ENVIRONMENTAL SCIENCES

Carbon emissions from land-use change and management in China between 1990 and 2010

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China has experienced enormous changes in land use in recent decades, which are largely driven by its unparalleled economic development. We analyze changes in vegetation and soil carbon storage between 1990 and 2010 resulting from combinations of land-use category conversion and management. Results demonstrate a major decline in grasslands (−6.85%; 20.83 × 10^6 ha) and large increases in urban areas (+43.73%; 6.87 × 10^6 ha), farmlands (+0.84%; 1.48 × 10^6 ha), and forests (+0.67%; 1.52 × 10^6 ha). The total soil organic carbon pool has been reduced by approximately 11.5 Tg of carbon (TgC) year^{-1}, whereas 13.2 TgC year^{-1} has accumulated in the biomass carbon pool because of land-use category change. Large carbon losses (approximately 101.8 TgC year^{-1}) have resulted from land management failures, including forest fires and insect pests. Overall land-use change and land management have contributed about 1.45 Pg of carbon to the total carbon released from 1990 to 2010. Our results highlight the importance of improving land-use management, especially in view of the recently proposed expansion of urban areas in China.

INTRODUCTION

Terrestrial ecosystems are potentially major carbon stocks that could play an important role in offsetting anthropogenic carbon emissions (*1*, *2*). Carbon storage capacity differs between different terrestrial ecosystems, and changes in land-use type from high-vegetation to low-vegetation biomass usually result in carbon emissions into the atmosphere. This land-use change not only directly reduces carbon storage in vegetation but also affects the amount of vegetation residues returned to the soil, which are, in turn, the main source of soil carbon storage [soil organic carbon (SOC)] (*3*). Land-use management, such as measures to control wildfires, pests, and diseases, can also affect carbon storage. For example: fires can directly release carbon from vegetation into the atmosphere; effective measures to control pests and diseases can help to avoid carbon emissions from dead plants; and proper fertilization and drainage can promote vegetation growth and may increase the accumulation of SOC (*4*). Thus, globally, land-use and land-cover change (LUCC) has major impacts on the extent and distribution of terrestrial carbon emissions (*5*–*9*). It is estimated that LUCC has contributed about one-third of all anthropogenic carbon emissions since the industrial revolution (*10*) and 12.5% of total emissions between 2000 and 2009 (*11*). As a result, the impact of land-use changes within terrestrial ecosystems on carbon balance has been a focus of global change research in recent decades (*6*, *12*–*14*). Several studies have researched the disturbance of carbon pools by human activities using bookkeeping models, which track changes in the areas of different land-use types and use standard growth and decomposition curves to calculate changes in carbon pools (*10*, *15*). Others have estimated the effects of LUCC using process models that internally calculate the carbon density of vegetation and soils in different ecosystems based on climate and other factors used within the models (*8*, *16*). Carbon emissions caused by deforestation, cultivation, and other land-use changes have been widely reported (*10*, *17*–*19*). Compared to biomass carbon pools, soil organic carbon stocks have been shown to undergo much larger changes due to LUCC (*20*–*23*).

China is the world's second largest economy and largest carbon emitter. At the last Asia-Pacific Economic Cooperation meeting in Beijing in November 2014, China pledged that its carbon emissions would peak and then begin to decline by around the year 2030. On 30 June 2015, the Chinese government submitted its Intended Nationally Determined Contribution to the Paris Climate Agreement. In addition to reaching peak carbon emissions by around 2030 and then achieving declines thereafter, China also promised to increase the share of nonfossil fuels, increase the volume of forest stocks, and reduce carbon dioxide emissions per unit of gross domestic product (*24*). Research on China's terrestrial ecosystem carbon stocks and the effects of LUCC is very important for China's carbon mitigation (*6*, *10*, *25*). Many studies have researched LUCC and the carbon cycle in China, although most were carried out on certain ecosystems (especially forest, grass, and crop vegetation) or at the regional scale (*20*, *26*–*30*). Some scholars have undertaken analyses at the national scale (*30*, *31*) and found that China's terrestrial ecosystems were major carbon sinks in the 1980s (*31*) and 1990s (*30*). These studies were mainly focused on forest, grassland, and cropland ecosystems and thus the carbon emissions from other land-use types (for example, built-up land and water) remain unknown. Land-use management, particularly of forest, grassland, and arable land, is equally important for the carbon cycle (*18*). Some studies have estimated the effects of cropland or fire management on carbon stock changes (*27*, *32*, *33*), but the comprehensive effects of carbon emissions from land-use management of forest, grassland, and arable land in China remain unknown. Furthermore, China has undergone marked changes over recent decades because of rapid urbanization, agricultural development, and a series of afforestation initiatives (*34*). A comprehensive analysis of the effects of land-use change and land management on carbon stocks is needed to update the national carbon data for China. On the basis of the analysis of land-use category conversions and an assessment of land-use management practices, this study addresses this need. It investigates the changes in carbon flow driven by land-use change and management in China during the period 1990–2010.

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RESULTS

Land-use change

The land-use data derived from Landsat Thematic Mapper (TM) imagery from 1990 to 2010 were used to estimate the spatiotemporal dynamics of land-use and carbon storage change. In 2010, the areas of the five main land categories (ordered by area) were (table S1) 2.92×10^8 ha (30.7% of the total area) for grassland, 2.27×10^8 ha (23.9%) for forest, 1.79×10^8 ha (18.8%) for arable land, 0.26×10^8 ha (2.8%) for water, and 0.23×10^8 ha (2.4%) for built-up land. A range of other land uses that include, for example, extensive sandy deserts and saline-alkali land accounted for 2.13×10^8 ha (22.3%). These remote sensing–derived land-use data demonstrate that, over the two-decade period, large changes in land cover were experienced in China (Fig. 1). Between 1990 and 2010, China experienced a net increase in forestland, farmland, urban land, and other land (sandy land, gobi, saline-alkali land, swampland, bare land, rock and gravel, and other unused land; table S1). The magnitudes of these increases were 1.52×10^6 ha (+0.7%), 1.48×10^6 ha (+0.8%), 6.87×10^6 ha (+43.0%), and 11.74×10^6 ha (+5.8%), respectively. Conversely, grassland experienced a decrease in area of 20.83×10^6 ha (−6.7%).

There were spatial variations in land-use change across China. Over the last few decades, the Chinese government developed a number of afforestation programs to revert historically forested areas that had previously been converted into farmland back to forest. Programs, such as the Slope Land Conversion Project and the Natural Forest Protection Project, were responsible for the increases in the area of forest in most regions, except Northeast and Northwest China. The area of grasslands decreased in all regions. Two additional noteworthy changes are the increase in the extent of urban areas in most regions [total increase of 6.87×10^6 ha (43.73%)] and the loss of natural ecosystems to farmland in Northeastern China.

Effects of land-use change on carbon stocks

Calculations of carbon storage change suggest that land-use conversion between 1990 and 2010 led to about 264.3 Tg of biomass carbon accumulation [approximately 13.22 Tg of carbon (TgC) year^{-1}]. This was

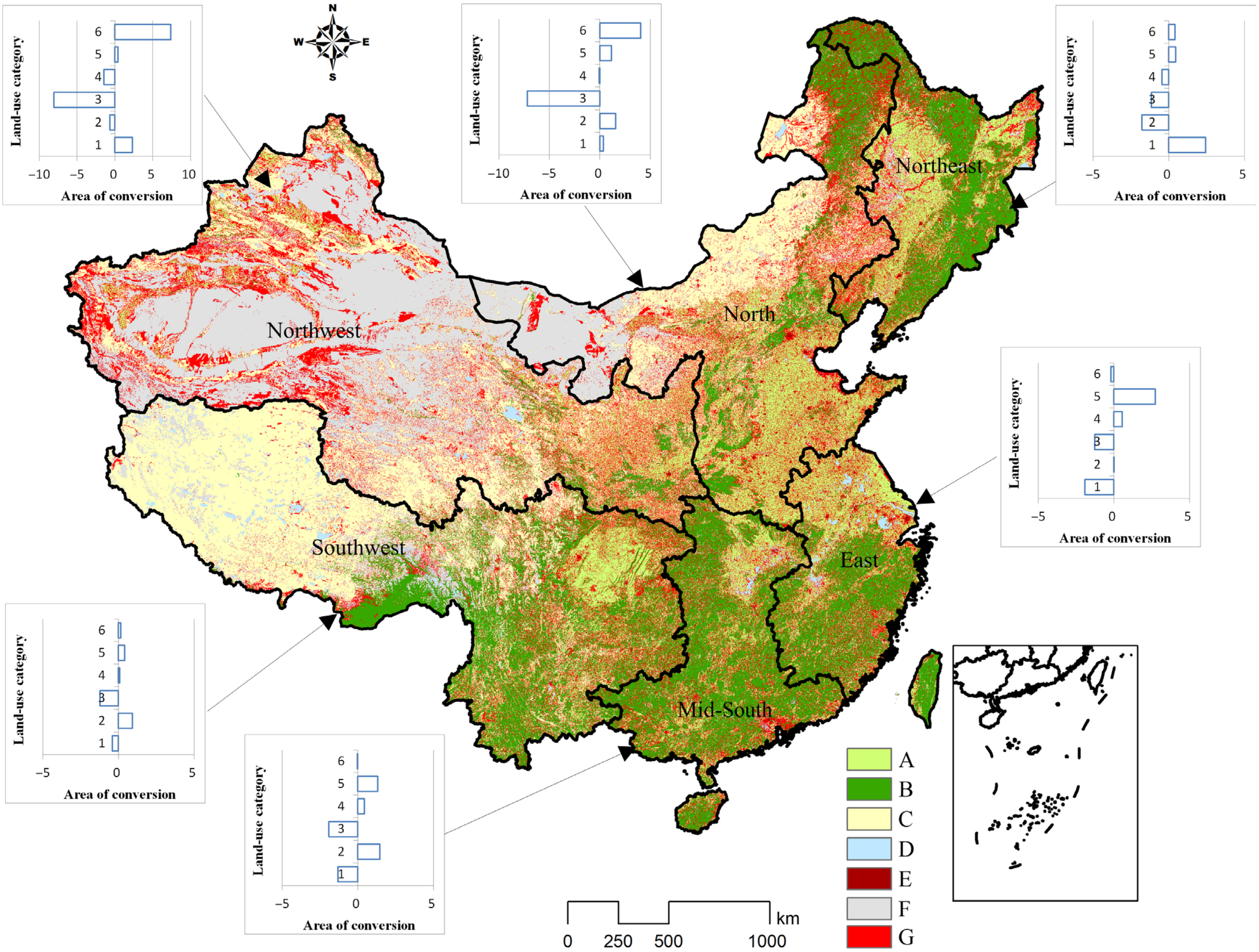

Fig. 1. Land-use category conversion in China from 1990 to 2010 (unit: 10^6 ha). The letters A to F represent the land-use categories remaining in farmland, forestland, grassland, water, built-up land, and other land from 1990 to 2010, respectively; and the letter G represents land converted into a different land-use type. The numbers 1 to 6 in each bar chart represent the net area change in farmland, forestland, grassland, water, built-up land, and other land, respectively.

mainly attributable to the afforestation programs and the consequent restoration of farmland to forest. However, changes in biomass carbon storage did vary regionally. Whereas Mid-South, Southwest, and North China experienced net accumulation of carbon in biomass (with annual growth of approximately 9.06, 5.40, and 3.49 TgC, respectively; Fig. 2), biomass carbon stocks declined in Northwest, Northeast, and East China. The average annual reductions in these regions were 2.90, 1.41, and 0.42 TgC, respectively (table S2).

Conversion between the six land-use categories led to an overall loss of SOC between 1990 and 2010 of about 230.0 Tg, equivalent to an average rate of loss of about 11.50 Tg year^{-1}. In North China, a balance in SOC was almost maintained, whereas Mid-South China was the only region experiencing soil carbon accumulation (at an average rate of about 1.27 TgC year^{-1}). Northeast, Northwest, and Southwest China suffered a loss of SOC of approximately 98.6, 77.1, and 69.7 Tg, respectively, over the two-decade period.

Effects of land-use management on carbon stocks

Changes in carbon storage can occur as a result of land-use management of forests, farmlands, and grasslands. Forest management activities include fire, pest and disease management, timber harvesting, firewood collection, fertilization, and drainage. Failed measures to control wildfires, pests, and diseases can reduce forest biomass and increase carbon loss from these disturbances; timber harvesting and firewood collection directly remove wood and reduce carbon stocks; and fertilization and drainage can increase vegetation growth and enhance carbon storage (*4*).

Here, we estimated the regional carbon emissions of forest harvest using data from the Fifth and Seventh National Forest Inventory (1994–1998 and 2004–2008). The total biomass carbon loss caused by forest fires, insect pests, timber harvesting, and other human activities was approximately 131 TgC year^{-1}. The nationwide organic carbon stocks in the topsoil (up to a depth of 100 cm) within farmland and grassland increased by about 15.3 and 12.4 Tg year^{-1}, respectively, over the period 1990–2010. However, there were marked regional differences in carbon stock changes due to farmland management. Northeast China experienced a loss of SOC of approximately 11.2 Tg year^{-1} that was attributed to poor management of tillage and fertilizer usage (Fig. 3). However, farmland management in East and North China resulted in accumulation of SOC of around 12.4 and 10.7 Tg year^{-1}, respectively. Carbon stock changes due to grassland management consistently

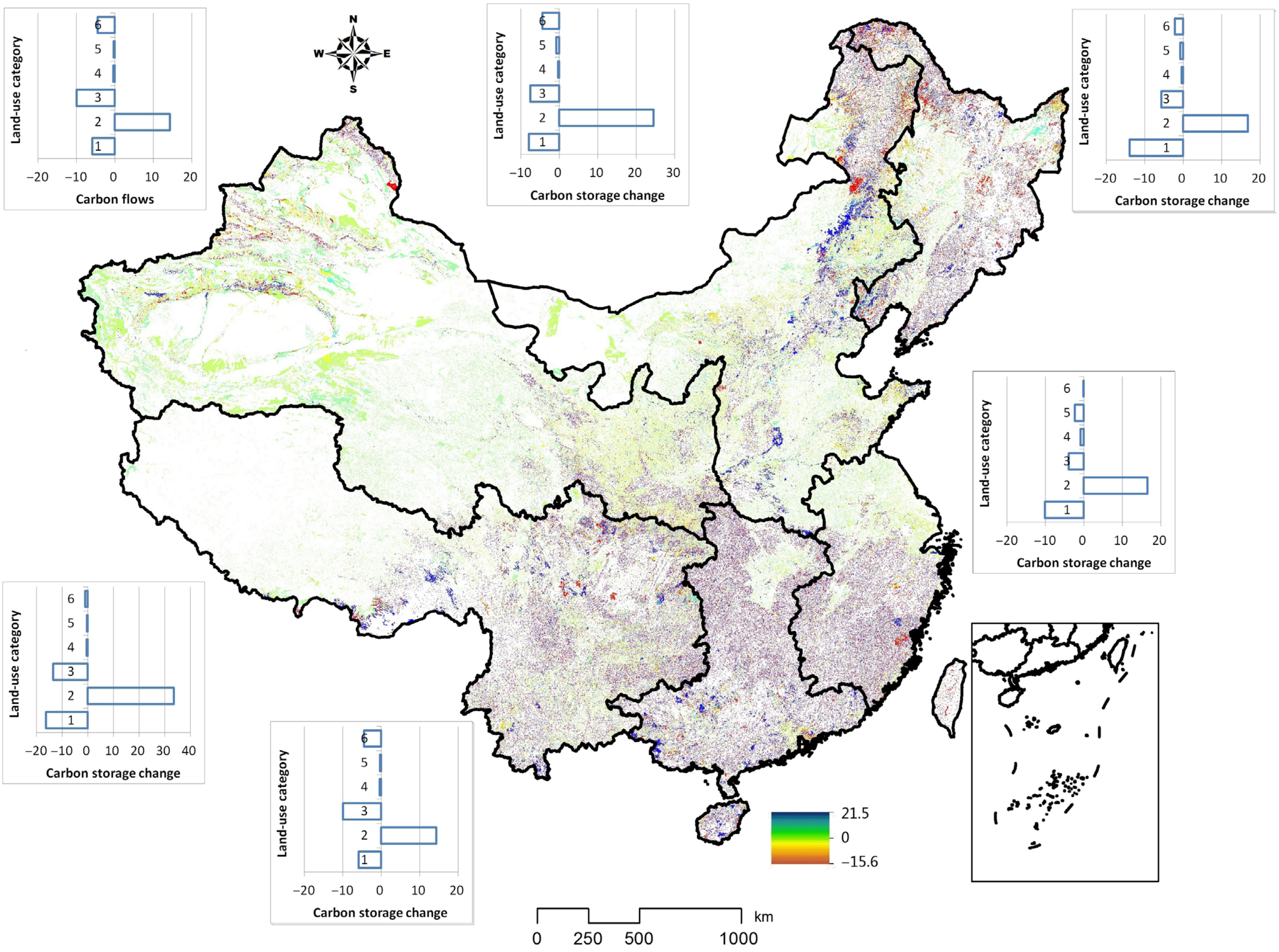

Fig. 2. China's terrestrial system carbon stock change caused by land-use category conversion between 1990 and 2010 (unit: MgC ha^{-1} per year). The numbers 1 to 6 in each bar chart represent different land-cover change paths, namely, cultivation, afforestation, transfer into grassland, water, built-up land, and other land, respectively.

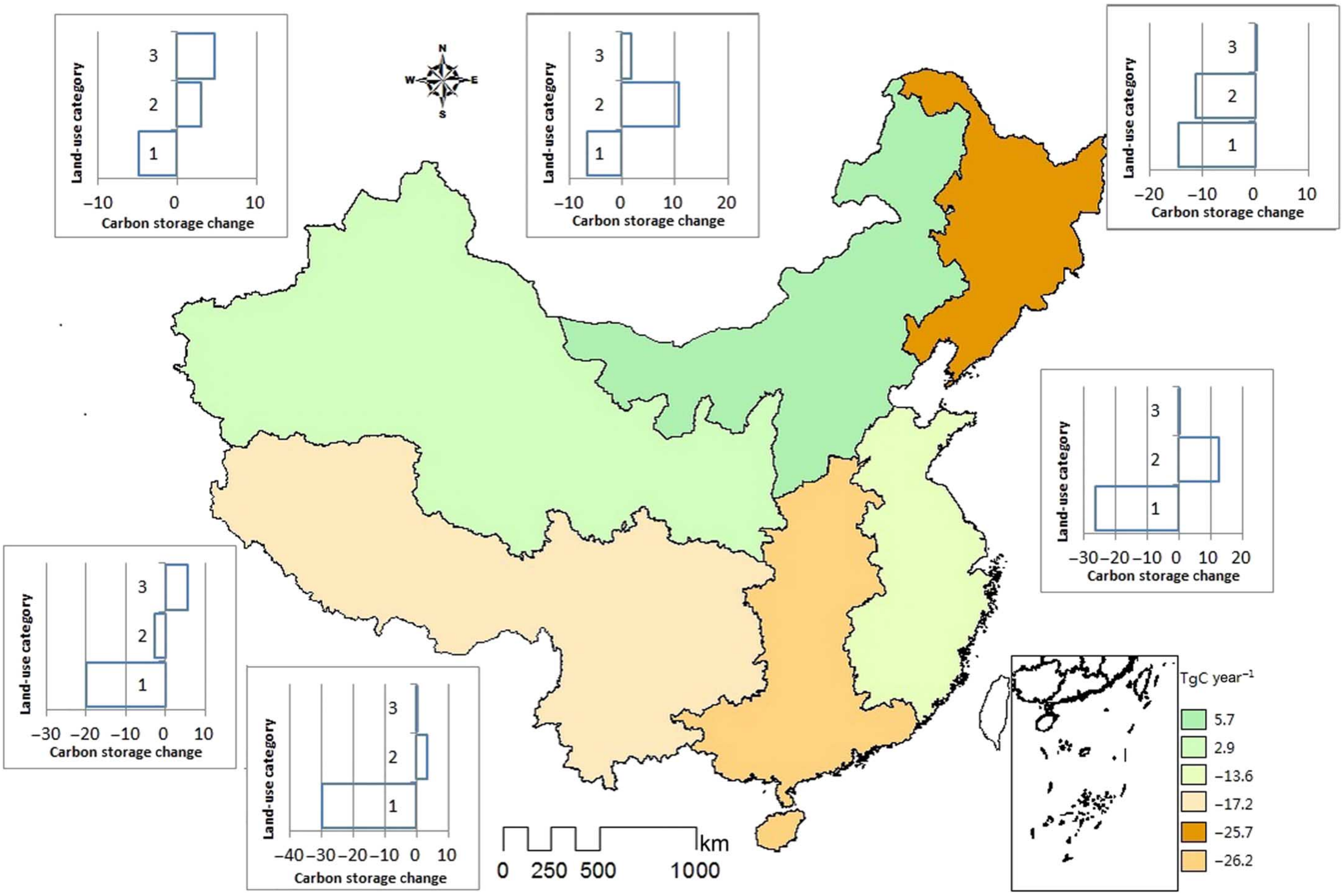

Fig. 3. China's carbon storage change caused by land-use management between 1990 and 2010 (unit: TgC year^{-1}). The numbers 1 to 3 in each bar chart represent forestland, farmland, and grassland management, respectively. Because of data limitations, the carbon storage change in Taiwan is excluded.

increased in each region, although two regions (Southwest and Northwest China) contributed the most (82.6%) to the nationwide accumulation of SOC.

Combined effects of LUCC and land-use management on carbon stocks

The combined effects of land-use category conversion and land-use management were large overall carbon emissions that totaled approximately 1.45 Pg of carbon (PgC) between 1990 and 2010. This equates to annual emissions of 72.4 TgC year^{-1}, accounting for 15% of China's total carbon emissions in 1990 and 4% in 2010. The direction and magnitude of changes in different carbon pools were affected by different LUCC factors (Fig. 4C). The terrestrial carbon pool showed a relatively small total emission due to land-use category conversion of about 1.8 TgC year^{-1}. Different LUCCs made variable contributions to the carbon change: afforestation was estimated to result in an annual uptake of about 144.0 TgC, whereas cultivation, urbanization, and conversion to grassland and other land uses were shown to result in annual carbon emissions of approximately 74.6, 7.1, 44.0, and 16.5 Tg, respectively. Forest management that was insufficient in tackling fires, pests, and diseases, as well as timber harvesting and firewood collection, caused large carbon emissions as a result of the processes described above. These were estimated to be about 101.8 Tg year^{-1} (excluding the repeated calculation for deforestation of about 20 Tg year^{-1}, which was calculated in both LUCC analysis and forest consumption in the Forestry Inventory; table S3). Farmland and grassland management, including fertilization and drainage, and their positive impacts on vegetation growth resulted in carbon sequestration of about 15.3 and 12.4 TgC year^{-1}, respectively.

DISCUSSION

LUCC is of global importance (*35*), with major implications for changes in carbon storage (*36*). In addition to the widely researched land-use types of forest, farmland, and grassland (*26*, *30*, *31*), three major land-use categories (water area, built-up land, and other land uses) were included in the estimation of carbon storage changes in China. On the basis of the combination of data for land use, vegetation carbon densities, and SOC with empirical models, this study has investigated carbon storage changes within China's terrestrial ecosystems caused by both land-use category conversion and land-use management between 1990 and 2010. The study has explored carbon emission effects of land-use change using a temporal-spatial analysis, compared with previous studies that mainly focused on numerical evaluation. The satellite data used in the current analysis cover a wide spatial area and better capture spatial variability in land use and its changes (*37*). By matching carbon density to the actual area, satellite-based estimates can improve the accuracy of flux estimates. Our approach combines models and ancillary data to calculate changes in SOC and vegetation carbon density. Furthermore,

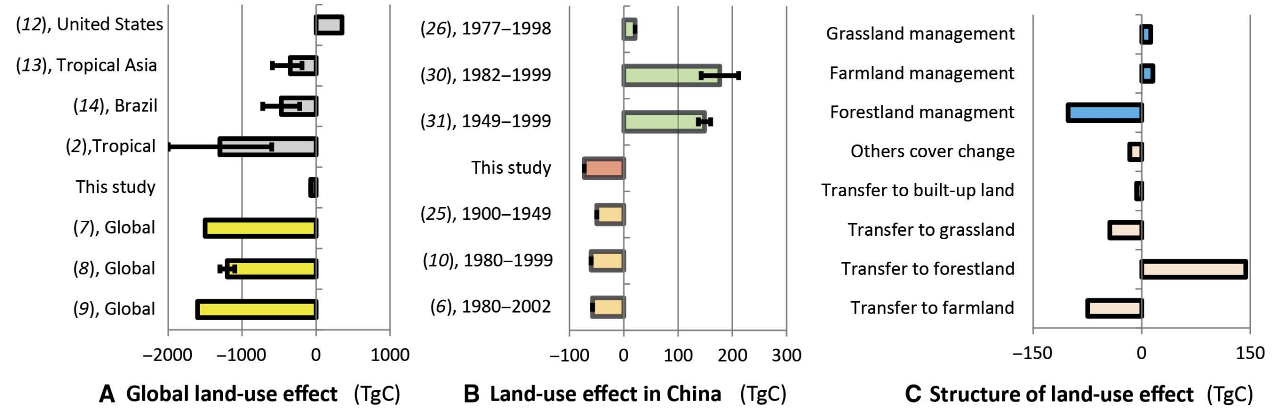

Fig. 4. Comparison of carbon emission from land-use change and management between China and other countries. The overall impact of LUCC in China was a net carbon emission of 72.4 Tg year^{-1} (**A**), similar to the results of other studies [orange bars in (**B**) (*6*, *10*, *25*)]. LUCC-related emissions from China were almost half the carbon sink in China's terrestrial system [green bars in (B) (*26*, *30*, *31*)]. The mean annual global carbon emissions from LUCC were 1.1 to 1.6 PgC year^{-1} [yellow bars in (**C**) (*7*–*9*)]. Accordingly, China accounted for 4.5 to 6.6% of the global carbon emissions from LUCC, smaller than those of Brazil and tropical Asia (*13*, *14*).

the temporal-spatial analysis approach enables the estimation of changes in carbon emissions in different regions and during different periods. This study has presented clear spatial distributions of land-use transfer and carbon stock changes due to both land-use category change and land management. The study focuses on a relatively recent time span, 1990–2010, and the results are very timely. They indicate how rapid urbanization and agricultural development in China over the last few decades have affected terrestrial ecosystems' carbon balance and also the importance of strengthening environmental protection. Compared with previous research, this study collected more and recent vegetation carbon densities data for 50 vegetation types (*38*), improving the accuracy of carbon stock estimates. In addition to the analysis of land-use change, to our knowledge, this study provides the first estimates of the effects of land management on carbon stocks for the whole of China.

Results demonstrate that LUCC has a major impact on carbon pools in both the biosphere and the pedosphere. However, changes in the biomass and soil carbon pools differ. Biomass carbon has been suggested to accumulate at a rate of approximately 13.2 TgC year^{-1} as a result of land-use category conversion, mainly the absolute increase in forest area. Insufficient land-use management (for example, disturbance by fire, pests, and diseases) has resulted in carbon losses of 101.8 TgC year^{-1}. Land-use category conversion, especially the decrease in the area of high-SOC grassland, has resulted in a decline in SOC of about 11.5 TgC year^{-1}. In addition, the reclamation of high-SOC arable land in Northeast China has exacerbated the decline in SOC. Land-use management, mainly fertilization and drainage of arable land, has been responsible for the sequestration of SOC (approximately 27.7 TgC year^{-1}). These findings suggest that, if land-use structure and management can be effectively optimized by land managers and governments, biomass and soil carbon pools could be sinks, which would promote the carbon sequestration capacity of China's terrestrial ecosystems. The optimization of carbon sequestration would benefit from land-use policies that ensure stable areas of different land-use categories, particularly forestland, grassland, and arable land. Furthermore, policies should ensure that the quality of high-carbon land-use categories is maintained and should include monitoring to reduce the conversion from high-carbon to low-carbon land-use categories, such as deforestation and improper land reclamation in the black soil area of Northeast China (*39*). Additional beneficial measures would include improved land-use management to reduce carbon emissions associated with management failures, particularly forest fires, pests, and illegal deforestation.

Our analysis has also revealed distinct differences in the direction and magnitude of carbon storage changes between China's major regions. The largest carbon emission due to land-use change occurred in Northeast China (a loss of approximately 32.1 TgC year^{-1}), consistent with other studies that have demonstrated this region as a net source of CO_2 to the atmosphere as a result of overharvesting and degradation of forests (Fig. 4B) (*26*, *30*, *31*). This is especially obvious for SOC loss with our results supporting those of a previous study that showed that this region's SOC loss from the 30-cm-deep surface soil layer accounted for 44% of China's total SOC losses between 1990 and 2000 (*23*). The Mid-South, Southwest, and East China regions experienced similar carbon pool changes (annual emissions of about 15.9, 15.3, and 14.5 Tg, respectively). These results also agree with a previous study that found that Southern China accounts for more than 65% of the total Chinese carbon sink (*30*). The carbon pools in these three regions may benefit well from several ecological restoration projects (such as the South China Timber Production Program), which have been predominantly implemented in this area and have promoted the accumulation of forest biomass. Although East China has experienced marked land-use change, it also contains a large carbon pool, which is mainly the result of the accumulation of SOC, especially for cropland, due to large distributed paddy land and long-term use of fertilizer in this region. Northwest China, which is characterized by fragile ecological environments, experienced a relatively small carbon loss (about 3.9 TgC year^{-1}), whereas North China was the only region in which a positive carbon accumulation rate was identified (an increase of 9.16 TgC year^{-1}). These spatial variations in carbon stock changes are similar to those of a recent study that focused on land-use type conversion over the relatively short period of 1995–2000 (*40*).

As the largest carbon emitter, China is facing mounting pressure to reduce carbon emissions. Changes in carbon storage due to Chinese LUCC have major implications for the global carbon cycle. In particular, our results suggest enormous carbon sink potential under optimized land use and management. This would require the establishment of effective land-use management measures (including fire, pest, and disease management, and tillage practices) to maximize carbon storage (*41*). In addition, China is undergoing rapid urbanization, with marked expansion of built-up land onto previously arable land or grassland (*42*). In each 5-year plan, the Chinese government usually makes land-use plans that include goals for the future extent of different land uses. It is important to continue adjusting land-use structure, adding the mitigation of carbon emissions from land-use change. Specifically, measures should be taken to protect or increase the area of ecologically valuable land with high capacity for carbon storage (such as forest and grassland) and, where possible, limit the extension of urbanization into these areas. Our previous study researched the optimization of China's land-use structure based on carbon storage maximization at the provincial level (*38*). We found that carbon storage can increase by 438.52 Tg through land-use structure optimization; therefore, it is an effective approach to reducing China's carbon emissions. Results of this study showed that the potential to increase carbon storage by adjusting land-use structure varies between the different regions in China. For example, increasing the carbon stock by adjusting land-use types will be particularly challenging in East China, especially in the heavily populated coastal regions, because of ongoing rapid social and economic development (*38*). Some methods, such as expanding urban green land, could contribute to the reduction of carbon emissions, but these measures are likely to be limited by rapid urbanization and the immense pressure for land.

Between 1990 and 2010, urbanization in China directly led to a 6.87×10^6 ha expansion of built-up area and a loss of approximately 142 TgC from terrestrial ecosystem carbon storage (Figs. 1 and 2). Over the next 20 years, if the Chinese urban population increases by the projected 0.3 billion, an additional 5.57×10^6 ha of urban land will be required (*43*). A preliminary estimate based on results from this study suggests that direct terrestrial carbon storage loss will reach about 115.2 Tg over this 20-year period. In addition, the indirect emission effects of urbanization (such as farmland displacement, population migration, and land degradation) may be much larger (*44*, *45*). These changes are likely to increase the uncertainty of the nation's carbon emissions and potentially undermine China's targets, which were submitted to the Paris Climate Agreement. Land-use changes will not only result in carbon storage loss from lost arable land or grassland but will also likely increase anthropogenic carbon emissions from a growing urban population with rising living standards (*46*). If measures are taken to control urban expansion and improve land management in specified regions, the rate of carbon loss could be slowed. The New Urbanization policy proposed by the Chinese government highlighted the need for harmonious development with minimal disturbance to nature and proper land-use management (*47*). The new Chinese Environmental Protection Law also emphasizes the conservation of forest, grassland, and other natural ecosystems (*48*, *49*). These policies may be instrumental in changing the spatial distribution of land-use change and mitigating carbon emissions. However, the future effects of the New Urbanization policy on carbon emissions will require further study.

Although this study has improved the accuracy of carbon emissions from land-use change and land management, our results need to be read with caution because of some potential limitations. First, Intergovernmental Panel on Climate Change (IPCC)–guided methods and default coefficients were used for our calculations (such as those in tables S4 to S6), which may not be perfectly applicable for China. Second, although the original land-use data set is highly accurate, we used the transferred 1-km-grid land-use map for our analysis. This is unlikely to lead to errors for changes in large, continuously distributed land-use types, such as forest and grassland. However, errors may be larger for relatively small-area land-use categories, including built-up land and some water bodies, such as lakes. Third, vegetation carbon density values were obtained from different studies that used variable methods. We compiled the results and adopted the mean values for the same vegetation type. More field investigations are needed to further improve the accuracy of these carbon density values. Fourth, because of data limitations, vegetation carbon densities in table S7 and SOC in table S8 were hypothesized as constant values without temporal changes during the study period. Changes in SOC take longer than changes in vegetation (*38*); thus, the changes in SOC caused by LUCC in our study might be better referred to as potential changes. More studies on temporal changes in SOC and vegetation carbon densities would improve the accuracy of calculations. Fifth, although carbon emissions from Chinese lakes and rivers have been studied (*50*–*52*), as reported in our previous study, accurate estimates of carbon stock changes due to changes between water and other land uses remain unavailable (*38*). In the current study, the analysis of carbon emissions from areas covered in water is relatively preliminary. We calculated carbon emissions during the conversion into and out of the water land-cover class, but the biomass inside water was assumed to be 0. More research is needed to improve the measurements for multiple ecosystems and at large scales such as the provincial and national levels.

In summary, land-use category change and management have resulted in very large carbon emissions in China over recent decades. In particular, large carbon emissions have been associated with the management of forest, grassland, and farmland. It is crucial that policy-makers take effective measures to adjust land-use structure and improve land-use management for better mitigation of carbon emissions in the coming decades.

MATERIALS AND METHODS

Land-use category and area

This study used a land-use data set acquired from the National Resources and Environment Database [National Land-Use/Cover Database of China (NLUD-C)] of the Chinese Academy of Sciences. This data set was based primarily on Landsat TM imagery between 1990, 1995, 2000, 2005, and 2010 (*37*). Landsat TM provided approximately 90% of all images used in the NLUD-C. China-Brazil Earth Resources Satellite and Huanjing images were used to fill gaps when Landsat TM imagery was not available. The NLUD-C was built up by visual interpretation of images, and we put more emphasis on band composition and geometric correction. Relief maps (1:100,000) at a spatial resolution of 30 m were used to geometrically rectify TM images. Geometric correction of the image set was manually performed using ground control points, and errors were less than 2 pixels. To assess the accuracy of the interpretation of land use/cover, we performed nationwide field verification. Approximately 10% of the counties in China were randomly extracted, and all polygons in each county were validated to calculate the accuracy. The classification accuracies of selected polygons were more than 90%.

Because of the complexity of LUCC, there was no uniform classification system. One widely used classification system with 17 land-use types was designed by the International Geosphere-Biosphere Programme (IGBP), and another was the Land Cover Classification System (LCCS) proposed by the Food and Agriculture Organization of the United Nations. In the current study, a hierarchical classification system of 25 land-use/cover classes was applied in the NLUD-C. This classification system integrates land-use and land-cover information and is suitable for visual interpretation (*37*). Compared with the IGBP and LCCS classification systems, the NLUD-C has less land-cover types for forest and more classes for arable land and water to reflect the Chinese context. The original 25 land-use types were grouped into six major categories: farmland, forestland, grassland, water, urban land, and other land (table S1).

Calculation of carbon stock change from vegetation and soil

A nationwide vegetation map was created using the 1:1 million Chinese vegetation map (*53*), which used 50 different classifications. A literature review provided the carbon density for each of these different vegetation types (table S7). Using these estimates of carbon density, we established changes in biomass carbon storage by comparing storage—before (1990) and after (2010)—in the same patch location (see the detailed equation in the Supplementary Materials).

A soil carbon map was derived from the 1:1 million Chinese soil-type map (*54*), and SOC estimates were obtained from China's Second National Soil Survey conducted between 1979 and 1985 (*22*, *55*, *56*). SOC estimates were based on the classification of 59 soil groups (table S8). Soil carbon storage change was assessed using a similar approach to biomass carbon through the combination of land-use patch change for the period 1990–2010 and estimates of soil carbon storage for different soil types (see the detailed equation in the Supplementary Materials).

Calculation of carbon stock change from land-use management

Carbon emissions associated with forest management were quantified for the period 1994–2008 using data from the Fifth and Seventh National Forest Inventory (covering the periods 1994–1998 and 2004–2008, respectively). These carbon emissions were calculated from forest harvesting, fuel wood collection, fires, and pests (*57*). An adjustment was made to reduce the double counting of emissions due to deforestation. We calculated carbon emissions from forest management based on consumption biomass volume, consumption rate, stem volume density, and a biomass expansion factor (see the detailed equation in the Supplementary Materials).

Carbon stock changes due to farmland and grassland management were assessed using the empirical model recommended by the IPCC (*58*), with the reference data for SOC taken from the Second National Soil Survey (see the detailed equation in the Supplementary Materials).

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/2/11/e1601063/DC1
Supplementary Materials and Methods
table S1. Land-use categories.
table S2. Biomass and SOC change due to land-use category change in China between 1990 and 2010.
table S3. Repeated calculation for part of forest consumption.
table S4. SOC impact factors for change in land-use conversion.
table S5. SOC impact factors for Chinese farmland management.
table S6. SOC impact factors for Chinese grassland management.
table S7. Biomass carbon density of Chinese vegetation types.
table S8. SOC density of Chinese soil types.
table S9. Parameters for Chinese forest consumption.
References (*59*–*67*)

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