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RESEARCH ARTICLE

The spatio-temporal responses of the carbon cycle to climate and land use/land cover changes between 1981–2000 in China

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Abstract This paper represents the first national effort of its kind to systematically investigate the impact of changes in climate and land use and land cover (LULC) on the carbon cycle with high-resolution dynamic LULC data at the decadal scale (1990s and 2000s). Based on simulations using well calibrated and validated Carbon Exchanges in the Vegetation-Soil-Atmosphere (CEVSA) model, temporal and spatial variations in carbon storage and fluxes in China may be generated empower us to relate these variations to climate variability and LULC with respect to net primary productivity (NPP), heterotrophic respiration (HR), net ecosystem productivity (NEP), storage and soil carbon (SOC), and vegetation carbon (VEGC) individually or collectively. Overall, the increases in NPP were greater than HR in most cases due to the effect of global warming with more precipitation in China from 1981 to 2000. With this trend, the NEP remained positive during that period, resulting in a net increase of total amount of carbon being stored by about 0.296 PgC within a 20-year time frame. Because the climate effect was much greater than that of changes of LULC, the total carbon storage in China actually increased by about 0.17 PgC within the 20-year time period. Such findings will contribute to the generation of carbon emissions control policies under global climate change impacts.

Keywords carbon cycle, climate changes, LULC, remote sensing, Earth system modeling

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1 Introduction

Many problems associated with ecosystem conservation have roots in anthropogenic disruptions of natural biogeochemical cycles such as those of water and carbon. The driving mechanism associated with the physical climate system and social-economic system collectively plays an important role in biogeochemical cycle research. Understanding of such mechanisms and their interactions via a holistic assessment by way of earth system modeling would be equally as important as studies of individual dynamic processes occurring in specific ecosystems (Melillo et al., 1993; Stephen and Samuel, 1995; Cao and Woodward, 1998a; DeFries et al., 1999; Houghton et al., 1999; Fang et al., 2001; Pacala et al., 2001, Peng et al., 2009).

The effects of climatic change on an ecosystem's carbon cycle involve impacts on plant photosynthesis, respiration, and decomposition of soil organic carbon. Land use pattern directly affects the distribution and structure of terrestrial ecosystems and changes the carbon storage and fluxes in terrestrial ecosystems. Land use and land cover (LULC) change can affect energy flow within biogeochemical and hydrological cycling in terrestrial ecosystems through altering land surface and species composition (Houghton et al., 1987; Houghton, 1991; Braswell et al.,1997; Cao and Woodward, 1998b; Bousquet et al., 2000; McGuire et al., 2001). Ecosystem carbon cycling responds differently to various types of LULC change showing a pattern of CO_2 release into the atmosphere when changes occur from a high-biomass forest to low-biomass grassland, cropland or urban area. Consequently, the terrestrial ecosystem plays a dual role in carbon uptake/release effects in the global carbon cycle, and LULC change is an important part of the interaction between human activity and climate change.

The problem of LULC change effecting carbon cycling in the terrestrial ecosystem was one of the most worrisome environmental problems of concern by scientists, land managers, and policy makers in many interdisciplinary studies in the past two decades (Phillips, et al., 1998; Ramankutty and Foley, 1998, 1999; Caspersen et al., 2000; Schimel et al., 2000, 2001; Klein Goldewijk, 2001; Guo and Gifford, 2002; Vleeshouwers and Verhagen, 2002; Houghton, 2003a, 2003b; Klein Goldewijk and Ramankutty, 2004; Feddema et al., 2005; Strassmann, et al., 2008). With its immense land resources, the climate and ecosystem in China are complex and diverse, and the degree of LULC change has varied widely from region to region in the past two decades resulting in an important impact on the national carbon cycle (Sha, 2002; Li et al., 2003, 2004; Liu et al., 2005a, 2005b).

Between 1981 and 2000, the climate and land use in different regions of China simultaneously experienced changes. Global warming was salient with regional variations. Sha (2002) found that the climate of northern China became colder, while southern China became warmer during the study period. On average, the rate of change of global temperature was 0.40°C in northern China and 0.34°C in southern China. The temperature between 1981 and 2000 in northern arid areas was higher than the average temperature of the 20th century by 1°C. Such a climate change seems to contribute to a significant degree of carbon cycling. But it is unclear how the role of LULC change could affect the overall spectrum of annual net carbon sink or source during the study period. Liu et al. (2005a, 2005b) analyzed the LULC change with Landsat remote sensing data over the period from 1990 to 2000 in China and found out that the LULC change had significant regional differences due to the impacts of land management policy and economic development. Within the 1990s, farmland increased in northern China and decreased in southern China, while the total area of farmland increased. Forested land and grassland decreased gradually and constructed land expanded (Liu et al., 2005a, 2005b). With this support, this paper represents the first national effort of its kind to systematically investigate the impact of LULC change on carbon cycle with high-resolution dynamic LULC data at the decadal scale (1990s and 2000s).

It is known that LULC data in the 1980s did not reflect the results of policy changes in these two decades and these changes mainly include the six large afforestation projects in China including: 1) The Natural Forest Protection Program (1998–2008), 2) the Engineering Program for Returning Farmland to Forest initiated in 1997, 3) the Protection of Forest Program in the Yangtze River system and other key areas, 4) the Dust Storm Source Control Project of Beijing and Tianjin (2003–2007), 5) the Wildlife and Natural Plant Species Protection and Reservation Project (2001–2010), and 6) the Fast Growing Timber Forest Bases Project in key areas initiated in 2002 (Liu et al., 2005a, 2005b). The objective of this study is to systematically assess the condition of LULC changes in between the 1980s and 1990s and reflect that difference onto the carbon cycle based on a common driving data sets of carbon fluxes and carbon storage in the literature for differential analysis. In particular, the Carbon Exchanges in the Vegetation-Soil-Atmosphere (CEVSA) model was employed to simulate carbon fluxes (net primary productivity (NPP), heterotrophic respiration (HR) and net ecosystem productivity (NEP) and carbon storage (vegetation carbon (VEGC) storage and soil carbon (SOC) storage) from 1981 to 2000 in order to assess the impact of LULC change on carbon fluxes and carbon storage given the possible climate change scenarios.

2 Materials and methods

To estimate the impacts of climate change and LULC change on the carbon cycle of the ecosystem in China, the CEVSA model was employed to simulate changes of NPP, vegetation carbon, HR, soil carbon, and NEP. The NEP is equal to the difference between NPP and HR, which can be viewed as either the carbon sink if the NPP is larger than the HR or the carbon source if the NPP is smaller than the HR. With the substantially quantified NEP information using the CEVSA model, we were able to test two hypotheses linking two different quantitative impacts on the carbon cycle. The two hypotheses are: 1) the LULC change encountered in China from 1981 to 2000 mildly decreased the carbon storage; 2) the climate change in association with the increase of precipitation in China from 1981 to 2000 increased the carbon storage to some extent. It was envisioned that the cumulative carbon storage and release could eventually lead to a net effect of carbon sink based on these two hypotheses holistically.

2.1 The CEVSA model

The carbon cycle of the terrestrial ecosystem is driven through the processes of photosynthesis, autotrophic respiration, litter production, and soil respiration. These processes are controlled by the eco-physiologic characteristics of biomes (e.g., photosynthetic pathway, leaf form, and phenology) and by environmental conditions (e.g., radiation, temperature, availability of water, and nutrients). To couple these biologic and environmental controls over ecosystem carbon fluxes, the CEVSA model includes the following three modules (Fig. 1): 1) the biophysical module calculates the transfer of radiation, water, and heat to determine canopy conductance, evapotranspiration, and soil moisture; 2) the plant growth module describes photosynthesis, autotrophic respiration, and carbon allocation among plant organs, leaf area index (LAI), and litter production; 3) the biogeochemical module simulates the transformation and decomposition of organic materials and

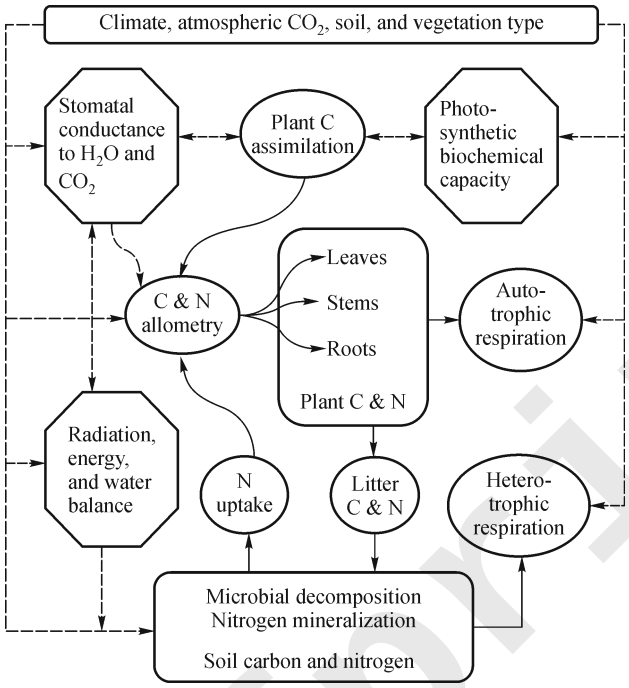

Fig. 1 A schematic representation of the model of CEVSA system (Cao and Woodward (1998a,1998b) used in this study). The solid lines are the carbon and nitrogen flows, and the dashed lines represent the effects of various factors or processes

nitrogen inputs and outputs to soils. Detailed descriptions of the model are given in Cao and Woodward (1998a, 1998b). The key processes are described in the literature (Woodward et al., 1995; Cao and Woodward,1998a, 1998b; Cao et al., 2004, 2005).

2.2 Land use/cover change derived from the Landsat/TM images

The 1:100000 land cover data sets in China applied in this study were generated based on the Landsat Thematic Mapper (TM) images. Land use data sets with 1 km × 1 km resolution in 1990 and 2000 were created. For each time period in the 1980s and 1990s, the total number of scenes to cover the entire country was more than 500. Visual interpretation and digitization of Landsat TM images at the scale of 1:00000 were carried out to generate the thematic maps of land cover under technical support from Intergraph MGE (Modular GIS Environment) software. A hierarchical classification system of 25 land-cover classes was applied to support the analysis in which six aggregated classes of land cover including croplands, woodlands, grasslands, water bodies, unused land, and built-up areas were categorized. The extraction of LULC change information was made possible by comparing the two derived LULC maps associated with 1990 and 2000, respectively (Liu et al., 2005a) (Fig. 2).

2.3 Modeling performance of the CEVSA and bookkeeping model

The CEVSA model has been calibrated and validated to simulate soil carbon, vegetation carbon, NPP, HR, and NEP (Cao and Woodward, 1998a, 1998b; Cao et al., 2001, 2002, 2005). To assess the model performance on simulating NPP, HR and NEP, Gu and Cao (2006) compared the CO_2 and water flux between the data simulated by the CEVSA and the measurements collected by the eddy covariance tower in a sub-tropical coniferous forest and Gao and Liu (2008) compared the actual NPP with corresponding values simulated by using three models including the CEVSA, Carnegie Ames Stanford Approach(CASA), and the Global production efficiency model (GLOPEM). With this baseline for China's total biomass production, model performance could be evaluated with respect to various criteria. The CEVSA model has been used worldwide to study the response of carbon cycling in the terrestrial ecosystem to climate change and LULC. With the aid of the prescribed GCM scenarios of

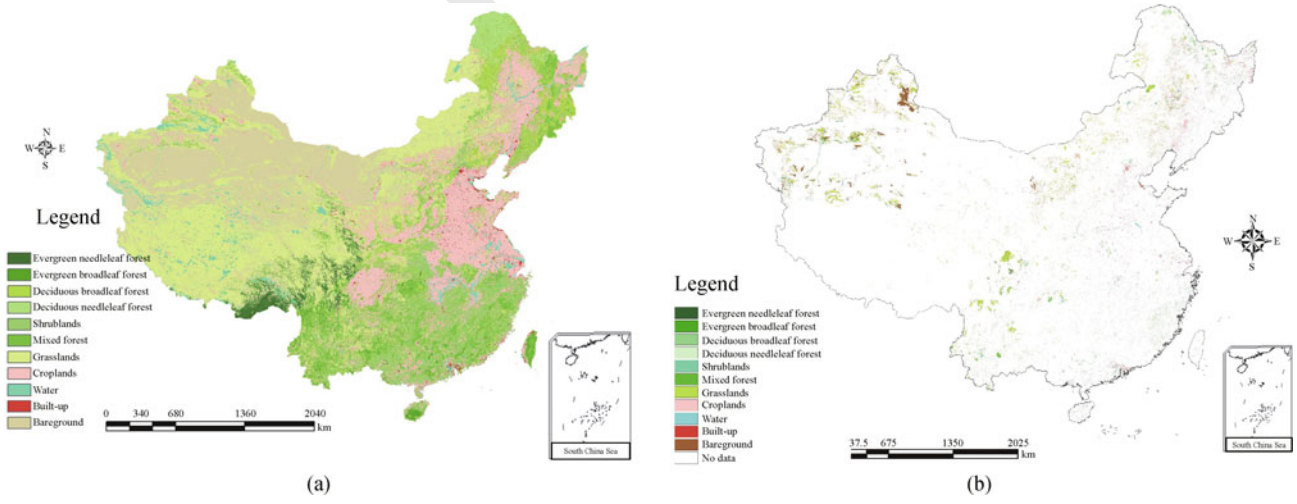

Fig. 2 The LULC maps (1990s) and dynamic changes (1980s–1990s) in China

CO_2 and climate change, Cao and Woodward (1998a) used the CEVSA model to perform simulations at a spatial resolution of 2.58 latitude 3.758 longitude and a time step of one month, allowing the authors to study the dynamic responses of terrestrial ecosystem carbon cycling to global climate change. With the CEVSA model, Cao et al. (2002, 2005) investigated the responses of global NPP, HR, and NEP to atmospheric CO_2 increases and climate variations in the period of 1981–1998. Gao et al. (2005) used the CEVSA to estimate the impacts of LULC change and climate changes on NPP, VEGC storage, HR, SOC storage, and NEP in the cropping-grazing transition zone of China. We therefore follow the CEVSA model to conduct our analysis.

The bookkeeping model that can be integrated with the CEVSA model to smooth out the holistic assessment of NEP with respect to LULC change was first used by Houghton et al. (1983, 1987, 1991, 1999) and Houghton and Hackler(1999) to study the carbon sources and sinks resulting from land use and land management in nine regions of the world. Calculations were carried out based on two types of data: one concerns land use changes and the other is the data of carbon storage density changes caused by land use and land management. Annual per hectare changes in vegetation and soil following a previous land use change were defined in the model for different types of ecosystems and land uses. The model tracks the areas of different land uses and the amounts of carbon held in live vegetation, slash, wood products, and soil. Changes in the pools from one year to the next define the net annual flux of carbon between land and the atmosphere. The time step is yearly. It is considered as an effective method to quantitatively describe the entire cycling of carbon in each carbon pool from "cradle" to "grave." The model calculates the flux of carbon that is attributable to direct human activity. It does not include the effects on carbon storage of increased atmospheric CO_2, increased deposition of nitrogen, or changes in climate (Houghton et al., 1983, 1999; Houghton and Hackler, 1999). Thus, after running the CEVSA model, we followed this bookkeeping approach to estimate the impact of LULC change and climate changes on the terrestrial carbon storage and flux in China for the period of 1981–2000.

3 Results analysis

3.1 The impact of climate changes on the carbon storage and carbon flux

China is located at the eastern edge of the Eurasian continent and faces the Pacific in the east. The monsoon climate is prevalent over China's mainland due to the unique pattern of sea-land interactions leading to larger periodical changes in precipitation interannually. The average precipitation from 1981 to 2000 was 623 mm/year and the annual variation of precipitation was 4.4%. The average rainfall was 620.5 mm/year for the time period 1981–1990 and 625.6 mm/year for the time period 1991–2000 (Sha, 2002). As a consequence, the increase of the precipitation rate was 0.65 mm/year in the study time period.

The spatial distribution of precipitation varied considerably from 1981 to 2000. The areas with an average annual rainfall greater than 800 mm accounted for 27% of the whole nation. They were mainly around the south of the Huaihe River and hilly areas of south China. The areas with an average annual rainfall between 400 mm and 800 mm accounted for 29% of the entire nation. They were mainly around North-east China, North China, and the eastern part of the Qinghai-Tibet Plateau. Those areas with an average annual rainfall smaller than 400 mm accounted for 44% of the nation. They were mainly around the western areas of Inner Mongolia, Xinjiang, and Qinghai mostly within arid and semiarid regions.

The annual changes in temperature were also very large within the same time period. The annual average temperature was 6.54°C, and the annual rate of temperature increase was 4.66%. Figure 3 confirms this tendency with an average annual increase of 0.055°C. The average temperature in the first ten years was 6.3°C from 1981 to 1990, whereas it became 6.77°C in the second ten years from 1991 to 2000. The decadal change of annual average temperature was as high as 0.47°C.

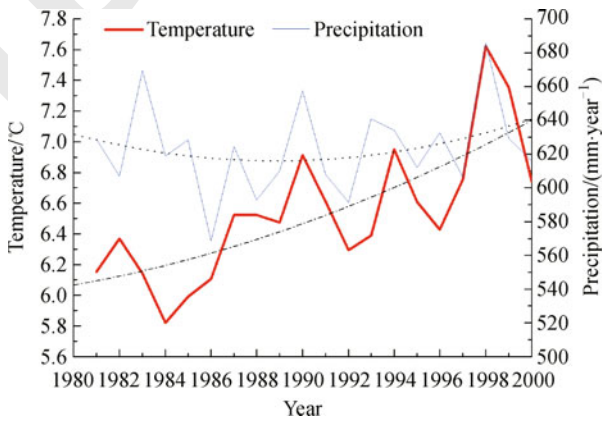

Fig. 3 The decadal changes of temperature and precipitation (Note: the temperature and precipitation are average values based on spatial interpolations over all grids covered total land area of China between 1981 and 2000)

Table 1 shows an increasing trend of NPP and HR in the same period. With an annual average rate of 0.01 PgC/year over the 20-year time period, HR increased by an annual average rate of 0.057 PgC/year from 1981 to 1990, and 0.079 PgC/year from 1991 to 2000 (see Table 1). The correlation coefficients between HR and temperature as well as between HR and precipitation were 0.92 and 0.39, respectively. These research findings suggest that HR

Table 1 The averaged changes of all parameters in relation to carbon cycle over four subperiods (unit: PgC)

Period	TEMP	PREC	NPP	HR	NEP	SOC	VEGC	Total C
1981–1985	6.09	630	3.134	3.080	0.054	75.090	11.574	86.664
1986–1990	6.51	611	3.138	3.137	0.001	75.285	11.518	86.803
1991–1995	6.57	617	3.186	3.158	0.028	75.411	11.583	86.994
1996–2000	6.98	634	3.200	3.237	−0.037	75.313	11.647	86.960

Note: NPP–net primary production, HR–heterotrophic respiration, NEP–net ecosystem productivity, VEGC–vegetation carbon, SOC–soil carbon, TEMP–temperature, PREC–precipitation

increased significantly due to the increasing temperature and precipitation in most areas of China in the study period from 1990 to 1999. Even though the temperature plays a more critical role than the precipitation, it is believed that the increase in precipitation promoted the growth of vegetation and soil respiration leading to a significant increase of HR.

To draw on further conclusions based on findings spatially, Figure 4 shows the spatial changes of five parameters in relation to the annual average carbon storage and carbon flux over the study period. The areas where HR was increasing during the study period accounted for 22% of the entire nation. They were mainly around from the eastern margin of the Qinghai-Tibet Plateau, to eastern part of the Inner Mongolia, to the Tianshan Mountains, and to the oasis of the Tarim Basin region (see Fig. 4(c)). Besides, the areas where the HR decreased in the same period accounted for 46% of the entire nation. They were mainly around the three provinces of Northeast China, North China, the Loess Plateau, and the southern area of the Nanling Mountains.

In summary, with the warmer climate and increased precipitation within the study period in China, the trends toward increases in HR and NPP were obvious. From 1981 to 1995, the increase in NPP was greater than that of HR, and the ecosystems in China had taken up more carbon in the carbon cycle, leading to the situation that the total carbon storage in China increased by 0.33 PgC. From 1996 to 2000, the temperature increased significantly, leading to a marked increase of HR, which was higher than that of NPP (see Fig. 4(a)). The status of the ecosystems as a whole was shifted from a carbon sink to a carbon source resulting in a total carbon decrease by about 0.034 PgC in China (Cao et al., 2003, 2004, 2005; Fang et al., 2001, 2003).

3.2 The impacts of LULC change on carbon storage and carbon flux

With the linkage between the CEVSA model and the LULC, we were able to numerically calculate VEGC, SOC, NPP and HR, helping understand the effects of LULC change on carbon storage and carbon flux which may be produced with the bookkeeping model for 1980s and 1990s in China (Liu et al., 2005b). Table 2 summarizes the LULC change matrix that was applied to meet this goal. The vertical dimension recorded the LULC in 1990 which was used as a benchmark to capture the decadal changes of LULC change in 2000 as listed along the horizontal axis. Within this matrix, LULC change eventually can be calculated at its bottom row.

Overall, the total area of LULC change is 138029 km^2 accounting for 1.45% of the total land area nationally (Liu et al., 2005a). This reflects changes of 31651 km^2 of cropland (22.9%), 27196 km^2 of woodland (19.7%), 56449 km^2 of grassland (40.9%), 6215 km^2 of water body (4.5%), 161 km^2 of constructed land (0.1%), and 16357 km^2 of unused land (11.9%). The area of the three major land covers including cropland, woodland, and grassland in 1990 occupied approximately 83% of total LULC, which revealed the fact that a fair amount of woodland and grassland were cultivated as cropland around North and West China, and were occupied as constructed land in the eastern coast of China during that time period.

The densities of VEGC, SOC, NPP, and HR were then calculated based on the two LULC data sets from 1990 and 2000. Figure 5 shows the comparison of these values generated between the CEVSA simulation outputs and values in the literature by Houghton (2003a). It can be seen that SOC density had not undergone significant changes. The VEGC density in cropland and woodland were also very close. Yet there were big differences of vegetation densities in grasslands and unused land between the CEVSA simulation outputs and those produced by Houghton (2003a).

Integrating the densities of NPP, HR, VEGC, and SOC simulated by the CEVSA model with the differences of land cover in 1990 and 2000 and the land transformation matrix data eventually allowed us to calculate the changes of carbon storage and carbon flux under the influence of LULC change between 1990 and 2000. Since the changed area of constructed land, water body and unused land accounted for 64.4% of the total cropland changes and the carbon densities of these three types of land cover were very low, the LULC change resulted in a net decrease of NPP, HR, VEGC and SOC by about 0.0135 PgC, 0.0139 PgC, 0.008 PgC and 0.215 PgC, respectively. According to Table 2, the area of cropland and woodland in the 2000s accounted for 80% of total change of grassland in the 1990s, and obviously the carbon densities of the cropland and woodland were much higher than that of grassland,

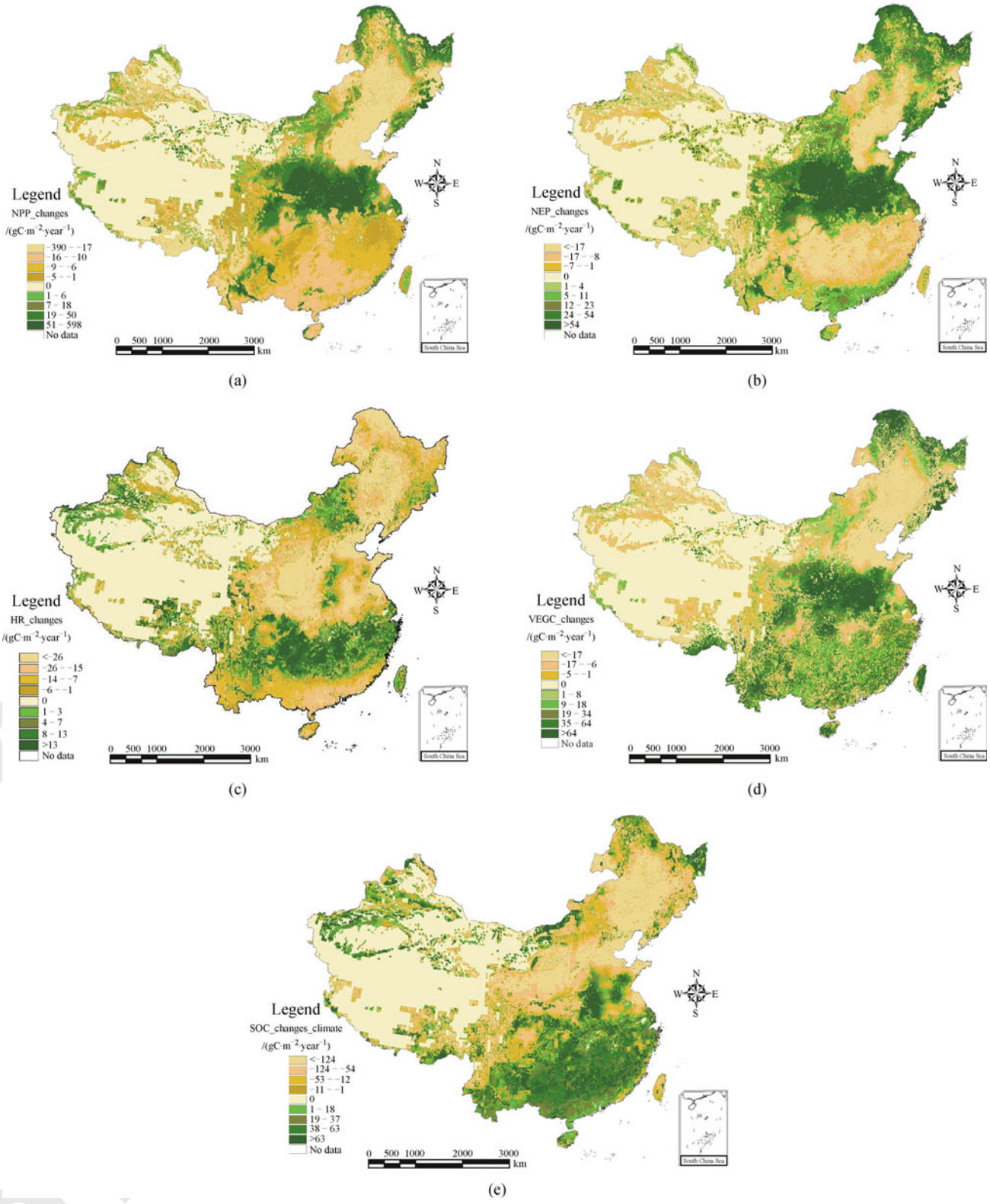

Fig. 4 Spatial variations of NPP, HR, NEP, VEGC and SOC changes under the influence of climate change (unit: gC/(m^2·year))

causing a net increase of NPP, HR, VEGC, and SOC by about 0.0144 PgC, 0.0146 PgC, 0.044 TgC, and 0.111 PgC, respectively . On the other hand, 16357 km^2 of the unused land was transformed into cropland (6587 km^2), woodland (401 km^2), grassland (6599 km^2), water body (2280 km^2), and constructed land (490 km^2),

Table 2 The LULC change matrix at the national scale during 1990–2000 (unit: km^2) (Liu et al., 2005a)

From 1990 to 2000	Cropland	Woodland	Grassland	Water body	Constructed land	Unused land	Total (1990)
Cropland		5159	6417	3643	15090	1342	31651
Woodland	17468		8112	402	930	284	27196
Grassland	34568	10470		1504	766	9141	56449
Water body	2858	254	916		398	1789	6215
Constructed land	86	20	36	19		0	161
Unused land	6587	401	6599	2280	490		16357
Total (2000)	61567	16304	22080	7848	17674	12556	138029
Change	29916	−10892	−34369	1633	17513	−3801	

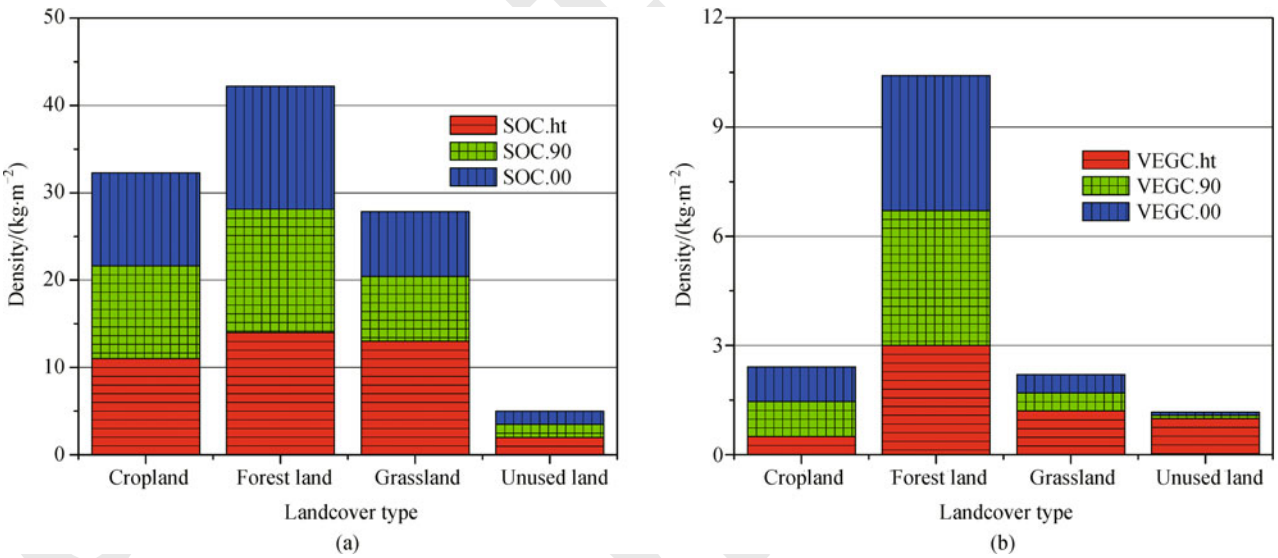

Fig. 5 Comparison of the carbon densities against the literature estimated for the year 1990 and 2000. (a) The estimated soil carbon density in 1990 and 2000. (b) The estimated vegetation carbon density in 1990 and 2000

resulting in higher carbon densities of the land cover. It caused a net increase of NPP, HR, VEGC, and SOC by about 0.0048 PgC, 0.0049 PgC, 0.0097 PgC and 0.1 PgC, respectively. Overall, when compared to the LULC over the two decades of interest, the final carbon densities of land cover in 1990s ended up a net decrease of NPP, HR, VEGC and SOC by about 0.0057 PgC, 0.0055 PgC, 0.08 PgC and 0.137 PgC, respectively.

With many changes in the pattern of LULC, Table 3 finally summarizes the comparative values of NPP, HR, VEGC, and SOC as a whole. It shows that the LULC change from 1990 to 2000 reflected the changed areas accounting for 1.45% of total nationwide. It rendered a net increase of NPP and HR by 0.0021 PgC and 0.0023 PgC, respectively, on one hand, and a net decrease of VEGC, SOC, and total carbon storage by 0.03 PgC, 0.097 PgC, and 0.126 PgC, respectively, on the other hand. Table 3 lists all the key values in this statistical analysis.

The area which experienced the increased NPP caused by LULC change is mainly located in Northeast China, Inner Mongolia and the north–south of the Tianshan Mountains due to the increase of cropland. Hence, the areas where NEP increased caused by LULC change were also around the same region (see Fig. 6). In summary, NPP was 0.051 PgC/year in 2000 and 0.0487 PgC in 1990 in areas where LULC change occurred and the LULC change

Table 3 Changes in NPP, HR, NEP, VEGC and SOC occurring in the LULC change area (unit: PgC)

LULC	NPP	HR	NEP	VEGC	SOC	Total C
2000	0.0510	0.0520	−0.0007	0.131	1.068	1.200
1990	0.0487	0.0490	−0.0002	0.161	1.165	1.326
Changes	0.0020	0.0023	−0.0005	−0.030	−0.097	−0.126

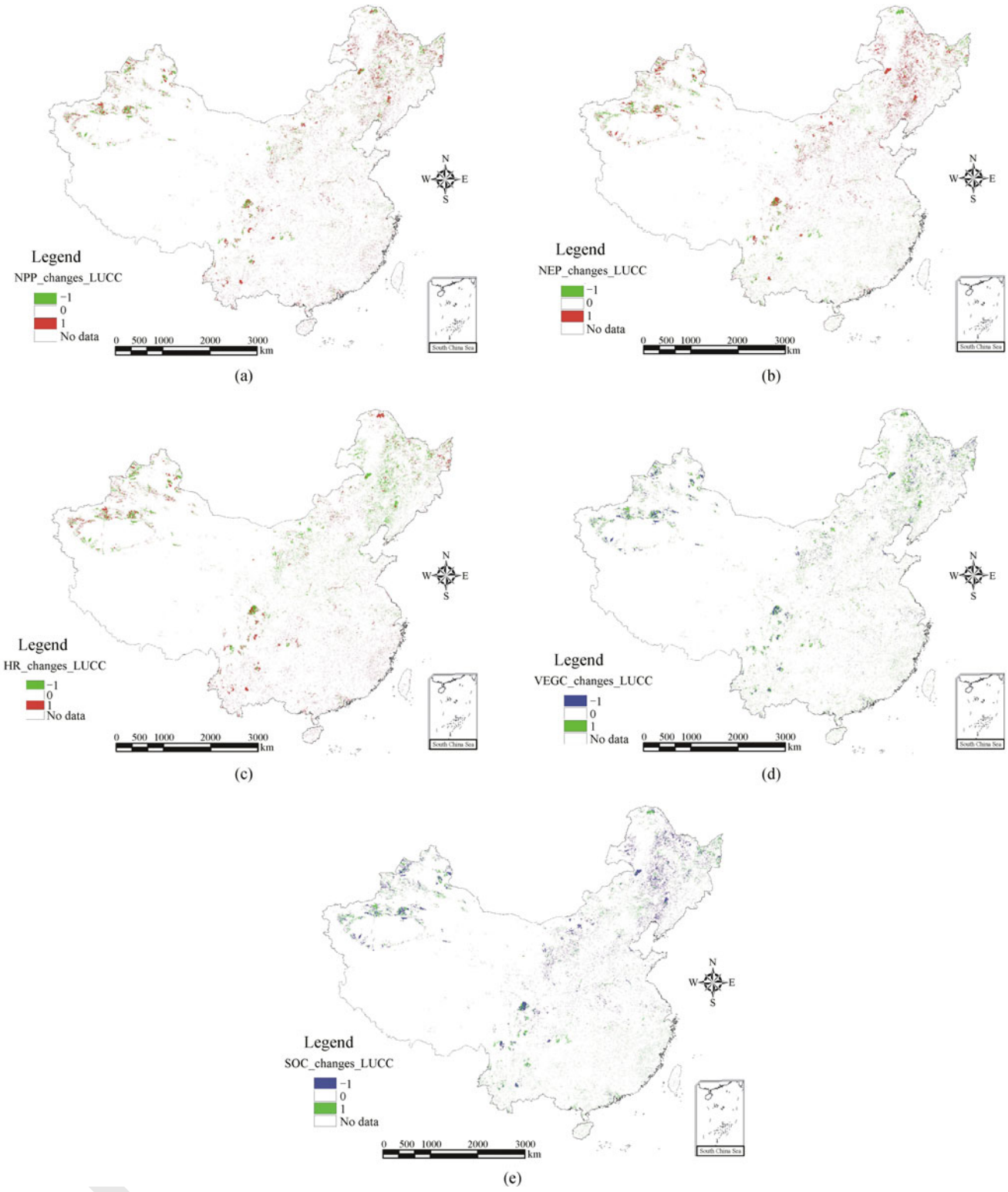

Fig. 6 The impact of LULC change on NPP, HR, NEP, VEGC, and SOC (Legend: –1: decrease; 0: unchanged; 1: increase). (a) The impact of LULC change on NPP distribution. (b) The impact of LULC change on NEP distribution. (c) The impact of LULC change on HR distribution. (d) The impact of LULC change on VEGC distribution. (e) The LULC change impact on SOC distribution

eventually led to an increase of NPP by about 0.002 PgC. The areas where an increase of HR caused by LULC change occurred were mainly around southern China, as opposed to northern China where HR decreased. Changes

in land use led to a net increase of HR by about 0.0023 PgC.

According to Table 3, the net increases of NPP and HR resulted in the changes of the NEP because the LULC change eventually led to net increases of NPP that were greater than net increases of HR. As a consequence, the LULC change behaved as a carbon "sink" in China's ecosystem during these two decades. This is mainly because fast economic development resulted in an increase of farmland and constructed land, and a decrease of woodland and grassland within the time period of 1991–2000. Although the trend of increasing NPP was clear due to the increase in farmland, the decrease of woodland and grassland outweigh the increased farmland, resulting in a net decrease of VEGC and SOC. These changes led to the net decrease of 0.030 PgC of VEGC and 0.097 PgC of SOC (see Table 3).

4 Discussion

The impacts of LULC change on carbon flux and carbon storage are deemed very complex (Houghton et al., 1999; Houghton and Hackler, 2000, 2003; Houghton, 2003a, 2003b). Changes in climate and LULC intermittently affect the ecological system and hydrological cycle. In the early stages, large-scale and continuous LULC monitoring data did not exist (Liu et al., 2005a, 2005b), making our study have to depend on two snapshots of LULC in 1990 and 2000 for assessment. In addition, the supervised classification during the study years (1990 and 2000) may add methodological uncertainties. The CEVSA model cannot account for all of the changes of material and energy fluxes in an ecosystem caused by LULC. The integration of the CEVSA model with the LULC change data derived from remote sensing in the context of a bookkeeping model add even more uncertainties. This results in an expanded array of uncertainty in the quantitative assessment of the impacts of climate change and LULC change on carbon flux and carbon storage. They can be summarized as follows:

1) The prediction accuracy of the LULC change developed by the use of Landsat TM scenes with a spatial resolution of 30 m × 30 m (Liu et al., 2005b) may be improved by image matching, image quality, and the experience of the interpreter.

2) Because the CEVSA model does not simulate changes of soil physical structures and model the ecosystem process, it yeilds large impacts on SOC estimation. This led to a certain degree of uncertainty on the calculation of the SOC pool (Cao and Woodward, 1998a, 1998b, Woodward et al., 1995).

3) The effects of the changes in the hydrological cycle caused by the LULC change on the carbon cycle are not interconnected with each other in the CEVSA model. This may directly affect the accuracy of estimates of storage capacity of SOC, and thus the rate of carbon emission or absorption (Cao and Woodward. 1998a; Gao et al., 2005).

4) All of these concerns accumulate in the context of the integrative framework involving a large number of parameters and default variables in our simulation. Whereas some parameters were obtained from field survey or estimated by experience, ground-based stations of carbon flux are not widely applied. (Gao et al., 2005).

Overall, the CEVSA model did not investigate the differences of SOC pools contiguously and the hydrological cycle effected by LULC change continuously over the 1980s and 1990s. The complexity and time lag of impacts of LULC change on the ecological environment account for the major portion of the uncertainty in this study. Even though the CEVSA model has no direct simulation of soil physical structures and the ecosystem process in the nexus of biogeochemical and hydrological cycles, some lumped parameters/variables in the CEVSA model could still reflect the relevant information indirectly.

5 Conclusions

This study applied the CEVSA model driven by both high resolution LULC and climate data to analyze the impacts of climate change and LULC change on carbon flux and carbon storage in China from 1981 to 2000. The LULC change accounted for 1.45% of the total national land area. With a bookkeeping model, we integrated the Chinese LULC change data set with the carbon densities of the land cover calculated by the CEVSA model over the1980s and 1990s. It can be concluded that the VEGC was 0.161 Pg/year in the 1980s and 0.131 Pg/year in the 1990s; the SOC was 1.165 Pg/year in the 1980s and 1.068 Pg/year in the 1990s. The VEGC was reduced by 0.0295 Pg and the SOC by 0.0968 Pg due to the LULC change between 1990 and 2000; therefore, the total carbon was reduced by 0.126 PgC. This led to the final conclusion that the total carbon was increased by 0.296 PgC due to climate change and was decreased by 0.126 PgC due to the LULC. As a result, the total carbon increased was 0.17 PgC.

It can be concluded that the changes of carbon flux and carbon storage caused by climate change were absolutely larger than that caused by the LULC change from 1981 to 2000 in China. This can be evidenced by the increase of both NPP and HR under the influence of climate change due to higher temperatures and higher annual precipitation. The increase of NPP was larger than that of HR so that the ecosystem in China leaned toward taking more carbon within the carbon cycle for at least 80% of the total study time period. This led to upward trends in VEGC and SOC. During the same time period, although China's terrestrial ecosystem where LULC change occurred was a carbon source, the rest of the regions, accounting for 98.55% of the total area, was actually a carbon sink, resulting in a net increase of total carbon (i.e., VEGC and SOC). This trend is in agreement with other research. The joint effects of

heat and water on China's carbon cannot be ignored, as the extreme climate conditions are other important factors which influence carbon flux. In addition to climate change, fire is another key factor. Possible future work may certainly lead to more detailed model intercomparisons, better understanding of robust model behaviors, and better understanding and quantification of uncertainty in future climate conditions.

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