



Climate change, human impacts, and carbon sequestration in China

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The scale of economic growth in China during the past three decades is unprecedented in modern human history. China is now the world's second largest economic entity, next to the United States. However, this fast economic growth puts China's environment under increasing stresses. China can be viewed as a massive "laboratory" with complex interactions between socioeconomic and natural systems, providing an excellent opportunity to examine how environmental changes and intensive human economic activities influence natural systems. This special feature explores the impacts of climate change and human activities on the structure and functioning of ecosystems, with emphasis on quantifying the magnitude and distribution of carbon (C) pools and C sequestration in China's terrestrial ecosystems. We also document how species diversity, species traits, and nitrogen (N) and phosphorus (P) stoichiometry mediate ecosystem C pool and vegetation production. This overview paper introduces the background and scientific significance of the research project, presents the underlying conceptual framework, and summarizes the major findings of each paper.

Importance of the Study on Climate Change and Carbon Budget of China

Reducing CO₂ emissions to mitigate regional and global climate change is one of the most challenging issues facing humanity (1). At present, China has the largest annual CO₂ emissions in the world (Upper graph in Fig. 1), placing it in the spotlight of efforts to manage global C emissions and design climate-change policy. It is therefore critical to improve our understanding of the C budget and its dynamics in China to mitigate climate change at both regional and global scales.

First, China accounted for 27.6% of the global CO₂ emissions from fossil fuel combustion in 2013 (2). Its policies on climate change and CO₂ emission reduction are therefore key to achieving global emission-reduction

targets. China's emissions are closely related to population size and economic growth. China is the most populous country in the world, with 1.37 billion people, about 4.3 and 2.7 times greater than that of the United States and the European Union, respectively (3). China's gross domestic product (GDP) has expanded at an average annual rate of 10.1% during the past 30 y and is ranked as second today, a large jump from its position at 13th in the early 1980s (4), although its GDP per capita is still relatively low among nations.

Fast economic development can be detrimental to the environment through land-use change, consumption of resources, and pollution. For example, land conversion to agriculture in northern China resulted in a drastic decline of the groundwater table and associated water shortage (5). China's application of chemical fertilizers and pesticides accounted for about 36% and 25%, respectively, of the global usage (6). Fast economic development, along with the lack of strong environmental regulation, has resulted in severe and widespread air, water, and soil pollution in China: a quarter of the nation's cities are affected by acid rain; soil erosion affects 19% of its land area; about 75% of lakes are polluted; and 15–20% of the country's species are endangered (7). CO₂ emission reduction in China is thus not only essential for achieving the global emission-reduction target but also critical for its own environmental protection and sustainable development.

Second, China's vast land area (960 Mha) is similar to that of the United States (915 Mha) and 2.3 times that of the European Union (424 Mha), and spans a broad range of latitude (from 18 to 53°N) and climatic conditions to which diverse ecosystem types have evolved. As a result, most of the global vegetation types can be found in China (8, 9), ranging from tropical rain forests and evergreen broadleaf forests in the south to evergreen or deciduous coniferous forests in the north, from diverse temperate vegetation in the Great Eastern Plains (i.e., the middle and lower

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The authors declare no conflict of interest.

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Published online April 16, 2018.

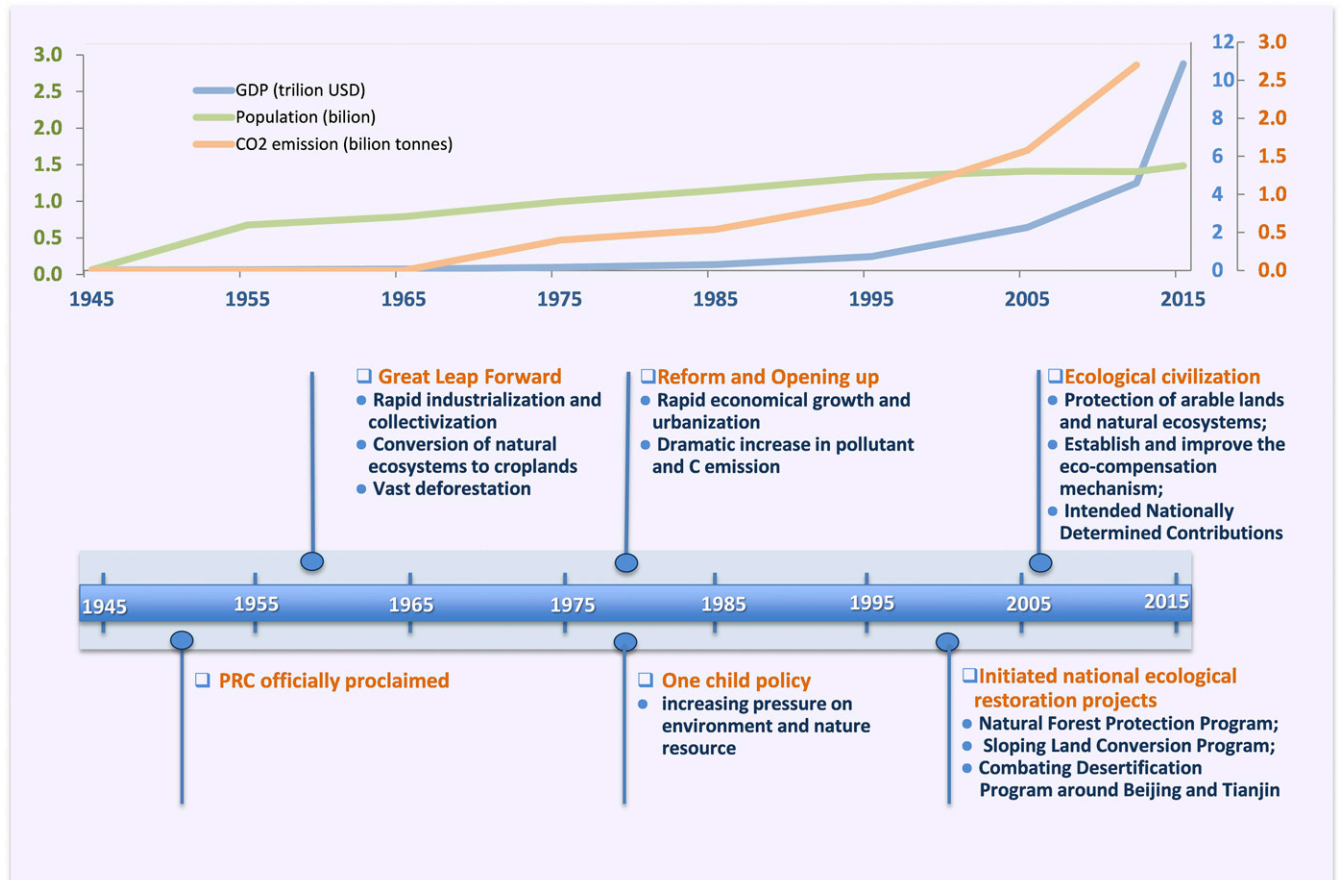


Fig. 1. Evolution in total national GDP, population, and fossil fuel CO₂ emissions, together with trajectory of the national policies in China between 1945 and 2015. (Upper) GDP, population, and CO₂ emissions. The CO₂ emissions data were from Oak Ridge National Laboratory (cdiac.ess-dive.lbl.gov/), and population and GDP data from the World Bank (<https://data.worldbank.org/country/>). (Lower) National economic policies and key ecological restoration projects. The environmental pressure of rapid economic growth required a paradigm shift in socioeconomic development. In the 1950s and 1960s, the national priority was to build an industrial system and catch up with industrialized countries. The associated “conquer nature” ideology greatly disturbed natural ecosystems with an absence of scientifically informed land use. The reform and opening-up policy initiated in the late 1970s stimulated the rapid economic development of the following decades, which exerted unprecedented impacts on ecosystems and environments. To restore degraded ecosystems, the central Government has initiated several national ecological restoration projects since the late 1990s, controlled the expansion of high pollution and high-energy consumption industry, and implemented stringent protection regulations in arable lands and natural ecosystems. In 2007, China adopted Ecological Civilization (social–ecological sustainability) as its national strategy for not only a greener China but also for the sustainability of society.

reaches of the Yangtze River Basin, northern plains, and north-eastern plains) to the cold grassland, meadow, and cushion vegetation in the Tibetan Plateau, and from the Mongolian steppe to the Gobi Desert in the west. Because of its long agricultural history, China also has a huge area of diverse cultivated lands, from rice paddies in the tropics to subalpine barley fields in the Tibetan Plateau. This diversity of ecosystems provides a unique opportunity to study geographic variations in the C cycle and its responses to climate changes and policy-regime shifts, as well as the interactions between the atmospheric and terrestrial systems.

In addition, China’s monsoon climate makes it sensitive to global climate change. Mean annual air temperature has increased by more than 1.0 °C in the past three decades, higher than the global average (Fig. 2). Although its annual precipitation has not notably changed as a whole, its regional and seasonal patterns have changed significantly across the country (10, 11). These climatic changes have profoundly affected the structure and functioning of China’s ecosystems.

Third, over 5,000 y of agricultural cultivation, coupled with China’s large population, have greatly altered its terrestrial ecosystems.

Although China occupies only 7% of the global total land area, it feeds about 20% of the global population (4). Consequently, long-term, intensive agricultural activities over large areas have markedly influenced regional vegetation cover and accumulation of soil organic matter (12). On the other hand, afforestation and reforestation in recent decades have taken place nationwide, increasing vegetation production and creating a significant C sink in the country (13–15).

These physiogeographic and socioeconomic factors have substantially influenced ecosystem patterns, processes, and functioning, and the interactions between climatic and ecological systems. In this special feature we present results of a coordinated research project that, for the first time, comprehensively addresses these issues at a national scale.

China’s Actions on Tackling Environmental Issues

The importance of balancing economic growth with environmental protection, resource preservation, and CO₂ emission mitigation is well recognized by the government, the academic community, and the public in China. The Chinese government has developed a series of policies and legislation to impede the trend of environmental

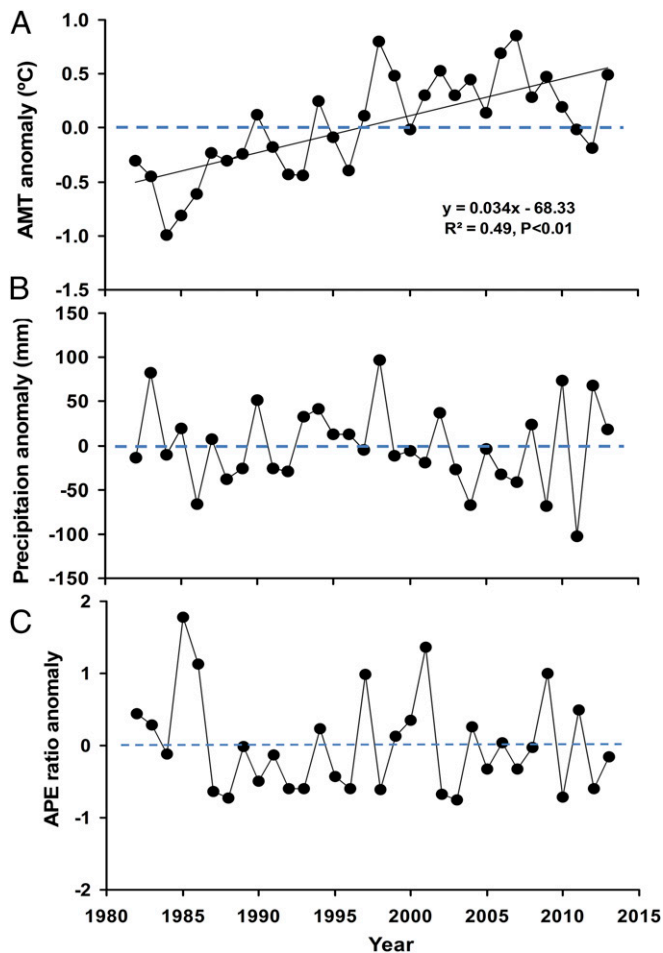


Fig. 2. Climate anomalies using climatic records in China over 1982–2011. (A) Annual mean temperature (AMT), (B) annual precipitation (AP), and (C) annual potential evapotranspiration (APE, mm) calculated by $APE = 58.93 \times ABT$, where ABT is annual biotemperature ($^{\circ}\text{C}$) (29).

deterioration (Lower graph in Fig. 1). For example, during the 2009 Copenhagen Accord Conference (16) China announced its intention to reduce CO_2 emission intensity by 40–45% by 2020. During the 2015 Paris COP21, China released its voluntary emission-reduction targets for 2030 (17): (i) C emissions are set to peak around 2030, making best efforts to peak earlier; (ii) C emissions per unit of GDP will be reduced by 60–65% from the 2005 level; (iii) the share of nonfossil fuels in the primary energy consumption will be increased to 20%; and (iv) forest stocking volume will increase by 4.5 billion m^3 [equivalent to 31.6% in C stock (18)] relative to the 2005 level. These emission-reduction targets, if achieved, will have far-reaching effects on China's future climate-change policy, businesses, and industries, and may contribute significantly to mitigation of regional and global climate change (2).

As an effort to implement its policies to slow down climate warming and to protect its environment, China has invested heavily and carried out several huge national ecological restoration projects, including the Natural Forest Protection Program, the Sloping Land Conversion Program, and the Desertification Combating Program around Beijing and Tianjin (Lower graph in Fig. 1). Meanwhile, local governments across the country have closed many energy-demanding but inefficient factories and businesses, and the Central Government has recently adopted a unified development strategy to curtail air pollution in the Beijing-Tianjin-Hebei region (the

Pan-Beijing area). The implementation of these policies and practices responds both to pressure from the international community and to China's need for environmental protection, public health, and ecological civilization (social-ecological sustainability).

General Framework and Major Findings of This Special Feature

As one of several national climate-change research programs, the Chinese government funded the Chinese Academy of Sciences to implement a 5-y Strategic Priority Project of Carbon Budget with about 35 million US dollars. About 350 researchers participated in the project during the past 5 y. Approximately 17,090 plots were sampled in forests, grasslands, shrublands, and croplands across the country, using consistent research designs and protocols to investigate vegetation, soils, and habitats (Fig. 3). In contrast to previous modeling and metaanalysis studies (14), this project provides detailed field observations that construct a strong foundation for accurately estimating ecosystem C stocks, C sequestration, and ecosystem functioning under both the present and future climate. This project is believed to be the largest field campaign in the world since the International Biological Program (a program in which China did not participate because of its Great Cultural Revolution from 1966 to 1976). The project fills fundamental data gaps in the studies of vegetation productivity, C sequestration, and biodiversity in China. We did not conduct our field survey in wetlands, deserts, and urbanized areas because of a small area of wetlands and urban area and low C stock/sequestration in deserts (19). We also excluded Taiwan, Hong Kong, Macao, and the South China Sea Islands from our study, primarily because of difficulties of access in these regions.

Ecosystem C sequestration and associated functioning take place through the interactions among abiotic components (e.g., climate, soils, and fires), intrinsic properties of ecosystems, and natural and anthropogenic disturbances (Fig. 4). Guided by this principle, the Strategic Priority Project of Carbon Budget addresses the following scientific questions: (i) What are the magnitude and distribution of ecosystem C storage and C sequestration? How do natural and human factors influence the C sequestration and other C-related ecosystem functions, both directly and indirectly through changes in productivity, biodiversity, and stoichiometry of plants? (ii) What are the C consequences of the major ecological restoration projects and the alterations in agricultural management practices that have been implemented in China for ecological conservation and crop productivity enhancement during the past few decades?

Using the intensive field investigation data collected in this project and integrated analyses, the six papers in this special feature address these questions and place China's C budget in a global context.

To answer the first series of questions, Tang et al. (20) investigated the size and spatial distribution of C storage and the underlying climatic and human drivers in China's forests, grasslands, shrublands, and croplands, based on field measurements extrapolated to the country level. They showed that total C stock of these terrestrial ecosystems amounts to 79.24 Pg C, with 38.9% in forests, 32.1% in grasslands, 8.4% in shrublands, and 20.6% in croplands. The ecosystem C density (C stock per area) was significantly associated with climate: it decreased with temperature but increased with precipitation. Their data also showed that both C density and the proportion of ecosystem C in plant biomass were lower than in their counterparts in other countries, reflecting past human disturbances in China, suggesting that future C storage might increase in China with appropriate management of human disturbance.

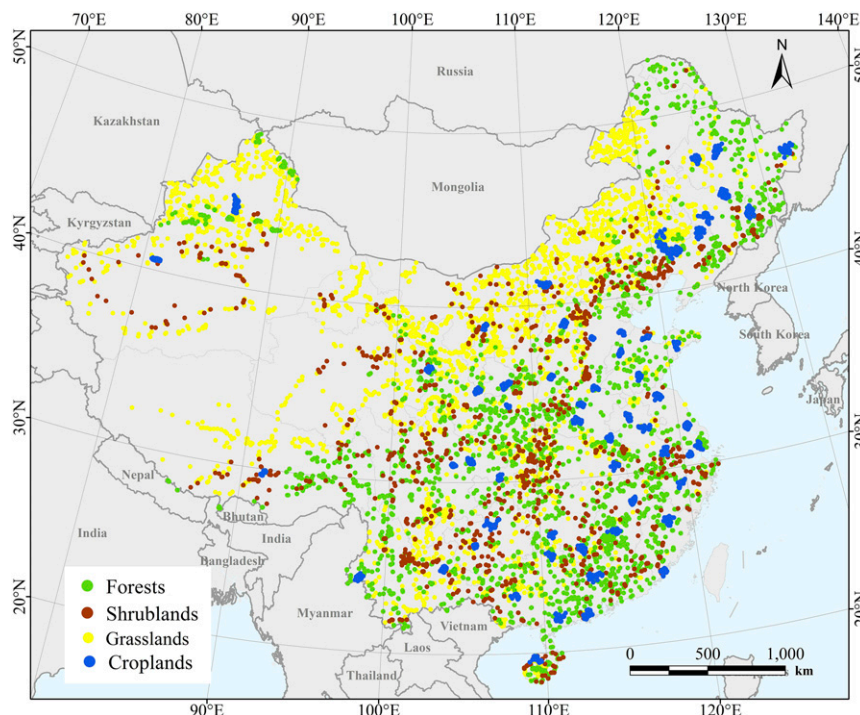


Fig. 3. Study sites in forests, shrublands, grasslands, and croplands across the country in the Strategic Priority Project of Carbon Budget supported by the Chinese Government. A total of 17,090 field plots were sampled in the project, of which 7,800 plots were from forests, 1,200 plots from shrublands, 4,030 plots from grasslands, and 4,060 soil sites from croplands. We excluded Taiwan, Hong Kong, Macao, and the South China Sea Islands from our study primarily because of difficulties of field access in these regions.

Plant biodiversity and stoichiometry can influence vegetation production, C sequestration, and other ecosystem processes. Chen et al. (21) quantified effects of climate, soils, human impacts, and ecosystem traits (species diversity and plant production) on soil organic carbon (SOC) stock based on field measurements from forests, shrublands and grasslands across the country. They found that favorable climate (high temperature and precipitation) was directly associated with reduced SOC in forests and shrublands but not grasslands. In addition, favorable climate (particularly high precipitation) was associated with high species richness and belowground biomass, which in turn enhanced SOC stock in the ecosystems, thus offsetting the direct negative effects of favorable climate on SOC. They suggested that ecosystem management can increase soil C sequestration by increasing plant diversity and productivity. Tang et al. (22) present the first study of large-scale patterns of C, N, and P stoichiometry in plant leaf, shoot, and root at the community level across China's forests, shrublands, and grasslands. They found that vegetation gross primary productivity (GPP) was closely coupled with leaf N and P content for all three ecosystems and documented the magnitude and distribution of the leaf N and P productivity across the country, with an overall mean of 250 gC GPP/gN-yr and 3,158 gC GPP/gP-yr, respectively. Leaf N and P productivity increased with both temperature and precipitation, suggesting that global warming could enhance GPP even without added N and P.

To answer the second series of questions, Lu et al. (23) evaluated the changes in ecosystem C stocks by comparing areas of six major ecological restoration projects with unrestored reference areas in China from 2001 to 2010. These authors showed that these restoration projects induced 56% of the C sequestration in the regions where they were implemented, an annual sink of 74 Tg C/yr (relative to the total sink of 132 Tg C/yr in the project

regions). This is equivalent to 50–70% of the total annual sink from all major terrestrial ecosystems in China or 9.4% of China's C emissions from fossil-fuel combustion. In another study, Zhao et al. (24) assessed the impacts of crop residue management on cropland soil C sequestration, using field data collected from 58 counties across the country. These authors documented that

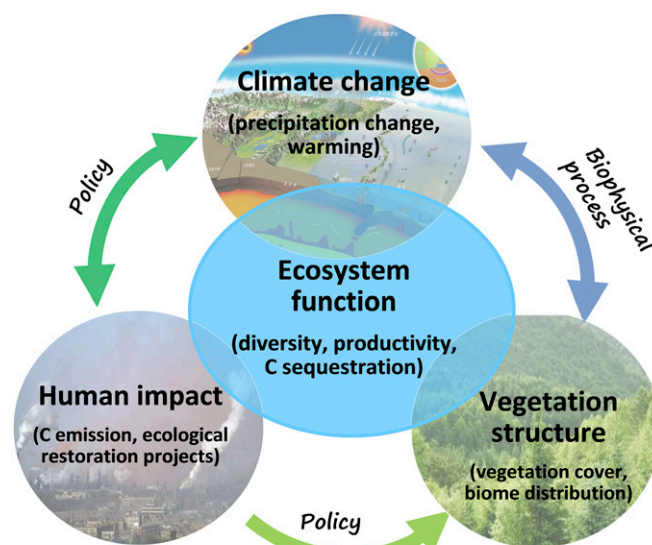


Fig. 4. Conceptual diagram showing how vegetation structures, climate changes, and human activities influence ecosystem functioning (e.g., productivity, carbon sequestration, and biodiversity), which are the foci of this special feature. The biophysical processes and governmental policies act on ecosystem functioning by affecting vegetation structure, climate change, and human activities.

Table 1. Summary for C pools and the changes in each ecosystem C sector: that is, vegetation biomass, dead organic matter (DOM), and SOC, in four major ecosystems (forests, shrublands, grasslands, and croplands) in China from 2001 to 2010

Item	Ecosystem				Total	Area-weighted mean	Source
	Forest	Shrubland	Grassland	Cropland			
Area (10 ⁶ ha)	188.2	74.3	281.3	171.3	715.1		(20)
C pool (PgC)							
Vegetation C	10.48	0.71	1.35	0.55	13.09		(20)
DOM C	0.37	0.06	0.02	0.00	0.46		(20)
SOC	19.98	5.91	24.03	15.77	65.69		(20)
Subtotal	30.83	6.68	25.4	16.32	79.24		
C stock change (Tg C/yr)							
Vegetation C	116.7	3.5	-0.80	0.00	119.4		(30, present study)
DOM C	9.0	0.0	0.00	0.00	9.0		(31, present study)
SOC	37.6	13.6	-2.56	23.98*	72.6		(14, 24, 32, 33)
Subtotal	163.4	17.1	-3.36	23.98	201.1		
C density (Mg C/ha)							
Vegetation C	55.7	9.6	4.8	3.1		18.3	(20)
DOM C	1.9	0.8	0.1	0.0		0.61	(20)
SOC	106.1	79.5	85.4	92.0		91.8	(20)
Subtotal	163.7	89.9	90.3	95.1		110.7	
C stock change per area (Mg C/ha-yr)							
Vegetation C	0.62	0.05	-2.84 × 10 ⁻³	0.00		0.17	(13, 30)
DOM C	0.05	0.00	0.00	0.00		0.01	(31, present study)
SOC	0.20	0.18	-9.09 × 10 ⁻³	0.14		0.10	(14, 24, 32, 33)
Subtotal	0.87	0.23	-11.93 × 10 ⁻³	0.14		0.28	

Note that we developed approaches to estimate the changes in biomass C stocks in shrubland and grasslands in China by combining field measurements obtained from this project with remote-sensing data.

*Topsoil 20 cm.

cropland soils are a significant C sink, with a net mean increase of 140 kg C ha⁻¹ yr⁻¹ in the topsoil (0–20 cm) over the last three decades from 1980 to 2011. This SOC increase was largely attributed to increased organic inputs (such as crop root and straw/stover) driven by economics and policy, which contrasts with crop soils in European countries, where insufficient organic C inputs were a primary cause of the SOC decrease (25, 26). These two studies (23, 24) provide the first ground-based evidence that ecological conservation practices and improved crop residue management significantly enhanced C sequestration in the managed ecosystems in this study, approaches that could be applied to other regions of the world.

As a case study of interactions between climatic and ecological systems at an ecosystem level, Liu et al. (27) showed the responses of an alpine grassland ecosystem to climate warming on the Tibetan Plateau, based on 32-y plot-level monitoring and a 4-y warming experiment. They showed that experimental and observed climate warming led to a decline in soil moisture but no systematic changes in net primary production. Meanwhile, species composition shifted from shallow-rooted sedges to more deep-rooted grasses. Liu et al. suggest that shifts in species composition and functional traits contribute to the resilience of productivity, making this alpine grassland less sensitive to climate change than expected.

In summary, results presented in this special feature indicate that China's terrestrial ecosystems are significant C sinks, and both climate change and human management contribute to these C sinks. To provide a complete picture of the C

sequestration in the country's terrestrial ecosystems, we documented C pools and the changes for all C sectors (vegetation biomass, dead organic matter, and SOC) of forests, shrublands, grasslands, and croplands in China (Table 1), by synthesizing the studies in the special feature and other recent studies. Among these four ecosystems, forest, shrubland, and cropland showed an increasing C stock (C sink), but the grassland ecosystem served as a weak C source (-3.4 TgC/yr). These ecosystems have collectively sequestered C of 201.1 Tg per year during the past decade, in which forests contributed the most (163.4 TgC/yr; 80%), followed by cropland (24.0 TgC/yr; 12%) and shrubland (17.3 TgC/yr; 8%). These increased C stocks are equivalent to 14.1% of the C emissions from fossil fuel consumption in China from 2001 to 2010 (2, 28), and largely attributed to climate change, ecological restoration projects, and agricultural land management. For example, ecological restoration projects have contributed a C increase of 74 Tg C/yr (23) and agricultural management have enhanced C sequestration by 20 Tg C/yr during the last decade (24). These studies provide fundamental datasets to test theories on the interactions between climate change, human activities, and ecosystem feedbacks, as well as a baseline for assessing future changes.

Acknowledgments

We thank X. Zhao and H. F. Hu for preparing some figures in the paper. This work was supported by Strategic Priority Research Program of the Chinese Academy of Sciences Grant XDA05050000 and National Natural Science Foundation of China Grants 31321061 and 31330012.

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