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Terrestrial carbon balance in tropical Asia: Contribution from cropland expansion and land management

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ABSTRACT

Tropical Asia has experienced dramatic cropland expansion and agricultural intensification to meet the increasing food demand and is likely to undergo further rapid development in the near future. Much concern has been raised about how cropland expansion and associated management practices (nitrogen fertilizer use, irrigation, etc.) have affected the terrestrial carbon cycle in this region. In this study, we used a process-based ecosystem model, the Dynamic Land Ecosystem Model (DLEM), to assess the magnitude, spatial and temporal patterns of terrestrial carbon fluxes and pools in Tropical Asia as resulted from cropland expansion and land management practices during 1901–2005. The results indicated that cropland expansion had resulted in a release of 19.12 ± 3.06 Pg C (0.18 ± 0.029 Pg C/yr) into the atmosphere in Tropical Asia over the study period. Of this amount, approximately 22% (4.18 ± 0.66 Pg C) was released from South Asia and 78% (14.94 ± 2.40 Pg C) from Southeast Asia. Larger land area was converted to cropland while less carbon was emitted from South Asia than from Southeast Asia, where forest biomass and soil carbon were significantly higher. Changes in vegetation, soil organic matter, and litter pools caused emissions of 15.58, 2.25, and 1.71 Pg C, respectively, from the entire region. Significant decreases in vegetation carbon occurred across most regions of Southeast Asia due to continuous cropland expansion and shrink of natural forests. When considering land management practices, however, less carbon was released into the atmosphere, especially in South Asia where land management practices contributed to an approximately 10% reduction in carbon emission. This implies that optimizing land management practices could greatly reduce the carbon emissions caused by cropland expansion and might be one of important climate mitigation options in Tropical Asia.

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). Between 1700 and 1992, about 1135 M ha (22.9%) of forest and woodland were converted to agricultural use (Ramankutty and Foley, 1999). 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 system (Zhang et al., 1995; Feddema et al., 2005; Pielke, 2005; Snyder, 2010), land degradation (Thornes, 1996; Drake and Vafeidis, 2004), and the loss of biodiversity (Pimm et al., 1995; Sala et al., 2000), etc.

The terrestrial ecosystems of Tropical Asia, including South and Southeast Asia, play a crucial role in regional and global carbon cycling (Brown et al., 1991; Flint and Richards, 1991; Richards and Flint, 1994; Brown et al., 1996; Houghton, 2002; Tian et al., 2003). As a region with large population and fast-growing economies, Tropical Asia has witnessed unprecedented rapid land-use change in the 20th century, characterized by cropland expansion and natural forest shrinkage to meet growing demands for food, bioenergy and urban development (Richards and Flint, 1994; Houghton, 2002; Tian et al., 2003, 2010a). Over the past 20 years, Tropical Asia has experienced faster cropland expansion, compared to other regions around the globe (Millennium Ecosystem Assessment, 2005). Globally, the tropical area in Southeast Asia had the highest deforestation rate, followed by Latin America and Africa (Achard et al., 2002). Across majority of

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the regions where a high rate of deforestation occurred, forest land was primarily converted to cropland. Compared to forest in other regions, most tropical forests generally have 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; Canadell, 2002; Achard et al., 2004). Moreover, intensive land management practices such as the use of nitrogen fertilizer and irrigation affect interaction among carbon, nitrogen and water cycles and thus make the impacts of cropland expansion more complicated.

In recent decades, a number of studies have investigated the potential impacts of land-use change on the carbon cycle in Tropical Asia using different approaches including the book-keeping model, remote sensing data, inventory data, and process-based models at various scales, ranging from site, local, and regional to continental (Brown et al., 1991; Houghton and Hackler, 1999; Adachi et al., 2011; Houghton, 2002; Canadell, 2002; Tian et al., 2003; Suh and Lee, 2004; Zhao et al., 2006). The bookkeeping and inventory methods (e.g., Houghton and Hackler, 1999) are capable of calculating changes in carbon storage induced by land area change; however, these approaches lack the capability of providing a quantitative understanding of ecosystem processes influencing carbon dynamics. Due to the shortage of spatially-explicit, time-series data of biomass and land use/land cover, these methods 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 managed grasslands to represent all types of crops and did not take into account crop-specific information on phenology and cropping systems. In addition, impacts of land management practices, which were concurrently changed with land cover change, have not been well studied for this region. To reduce the uncertainty in estimating spatial and temporal patterns of carbon fluxes and pools in association with cropland expansion in Tropical Asia, therefore, it is crucial to better understand cropland expansion-driven carbon dynamics by using updated driving forces and improved process-based ecosystem models.

In this study, we applied a process-based model (Dynamic Land Ecosystem Model, DLEM), which fully couples biogeochemical processes with an agricultural sub-model (Ren et al., 2011a; Tian et al., 2011a), to quantify the effects of cropland expansion and associated-land management practices on carbon fluxes and pools in Tropical Asia during 1901–2005. The objectives of this study were: 1) to quantify the effects of cropland expansion induced land-use change on temporal and spatial patterns of carbon fluxes and pools in the terrestrial ecosystems; 2) to examine the relative role of land management practices (nitrogen fertilizer use and irrigation) on the terrestrial carbon storage; and 3) to identify major uncertainties and future research needs.

2. Regional settings

The region of Tropical Asia, including South and Southeast Asia, extends from 38° N to 16° S latitude and from 60° to 140° E longitude, encompassing a land area of approximately 5.0×10^6 km^2 and 4.7×10^6 km^2, respectively. South Asia, which includes the countries of Afghanistan, Bangladesh, Bhutan, India, Nepal, Sri Lanka, and Pakistan, is one of the most populated regions in the world and has a long history of cultivation. Southeast Asia covers the countries of 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.

3. Materials and methods

3.1. Model description

The DLEM model 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 at various scales from site to region and globe. It 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 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., Ren et al., 2007; Zhang et al., 2007; Liu et al., 2008; Tian et al., 2010a,b; Xu et al., 2010; Zhang et al., 2010; Ren et al., 2011a,b; Tian et al., 2011a,b,c; Lu et al., 2012; Tian et al., 2012).

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, approximately 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 historical 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, i.e. land conversion from natural vegetation to cropland, land conversion among different natural vegetation types, cropland abandonment, and urbanization (Fig. 1). During land conversions, partial vegetation carbon is removed as product pools, partial vegetation and soil carbon is released to the atmosphere through land conversion flux, and the rest enters 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 (Houghton et al., 1983; McGuire et al., 2001; Tian et al., 2003, 2011a,b,c). We did not consider international trades such as crop products exported from one region to another, which needs to involve an economic model. Partial vegetation biomass is burnt (site preparation) immediately after land-use change and then directly enters the atmosphere as land conversion fluxes. The rest of the vegetation biomass enters 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 are correspondingly changed. The changed biogeochemical and hydrological cycles 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 be cultivated after site preparation. The cropland ecosystems will then develop according to the prescribed phenology of individual crop types. If land conversion occurs from cropland to natural vegetation