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Regional carbon dynamics in monsoon Asia and its implications for the global carbon cycle

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Abstract

Data on three major determinants of the carbon storage in terrestrial ecosystems are used with the process-based Terrestrial Ecosystem Model (TEM) to simulate the combined effect of climate variability, increasing atmospheric CO_2 concentration, and cropland establishment and abandonment on the exchange of CO_2 between the atmosphere and monsoon Asian ecosystems. During 1860–1990, modeled results suggest that monsoon Asia as a whole released 29.0 Pg C, which represents 50% of the global carbon release for this period. Carbon release varied across three subregions: East Asia (4.3 Pg C), South Asia (6.6 Pg C), and Southeast Asia (18.1 Pg C). For the entire region, the simulations indicate that land-use change alone has led to a loss of 42.6 Pg C. However, increasing CO_2 and climate variability have added carbon to terrestrial ecosystems to compensate for 23% and 8% of the losses due to land-use change, respectively. During 1980–1989, monsoon Asia as a whole acted as a source of carbon to the atmosphere, releasing an average of 0.158 Pg C per year. Two of the subregions acted as net carbon source and one acted as a net carbon sink. Southeast Asia and South Asia were sources of 0.288 and 0.02 Pg C per year, respectively, while East Asia was a sink of 0.149 Pg C per year. Substantial interannual and decadal variations occur in the annual net carbon storage estimated by TEM due to comparable variations in summer precipitation and its effect on net primary production (NPP). At longer time scales, land-use change appears to be the important control on carbon dynamics in this region.

Keywords: carbon cycle; climate variability; CO_2 fertilization; land use; monsoon Asia; terrestrial ecosystems

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1. Introduction

Monsoon Asia refers to the portion of the Asian continent where a significant seasonal shift of wind patterns occurs throughout the entire area. The region includes the Indian subcontinent, Southeast Asia, and

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China. The total area of land ecosystems in monsoon Asia is 21.4×10^6 km^2, about 16% of earth's land surface. Monsoon Asia is home to more than half of the world population (United Nations Population Division (UNPD), 1998). This region is covered by a range of ecosystems from tropical forests in Southeast Asia to boreal forests in the northern Asia and from temperate forests in eastern Asia to deserts in western Asia and tundra in the Himalayan Mountains. These ecosystems account for about 20% of the potential global terrestrial net primary productivity and for a similar fraction of the carbon stored in land ecosystems (Melillo et al., 1993; McGuire et al., 2001). Clearly, monsoon Asia is of critical importance to the understanding of how changing climates and human impacts interact to influence the structure and functioning of ecosystems and the biosphere (Hirose and Walker, 1995; Galloway and Melillo, 1998; Tian et al., 2000a).

Monsoon climate and land use have been suggested as two major factors that control net primary production (NPP) and carbon storage in the ecosystems of monsoon Asia. For example, Fu and Wen (1999) showed a strong correlation between the strength of monsoons in East Asia and net primary production estimated by remote sensing. The land ecosystems in monsoon Asia have been intensively disturbed or managed by human activities for many centuries and are now involved in rapid economic, social, and environmental changes. Previous studies have suggested that tropical Asia acted as an important source of carbon to the atmosphere, ranging from 25% (Esser, 1995) to 31% (Houghton and Hackler, 1999) of the global carbon emissions released from land ecosystems since the middle of the 18th century. Recent estimates have indicated that, for the 1980s, tropical deforestation in South and Southeast Asia released from one-third (Fearnside, 2000) to more than half (Houghton, 1999) of the carbon lost from land-use change across the globe. On the other hand, other recent analyses based on atmospheric transport models and CO_2 observations suggest that the northern portion of monsoon Asia has acted as a carbon sink (Bousquet et al., 1999). The resolution of the uncertainty in the magnitude of the carbon source or sink in monsoon Asia, clearly, is a key to balancing the global carbon budget.

The complexity of the interactions and feedbacks among ecosystem, climate, and human activities requires the use of process-based ecosystem models to study regional carbon dynamics (Melillo et al., 1996; Prentice et al., 2001). A rapidly increasing literature indicates that spatially explicit models of ecosystem processes have become a key tool for the evaluation of the response of large-scale terrestrial ecosystems to changing climate and changing human impact (e.g., Melillo et al., 1993; Ji, 1995; VEMAP Members, 1995; Post et al., 1997; Cao and Woodward, 1998; Cramer et al., 1999; Kicklighter et al., 1999; Tian et al., 1998, 1999; Prentice et al., 2000; McGuire et al., 2000, 2001; Schimel et al., 2000). For monsoon Asia, previous modeling studies have investigated net primary production under contemporary conditions and/or its responses to elevated atmospheric CO_2 concentration and projected climate change assuming equilibrium conditions (e.g., Peng and Apps, 1997; Xiao et al., 1998; Gao et al., 2000; Ni et al., 2000; Pan et al., 2000). To better understand carbon dynamics in this region, we need to also simulate how ecosystem processes change over time in response to variations in monsoon climate and to disturbances caused by human activities. Such a modeling effort, however, requires the development of both dynamic ecosystem models and transient input data such as climate and land-use history. Recent progress in ecosystem modeling (e.g., Tian et al., 1999; Prentice et al., 2000; Schimel et al., 2000; McGuire et al., 2001) and data set development (e.g., Hulme, 1995; Jones, 1994; Liu, 1996; Ramankutty and Foley, 1998, 1999) has made it possible to estimate transient changes in carbon storage at the regional or global scale by quantifying the mechanisms controlling ecosystem carbon storage. In this study, we investigate how historical climate variability, increasing CO_2, and cropland establishment and abandonment have affected carbon storage in monsoon Asia for the period from 1860 to 1990 by using a new version of the Terrestrial Ecosystem Model (TEM 4.2) in conjunction with newly developed spatially explicit data sets (McGuire et al., 2001). We also identify gaps and limitations in existing information that need to be investigated in the future to improve our understanding of carbon dynamics and our ability to estimate terrestrial carbon fluxes in this region.

2. Methods and data

2.1. Overview

The annual net carbon exchange (NCE) of the terrestrial biosphere with the atmosphere can be described by the equation:

$$\mathrm{NCE} = \mathrm{NPP} - R_{\mathrm{H}} - E_{\mathrm{NAD}} - E_{\mathrm{AD}} - E_{\mathrm{P}} \qquad (1)$$

where NPP is net primary production, R_{H} is heterotrophic respiration (i.e., decomposition), E_{NAD} represents emissions associated with nonanthropogenic disturbance (e.g., lightning fires, insect infestations), E_{AD} represents emissions from anthropogenic disturbance, and E_{P} represents the decomposition of products harvested from ecosystems for use by humans and associated livestock. A negative NCE indicates that terrestrial ecosystems are sources of atmospheric CO_2, whereas a positive NCE indicates a terrestrial sink. The NCE as used here is the same carbon flux as the net carbon exchange described by McGuire et al. (2001), but has the opposite sign as it describes this flux from the perspective of terrestrial ecosystems rather than the atmosphere.

The fluxes NPP and R_{H} are influenced by spatial and temporal variations in natural environmental conditions such as atmospheric CO_2 concentration, climate, and nitrogen availability. Human activities modify these fluxes further by: (1) influencing the availability of water and nitrogen to the plants, (2) breaking up soil aggregates during cultivation or construction to expose more soil organic matter to oxidation, (3) managing the community composition and amount of biomass present on a site, and (4) introducing air pollutants that can either enhance (e.g., CO_2, N deposition) or reduce (e.g., ozone) plant growth. In addition, NPP and R_{H} of a site will change with time as vegetation regrows after a human or natural disturbance.

The magnitude of the carbon loss from a disturbance (i.e., E_{NAD}, E_{AD}) depends on the intensity and frequency of the disturbance. Disturbances are episodic events that cause immediate carbon losses from an ecosystem, but may also change environmental conditions at a site so that additional carbon is lost from the ecosystem over a longer time period. The intensity and frequency of disturbances depend on the environmental conditions at the disturbed site, although economic and/or social forces also have a large influence on the intensity and frequency of human disturbances.

Human activities also directly influence terrestrial carbon storage by the production and redistribution of agricultural, paper, and other wood products. The carbon stored in these products is returned to the atmosphere at a variety of rates that are related to the consumption of food, the burning and decomposition of trash, and the deterioration of wooden structures in buildings, bridges, etc. As a result of trade, many of these products may decompose or deteriorate in places far removed from the site where the biomass was created. Thus, regional terrestrial carbon sinks may be overestimated if this product flux (E_{P}) of carbon back to the atmospheric is not considered properly.

2.2. Simulation approach

In this study, we have modified version 4.1 of the Terrestrial Ecosystem Model (TEM 4.1, Tian et al., 1999) to better estimate monthly fluxes of NPP and R_{H} of contemporary vegetation. The new version of TEM (TEM 4.2) is able to simulate changes in carbon storage during three stages of disturbance: (1) conversion from natural vegetation to cultivation, (2) production and harvest on cultivated land, and (3) abandonment of cultivated land. The modeled estimates of carbon storage in vegetation and soils before disturbance are influenced by the spatial and temporal variations in environmental conditions from 1860 to 1992 as prescribed by the historical spatially explicit climate data sets of Jones (1994) and Hulme (1995). These environmental variations influence the simulated rates of terrestrial carbon gain or loss in both disturbed and undisturbed ecosystems by affecting simulated NPP and R_{H}. The timing and location of human disturbance associated with row crop agriculture are prescribed for the period 1860–1992 by the historical agricultural data set of Ramankutty and Foley (1998, 1999).

To simulate the effects of biomass harvest and associated conversion fluxes, we have incorporated algorithms from the Terrestrial Carbon Model (Houghton et al., 1983; Melillo et al., 1988) into TEM 4.2 as described in McGuire et al. (2001). Biomass harvested from land as a result of conversion to agriculture (i.e., products) is placed into two product pools with different residence times: a 10-year pool that represents paper and paper products and a 100-year product pool that represents lumber and long-lasting products. Annual releases of CO_2 from these two product pools are calculated as a linear decay of the initial carbon inputs into these pools over 10 and 100 years, respectively. The conversion flux (i.e., E_{AD}) is the simulated release of CO_2 associated with the clearing of land for agriculture (i.e., burning of slash and fuelwood).

For cultivated ecosystems, crop NPP estimates are based on the relative agricultural production approach of Esser (1995), using the NPP estimate of potential vegetation developed by TEM. Forty percent of annual crop NPP is assumed to be harvested for human and livestock consumption. The harvested NPP is placed into an agricultural products pool, which is assumed to have a 1-year residence time (see Fig. 1). The biomass resulting from the annual NPP that is not harvested (i.e., residue) is transferred to the reactive soil organic carbon pool. The sum of the carbon fluxes released to the atmosphere from the three product pools are collectively referred to as the total product flux (E_P).

After abandonment, the rate of regrowth of potential vegetation of the site is again based on the relative rates of NPP and R_H as influenced by the environmental conditions at the site. We do not currently have the capability to simulate the carbon dynamics associated with E_{NAD} in this region. Thus, for this study, we estimate NCE by modifying Eq. (1) to be:

$$\mathrm{NCE} = \mathrm{NPP} - R_H - E_{AD} - E_P \quad (2)$$

2.3. Modifications to the Terrestrial Ecosystem Model

In TEM, net primary production is calculated as the difference between gross primary production (GPP) and plant respiration (R_A). Gross primary production represents the uptake of atmospheric

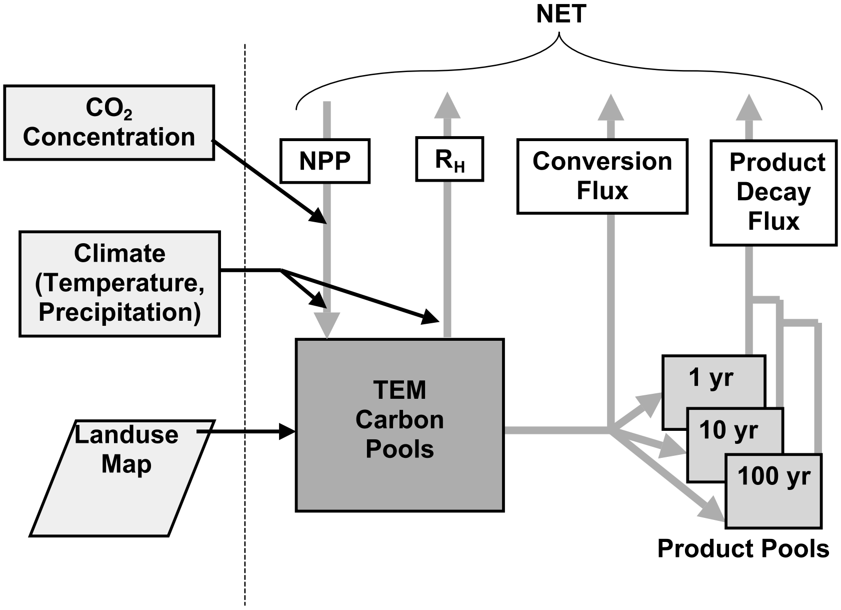

Fig. 1. Overview of the simulation protocol implemented by the Terrestrial Ecosystem Models (TEM) in this study to assess the concurrent effects of increasing atmospheric CO_2, climate variability, and cropland establishment and abandonment during 1860–1990. Data sets of historical CO_2, climate, and cropland extent were used to drive the models at 0.5° resolution (latitude × longitude). The conversion flux is the simulated release of CO_2 associated with the clearing of land for agriculture, i.e., the burning of slash and fuelwood. Biomass harvested from land as a result of conversion to agriculture or subsequent cultivation were decayed to the atmosphere from three pools with different residence times: a 1-year product pool (decay of agricultural products), a 10-year product pool (paper and paper products), and a 100-year pool (lumber and long-lasting products).

CO_2 during photosynthesis and is influenced by light availability, atmospheric CO_2 concentration, temperature, and the availability of water and nitrogen. Plant respiration includes both maintenance and construction respiration and is calculated as a function of temperature and vegetation carbon. To simulate the effects of canopy development on NPP in TEM 4.2, we modified the GPP equation in TEM 4.1 (Tian et al., 1999) by adding an additional scalar, *f*(CANOPY):

$$\mathrm{GPP} = C_{\max} f(\mathrm{PAR}) f(\mathrm{CANOPY}) f(\mathrm{LEAF}) \times f(T) f(C_a, G_v) f(\mathrm{NA}) \quad (3)$$

where $C_{\max}$ is the maximum rate of C assimilation, PAR is photosynthetically active radiation, *f*(CANOPY) describes the effect of canopy development on the vegetation capacity to assimilate CO_2 and is relative to the maximum amount of leaf biomass that would be found in a fully developed canopy, *f*(LEAF) describes seasonal changes of the vegetation capacity to assimilate CO_2 and is relative to maximum leaf area during a particular year, T is air temperature, C_a is atmospheric CO_2 concentration, G_v is relative canopy conductance, and NA is nitrogen availability. To calculate *f*(CANOPY), the amount of leaf biomass is assumed to be related to the total amount of carbon stored in vegetation biomass using the following logistic relationship:

$$f(\mathrm{CANOPY}) = \frac{1}{1.0 + (Ae^{(B\times \mathrm{Cv})})} \quad (4)$$

where Cv is the state variable for carbon in the vegetation and A and B are parameters. Parameter A was set to 1.6662 for all vegetation types, while parameter B varies among vegetation types from -0.000227 for tropical forests to -0.016209 for grasslands. Thus, parameter B is implicitly responsible for the pattern of allocating biomass to leaves during stand development.

The flux R_H represents microbially mediated decomposition of organic matter in an ecosystem and is influenced by the amount of reactive soil organic carbon, temperature, and soil moisture. Additional details on how TEM estimates terrestrial ecosystem processes may be found in Tian et al. (1999). Although no algorithms have been changed to simulate R_H in TEM 4.2, changes in litterfall, caused by the model modifications described above, influence R_H by affecting the amount of soil organic matter available to decomposers.

2.3.1. Regional extrapolation

For regional extrapolations with TEM, we use spatially explicit input data sets of vegetation, elevation, soil texture, mean monthly temperature, monthly precipitation, and mean monthly solar radiation (Tian et al., 1999). The input data sets are gridded at a resolution of 0.5° latitude by 0.5° longitude. In addition to the input data sets, TEM also requires soil- and vegetation-specific parameters appropriate to a grid cell. Although many of the parameters in the model are defined from published information, some of the vegetation-specific parameters are determined by calibrating the model to the fluxes and pool sizes of an intensively studied field site. The data used to calibrate the model for different vegetation types are documented in previous work (Raich et al., 1991; McGuire et al., 1992, 1995; Tian et al., 1999). To apply TEM to a transient scenario of atmospheric CO_2 and/or climate, it is first necessary to run the model to equilibrium with a long-term baseline climate appropriate to the initial year of the simulation. Detailed documentation on the development, parameterization, and calibration of the dynamic version of TEM has also been published in previous work (Tian et al., 1999; McGuire et al., 2000).

2.4. Study area and data sets

2.4.1. Study area

In this study, we divide monsoon Asia into three subregions: East Asia, South Asia, and Southeast Asia. East Asia includes four countries: China, Japan, Korea, and Mongolia, and covers an area of about 11.7×10^6 m^2. The East Asia summer monsoon brings most of the annual precipitation to this subregion (Fu and Wen, 1999). South Asia includes seven countries: Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan, and Sri Lanka, and covers an area of about 5.0×10^6 m^2. Land ecosystems in South Asia depend on the Indian monsoon, which brings 80% of the annual precipitation to this region (Parthasarathy et al., 1992). Southeast Asia includes nine countries: Brunei, Burma, Indonesia, Cambodia, Laos, Malaysia, Philippines, Thailand, and Vietnam, and covers an area of about 4.7 × 10^6 m^2. Most of the tropical rainforests in Asia are located in Southeast Asia. Ecosystems in Southeast Asia also depend on rainfall brought by the East Asia summer monsoon.

2.4.2. Data sets

In this study, soil, elevation, and cloudiness are assumed not to vary from year to year, so we use the same input data sets as in previous equilibrium studies with TEM (e.g., McGuire et al., 1997). The elevation data represent a 0.5° aggregation of the 10′ NCAR/Navy (1984) data. Soil texture is based on the FAO/CSRC digitization of the FAO-UNESCO (1971) soil map. Mean monthly cloudiness in this study is from the global data set of Cramer and Leemans (Wolfgang Cramer, personal communication), which is a major update of Leemans and Cramer (1991). Monthly percent cloudiness is calculated as 100 minus monthly percent sunshine duration in the Cramer and Leemans database. We use our potential vegetation data set (Melillo et al., 1993) to generate baseline conditions in the equilibrium portion of the simulations and to represent natural vegetation in the transient portion of the simulations.

Historical changes in other environmental factors from 1860 to 1990 are prescribed with transient input data sets in this study. The transient input data include: (1) historical mean atmospheric CO_2 concentration (Etheridge et al., 1996; Keeling et al., 1995, updated), (2) gridded historical monthly data for air temperature and precipitation (Jones, 1994, updated; Hulme, 1995, updated), and (3) gridded historical yearly data for cropland area (Ramankutty and Foley, 1998, 1999).

2.5. Simulation experiments

To determine the relative effects of climate variability, CO_2 increase, and land-use change on the carbon storage in monsoon Asia, we conducted four simulations. To determine the effect of climate variability alone, we ran TEM using the gridded historical monthly data for air temperature and precipitation, but kept atmospheric CO_2 concentration constant at the level observed in 1860 (286 ppmv) and represented land cover with our potential vegetation data set over the entire study period. To determine the effect of CO_2 fertilization alone, we ran TEM using the historical atmospheric CO_2 concentrations, but used a long-term mean monthly climate and represented again land cover with potential vegetation. To determine the effect of land-use change alone, we ran TEM using the gridded cropland data set, the long-term mean monthly climate, and a constant atmospheric CO_2 concentration of 286 ppmv. Finally, we examined the combined effects of these factors on terrestrial carbon storage by running TEM with the gridded historical monthly data for air temperature and precipitation, the historical atmospheric CO_2 concentration data, and gridded historical cropland data sets. This last simulation was also used to analyze the carbon budget of monsoon Asia and each of the subregions. To relate this regional carbon budget to the global carbon budget, we also ran TEM with the historical atmospheric CO_2 concentration data set and our global gridded data sets for soil, elevation, cloudiness, potential vegetation, historical air temperature, historical precipitation, and historical cropland distribution.

For each simulation, we first ran TEM in equilibrium mode to generate an initial condition for transient runs, using gridded input data of vegetation,

Table 1
Change in carbon storage between 1860 and 1990 as estimated by the Terrestrial Ecosystem Model (Pg C)

Year	Monsoon Asia			East Asia			South Asia			Southeast Asia		
	VEGC	SOLC	TOTC	VEGC	SOLC	TOTC	VEGC	SOLC	TOTC	VEGC	SOLC	TOTC
Baseline (1860)	151.7	109.4	261.1	50.5	66.1	116.6	19.5	31.9	51.4	81.7	11.3	93.0
1900	− 7.5	− 0.7	− 8.2	− 2.9	0.0	− 2.9	− 1.7	− 0.3	− 2.0	− 2.9	− 0.3	− 3.2
1930	− 13.5	− 1.3	− 14.8	− 4.9	− 0.1	− 5.0	− 2.5	− 0.3	− 2.8	− 6.1	− 0.7	− 6.8
1960	− 21.4	− 3.0	− 24.4	− 7.0	− 0.8	− 7.8	− 4.1	− 0.6	− 4.7	− 10.3	− 1.5	− 11.8
1990	− 25.9	− 3.1	− 29.0	− 4.6	0.3	− 4.3	− 6.0	− 0.6	− 6.6	− 15.3	− 2.8	− 18.1

VEGC: vegetation carbon, SOLC: reactive soil organic carbon, TOTC: total carbon storage.

soil, elevation, the long-term means of monthly temperature, monthly precipitation and monthly cloudiness, and the level of atmospheric CO_2 concentration in the year of 1860. Then we ran TEM in transient mode using the appropriate historical input data from 1860 to 1990 as described above.

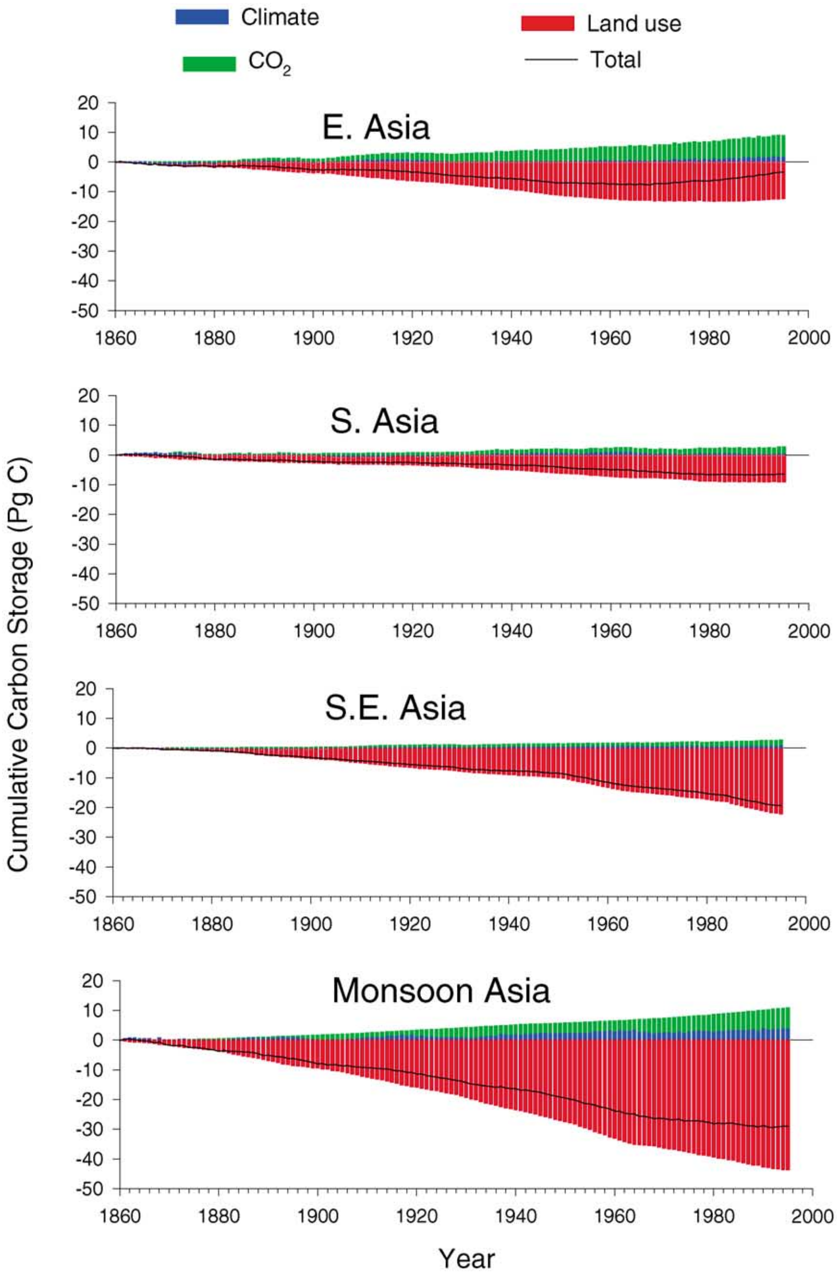

Fig. 2. The cumulative change in carbon storage since 1860 in East Asia, South Asia, Southeast Asia, and monsoon Asia as a whole as estimated by TEM in simulations that considered the effects of increasing atmospheric CO_2, climate variability, and cropland establishment and abandonment.

3. Results and analyses

3.1. Historical change in carbon storage since 1860

Based on the TEM simulations, we estimate that total carbon storage in monsoon Asia for the year 1860 was about 261.1 Pg C, with about 151.7 Pg C in vegetation and 109.4 Pg C in the reactive soil organic carbon pool (Table 1). From 1860 to 1990, the TEM simulations indicated that the combination of climate variability, increasing atmospheric CO_2 concentration, and cropland establishment and abandonment resulted in a large decrease of about 29.0 Pg C (– 11.1%) in total carbon storage for monsoon Asia. This reduction in total carbon storage was mainly due to a large decrease of 25.9 Pg C (– 17.1%) in vegetation, but soil organic carbon also shows a small decrease of 3.1 Pg C (– 2.8%). The reduction of 29.0 Pg C in carbon storage in monsoon Asia is about 50% of our estimate of the global carbon loss (57.7 Pg C) for the period 1860–1990.

All three subregions, East Asia, South Asia, and Southeast Asia, show a decrease in carbon storage since 1860, but the loss of carbon from Southeast Asia (– 18.1 Pg C) is much larger than the loss from the other subregions (– 4.3 Pg C for East Asia and – 6.6 Pg C for South Asia). Again, the reduction in total carbon storage in all subregions is mainly associated with a decrease in vegetation carbon (Table 1). Similar to the regional estimate for all of monsoon Asia, the reactive soil organic carbon stocks in South Asia and Southeast Asia show a relatively small decrease. In contrast, East Asia shows a slight gain in reactive soil organic carbon.

The patterns of carbon storage in this region also varied over time (Fig. 2). From 1860 to 1960, total carbon storage decreased in all subregions. However, after 1960, the carbon dynamics varied among the regions. In East Asia, terrestrial ecosystems began to sequester atmospheric CO_2. In South Asia, total carbon stocks continued to decline until the 1980s and then remained relatively stable. In Southeast Asia, total carbon stocks decreased at an increasing rate after 1960. These differences are related to variations in the simulated responses of the ecosystems to the historical changes in land use, atmospheric CO_2 concentration, and climate (Fig. 2).

3.2. Factors influencing historical changes in terrestrial carbon storage

From the series of factorial experiments with TEM, land-use change is obviously the major factor that determined the magnitude of carbon release from monsoon Asia for the time period from 1860 to 1990 (Table 2). We estimate that land-use change alone resulted in a loss of 42.6 Pg C in monsoon Asia, which is 36.6% of the global carbon loss of 116.3 Pg C caused by land-use change alone as estimated by TEM. These carbon losses, however, are reduced by enhanced uptake of atmospheric CO_2 by plants due to CO_2 fertilization and climate variability so that the estimated overall historical loss of carbon from these ecosystems by TEM has only been 29.0 Pg C. Carbon dioxide fertilization accounted for most of the compensatory effects (about 23% of the losses due to land-use change), but climate variability also had a large compensatory effect (about 8% of the losses by land-use change). The compensation of carbon losses by CO_2 fertilization varied by regions, ranging from 7% in Southeast Asia to 51% in East Asia. The compensation of carbon losses by climate variability also varied by regions, ranging from 5% in Southeast Asia to 16% in East Asia. Cropland establishment and abandonment in South and Southeast Asia together during 1860–1990 resulted in a net carbon release of 29.7 Pg C to the atmosphere.

The relative contribution of climate variability, increasing atmospheric CO_2, and land-use change to carbon storage in monsoon Asia also varied over time (Fig. 2). For example, terrestrial carbon storage in East Asia showed a slow recovery since the 1970s because of the increasing role of CO_2 fertilization and forest regrowth in enhancing annual net carbon storage.

Table 2
Relative contribution of CO_2, climate, and land use to carbon storage during 1860–1990

	East Asia	South Asia	Southeast Asia	Monsoon Asia	Globe
CO_2	6.6	1.9	1.5	10.1	46.3
Climate	2.0	0.6	1.0	3.6	10.3
Land use	– 12.9	– 9.1	– 20.6	– 42.6	– 116.3
Total	– 4.3	– 6.6	– 18.1	– 29.0	– 57.7

3.3. Temporal and spatial patterns of annual net carbon exchange

The TEM simulations indicate substantial year-to-year variations in annual net carbon exchange (NCE) within monsoon Asia for the entire period primarily because of climate variability (Fig. 3). For monsoon Asia as a whole, annual NCE ranged from − 0.8 Pg C in the year of 1965 to + 0.6 Pg C in the year of 1990. The interannual variation in net carbon exchange is

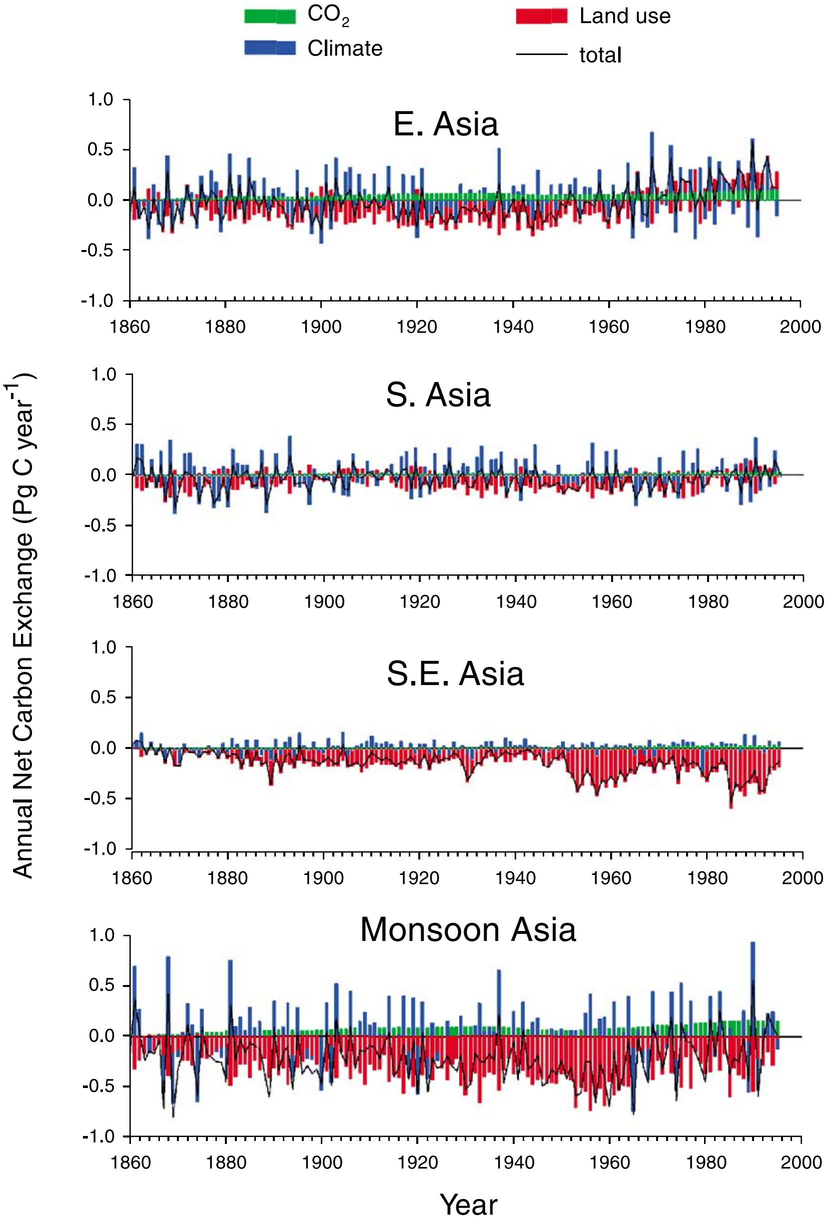

Fig. 3. The relative contributions of increasing atmospheric CO_2, climate variability, and cropland establishment and abandonment to annual net carbon exchange in East Asia, South Asia, Southeast Asia, and monsoon Asia as a whole.

different from region to region. East Asia showed the largest variation in annual NCE, ranging from -0.3 Pg C in the year of 1944 to $+0.6$ Pg C in the year of 1990. For South Asia, annual NCE ranged from -0.2 Pg C in the year of 1965 to $+0.2$ Pg C in the year of 1990. For Southeast Asia, annual NCE ranged from -0.5 Pg C in the year of 1985 to $+0.04$ Pg C in the year of 1904. The relative role of climate variability on NCE for all subregions also showed large year-to-year variations (Fig. 3). In a specific year, the effect of drought or wet climate on carbon storage could be much larger than that of either increasing CO_2 or land-use change. The effects of land-use change on NCE showed small interannual variations, but large decadal variations, especially in Southeast Asia.

Interannual variations in net carbon exchange are coupled to variations in climate. Annual NCE for monsoon Asia was significantly correlated with annual precipitation ($r = 0.66$, $P < 0.01$). A closer analysis of the monthly simulation results reveals that the amount of precipitation in summer (June, July, and August) and fall (September, October, and November) mainly control annual NPP. Our analyses show that annual NPP was not correlated with temperature, but annual R_H was significantly correlated with temperature ($r = 0.61$, $P < 0.05$). Annual NCE was coupled to annual NPP ($r = 0.72$, $P < 0.01$). Change in annual R_H was relatively small for the study period. Thus, temperature-induced change in R_H did not have a significant effect on NCE for this study period. The

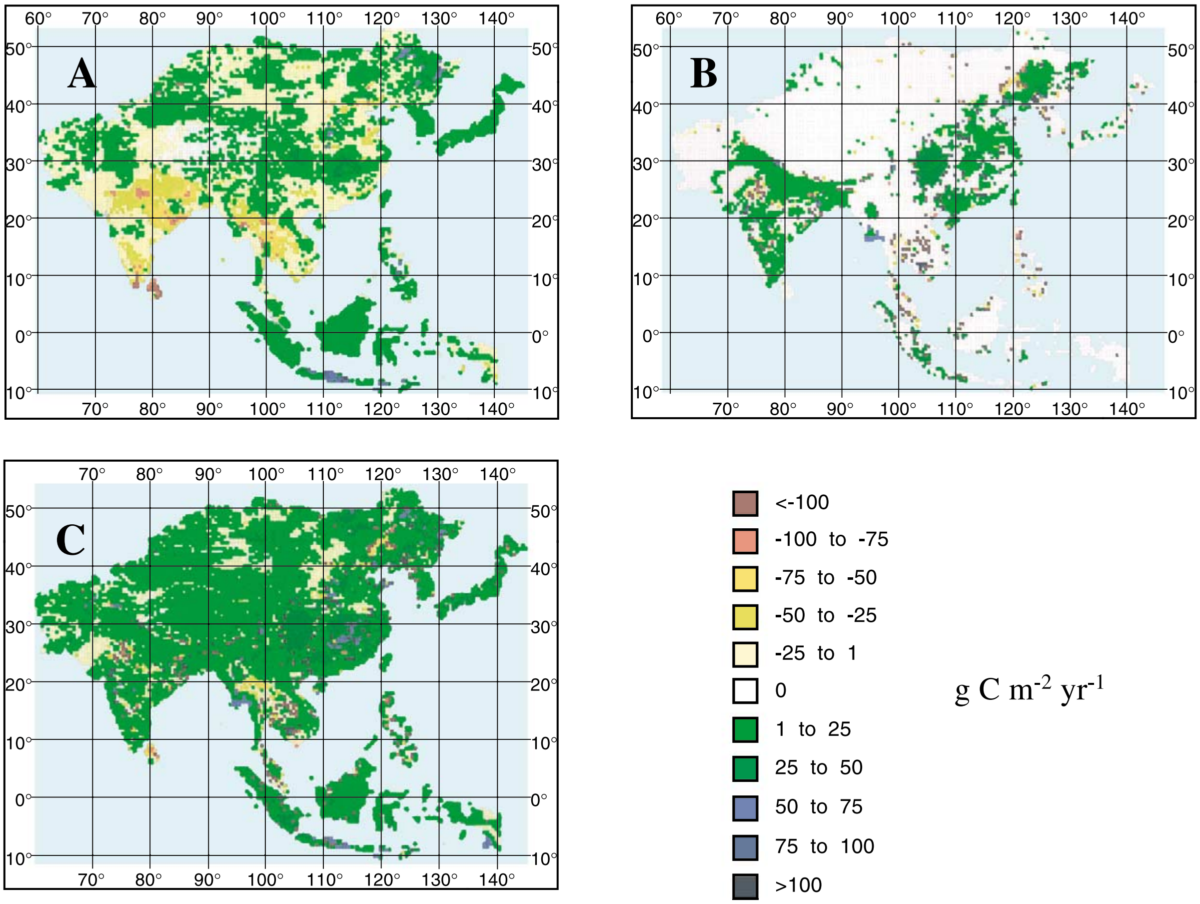

Fig. 4. Distribution of net carbon exchange across monsoon Asia during 1980–1989 as simulated by TEM. (A) Climate effect, (B) effect of cropland establishment and abandonment, (C) combined effect of climate, CO_2, and cropland establishment and abandonment.

precipitation effect on annual NPP, however, determined the magnitude of interannual variation in NCE for monsoon Asia.

The TEM simulations indicate that climate variability and land-use change led to substantial spatial variations in net carbon exchange (Fig. 4). For the 1980s, climate variability caused much of south Asia to act as a carbon source to the atmosphere. Land-use change in India and eastern China resulted in carbon accumulation, while deforestation in some regions of Southeast Asia led to carbon release to the atmosphere. Year-to-year changes in the spatial pattern of net carbon exchange are mostly caused by changes in the spatial pattern of precipitation, which can change dramatically with monsoon events. In strong monsoon years, which bring rainfall to much of monsoon region, most ecosystems act as a sink of carbon from the atmosphere. Conversely, in weak monsoon years, which bring hot, dry weather to much of monsoon Asia, most ecosystems act as sources of carbon to the atmosphere. However, increasing atmospheric CO_2 generally leads to increased carbon storage over entire region.

3.4. Regional carbon budget in the 1980s

The TEM simulations indicate that, for the decade of 1980–1989, the combination of climate variability, increasing atmospheric CO_2, and cropland establishment and abandonment could result in a mean carbon sink of about 0.149 Pg C per year in East Asia, but a mean source of about 0.021 Pg C per year in South Asia and a mean source of 0.288 Pg C per year in Southeast Asia (Table 3). Monsoon Asia as a whole acted as a mean source of 0.158 Pg C per year for the period 1980–1989. The relative contribution of CO_2, climate, and land use to the simulated carbon storage varied among three subregions. All three factors, CO_2, climate, and land use, led to a carbon sequestration by ecosystems in East Asia (Table 3). In South Asia, however, climate and land use resulted in carbon release to the atmosphere. Increasing atmospheric CO_2 concentration partially compensated for the carbon loss associated with tropical deforestation. For tropical Asia (South plus Southeast Asia), our analysis indicated that cropland establishment and abandonment alone resulted in a net release of 0.346 Pg C per year to the atmosphere during 1980–1989. While accounting for the combined effect of climate, CO_2, cropland establishment and abandonment, TEM simulations suggest that tropical Asia acted as a net carbon source of 0.308 Pg C per year for the period 1980–1990.

4. Discussion

Our study indicates that land-use change has a dominant influence on terrestrial carbon storage in monsoon Asia. During 1860–1990, land ecosystems in monsoon Asia acted as a major source of carbon to the atmosphere. This is because land ecosystems in monsoon Asia have been intensively disturbed and managed by human activities (Brown et al., 1993; Richards and Flint, 1994; Liu and Buheaosier, 2000). Our results are comparable to other estimates derived from bookkeeping models (Houghton et al., 1983; Houghton, 1999) that balance deforestation and forest regrowth over time, assuming generic time-dependent functions for carbon gains and losses in different ecosystem types. According to the analysis by Houghton (1999), global land-use change for the period 1850–1990 resulted in a loss of 124 Pg C, with 38.6 Pg C from land-use change in tropical Asia. Of the land-use changes considered in an analysis by Houghton (1999), cropland establishment/abandonment was responsible for 68% of the net land-use

Table 3
Relative contribution of CO_2, climate, and land-use to carbon storage during 1980–1989

	East Asia		South Asia		Southeast Asia		Monsoon Asia	
	Mean (Pg C)	Percentage	Mean (Pg C)	Percentage	Mean (Pg C)	Percentage	Mean (Pg C)	Percentage
CO_2	0.088	59	0.029	− 138	0.030	− 10	0.147	− 93
Climate	0.031	21	− 0.034	162	0.012	− 4	0.010	− 6
Land use	0.030	20	− 0.016	76	− 0.330	115	− 0.315	199
Total	0.149	100	− 0.021	100	− 0.288	100	− 0.158	100

flux, while harvest of wood, conversion of forests to pastures, and shifting cultivation accounted for 16%, 13%, and 4% of the net flux, respectively. Our estimates indicate that cropland establishment and abandonment alone led to a loss of 116.3 Pg C at the global scale, with 29.7 Pg C from tropical Asia (Table 2). Thus cropland establishment and abandonment for the past one and a half century was responsible for most of the losses in carbon caused by land-use change at global scale as well as monsoon Asia, assuming that Houghton's estimate is correct.

For the time period 1980–1989, we estimate that cropland establishment and abandonment in tropical Asia resulted in a loss of 0.35 Pg C (Table 3). Our estimate is much lower than the loss of 1.08 Pg C per year as estimated by Houghton (1999) or the loss of 0.66 Pg C per year as estimated by Fearnside (2000). Recent reviews of the global carbon budget indicate that, during 1980–1989, global land-use change caused a release of 1.7 Pg C from land to the atmosphere (Prentice et al., 2001). This magnitude of carbon released from land-use change includes a loss of 1.08 Pg C from tropical Asia. If our estimate of carbon release from tropical Asia is correct, it would not require a terrestrial carbon sink as large as 1.9 Pg C per year to balance the global carbon budget, as reported by Intergovernmental Panel of Climate Change (Prentice et al., 2001).

Our estimates of carbon sequestration during the 1980s in East Asia (0.149 Pg C per year), based on the combined effects of climate variability, CO_2 fertilization, and land-use change, are similar to estimates that we developed for ecosystems in the United States (0.136 Pg C per year) using TEM. Both sets of estimates are consistent with the results of inverse modeling studies that suggest a "missing" terrestrial sink exists in the northern hemisphere (Tans et al., 1990; Bousquet et al., 1999), but disagree with the magnitude of these sinks as suggested by some studies (Fan et al., 1998). Our analyses indicate that carbon is sequestered in both vegetation and soils in East Asia as a result of both CO_2 fertilization and the regrowth of vegetation on abandoned croplands. The accumulation of 10 Pg C in monsoon Asia between 1860 and 1990, as a result of CO_2 fertilization, corresponds to a concurrent increase in NPP of 4%. This simulated NPP response is consistent but less than the 25% NPP response observed in a young loblolly pine forest stand by Delucia et al. (1999). However, other analyses based on forest inventories (Casperson et al., 2000) have suggested that CO_2 fertilization has a minor effect on carbon sequestration in forests. Information from field studies that examine the ecosystem response to enhanced atmospheric CO_2 concentration, such as the free-air CO_2 exchange (FACE) experiments, need to be obtained for the monsoon Asia region before the response to CO_2 fertilization as simulated by TEM can be fully evaluated for this region.

Our modeled results show that carbon dynamics in terrestrial ecosystems of monsoon Asia exhibit substantial interannual, decadal, and spatial variations. These variations are related to the magnitude and spatial distribution of rainfall that also show substantial temporal variations at various scales from seasonal to decadal (Fu and Wen, 1999). The sensitivity of annual carbon storage to precipitation drawn from our modeled results is consistent with the empirical studies that indicate a significant correlation between interannual changes in precipitation and atmospheric CO_2 growth rate (Yang and Wang, 2000). Our analysis did not show a temperature control on interannual variations in carbon storage in monsoon Asia. This result is inconsistent with the analysis of Braswell et al. (1997), who indicated that temperature is an important control on interannual variations in ecosystem production for land ecosystems at the global scale. However, a continual increase in temperature in the future could change the relative importance of these two climatic factors on the carbon dynamics of these ecosystems in a significant way (Yan et al., 2000). The year-to-year variations in temperature and precipitation also influenced the effect of CO_2 fertilization on net carbon storage in monsoon Asia. The response to CO_2 fertilization tends to be larger during a weak monsoon year when water availability is more limited.

The relationship between net carbon exchange and precipitation in monsoon Asia also generally agrees with our findings for the tropical ecosystems of the Amazon Basin (Tian et al., 1998, 2000b). In these studies, the interannual variations in net carbon storage within the Amazon Basin are found to be correlated with year-to-year variations in precipitation that are associated with ENSO events. For monsoon Asia, an El Niño event is often connected to a weak monsoon, which results in very dry climate condition in South and Southeast Asia (Kumar et al., 1999). Thus, an El Niño event linked with a weak monsoon can cause a large carbon release from tropical ecosystems, but an El Niño event also often brings heavy rainfall to East Asia. In contrast, a La Niña event brings dry weather to the northern parts of monsoon Asia, which leads to a loss of carbon to the atmosphere from this region. The interactive effects of ENSO and monsoon on carbon dynamics remains unclear and deserve more attention.

In this study, we have shown the importance of considering spatial and temporal variability in the effects of land-use change, CO_2 fertilization, and climate variability on carbon dynamics in monsoon Asia. However, our analysis has been limited by uncertainties related to the representation of environmental factors by our spatially explicit data sets and by our current inability to simulate the effects of some potentially important factors on the regional carbon budget of monsoon Asia. For example, there are large discrepancies among estimates on cropland area in China (Table 4). Cropland area in China varies from 950×10^3 km^2 as estimated by State Statistical Bureau (1994) to 2445×10^3 km^2 as estimated by this study based on the cropland data set of McGuire et al. (2001). The best estimate is based on Landsat TM data and indicates that cropland area in the early 1990s was about 1373×10^3 km^2 (Liu, 1996; Liu and Buheaosier, 2000). This uncertainty in cropland area influences our estimate of regional carbon fluxes in this region. The construction of reliable data sets of historical distribution of croplands, therefore, is essential for better estimation of regional carbon budgets.

Table 4
China's cropland area in early 1990s as estimated by different investigators

Sources	Area (10^3 km^2)	Percentage relative to the estimate of Liu (1996)
SSB	950	− 31
SLA	1225	− 11
FAO	1236	− 10
IGBP-DIS (pure)	1402	2
IGBP-DIS (mixed)	1941	41
CCMLP	2445	56
Landsat TM based (Liu, 1996)	1373	0

SSB: State Statistical Bureau (1994), SLA: State Land Administration, FAO: Food and Agricultural Organization (1998), IGBP-DIS (pure): include only pixels classified as pure cropland in IGBP Discover land cover data set derived from AVHRR satellite data for the period of 1992–1993, IGBP–DIS (mixed): include pure pixels plus half the area of the pixels classified as cropland and natural vegetation mosaic (Loveland and Belward, 1997; Frolking et al., 1999), CCMLP: Carbon Cycle Model Linkage Project (McGuire et al., 2001).

The land-use analysis presented here is incomplete because it only considered the effects on the regional carbon budget associated with row crop agriculture. It did not consider: (1) the conversion of forests to pastures, (2) possible changes in harvest and regrowth cycles within managed forests, and (3) urbanization and desertification. To address these issues, spatially explicit data sets of the historical distribution of pastures, forest harvest, urban areas, and the extent of desertification need to be developed to improve estimates of regional carbon budgets. In addition, more information from field studies is required to develop algorithms that better simulate the effect of these other land-use changes on the regional carbon budget.

In this study, we assumed that cropland abandonment always led to carbon sequestration associated with the regrowth of natural vegetation. However, many croplands in this region are instead being converted to other uses. The fate of cleared lands is an important factor that affects carbon fluxes and storage (Melillo et al., 1988; Hall et al., 1995; Houghton, 1999). While reforestation and plantation establishment can lead to carbon sequestration (Fang et al., 1998; Lal and Singh, 2000) as simulated in our study, urbanization, desertification, and other land degradation could cause long-term carbon loss to the atmosphere. In China, preliminary analyses of land-cover changes detected using both satellite imagery and aerial photography indicate a number of interesting trends in various regions of China in recent decades. These trends include changes (both gains and losses) in cropland area, urban expansion, and increased desertification. For example, Liu Jiyuan's research team found an increase in cropland area in the five provinces of northern China (Inner Mongolia, Liaoning, Jilin, Heilongjiang, and Xinjiang) of about 64×10^6 km^2 during the 1980s to 1990s. The new cropland areas in northern China were converted from forests, grasslands, and wetlands. In contrast, in the 12 provinces or regions of eastern China (Beijing, Tianjin, Hebei, Shanghai, Zhejiang, Fujian, Shandong, Henan, Hunan, Guangdong, Guangxi, and Hainan), cropland area decreased by about 52×10^6 km^2 during the 1980s and 1990s. This reduction in cropland area is in part due to urbanization in eastern China. For example, the urban areas in Pear River Delta region from 1980s to 1990s, increased by 987 km^2. Urbanization in Asia has become an important factor that could lead to carbon loss to the atmosphere due to increasing human population.

Desertification is also emerging as a dominant process in western China (Liu, 1996). The area of desert in this region has increased markedly in the past decades. In the Yezi county of the Ningxia province, for example, the area of desert increased by 156% over three decades, from 1501 km^2 in 1961 to 3836 km^2 in 1993. In addition, the degradation of grassland occurred in most parts of the county. In this study, we have been able to simulate some of the effects of land degradation (e.g., loss of soil carbon and nitrogen) associated with the long-term removal of biomass in agricultural products, but have not been able to address other issues related to desertification. To reduce uncertainty in regional carbon budgets, clearly, more work needs to be done to better account for these factors in future studies.

Besides CO_2 fertilization, recent reviews of the global carbon budget also indicate that terrestrial carbon storage could also be affected by nitrogen deposition and other changes in atmospheric chemistry (Melillo et al., 1996; Prentice et al., 2001) not considered in this study. In recent decades, the rapid industrialization in monsoon Asia has resulted in increased anthropogenic N deposition and tropospheric ozone levels. Nitrogen inputs, such as N deposition, should enhance terrestrial carbon storage (Melillo and Gosz, 1983; Galloway et al., 1995; Townsend et al., 1996; Holland et al., 1997), but it is also possible that chronic high inputs of nitrogen may cause terrestrial ecosystems to lose carbon (Aber et al., 1993). Anthropogenic nitrogen deposition may be contributing approximately 0.2–0.5 Pg C per year to global carbon storage (Townsend et al., 1996; Holland et al., 1997; Nadelhoffer et al., 1999). A large amount of nitrogen deposition from fertilizer use and fossil fuel burning occurs in East Asia. This nitrogen deposition may have substantial interactions with increasing atmospheric CO_2 on the regrowth of forests after cropland abandonment to influence carbon sequestration in terrestrial ecosystems. On the other hand, both field and modeling studies have shown that ozone decreases crop yield (Chameides et al., 1999a) and forest productivity (Ollinger et al., 1997; Mclaughlin and Percy, 2000). In addition, atmospheric aerosols and regional haze may also reduce crop productivity (Chameides et al., 1999b). The responses of TEM to increasing atmospheric CO_2 indicate that nitrogen availability represents a major constraint on the ability of terrestrial ecosystems to incorporate elevated CO_2 into production (Melillo et al., 1993; McGuire et al., 1995, 1997; Kicklighter et al., 1999; Tian et al., 1998, 1999). To better understand the carbon dynamics in monsoon Asia, future studies should take these atmospheric chemistry factors into account. To include these factors into ecosystem models, however, will require the development of spatially explicit historical data sets of nitrogen deposition, ozone and other pollutants.

Our results have shown the importance of considering spatial and temporal variability in the effects of land-use change, climate variability, and CO_2 fertilization on regional carbon budget for monsoon Asia. To improve our ability in estimating regional carbon budget for monsoon Asia, the effects of rotational forestry, pasture, urbanization, desertification, and air pollution should be incorporated in future analyses.

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