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Quantifying Terrestrial Ecosystem Carbon Dynamics in the Jinsha Watershed, Upper Yangtze, China from 1975 to 2000

Shuqing Zhao · Shuguang Liu · Runsheng Yin · Zhengpeng Li · Yulin Deng · Kun Tan · Xiangzheng Deng · David Rothstein · Jiaguo Qi

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Abstract Quantifying the spatial and temporal dynamics of carbon stocks in terrestrial ecosystems and carbon fluxes between the terrestrial biosphere and the atmosphere is critical to our understanding of regional patterns of carbon budgets. Here we use the General Ensemble biogeochemical Modeling System to simulate the terrestrial ecosystem carbon dynamics in the Jinsha watershed of China's upper Yangtze basin from 1975 to 2000, based on unique combinations of spatial and temporal dynamics of major driving forces, such as climate, soil properties, nitrogen deposition, and land use and land cover changes. Our analysis demonstrates that the Jinsha watershed ecosystems acted as a carbon sink during the period of 1975–2000, with an average rate of 0.36 Mg/ha/yr, primarily resulting from regional climate variation and local land use and land cover change. Vegetation biomass accumulation accounted for 90.6% of the sink, while soil organic carbon loss before 1992 led to a lower net gain of carbon in the watershed, and after that soils became a small sink. Ecosystem carbon sink/source patterns showed a high degree of spatial heterogeneity. Carbon sinks were associated with forest areas without disturbances, whereas carbon sources were primarily caused by stand-replacing disturbances. It is critical to adequately represent the detailed fast-changing dynamics of land use activities in regional biogeochemical models to determine the spatial and temporal evolution of regional carbon sink/source patterns.

S. Zhao (✉) · R. Yin · D. Rothstein
Department of Forestry, Michigan State University, East Lansing, MI 48824, USA
e-mail: szhao@usgs.gov

S. Zhao · Z. Li
ASRC Research and Technology Solutions, Contractor to USGS EROS Center, Sioux Falls, SD 57198, USA

S. Zhao · K. Tan
College of Urban and Environmental Sciences, Peking University, Beijing 100871, China

S. Liu
U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center, Sioux Falls, SD 57198, USA

Y. Deng
College of Forestry and Horticulture, Sichuan Agricultural University, Ya'an 625014, China

X. Deng
Institute of Geographic Sciences of Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

J. Qi
Center for Global Change and Earth Observations, Michigan State University, East Lansing, MI 48823, USA

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Introduction

The terrestrial carbon budget results from complex interactions and feedbacks among plant productivity, decomposition, climate, soil properties, and human activities. These biogeochemical and biophysical processes occur across boundaries of traditional disciplinary investigations and on multiple time scales (Bala and others 2007; Chapin and others 2006). To comprehensively understand the causes and magnitudes of ecosystem carbon fluxes and carbon storage, it is critical to study the systems in meaningfully large units and over sufficiently large time scales.

However, there have been two major challenges in estimating ecosystem carbon dynamics over large spatio-temporal scales. First, quantifying the carbon exchanges between the terrestrial biosphere and the atmosphere due to land use change is still the largest uncertainty in the regional and global carbon budgets (Canadell 2002; Achard and others 2004; Ramankutty and others 2007). Land use and land cover change (LUCC), including land conversion from one type to another and land cover modification through land use management, has altered a large proportion of the earth's land surface (Meyer and Turner 1992; Vitousek and others 1997; Foley and others 2005; Zhao and others 2006) and disturbed the biogeochemical interactions between the terrestrial biosphere and the atmosphere (Schimel and others 2001; Houghton and Goodale 2004). From 1850 to 2000, roughly 35% of global anthropogenic CO_2 emissions resulted directly from land use changes (Houghton 2003), whereas contemporary land use changes are considered to be the dominant driver for some regional terrestrial carbon sinks, contributing to a large portion of current northern hemisphere terrestrial sinks (Fang and others 2001a, 2005; Choi and others 2002; Kauppi and others 2006). This highlights the importance of incorporating spatially explicit LUCC information into the estimation of regional carbon budgets.

Secondly, it has been a primary challenge to scale up the carbon fluxes and stocks measured or simulated at the site level to a regional level, mainly due to the heterogeneity of a range of environmental variables driving ecosystem processes (Jenkins and others 2001; Tickle and others 2001; Binford and others 2006; Gimona and others 2006). Integrating ecosystem models with geographic information systems (GIS) has provided the capability for extrapolating local information to a wider region. However, many previous models for estimating regional carbon fluxes are based on the direct application of site-scale methods over grid cells larger than site plots (e.g., Potter and others 1993; Pan and others 1998; Tian and others 1998) and are thus unable to capture the influences of heterogeneous environmental conditions at finer spatial scales. This can lead to significant biases both in scientific research and policy decision making.

In this article, we quantify the terrestrial ecosystem carbon dynamics in the Jinsha watershed of China's upper Yangtze basin from 1975 to 2000, using the General Ensemble biogeochemical Modeling System (GEMS), which is capable of dynamically assimilating LUCC information into the simulation process across large spatial extents and of upscaling carbon stocks and fluxes from local to regional levels (Liu and others 2004a, b). The objectives of this study were to (1) quantify the spatial and temporal patterns of carbon storage and carbon sources and sinks, and (2) examine the spatial variability of the major driving forces (e.g., climate and land use change) of carbon storage change over the Jinsha watershed from 1975 to 2000.

Methods

Study Area

The Jinsha watershed is situated at the upper reaches of the Yangtze River (Fig. 1). It has an area of 171,000 km^2 and includes 37 counties across the Sichuan Province, the Yunnan Province, and the Tibet Autonomous Region (97°40′–104°48′E, 25°18′–32°48′N). Elevations within the watershed range between 500 and 6740 m. Its subtropical climate has an average annual rainfall of 800–1000 mm and temperatures of 14–18°C (Lu 2005). The region features a wide variety of ecosystems that have been recognized as an important biodiversity hotspot (Conservation International 2002). Extreme variations in topography and landscapes accompany the diverse ecosystems. Human land use practices and climatic variation have altered the regional environment (Xiang and others 2008). Therefore, it is important to understand how the regional LUCC and climate variation have affected terrestrial ecosystem carbon dynamics.

Model Description

GEMS is a modeling system that was developed to integrate well-established ecosystem biogeochemical models with various spatial databases for simulations of biogeochemical cycles over large areas (Liu and others 2004a, b). GEMS is driven by the spatial and temporal joint frequency distribution (JFD) of major driving variables including climate, soil properties, nitrogen deposition, land cover changes, and land use practices with a range of resolutions. The JFD was generated by overlaying these geospatial data layers with a common grid size of 100-m by 100-m spatial resolution. Model simulation units were the unique combinations of these data layers with the finest simulation unit being one grid cell (i.e., 100-m by 100-m). The uncertainties of data layers at coarser resolutions were incorporated into GEMS simulations via a Monte Carlo approach. This approach embedded in GEMS maximally uses the finest information contained in some data layers (land cover change in this study, for example), and other coarser resolution data layers are scaled down to the finest resolution through representation of uncertainty (Liu in press).

GEMS consists of three major components: one (or multiple) encapsulated ecosystem biogeochemical model, an automated model parameterization system (AMPS), and

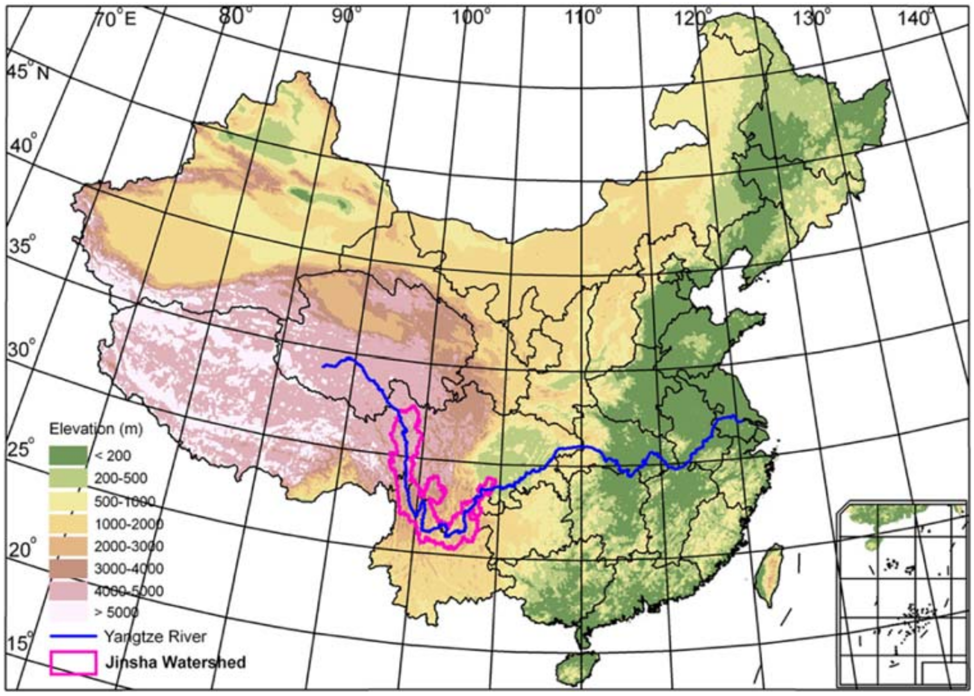

Fig. 1 Location of the Jinsha watershed, along with an altitudinal map of China in Albers equal-area conic projection

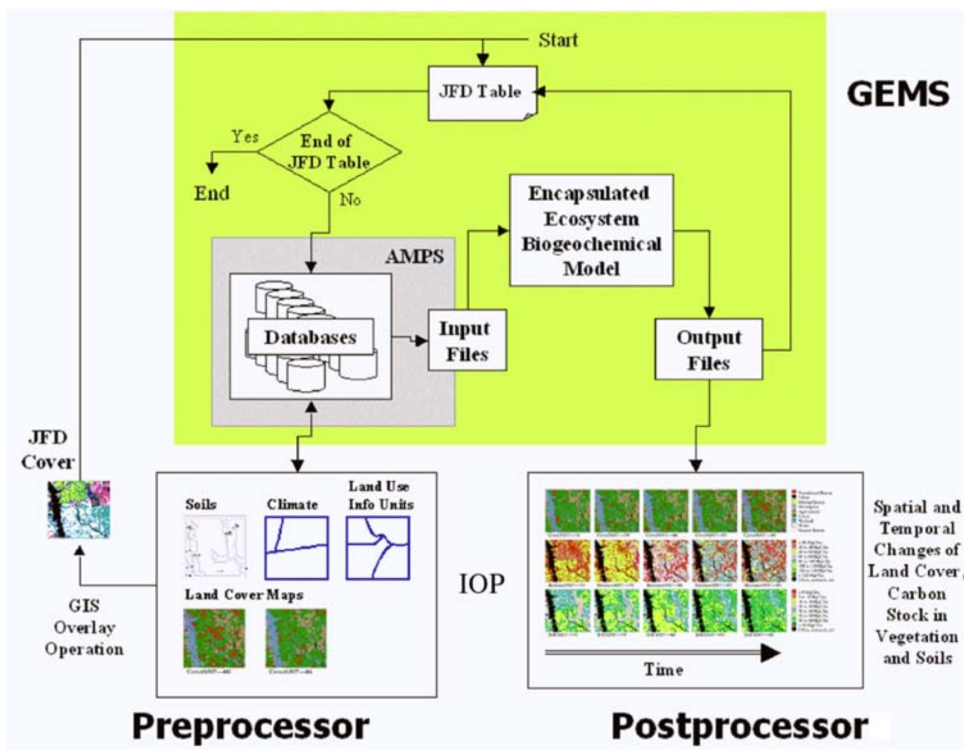

Fig. 2 Diagram of the General Ensemble Biogeochemical Model System (GEMS). Spatial deployment of the encapsulated plot-level biogeochemical model over large areas is based on the joint frequency distribution (JFD) grid or table and the automated model parameterization system (AMPS)

an input/output processor (IOP) (Fig. 2). The plot-scale Erosion-Deposition-Carbon Model serves as the encapsulated ecosystem biogeochemical model in GEMS (Liu and others 2003). The AMPS in GEMS consists of three major interdependent components: (1) data search and retrieval algorithms, (2) data processing mechanisms, and (3) data inclusion routines. The first component searches for and retrieves relevant information from several databases according to the keys provided in a JFD table. Because most information in spatial databases is aggregated to the map unit (spatial resolution of the map) level, the data processing mechanisms in the second component downscale the aggregated information at the map unit level to the field scale using a Monte Carlo approach. The third component of the AMPS injects the retrieved or assimilated data into the encapsulated model by updating its input files. The IOP is designed to process the input files of GEMS and to write the values of selected output variables to a set of output files after each execution of the encapsulated model. Land cover sequences in GEMS are generated by filling the land cover gaps between consecutive land cover maps using a Monte Carlo approach. For details on the model description, see Liu (in press).

Environmental Variables

The LUCC Data The LUCC data in the Jinsha watershed between 1975 and 2000 were obtained using cloud-free Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM) remote sensing images. The data covered five periods: 1975, 1985, 1990, 1995, and 2000. Land-cover data with a resolution of 100 m × 100 m were divided into six types: cropland, grassland, shrub, forest, disturbed or transitional (i.e., land in an altered unvegetated state which is in transition from one cover type to another), and others (e.g., urbanized area, body of water, snow, ice, and barren land).

Climate Data Long-term monthly minimum temperature, monthly maximum temperature, and mean monthly precipitation were obtained from a 1961–1999 climate database of China at 0.1° × 0.1° resolution, generated from 680 climatic stations across the country (Fang and others 2001b).

Soil Properties Soil data were taken from a national soil database with multiple layer information at 10 km × 10 km resolution developed by Shi and Yu (2002). The soil properties that we use include soil texture (sand, silt, and clay fraction), bulk density, organic matter content, wilting point, and field capacity by each layer. Soil drainage classes, from excessively well drained to very poorly drained, came from a GIS-derived integrated moisture index (Iverson and others 1997), which was generated by integrating hill shade, flow accumulation, curvature, and water holding capacity based on digital elevation model (DEM, with a resolution of 100 m × 100 m) and soil texture data.

Nitrogen Deposition The information was downloaded from http://eos-webster.sr.unh.edu/data_guides/china_dg.jsp, which was created by Changsheng Li and Steve Frolking of the Complex Systems Research Center, University of New Hampshire, Durham, NH, USA. It covers both wet and dry sources at the county level.

Forest Inventory Species composition and forest age and biomass distribution data at the county level were obtained from the National Forest Resource Inventory database for Sichuan, Yunnan, and Tibet. Initial data used for each county fall within the 1970s and 1980s, which generally correspond to the start time of this study. Timber volume was converted to biomass for each forest species based on the biomass expansion factor method developed by Fang and others (2001a).

Results and Discussion

Land Cover Changes

There was no single dominant land cover in the study area (Table 1). Forest (37%), grassland (32%), shrubland (13%), and cropland (11%) were the four major land cover types, covering about 94% of the region. From 1975 to 2000, little significant change was observed on the composition of land cover types (Table 1). Disturbed landscapes, primarily caused by forest harvesting, decreased from 0.6% in 1975 to 0.2% in 2000, suggesting a reduction in forest clear-cutting activities during the period.

However, the regionwide summary of land cover composition (Table 1) does not reflect the changes that happened at finer spatial scales. It is very clear that although there were not significant net changes in land cover types at the regional scale for the study period, there were various changes in land cover types at finer scales (Table 2). This highlights the need to characterize land cover changes using spatially explicit information at the scale where land cover change activities happen (i.e., at the field scale). The land cover transitions reveal detailed and dynamic land cover changes for four time periods (Table 2). The most dominant land cover changes between 1975 and 1985 were land transformations from disturbed land to grassland and forest, with a transition rate of 29.4 and 9.3%, respectively. This suggests that grassland restoration and reforestation had occurred during the period, although the contribution rate of these land conversions to the coverage of grassland and forest in 1985 was only 0.5 and 0.1%. At the same time, 6% of the cropland was

Table 1 Land cover proportions (%) in the Jinsha watershed during the period of 1975–2000

Land cover category	1975	1985	1990	1995	2000
Cropland	11.1	11.1	10.9	10.9	10.9
Grassland	32.2	32.4	32.6	32.7	32.8
Shrub	13.5	13.3	13.2	13.3	13.4
Forest	37	37.4	37.6	37.7	37.8
Disturbed	0.6	0.3	0.2	0.2	0.2
Other land cover	5.7	5.5	5.5	5.3	5.0

Table 2 Land cover transition and contribution matrix for four time intervals from 1975 to 2000

Land cover category	Cropland a (b)%	Grassland a (b)%	Shrub a (b)%	Forest a (b)%	Disturbed forest a (b)%	Other land cover a (b)%
	1985					
1975						
Cropland	91.4 (91.3)	1.6 (0.5)	0.7 (0.6)	6.0 (1.8)		0.3 (0.6)
Grassland	1.5 (5.3)	89 (88.7)	1.6 (3.9)	4.5 (3.9)		3.4 (19.8)
Shrub	0.3 (0.4)	7.7 (3.2)	83.1 (84.2)	8.7 (3.1)		0.2 (0.6)
Forest	0.2 (0.8)	4.2 (4.7)	3.8 (10.6)	91.5 (90.5)		0.3 (1.9)
Disturbed	3.0 (0.1)	29.4 (0.5)		9.3 (0.1)	57.7 (100)	0.6 (0.1)
Other land cover	6.1 (3.1)	13.1 (2.3)	1.4 (0.6)	4.0 (0.6)		75.3 (77)
	1990					
1985						
Cropland	91.0 (93.1)	4.6 (1.6)	0.4 (0.3)	0.8 (0.2)	0.1 (6.0)	3.1 (6.3)
Grassland	0.4 (0.1)	89 (88.3)	3.3 (8.0)	4.9 (4.2)	0.4 (59.1)	2.0 (12.1)
Shrub	0.5 (0.6)	4.0 (1.6)	84.3 (84.7)	10.6 (3.7)		0.6 (1.4)
Forest	1.5 (5.2)	4.0 (4.6)	2.4 (6.7)	91.4 (90.8)	0.1 (9.0)	0.6 (4.3)
Disturbed			0.7 (0.0)	84.3 (0.7)	15 (24.6)	
Other land cover	0.1 (0.1)	22.4 (3.8)	0.6 (0.3)	1.9 (0.3)	0.0 (1.3)	74.9 (75.9)
	1995					
1990						
Cropland	96 (96.3)	1.0 (0.3)	1.0 (0.8)	1.9 (0.5)	0.0 (1.0)	0.1 (0.2)
Grassland	0.5 (1.6)	90.7 (90.4)	3.0 (7.3)	4.7 (4.1)		1.0 (6.5)
Shrub	0.5 (0.7)	5.2 (2.1)	81.5 (81)	12.4 (4.4)	0.0 (0.7)	0.4 (1.0)
Forest	0.4 (1.2)	5.1 (5.8)	3.6 (10.1)	90.5 (90.3)	0.0 (1.5)	0.4 (3.2)
Disturbed	1.2 (0.0)	0.2 (0.0)	2.6 (0.0)	5.5 (0.0)	90.6 (96.8)	
Other land cover	0.2 (0.1)	7.8 (1.3)	1.8 (0.8)	4.7 (0.7)		85.5 (89.1)
	2000					
1995						
Cropland	96.5 (96.4)	1.9 (0.6)	1.0 (0.8)	0.4 (0.1)	0.0 (1.2)	0.2 (0.4)
Grassland	0.3 (0.8)	90.8 (90.5)	2.0 (4.8)	5.8 (5.0)	0.0 (0.1)	1.2 (8.1)
Shrub	0.8 (0.9)	6.5 (2.7)	81.4 (80.8)	10.9 (3.8)		0.4 (1.0)
Forest	0.5 (1.8)	3.8 (4.4)	4.7 (13.2)	90.7 (90.6)	0.0 (0.1)	0.2 (1.8)
Disturbed	0.9 (0.0)	0.4 (0.0)		1.3 (0.0)	97.3 (97.5)	0.1 (0.0)
Other land cover	0.1 (0.0)	11.4 (1.8)	1.0 (0.4)	3.2 (0.4)		84.3 (88.7)

a: Transition rate is the area percentage of a transition type from one land cover to another based on the area of certain land cover in the beginning period

b: Contribution rate is the area percentage of a transition type from one land cover to another based on the area of certain land cover in the ending period

converted to forest, with a contribution rate of 1.8% to forest cover in 1985. During the period of 1985–1990, the land conversion from disturbed land to forest amounted to 84.3%, probably as a result of the Rivers Protective Reforestation Project along the Upper Yangtze River (Fang and others 2001a). However, 0.4% of the grassland was disturbed during the same period, contributing 59.1% of disturbed landscape in 1990. The high transition rate (i.e., 22.4%) from other land cover to grassland from 1985 to1990 indicated that the increase in grassland during this period was contributed in part by the reclamation of open land available. The overall land cover pattern was relatively stable since 1990, indicated by relatively high retention rates (the percentage of the area that keeps the same land cover types between two periods) for all the land cover types during the periods of 1990–1995 and 1995–2000.

Comparison of Simulated and Observed Crop Yield

Except for Panzhihua county, we were unable to obtain grain yield information from the study area. Figure 3

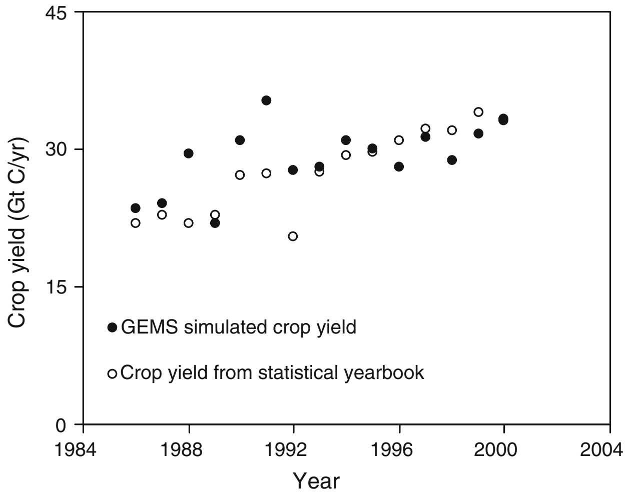

Fig. 3 A comparison of GEMS-simulated crop yield and crop yield obtained from the statistical yearbook for one county in the Jinsha watershed (i.e., Panzhihua) from 1986 to 2000. Total crop yield was converted to dry weight by multiplying a conversion factor of 0.85, and then to carbon by further multiplying a factor of 0.45. The crops include wheat, corn, soybean, tuber, fiber, and rapeseed (ECPSY 2002)

shows the comparison of temporal changes of GEMS simulated crop yields and yields obtained from statistical yearbooks for Panzhihua county from 1986 to 2000 (ECPSY 2002). It can be seen that model simulations were in general agreement with statistical yearbook data in trending ($Y = 0.49X + 15.4$, $R^2 = 0.40$). Although the correlation was not very strong, the simulated grain yields for most of the years agreed well with the census data. However, we should notice that the comparison can be difficult in certain years due to major sources of uncertainty from statistical grain yield data, remotely sensed cropping area, crop composition from census data, and modeling.

Changes in Ecosystem Net Primary Production (NPP)

From 1975 to 2000, ecosystem NPP in the Jinsha watershed increased from 281.8 to 372.5 g C/m^2/yr, with a growth rate of 32.2% (Fig. 4a). Interannual variability in NPP corresponded closely with the variations in climate. Over the period of 1975 to 2000, both annual precipitation and mean annual temperature significantly increased (Fig. 4b). NPP was anomalously low in 1978, 1992, and 1996, and high in 1998 (Fig. 4a), years that are strongly associated with changes in climate. Low NPP in 1978, 1992, and 1996 was coupled with low precipitation and cooling temperature, whereas the high NPP in 1998 was associated with anomalously high precipitation (Fig. 4b). The relationships between NPP and climate variables indicate that ecosystem NPP is closely correlated with annual precipitation and mean annual temperature, and the association with precipitation is stronger than that with temperature (Fig. 4c, d). Precipitation is a more limiting factor than temperature in the region where annual precipitation was relatively low and soil water holding capacity was limited by thin soil layers and high rock content. Climate-driven increases in ecosystem production have been reported in many previous studies (Fang and

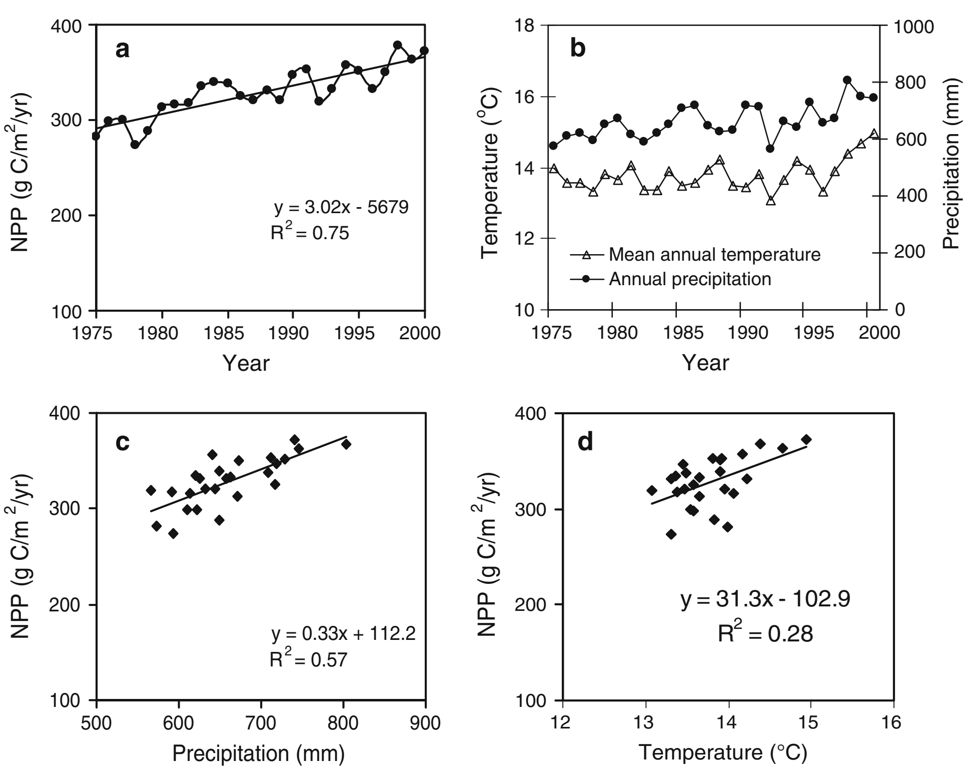

Fig. 4 The relationship between net primary productivity (NPP) and climate in the Jinsha watershed between 1975 and 2000. **a** The temporal change of NPP; **b** the temporal changes of annual precipitation and mean annual temperature; **c** the relationship between NPP and annual precipitation; and **d** the relationship between NPP and mean annual temperature. $P < 0.05$ in each case

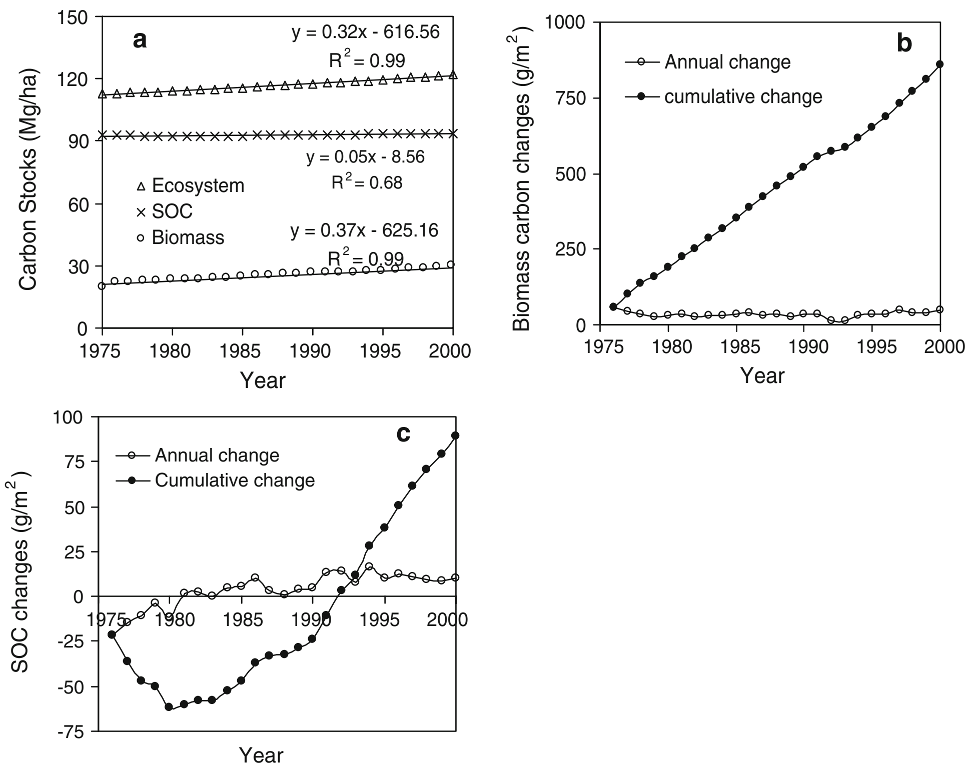

Fig. 5 Temporal changes of carbon stocks between 1975 and 2000 in the Jinsha watershed. **a** The overall ecosystem dynamics ($P < 0.05$); **b** annual and cumulative changes in biomass carbon; and **c** SOC

others 2003; Nemani and others 2003; Cao and others 2004). Other factors that might contribute to the increase of NPP during this time period include forest age structure change, crop genetic improvement, and cropping practices.

Changes in Carbon Stocks

Ecosystem carbon stock, including biomass carbon and soil organic carbon (SOC), increased from 112.7 Mg/ha in 1975 to 122.2 Mg/ha in 2000, with a growth rate of 8%. Biomass carbon (including live and dead vegetation biomass) had a growth rate of 44% and SOC had a growth rate of 1% (Fig. 5a). It is well known that increases in plant productivity will lead to a greater storage of carbon in vegetation biomass, especially in ecosystems dominated by woody vegetation (Rustad and others 2001). Figure 5b, c show the relative contributions of biomass carbon and SOC to the accumulation of ecosystem carbon stock. The annual change of biomass carbon (i.e., biomass carbon of current year minus that of previous year) varied from 13.2 to 55.5 g/m^2/yr. The temporal changes of biomass carbon were all positive and increased over time, indicating that vegetation biomass consistently gained C during the period of 1975–2000. The cumulative increase of biomass carbon amounted to 857.3 g/m^2 by 2000 (Fig. 5b). In contrast, the annual change of SOC was negative before 1981 and it became positive thereafter. The cumulative change of SOC decreased from −21.4 g/m^2 in 1976 to −62.1 g/m^2 in 1980, then increased from −60.6 g/m^2 in 1981 to 89.2 g/m^2 in 2000, shifting from negative to positive in 1992 (Fig. 5c). This variation suggests that soils in the Jinsha watershed ecosystem changed from a net carbon source to a net carbon sink during the period of 1975–2000.

The results also indicate that the increase in ecosystem carbon stock from 1975 to 2000 was primarily augmented by biomass carbon accumulation, and SOC loss before 1992 led to a lower net gain of carbon in the watershed. The storage of carbon in soils results from the balance between annual plant detritus input to the soil and the decomposition of soil organic matter. It is commonly observed that the decomposition process is more sensitive to environmental change than plant production and its consequent debris input to the soil (Jenkinson and others 1991; Davidson and Janssens 2006). Thus, environmental changes such as climate or disturbance often result in a net release of carbon to the atmosphere by the terrestrial ecosystem, or at least less net carbon sequestration from the atmosphere by the terrestrial ecosystem. Although our results showed that NPP increased 32.2% during the study period, SOC increase was very small (<4 g C/m^2/yr), strongly suggesting that NPP increase does not necessarily translate into SOC increase. The simultaneous increase of precipitation and temperature in the region probably accelerated the decomposition of SOC, partially offsetting the increase of SOC induced by NPP increase. Nevertheless, SOC change played a minor role in the net carbon exchange between biosphere and the atmosphere in the region.

Carbon Sink/Source Pattern Between 1975 and 2000

Although ecosystem NPP and carbon storage showed an overall increase from 1975 to 2000 in the Jinsha watershed, the carbon sink/source pattern had a high degree of spatial heterogeneity. Carbon sink/source strength over the period of 1975 and 2000 was derived from the difference of ecosystem carbon stock between 2000 and 1975 divided by the number of years in between (25), which was equal to the net biome productivity (NBP) using the carbon cycle concepts and terminology of Chapin and others (2006).

Carbon sources were mostly concentrated in the northwestern portion, especially within the two counties in Tibet (i.e., Jiangda and Mangkang), although source areas were scattered across the study area. The south-central portion was primarily a carbon sink, and the east was close to neutral except for some local "hotspots" of carbon sinks. Overall, 20.6% of the total area acted as a carbon source during the period, 33.1% was carbon neutral, and carbon sequestration occurred in 46.3% of the study area. The magnitude of carbon sink was mostly in the range of 0–2 Mg/ha/yr (Fig. 6a).

As discussed earlier, the increase in ecosystem carbon stock over time was primarily driven by the accumulation of vegetation biomass carbon. Most vegetation biomass was in the forests. Therefore, we overlaid the land cover maps of 1975 and 2000 to investigate the possible relationship between forest change and the ecosystem carbon

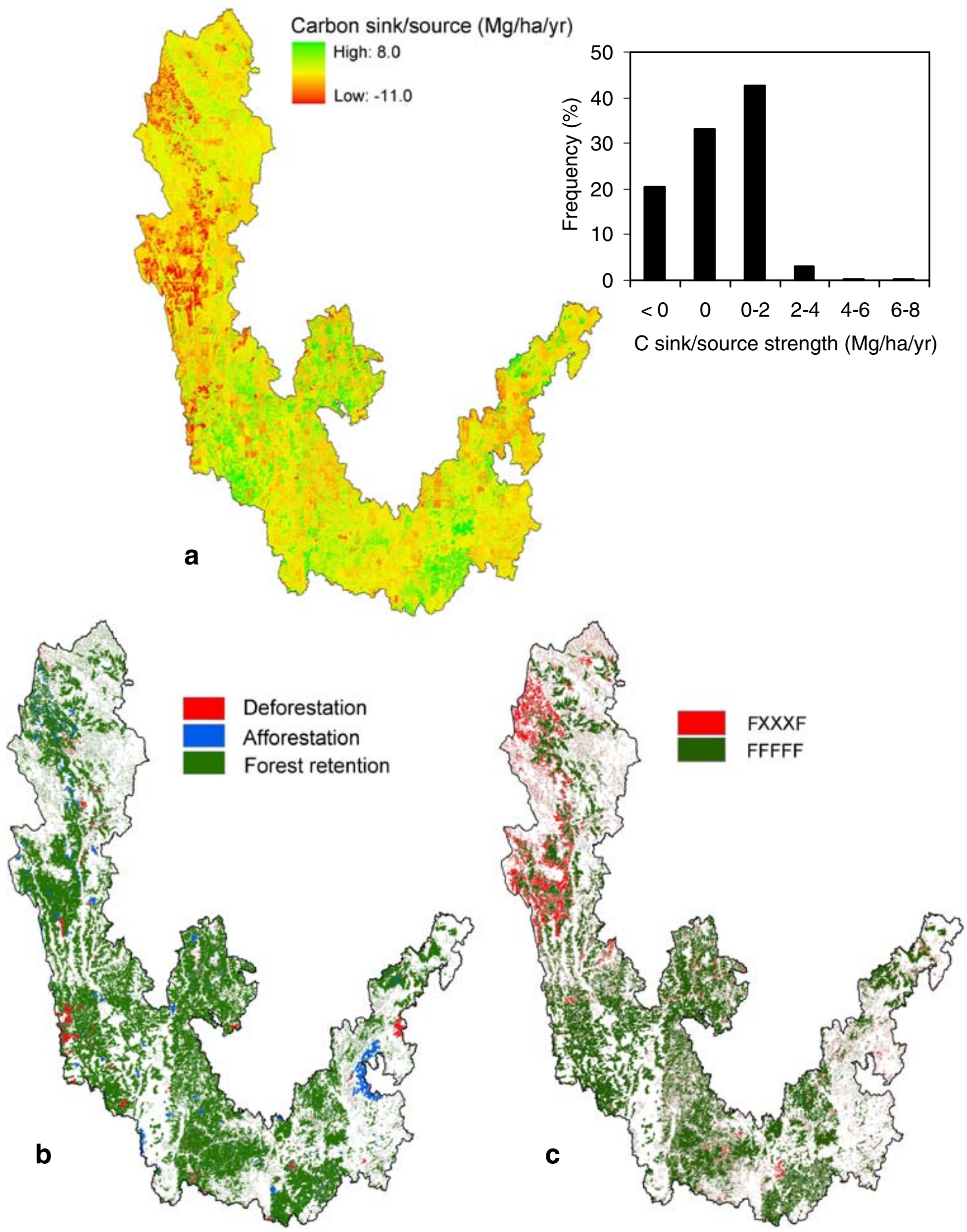

Fig. 6 Spatial distributions of carbon sink/source strength between 1975 and 2000 in the Jinsha watershed. (**a**) The sink/source strength over time, with the inset graph denoting the area frequency distribution of carbon sink/source strength; (**b**) Afforestation and deforestation between 1975 and 2000; and (**c**) Consecutive forest cover changes for five time periods, with F and N representing forest and non-forest. X in XXX could be either F or N, but at least with one N

sink/source patterns. Our results show that carbon sinks were generally associated with forest areas and that local "hotspots" of carbon sinks and sources tended to correspond to afforested and deforested areas, respectively. The nonforested areas were generally carbon neutral (Fig. 6b). However, carbon sources concentrated in the northwestern portion were also located in the forest retention area. To help explain these seemingly conflicting trends, we investigated the consecutive cover changes of the retained forests for the five time periods (Fig. 6c). We found that carbon sinks were associated with forest areas with little disturbance (that is, consistently being a forest area throughout the five periods, FFFFF), whereas carbon sources primarily resulted from clear-cutting and/or shifting cultivation (that is, from forest to nonforest and then back to forest, FXXXF). Carbon sources in the northwestern portion, especially within the two counties in Tibet (i.e., Jiangda and Mangkang), were created by deforestation during the study period (FXXXF). This highlights the importance of incorporating detailed fast-changing land use activities in the simulation of regional carbon sources and sinks, which is still not well-practiced in regional to global carbon studies.

Although the northwestern portion of the study area was covered by forest both in 1975 and 2000, dramatic disturbances occurred to the forested land within the period. Stand-replacing forest harvesting altered forest age, so that the age of the forest in 2000 was a bit younger than the one in 1975. Therefore, the capability for carbon sequestration in the northwestern forest ecosystem in 2000 was lower than that in 1975 and the area acted as a carbon source. These results are in agreement with previous studies documenting that young forests generally emitted carbon to the atmosphere from the terrestrial biosphere due to higher ecosystem respiration than production (Pregitzer and Euskirchen 2004; Magnani and others 2007). This finding highlights the importance of land-use history in determining the regional carbon sink/source patterns.

Summary

Climate change and land use and land cover change play important roles in determining the spatial and temporal dynamics of carbon stocks in terrestrial ecosystems and carbon fluxes between biosphere and atmosphere. Both annual precipitation and mean annual temperature increased in the Jinsha watershed from 1975 to 2000. Although there were not significant net changes in land cover at the regional level, various land cover types did change at the finer scales. The Jinsha watershed ecosystem acted as a carbon sink during the period of 1975–2000, with an average rate of 0.36 Mg/ha/yr. Temporal variability of carbon dynamics was primarily attributed to regional climate change, while the spatial heterogeneity of the ecosystem carbon sink/source pattern mainly resulted from local land use and land cover change. Carbon sinks were associated with forest areas with little disturbance, whereas carbon sources were caused by stand-replacing activities.

Our study has demonstrated the potential benefit of using a systematic modeling approach to quantifying ecosystem carbon dynamics. We integrate biophysical and biogeochemical models with geographic information systems, incorporating the driving forces at various spatiotemporal scales. Our results imply that the forest protection and afforestation practices in the Jinsha watershed were conducive to terrestrial carbon storage, whereas the deforestation and land degradation activities were detrimental.

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