labile, labile, and resistant litter carbon pools. Accompanying carbon redistribution after land-use change, the ecosystem nitrogen and hydrological cycles will be correspondingly changed. The changed biogeochemical and hydrological cycles will in turn feedback to ecosystem restoration and development after land-use change. This coupling approach differs from book-keeping or statistical estimation methods that are used to predict land-use change effects because the latter do not address these mentioned feedbacks. If land conversion occurs from natural vegetation to cropland, crop will establish in the ecosystem after site preparation. The cropland ecosystem will then develop according to the prescribed phenology of individual crop types. If land conversion occurs from cropland to natural vegetation (i.e., cropland abandonment) or conversions between different natural vegetation types, natural vegetation will be established in the ecosystem as a secondary succession according to the phenology and vegetation dynamics module in DLEM. The ecosystems that experience land-use change might not be able to restore the initial carbon, water and nitrogen conditions even after a long time period, for example, 100 years. A process-based modeling could fully track the successional stages of natural vegetation and could make a more accurate estimation of carbon dynamics after land-use change than statistical methods can.

In the DLEM, the annual net carbon exchange (NCE) between terrestrial ecosystems and the atmosphere represents the overall carbon budget in the terrestrial ecosystem, which is calculated as:

$$\mathrm{NCE} = \mathrm{GPP} - R_\mathrm{a} - R_\mathrm{h} - E_\mathrm{c} - E\mathrm{p} \quad (1)$$

where R_a, R_h are carbon loss from autotrophic respiration and soil heterotrophic respiration; E_c is the total carbon loss due to land use conversion; $E\mathrm{p}$ is the total carbon loss from products decay. A positive NCE value means a terrestrial carbon sink, whereas a negative NCE indicates that terrestrial ecosystems are carbon sources to the atmosphere. The land-use change related parameterization for DLEM follows the empirical parameters established by Houghton (2003), other process-based models (e.g. Terrestrial Ecosystem Model, TEM, Tian et al., 2003) and field observational data.

2.3 Data sources and description

2.3.1 Land use and land cover data

In this study, the historical (1901–2000), gridded (0.5° × 0.5°) land-cover data set driving the DLEM was reconstructed by incorporating historical cropland and urban distribution (HYDE v3.0, Klein Goldewijk, 2001) and a potential vegetation map. The potential vegetation map was generated from multiple data sources. We first combined the MODIS global land cover map (http://modis-and.gsfc.nasa.gov/landcover.htm) with the global potential vegetation map developed by Ramankutty and Foley (1998) to derive the first draft of the potential vegetation map. Both data sets (with 1 km × 1 km resolution) were aggregated using the majority rule and their vegetation classes were regrouped to match the respective plant functional types defined in DLEM. Then, the global C4 grassland percentage map developed by Still et al. (2003) was used to determine the distribution of C4 grassland in the study region. Finally, we identified the wetland area based on the half degree resolution Global Lakes and Wetlands Database (GLWD) developed by Lehner and Döll (2004).

Over the past century, cropland area increased by 191.7 M ha in South and Southeast Asia, while the areas of forest, shrubland and grassland decreased by 110.3, 49.1 and 18.7 million ha, respectively. In the early 20th century, forests covered about 90 % of Southeast Asia and cropland covered approximately 5 % of the total land area. From 1901 to 2000, the cropland area increased rapidly while forest area decreased. By 2000, forest area had decreased by 15.6 % and cropland increased nearly 3 times when compared with the rate of increase in the early 20th century. Most of these changes in land use occurred in Thailand, Indonesia, and the Philippines (Fig. 3). South Asia has a long history of cultivation and 27.1 % of the total land area has been converted to cropland in the early 20th century (Ramankutty et al., 2006). From 1901 to 2000, cropland continued to increase rapidly until the 1960s, when the increasing trend slowed and then leveled off after the 1980s (Fig. 4b). Natural forests, grassland and shrubland were converted to cropland by 54 %, 5.8 %, and 30 %, respectively, during the study period. Most of these conversions occurred in southwestern India. The decrease in shrubland occurred primarily in Pakistan and in northwestern India (Fig. 3). In South and Southeast Asia as a whole, cropland area followed a continuous increasing trend during the 20th century, with a relatively slower rate ensuing after the 1960s (Fig. 4c). The major land conversions were forest-to-crop and shrub-to-crop, which accounted for 71.0 % and 17.4 % of cropland expansions, respectively. Forest coverage on average declined from 56.3 % in 1901 to 45.4 % in 2000.

2.3.2 Other datasets

Cropping system: The cropping system database in South and Southeast Asia includes thirteen crop categories (e.g., wheat, corn, soybean, cotton, groundnuts, millet, barley, sorghum and rice), three rotation types (one harvesting, double harvesting and triple harvesting) and their corresponding crop phenology information, which was developed based on MODIS data, agricultural census data and a global crop distribution map. The main crop categories in each grid were identified according to the global crop geographic distribution map with a spatial resolution of 5 min based on the work of Leff et al. (2004). The rotation type in each grid was developed using phenological characteristics and census data at the national level and state level. The phenology information obtained from MODIS LAI (at a spatial resolution of 1 km) was used to identify the rotation type and was calibrated using census data and site data before application.

Soil properties: We obtained the spatial maps for soil bulk density, soil pH, and texture, (i.e., percentage of clay, sand, and silt content), of the study region from the International Satellite Land Surface Climatology Project (ISLSCP) Initiative II Data Collection distributed by the Oak Ridge National Laboratory Distributed Active Archive Center (http://daac.ornl.gov/). This Collection provided spatially-explicit global soil information derived from data and methods developed by the Global Soil Data Task, which was coordinated by the Data and Information System (DIS) of the International Geosphere-Biosphere Programme (IGBP).

Topography map: Topography maps required by DLEM include elevation, slope and aspect. We first aggregated the Global 30 Arc Second Elevation Data (GTOPO30) developed by the United States Geological Survey (Bliss and Olsen 1996) to half degree resolution to develop the digital elevation model of the study region. Then we derived the half degree resolution aspect and slope maps from the digital elevation model.

2.4 Simulation experiments and implementation

To address the effects of land-cover change on carbon dynamics in South and Southeast Asia during the 20th century, we ran DLEM using the historical gridded land-cover data set from 1900 to 2000 and kept other input data unchanged. We generated the long-term average climate spanning 1961 to 1990 to represent the initial state of the year 1900, and the daily pattern in 2000 was selected to manifest the daily climate variation. The climate data in 1900 were used for the non-climate-transient simulation experiments. There were no ozone effects in this simulation experiment because the entire daily ozone AOT40 index was zero before 1940 (Felzer et al., 2005). In addition, CO_2 and nitrogen deposition in 1900 were used in this experiment.

The model simulation began with an equilibrium run to develop the baseline carbon, nitrogen, and water pools for each grid. Finally, the model ran in transient mode driven by transient data of land-conversion while other datasets remained constant.

3 Results and analysis

3.1 Changes in net carbon exchange (NCE)

The carbon storage in terrestrial ecosystems in South and Southeast Asia decreased due to land-use change since 1901 (Table 1). The simulation result indicated that a total of 18.26 Pg C (0.18 $\mathrm{Pg\,C\,yr^{-1}}$) was released to the atmosphere from changes in land use induced by crop expansion during the 20th century in South and Southeast Asia (Table 1). The mean annual emission of 0.18 Pg C in South and Southeast Asia in the 20th century is slightly lower than the previous estimation (0.23 Pg C yr^{-1}) for 1860–1990 (Tian et al., 2003). The carbon emissions from South Asia (4.19 Pg C) and Southeast Asia (14.07 Pg C) accounted for 23 % and 77 %, respectively, of the total emissions from both regions during the 20th century. Although a much larger land area in South Asia (Fig. 4) was converted to cropland, carbon losses in this region were significantly lower than those in Southeast Asia. Nearly half of the cropland areas in South Asia were converted from shrubland, grassland and other natural vegetations, while in Southeast Asia almost all the cropland areas were converted from forest. In addition, most areas of Southeast Asia are located in the tropical climate zone where densities of forest biomass and soil carbon are significantly higher than those in South Asia.

When partitioning the NCE into different components, we found that most of the carbon emissions were from land conversion fluxes (Ec, 10.83 Pg C), which accounted for 59 % of total carbon emission (Table 1). This suggested that carbon flux from land conversion was the major contribution to carbon emission in both South and Southeast Asia. Net ecosystem production (NEP = NPP–Rh) and product decay (Ep) accounted for 23 %, and 18 % of the total emission, respectively.

The accumulated net carbon exchange rate per decade varied significantly over time across South and Southeast Asia (Fig. 5). Decadal accumulated carbon emission showed an increasing trend and peaked in the 1980s (2.56 Pg C) and the 1990s (2.38 Pg C) for Southeast Asia, while carbon emission peaked in the 1950s (0.90 Pg C) and has no obvious increasing tendency during the entire study period in South Asia. Different land-use change patterns for Southeast and South Asia can explain the difference (Fig. 3, Fig. 4). Land area converted to cropland nearly leveled off around the 1950s in South Asia (Fig. 4b). Carbon emissions after the 1950s were primarily from land use legacy effects. In contrast, land area converted to cropland kept a relatively constant rate of increase from 1901 to 2000 in Southeast Asia (Fig. 4a). Partially driven by land-use change legacy effects, decadal carbon emissions continuously increased from the 1900s to the 1990s in this region.

3.2 Changes in carbon pools

Most carbon emissions induced by land-use change were from carbon losses in the vegetation carbon pool, which accounted for about 83 % (15.09 Pg C) of the total carbon emission (18.26 Pg C), while soil organic and litter carbon pools only accounted for 11.0 % (2.01 Pg C) and 8.8 % (1.60 Pg C), respectively (Table 2). In South Asia, vegetation, soil, and litter carbon pools decreased 3.2, 0.48 and 0.32 Pg C, respectively. The vegetation carbon pool accounted for about 76.4 % of the total decreases in carbon storage in this region. In Southeast Asia, vegetation, soil and litter carbon pools decreased 11.89, 1.53 and 1.28 Pg C, respectively. The vegetation carbon pool accounted for 84.5 % of the total decrease. In general, vegetation and soil carbon in Southeast Asia decreased much more than they did in South Asia.

Vegetation, soil and litter carbon pools varied over time in the entire region (Fig. 6). The significant decrease in vegetation, soil and litter carbon pools occurred during the 1980s in Southeast Asia, while the significant decreases in these pools occurred in South Asia during the 1950s. The decrease in carbon pools gradually leveled off after the1980s in Southeast Asia and after 1950 in South Asia. For both South and Southeast Asia, two peaks of decreases in vegetation and soil carbon pools were found in the 1950s and the 1980s, which account for 35 % of the total decreases in vegetation and soil carbon during the period 1901–2000.

3.3 Spatial variation in changes of carbon storage

Land-use change has resulted in large spatial variation in the net carbon exchange rate in South and Southeast Asia during the 20th century (Fig. 7). Most areas in South and Southeast Asia were carbon sources during 1901–2000 because cropland expansion was the major land conversion type. Few areas were found to be carbon sinks in South Asia due to cropland abandonment, cropland expansion from shrubland, and reforestation/afforestation (Fig. 7a; Fig. 3). The largest carbon sources (>100 g C m^{-2}) were found in Southeast Asia where cropland expansion from tropical forest may have resulted in a large amount of carbon loss. Tropical forest has very high carbon density, as high as 22 kg C m^{-2} in vegetation and 11 kg C m^{-2} in soil.

During the first half of the 20th century (1901–1950), most areas undergoing land-use change were carbon sources because cropland expansion was the predominant land-use change type (Fig. 7b and Fig. 3). During the second half of the 20th century, more areas acted as carbon sources and the magnitude of change was much wider than that in the first half of the century (Fig. 7b, c). The biggest carbon sources were found in Indonesia and the Philippine Islands where tropical forests were the major land cover types. Deforestation and cropland expansion occurred in Southeast Asia during the second half of the century. In South Asia, however, more area acted as a carbon sink during the second half of the century due to cropland abandonment and afforestation/reforestation, and over 80 % of cropland abandonment occurred during this period.

3.4 Carbon fluxes resulting from different categories of land-use change

Land-use change effects on carbon fluxes varied among different categories of land-use change. The results indicated that the conversions from forest to cropland and from shrubland to cropland accounted for 79.7 % and 8.3 % of total carbon emission, respectively. Land conversion from grassland to cropland only contributed 4.2 %. Our results indicated that the 1.56×10^6 km^2 land area (about 10 % of total land area experiencing land-use change) was converted to cropland and the cropland was abandoned afterwards. This category of land conversion resulted in 1.5 Pg C emission during the study period, which implied that original carbon storage could not be completely restored after cropland abandonment during the study period.

4 Discussion

4.1 Process-based modeling of land-use change impacts on the global carbon cycle

In this study, we link the land use data with other spatially-explicit environmental information (e.g., climate, soil prosperities, cropping system, and topography etc.) as well as ecological processes in a process modeling framework. We improved the process-based modeling methods and accordingly developed new spatial data sets to address the dynamic effects of land-use change on terrestrial ecosystem carbon cycling in South and Southeast Asia during the 20th century. To track the impacts of land-use change, DLEM coupled the ideas from statistical methods such as the book-keeping method (Houghton, 1995, 1999, 2003) and the process-based modeling methods of TEM (Terrestrial Ecosystem Model, McGuire et al., 2001; Tian et al., 2003). The fully coupled carbon, water and nitrogen cycles addressed in DLEM enable the model to simulate the impacts of land-use changes on carbon fluxes and other biogeochemical cycles (Ren et al., 2011a). Furthermore, like the LPJ model (Bondeau, 2007), DLEM has the ability to simulate carbon dynamics related to the land conversion between natural ecosystem and human-managed ecosystem. For a historical study at the regional scale, DLEM tried to introduce the available observational database into a mechanism analysis. For example, the least area index (LAI) derived from remote sensing was used in DLEM as input data to represent daily vegetation phenology. This enhanced the ability to capture land surface change in the real world. In addition, other new spatially-explicit environmental databases, which are crucial to describe the impacts of land-use change, were developed and applied in this study. Specifically, land management (e.g., fertilizer, irrigation, tillage) and cropping systems (crop categories and rotation types) based on substantial data sources (e.g., FAOSTAT; Leff et al., 2004) had be used.

4.2 Total carbon emissions resulting from land-use change

For the purpose of simulation evaluation, we compared our simulation results with previous studies using a bookkeeping model, remote sensing data, and a terrestrial carbon model (Houghton and Hackler, 1999; Houghton, 2002; DeFries et al., 2002; Tian et al., 2003) (Table 3). Our simulated results suggested that annual carbon emission induced by land- use change was about 0.28 Pg C yr^{-1} in the two decades before 2000, which is comparable to those estimations of 0.32 Pg C yr^{-1} from the book-keeping model (Houghton and Hackler, 1999), and 0.25 Pg C yr^{-1} from integrating remote sensing and the book-keeping model (DeFries et al., 2002). However, our results were modestly higher than the estimation of 0.13–0.17 Pg C yr^{-1} in 1981, drawn from the statistical method and inventory data (Hall and Uhlig, 1991). The century-scale analysis showed that our estimation of 0.18 Pg C yr^{-1} during 1901–2000 was similar to the estimation of 0.17 Pg C yr^{-1} during 1850–1980 (Houghton and Hackler 1999) and slightly lower than the estimation of 0.23 Pg C yr^{-1} during 1860–1990 from Tian et al. (2003). The discrepancies among those studies were mainly attributed to differences in study period, data source, and methods. Even though the estimate for carbon emission in Southeast and South Asia (0.28 Pg C yr^{-1}) was similar, e.g., at 0.28 Pg C yr^{-1} to the estimate of 0.25 Pg C yr^{-1} for the tropical Asia during 1981–2000 in DeFries et al. (2002), the underlying mechanisms controlling this total amount of carbon emission were found to be different. For example, in the DLEM model, we assumed that the recovery of vegetation growth would be limited by nutrient and water resources when cropland was converted to natural vegetation. In the book-keeping model (Houghton, 2002; Houghton and Hackler, 2003), abandoned croplands returned to the ecosystems from which they were initially cleared, accumulating carbon in biomass and soil at specific rates. In our study, net carbon emission to the atmosphere included the emission from other trace greenhouse gases, such as methane, which possibly resulted in higher total carbon loss (5.53 Pg C) as estimated by DLEM, comparing to the estimation of 5.0 Pg C for the tropical Asia from DeFries et al. (2002) in the period of 1981–2000. These processes at least partially contribute to the discrepancies between our results and those of other studies.

4.3 Uncertainties and future needs

Although we improved the estimation accuracy, there are still many uncertainties in this study. Firstly, uncertainty may arise from the input data. Different data sources usually have big gaps for the cropland area in South and Southeast Asia. For example, according to FAO (1982), cropland accounted for about 13.2 % of the total land area in the 1980s. Wood et al. (2002) showed that almost half of Southeast Asia and 73 % of South Asia are cropland areas. Data from Ramankutty and Foley (1998) indicated cropland coverage in South Asia and Southeast Asia at 39.2 % and 19.2 %, respectively, in the 1960s, with the highest values of 42.3 % and 26.5 % in the 1990s. Secondly, some processes related to land-use change were simplified in the DLEM model. For example, the parameters for allocating litters to different litter carbon pools after land-use change were kept constant. In addition, land conversions from one natural biome to another (e.g., forest to grassland or shrubland) were not included in this study due to limited data sources.

To improve our ability for simulating the interactions between the regional carbon cycle and land-use change, several key land use processes (e.g., management for plantation, urbanization, biofuel production, rotational uses of forest) should be included in the future study to better reflect the effects of land-use change on the spatial and temporal patterns of the carbon balance in South and Southeast Asia. For specific regions like South Asia that have experienced a long history of cultivation and management practices, we need to consider the legacy effects of land use before 1900 and remove associated artifacts. Also, the major source of uncertainty in estimating global carbon release is from aboveground biomass density during the land conversions from forest to other uses (Houghton et al., 2009). The importance of biomass in the carbon cycling should be given more attention in process-based modeling at regional and global scales. Moreover, further evaluation of DLEM model results is needed using accessible data sources such as long-term field experiments and observations on plant regrowth after land-use change.

5 Conclusions

In this study, we investigated the temporal and spatial patterns of changes in carbon fluxes and pools resulting from land-use change and specifically cropland expansion in South and Southeast Asia over the 20th century. Cropland expansion increased continuously over the 20th century, showing a relatively higher rate of increase before the 1960s. The major land conversion types were forest-to-crop and shrub-to-crop, which accounted for 71.0 % and 17.4 % of cropland increases, respectively. Results estimated with DLEM indicated that temporal and spatial patterns of change in carbon storage were significantly influenced by cropland expansion. In the 20th century, South and Southeast Asia released 18.26 Pg C to the atmosphere, of which South and Southeast Asia accounted for 23 % (4.19 Pg C) and 77 % (14.07 Pg C), respectively. This suggested that the entire region acted as a carbon source from cropland expansion. More carbon emissions were from Southeast Asia though larger land areas in South Asia were converted to cropland.

Decreases in vegetation carbon (15.09 Pg C) contributed the most (83 %) to the total carbon emission. The largest decrease in vegetation carbon occurred in Southeast Asia due to crop expansion that converted natural tropical forests, while an increase in soil carbon was found in some areas of South Asia as a result of afforestation/reforestation or land conversion from cropland to shrubland over the last two decades. Most areas in South and Southeast Asia were carbon sources due to vast cropland expansion, with the highest carbon loss in Southeast Asia occurring where tropical forests were cleared for cropland. During the 20th century, the carbon dynamics resulting from land-use change in these two regions were dominated by Southeast Asia where cropland expansion occurred as natural tropical forests were converted.

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Table 1. Different components of net carbon exchange (NCE, Pg C) in South and Southeast Asia during 1901–2000.

Region	NEP	Ec	Ep	NCE
Southeast Asia	−2.93	8.11	3.03	−14.07
South Asia	−1.30	2.72	0.16	−4.19
Total	−4.23	10.83	3.19	−18.26

Note: NCE = NEP – Ec – Ep; negative values in NCE mean carbon release into the atmosphere; NEP: Net Ecosystem Productivity; Ec: the total carbon loss due to land use conversion; Ep: total carbon loss due to land use conversion due to products decay

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Table 2. Changes in carbon storage in Southeast and South Asia during 1901–2000 (Pg C).

		Changes in carbon pools (Pg C)				
Region	Period	Vegetation	Soil	Litter	Product	Total change
Southeast Asia	1901–2000	−11.89	−1.53	−1.28	0.63	−14.07
South Asia	1901–2000	−3.2	−0.48	−0.32	0.17	−4.19
Total	1901–2000	−15.09	−2.01	−1.60	0.8	−18.26

Table 3. Estimations of changes in carbon storage (Pg C) resulted from land-use change in South and Southeast Asia using process-based model, book-keeping model, and statistical method.

	Study period	Total carbon change (Pg C)	Averaged annual carbon emission(Pg C yr^{-1})	Study method
This study	1901–2000	−18.26	0.18	Process-based model
	1980-1989	−2.82	0.28	
	1981–2000	−5.53	0.28	
Houghton (2002)	1850–1980	−21.49[a]	0.17	Book-keeping model
	1980–2000	−6.63[a]	0.32	
Houghton (1999)	1850-1995	−33.5[a]	0.23	Book-keeping model
Tian et al. (2003)	1860–1990	−29.7[b]	0.23	Process-based model
	1980-1989	−3.5[b]	0.35	
DeFries et al. (2002)	1981–2000	−5.0[c]	0.25	Remote sensing and book-keeping model
Hall and Uhlig (1991)	1981	−0.13 to −0.17	−0.13 – −0.17	Statistical model

Note: a: clearing for permanent croplands; b: cropland establishment and abandonment; c: Deforestation and regrowth

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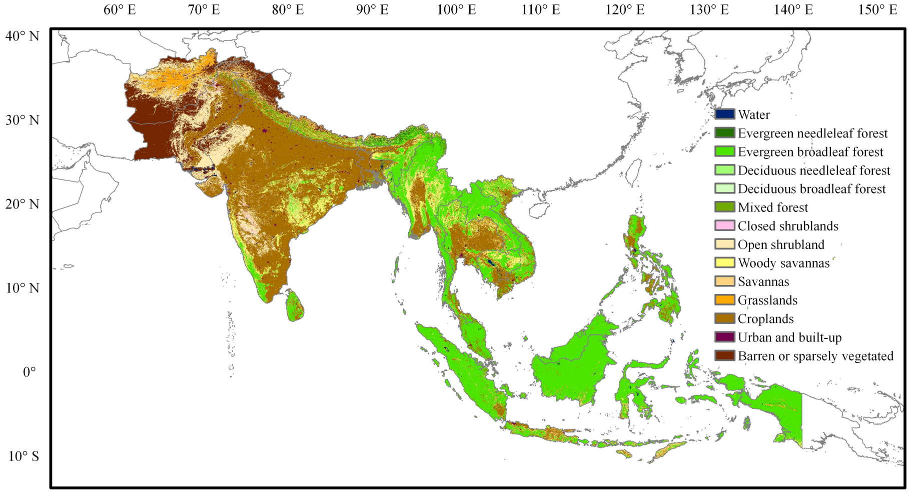

Fig. 1. Contemporary vegetation distribution in the study area.

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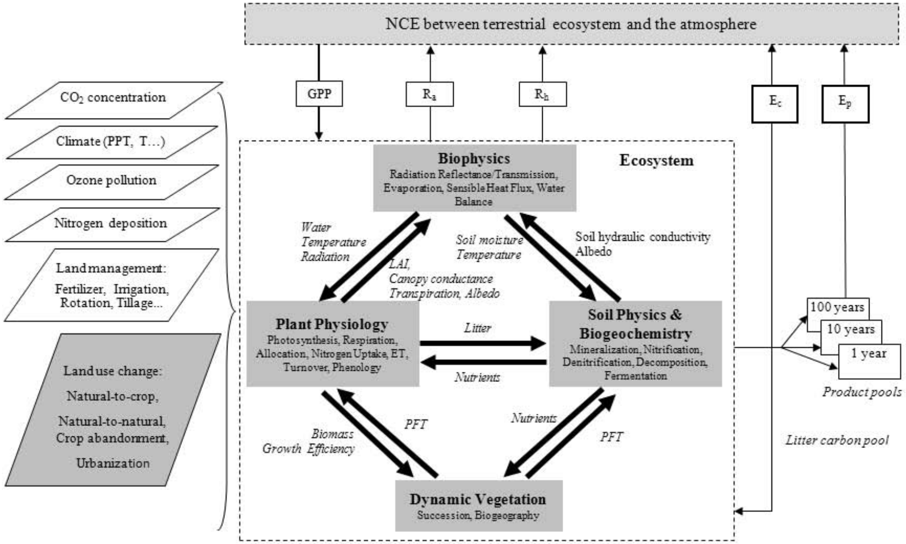

Abbreviations - *NCE: net carbon exchange; GPP: gross primary productivity; Ra: autotrophic respiration; Rh: soil heterotrophic respiration; Ec: total carbon loss due to land use conversion; Ep: the total carbon loss from product decay;ET: Evapotranspiration; LAI: Leaf Area Index; GHG: Green House Gas; PFT: Plant Function Type; PPT: precipitation; T:temperature.*

Fig. 2. Simplified simulations of land-use change processes in Dynamic Land Ecosystem Model (DLEM).

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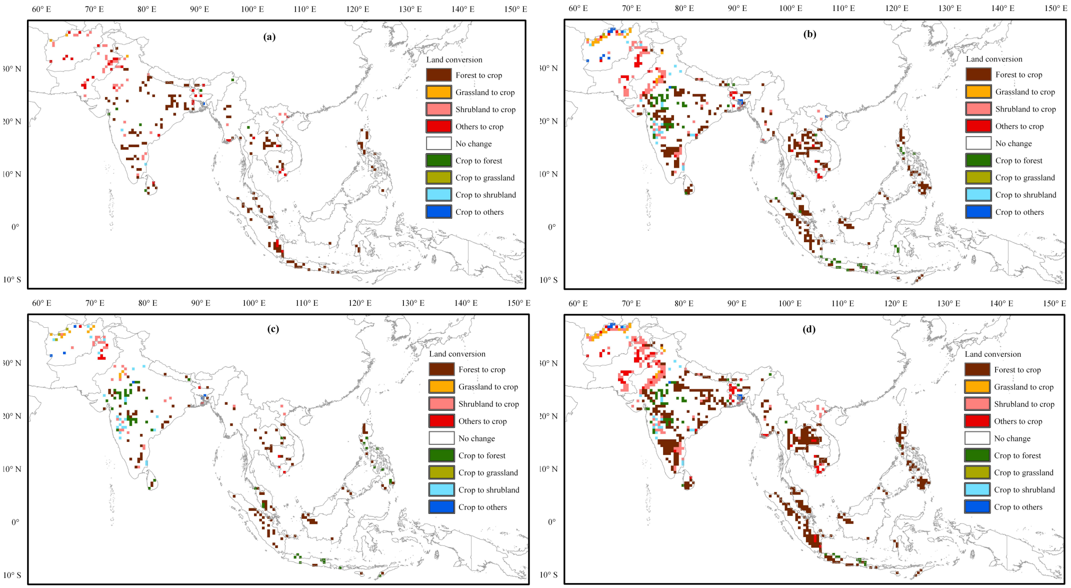

Fig. 3. Historical land conversions in South and Southeast Asia for **(a)**: 1901–1950, **(b)**: 1951–2000, **(c)**: 1981–2000, **(d)**: 1901–2000.

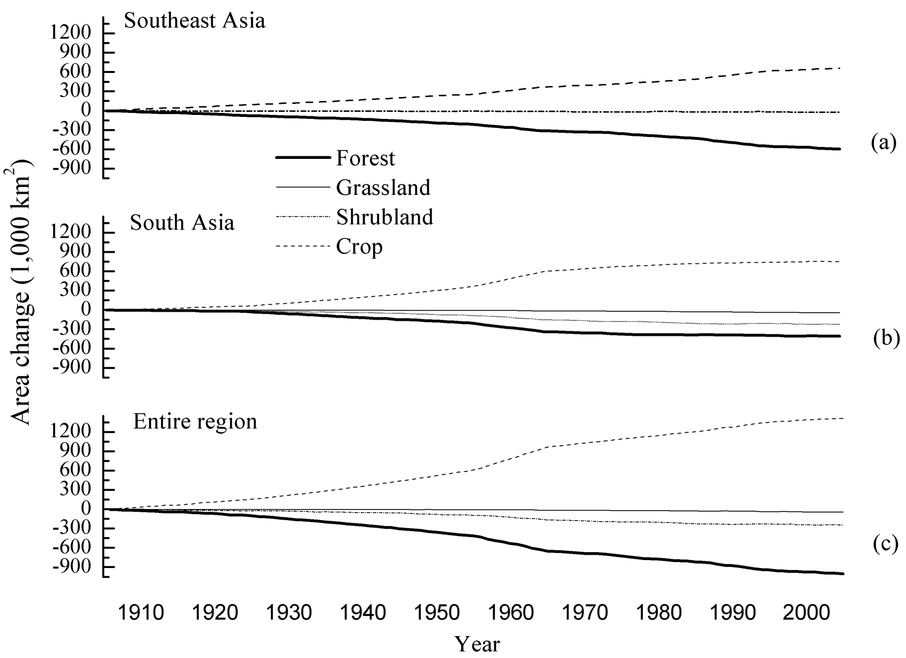

Fig. 4. Accumulated areas of changes in major biomes across South and Southeast Asia in the 20th century.

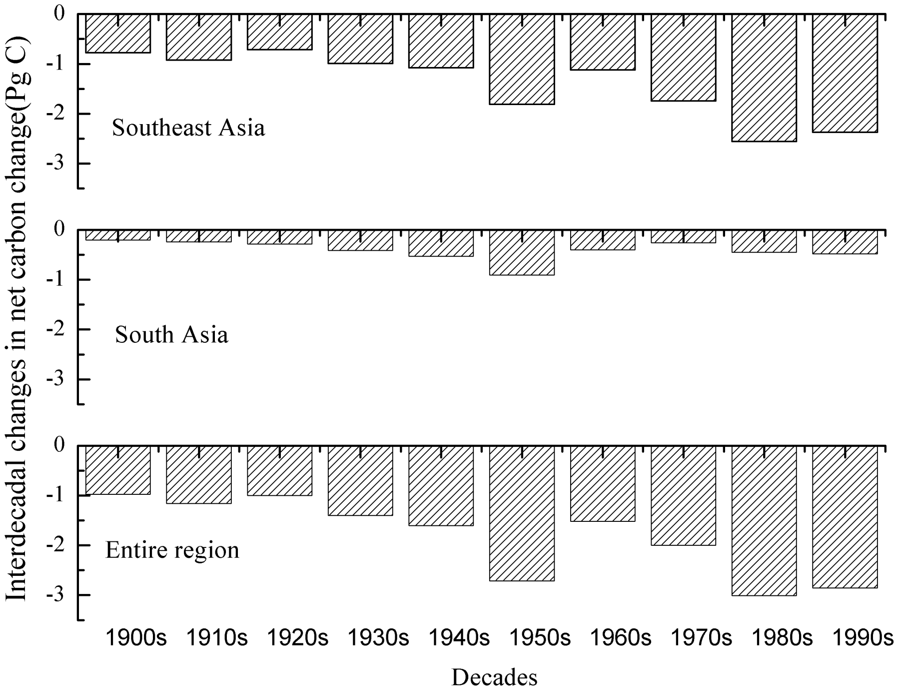

Fig. 5. Accumulated net carbon exchange in each decade in South and Southeast Asia during the 20th century.

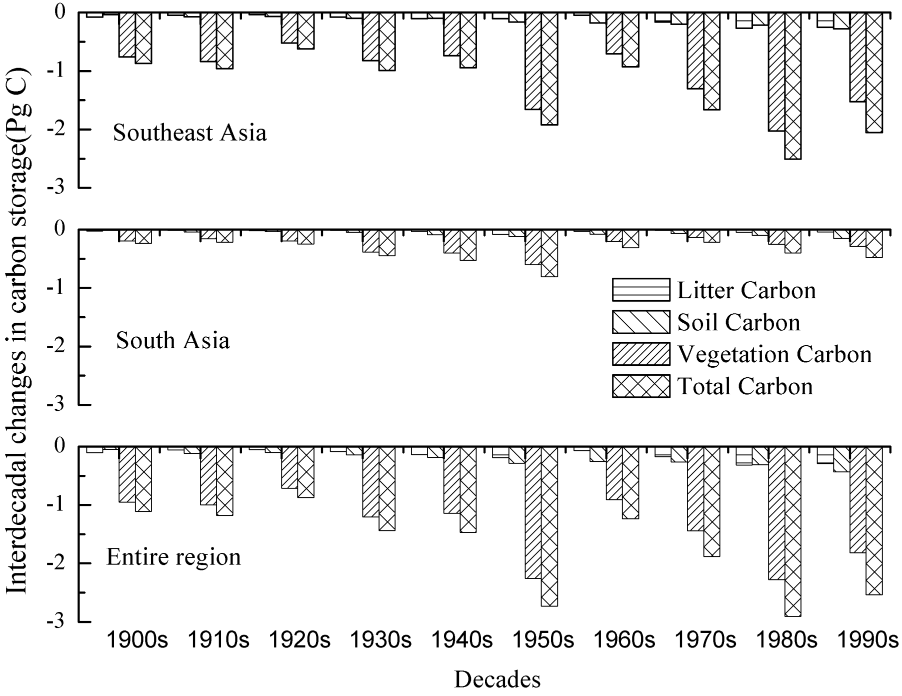

Fig. 6. Decadal accumulated changes of carbon pools in South and Southeast Asia during the 20th century.

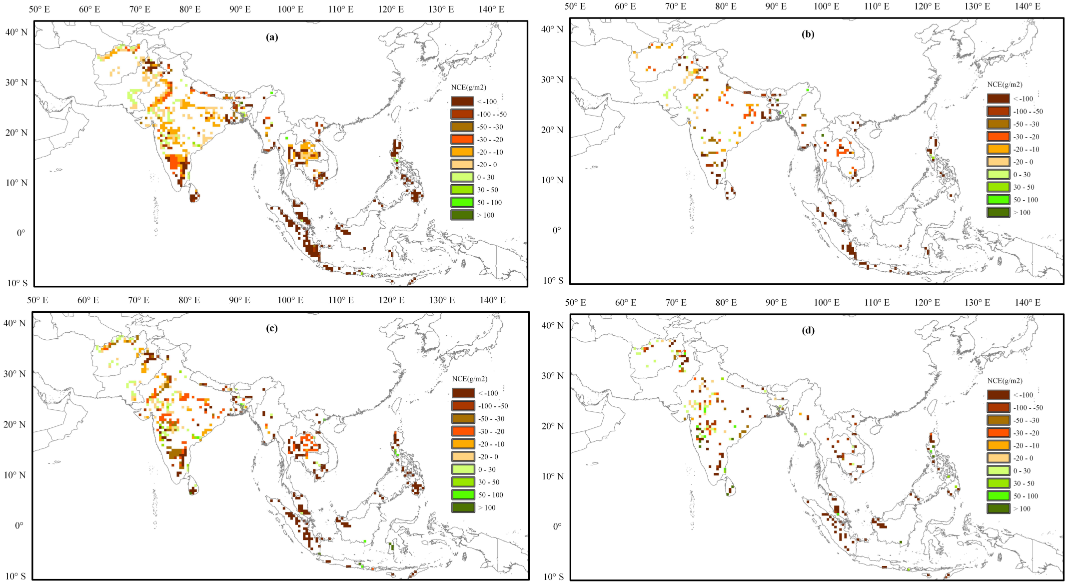

Fig. 7. Averaged annual net carbon exchange resulted from land-use change in South and Southeast Asia ($\mathrm{g\,C\,m^{-2}}$) for **(a)** 1901–2000, **(b)** 1901–1950, **(c)** 1951–2000, and **(d)** 1981–2000.