SPECIAL FEATURE

# Effects of national ecological restoration projects on carbon sequestration in China from 2001 to 2010

**Fei Lu[a], Huifeng Hu[b], Wenjuan Sun[b], Jiaojun Zhu[c,d], Guobin Liu[e], Wangming Zhou[d], Quanfa Zhang[f], Peili Shi[g], Xiuping Liu[h], Xing Wu[a], Lu Zhang[a], Xiaohua Wei[i], Limin Dai[d], Kerong Zhang[f], Yirong Sun[c,d], Sha Xue[e], Wanjun Zhang[h], Dingpeng Xiong[g], Lei Deng[e], Bojie Liu[a], Li Zhou[d], Chao Zhang[e], Xiao Zheng[c,d], Jiansheng Cao[h], Yao Huang[b], Nianpeng He[g], Guoyi Zhou[j], Yongfei Bai[b], Zongqiang Xie[b], Zhiyao Tang[k], Bingfang Wu[l], Jingyun Fang[b,k], Guohua Liu[a,m,n,1], and Guirui Yu[g,m,1]**

[a]State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, 100085 China; [b]State Key Laboratory of Vegetation and Environmental Change, Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China; [c]Qingyuan Forest Chinese Ecosystem Research Network, Chinese Academy of Sciences, Shenyang 110016, China; [d]Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, China; [e]State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, Yangling 712100, China; [f]Key Laboratory of Aquatic Botany and Watershed Ecology, Wuhan Botanical Garden, Chinese Academy of Sciences, Wuhan 430074, China; [g]Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China; [h]Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, Chinese Academy of Sciences, Shijiazhuang 050021, China; [i]University of British Columbia, Okanagan Campus, Kelowna, BC, Canada V1V 1V7; [j]South China Botanical Garden, Chinese Academy of Sciences, Guangzhou 510650, China; [k]Department of Ecology, College of Urban and Environmental Sciences, Peking University, Beijing 100871, China; [l]Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing 100094, China; [m]College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China; and [n]Joint Center for Global Change Studies, Beijing 100875, China

Edited by F. Stuart Chapin III, University of Alaska Fairbanks, Fairbanks, AK, and approved December 1, 2017 (received for review February 14, 2017)

**The long-term stressful utilization of forests and grasslands has led to ecosystem degradation and C loss. Since the late 1970s China has launched six key national ecological restoration projects to protect its environment and restore degraded ecosystems. Here, we conducted a large-scale field investigation and a literature survey of biomass and soil C in China's forest, shrubland, and grassland ecosystems across the regions where the six projects were implemented (~16% of the country's land area). We investigated the changes in the C stocks of these ecosystems to evaluate the contributions of the projects to the country's C sink between 2001 and 2010. Over this decade, we estimated that the total annual C sink in the project region was 132 Tg C per y (1 Tg = $10^{12}$ g), over half of which (74 Tg C per y, 56%) was attributed to the implementation of the projects. Our results demonstrate that these restoration projects have substantially contributed to $CO_2$ mitigation in China.**

carbon sequestration | carbon sink | ecological restoration | national ecological project | China

Terrestrial ecosystems play a critical role in the global C cycle and climate change mitigation. The annual net C uptake by global terrestrial ecosystems ranges from 2.0 to 3.4 Pg C (1 Pg = $10^{15}$ g) (1). Previous studies have suggested that the increased C stock in Asian terrestrial ecosystems can primarily be attributed to considerable afforestation and reforestation (2, 3), especially that implemented under China's national ecological restoration projects (4). For instance, due to the implementation of large-scale afforestation and reforestation practices beginning since the late 1970s, China's forest biomass C stock has increased by 40% between the 1970s and the 2000s (3). According to the recent predictions (5, 6), the forest biomass C stock could further increase to 9.97–13.09 Pg C by 2050, with a net C sequestration rate of 84–154 Tg C/y (1 Tg = $10^{12}$ g). However, due to rapid population growth and high demands for food and energy, the long-term stressful utilization of forests and grasslands has led to large-scale ecosystem degradation in China (7), resulting in considerable loss of biomass and soil C stocks (8, 9). The restoration of these degraded ecosystems is expected to improve C accumulation.

Since the late 1970s China has launched six national key restoration projects across the country to protect its environment and restore the degraded ecosystems (Fig. 1 and *SI Appendix, A*). The first project was the Three-North Shelter Forest Program (abbreviated as "North Shelter Forest"), which was initiated in the late 1970s. The project is known as the "Green Great Wall" because its massive area spans half of northern China. The fourth term of this project started in 2001 and ended in 2010. The next project was the Yangtze River and Zhujiang River Shelter Forest Projects (abbreviated as "River Shelter Forest"), launched in 1989 across the southern parts of China with the aim of battling floods and reducing soil erosion. The second term of this project also began in 2001 and ended in 2010. The Natural Forest Protection Project (abbreviated as "Forest Protection") was subsequently initiated in 1998 and has shown numerous benefits, including biodiversity conservation, reduction of soil erosion and flood risk, and prevention of other natural disasters associated with deforestation. The Grain for Green Program (abbreviated as "GGP," also known as China's Sloping Lands Conversion Project) was initiated in 2000 and has advanced the

## Significance

China has launched six key ecological restoration projects since the late 1970s, but the contribution of these projects to terrestrial C sequestration remains unknown. In this study we examined the ecosystem C sink in the project area (~16% of the country's land area) and evaluated the project-induced C sequestration. The total annual C sink in the project area between 2001 and 2010 was estimated to be 132 Tg C per y, over half of which (74 Tg C per y, 56%) was caused by the implementation of the six projects. This finding indicates that the implementation of the ecological restoration projects in China has significantly increased ecosystem C sequestration across the country.

Author contributions: F.L., H.H., W. Zhou, P.S., X. Wu, X. Wei, K.Z., S.X., W. Zhang, L. Deng, Y.H., and Guohua Liu designed research; F.L., H.H., J.Z., Guobin Liu, W. Zhou, Q.Z., P.S., X.L., L. Zhang, L. Dai, K.Z., Y.S., S.X., W. Zhang, D.X., L. Deng, B.L., L. Zhou, C.Z., X.Z., J.C., Z.X., Z.T., B.W., and G.Y. performed research; F.L. and D.X. contributed new reagents/analytic tools; F.L., W.S., J.Z., Guobin Liu, W. Zhou, Q.Z., X.L., L. Zhang, L. Dai, K.Z., Y.S., D.X., L. Deng, L. Zhou, C.Z., X.Z., J.C., N.H., G.Z., Y.B., and Guohua Liu analyzed data; and F.L., H.H., W.S., X. Wu, X. Wei, Y.H., N.H., G.Z., Y.B., J.F., Guohua Liu, and G.Y. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

[1]To whom correspondence may be addressed. Email: ghliu@rcees.ac.cn or yugr@igsnrr.ac.cn.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1700294115/-/DCSupplemental.

ECOLOGY

SUSTAINABILITY SCIENCE

www.pnas.org/cgi/doi/10.1073/pnas.1700294115

conversion of croplands in hilly areas to forests. GGP is regarded as the world's largest ecological restoration program in terms of scale and investment and is a typical example of ecological compensation (10). The Beijing–Tianjin Sand Source Control Project (abbreviated as "Sand Control") was initiated in 2001 to promote environmental conservation near the capital of China (Beijing) by controlling the risk of wind–sand and soil erosion disasters. The last project, known as the Returning Grazing Land to Grassland Project (abbreviated as "Grassland Conservation"), was launched in 2003 to reduce the impacts of overgrazing and promote grassland productivity. These projects together cover 44.8% of China's forests (refs. 11 and 12 and Table 1) and 23.2% of China's grasslands (ref. 13 and Table 1).

Recent studies have indicated that the implementation of the national ecological restoration projects has improved ecosystem services, such as soil erosion control (14), water retention (4), flood mitigation (4), and biodiversity conservation (15). Additionally, a series of management practices employed under the framework of these ecological restoration projects, including afforestation, reforestation (Shelter Forests, Forest Protection, and Sand Control), forest enclosure and tending (Forest Protection and Sand Control), transforming cropland to forest (GGP), reducing the timber harvest (Forest Protection), and fencing in grasslands (Grassland Conservation), can increase the forest area, prevent C loss from vegetation and soil, and subsequently enhance C stocks and C sinks (16, 17). However, the vital total C sequestration benefit arising from the six key restoration projects has not yet been systematically evaluated, although the C sequestration achieved in some individual projects has been investigated (4, 18).

In this study we investigated C stocks and their changes across the areas where the six projects have been implemented (referred to as the "project region" hereafter) based on a nationwide field investigation of the C stocks of China's terrestrial ecosystems, along with a detailed literature survey. First, we quantified the net ecosystem C accumulation for each project region by comparing the change in C stocks between the initial year of the project (or certain phase) and 2010. Second, we estimated each project-induced C contribution to total ecosystem C sequestration mainly by comparing the change in ecosystem C stocks between the project region and the reference area (i.e., the area where the project was not implemented).

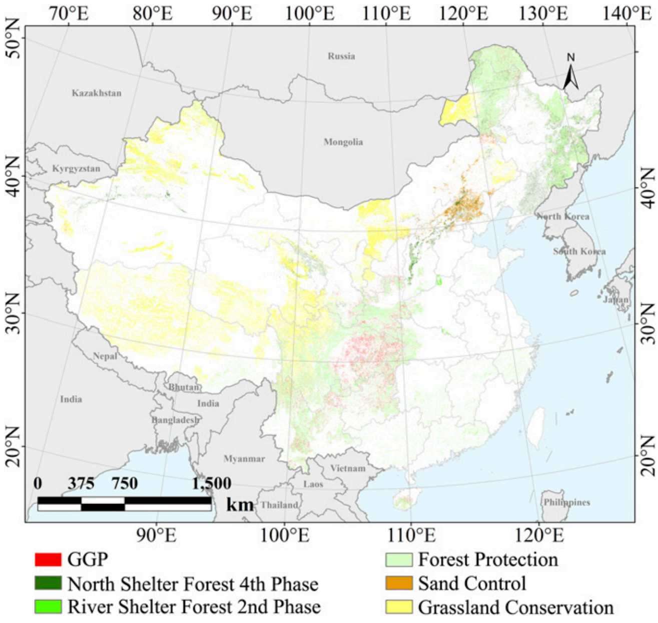

**Fig. 1.** Location of six key ecological restoration projects in China. The figure shows the location of the Three-North Shelter Forest Program fourth phase (North Shelter Forest fourth), Yangtze River Shelter Forest Project and Zhujiang River Shelter Forest Project second phase (River Shelter Forest second), Natural Forest Protection Project (Forest Protection), GGP, Beijing and Tianjin Sand Source Control Project (Sand Control), and Returning Grazing Land to Grassland Project (Grassland Conservation).

## Results and Discussion

**Ecosystem C Sinks in the Project Regions.** In the first decade of the 21st century (13 y for Forest Protection, 11 y for GGP, 8 y for Grassland Conservation, and 10 y for all other projects), the ecosystem C density greatly increased in all project regions (Table 1). During this decade, the grassland biomass C density increased by 1.1 Mg C per ha in the Grassland Conservation region, and the forest biomass C density increased by 6.6–22.0 Mg C per ha in the other five project regions (Table 1). The soil C density increased by 9.7 Mg C per ha in the GGP region, followed by 5.6 Mg C per ha in the Forest Protection region, and by 1.0–3.2 Mg C per ha in the other four project regions (Table 1). Altogether, the ecosystem C density increased by 2.1–29.4 Mg C per ha across the different project regions, with the largest increment occurring in the GGP region and the smallest in the Grassland Conservation region (Table 1).

In total, the decadal C sink in the six project regions was estimated as 1,519 Tg C, of which 919.3 Tg C (60.5%) was stored in vegetation biomass and 599.5 Tg C (39.5%) in soils (Table 2). Among the six projects, 889.1 Tg C (or 58.5%) of the total C sink was due to Forest Protection, followed by GGP (270.8 Tg C, or 17.8%), and North Shelter Forest fourth phase (124.3 Tg C, or 8.2%) (Table 2). During the study period, the total annual ecosystem C sequestration rate was estimated to be 132 Tg C/y within the project area, with a relatively higher C sequestration capacity observed in the regions of Forest Protection (68.4 Tg C/y), GGP (24.6 Tg C/y) and Grassland Conservation (15.5 Tg C per y), partly because of the large areas of these projects (Tables 1 and 2). The Forest Protection, GGP, North Shelter Forest fourth phase, River Forest second phase and the Sand Control regions, which cover 44.8% of China's forest area, experienced a biomass C stock increase of 855.5 Tg C with an annual mean biomass C sink of 72.8 Tg (Table 2), which accounted for 63.4–71.2% of the national forest biomass C sink during this period (1, 19). Additionally, these five projects have also enhanced soil C storage (Table 2). Increasing soil C stock in the Forest Protection region from 1998 to 2010 suggested the important role of China's old-growth forests in the soil C accumulation (20).

However, there was considerable spatial variability in ecosystem C sinks across the project regions. As key regions for the implementation of China's ecological restoration projects, occupying 25%, 12%, 31%, and 27% of the projects' total area, north (307.2 Tg C, or 20.2% of the national total), northeast (328.1 Tg C, or 21.6%), northwest (323.2 Tg C, or 21.3%) and southwest China (463.9 Tg C, or 30.5%), respectively, together represented 93.7% of the total ecosystem C sink (Fig. 2 and *SI Appendix, B*). South (65.0 Tg C, or 4.3%) and east China (31.4 Tg C, or 2.1%) together represented the other 6.3% of the total ecosystem C sink, differing from the findings of previous studies (6, 21). These differences may be attributed to the relatively small project area, long history of intensive agricultural development and high economic cost associated with these projects. First, although three of the six restoration projects (i.e., Forest Protection, GGP and River Shelter Forest second phase) were implemented in these two regions (Fig. 2 and *SI Appendix, B*), the project areas only accounted for 5% of the total project area and only covered 10% of the forests in these regions (12, 13). Second, despite only occupying 18.4% of the total national land area, these two regions currently feed 57.6% of China's population and provide 62% of the national GDP (22).

**Table 1. Areas and ecosystem C densities (area weighted mean ± SD) at the beginning (PR-B) and in the year 2010 (PR-2010) and the reference sites (RS-2010) for six key ecological restoration projects in China**

| | National key ecological projects | | | | | |
|---|---|---|---|---|---|---|
| Properties, C densities and sequestrations of the projects | Forest Protection | Grassland Conservation | North Shelter Forest fourth | Sand Control | GGP | River Shelter Forest second |
| Area, $10^6$ ha | 72.9 | 60 | 5.2 | 3.3 | 9.2 | 2.3 |
| Duration | 1998–2010 | 2003–2010 | 2001–2010 | 2001–2010 | 2000–2010 | 2001–2010 |
| C densities, Mg C per ha | | | | | | |
| Biomass | | | | | | |
| PR-B | 43.7 ± 19.3 | 2.6 ± 1.1 | 37.3 ± 16.9 | 3.1 ± 2.9 | 0[*] | 5.9 ± 3.5 |
| PR-2010 | 50.3 ± 17.4 | 3.7 ± 1.62 | 56.6 ± 15.6 | 16.2 ± 4.5 | 19.7 ± 5.9 | 27.9 ± 8.8 |
| Increment | 6.6 | 1.1 | 19.3 | 13.1 | 19.7 | 22.0 |
| RS-2010 | —[†] | 2.6 ± 1.8 | 41.6 ± 18.3 | 3.5 ± 2.2 | 0[*] | 7.7 ± 2.8 |
| Soil | | | | | | |
| PR-B | 144.8 ± 42.7 | 82.5 ± 50.2 | 44.8 ± 16.3 | 35.9 ± 7.3 | 44.0 ± 29.3 | 63.5 ± 12.2 |
| PR-2010 | 150.5 ± 25.8 | 83.5 ± 50.5 | 49.3 ± 20.1 | 38.7 ± 10.4 | 53.7 ± 26.3 | 66.7 ± 18.9 |
| Increment | 5.6 | 1.0 | 3.2 | 2.9 | 9.7 | 3.2 |
| RS-2010 | —[†] | 82.6 ± 50.0 | 41.4 ± 20.7 | 30.3 ± 8.9 | —[‡] | 51.3 ± 41.8 |
| Total | | | | | | |
| PR-B | 188.5 ± 53.9 | 85.1 ± 51.3 | 82.1 ± 28.3 | 39.0 ± 10.3 | 44.0 ± 29.3 | 69.4 ± 13.0 |
| PR-2010 | 200.7 ± 49.0 | 87.2 ± 52.2 | 105.9 ± 31.6 | 54.8 ± 14.2 | 73.4 ± 28.0 | 94.6 ± 19.0 |
| Increment | 12.2 | 2.1 | 23.8 | 15.8 | 29.4 | 25.3 |
| RS-2010 | —[†] | 85.2 ± 51.1 | 83.0 ± 33.0 | 33.8 ± 9.9 | —[‡] | 59.0 ± 42.9 |
| Total C sequestration rate, Mg C per ha per y | 0.94 | 0.26 | 2.38 | 1.58 | 2.67 | 2.53 |

[*] The GGP is implemented in hilly cropland; therefore, the biomass C density in the project area in 2000 (beginning of GGP) and at reference sites in 2010 were set as 0.

[†] The contribution of the Forest Protection project to C sequestration was estimated based on the C storage in the newly planted forest vegetation (CPVN), the C retention (CR) resulting from harvest volume reduction, and soil organic C retention (SCR); see Eqs. **10–14**. No reference sites were set for estimation.

[‡] The contribution of GGP to C sequestration in soil is considered to be the soil organic C retention (SCR), that is, the reduced C loss due to the control of soil erosion attributed to GGP, which was estimated using the results of Deng et al. (38), as in Eqs. **15** and **16**.

Therefore, the higher population density in these regions increases the land demand for agriculture and housing construction and results in higher economic costs for the local implementation of large-scale ecological restoration projects (23).

On average, the overall area-weighted annual C sink for all six projects was 0.86 Mg C per ha per y, with a rate above 1.5 Mg C per ha per y for the River Shelter second phase, GGP, North Shelter Forest fourth phase, and Sand Control, 0.94 Mg C per ha per y for the Forest Protection, and 0.26 Mg C per ha per y for the Grassland Conservation (Table 1). For grasslands, the C sequestration rate in the project area was much higher than the national average (~0.04 Mg C per ha per y, ref. 20), partly due to the influence of human management on grassland C cycling (24). For example, medium- and long-term experimental studies have suggested that fencing management can increase the C sink of grasslands by 0.16~0.47 Mg C per ha per y (25).

**Project-Induced Contribution to C Sequestration.** All six restoration projects have made positive contributions to the C sequestration at the decadal scale (Table 2). During the study period, the project-induced contribution to C sequestration was 770.4 Tg C, with an annual sink of 74 Tg C, representing over half of the total ecosystem C sink for all six project regions and demonstrating the significant success of the restoration projects regarding C sequestration. Among the six projects, GGP made the largest contribution in terms of project-induced C sequestration, with 198.5 Tg C, accounting for 25.8% of the total project-induced C

**Table 2. Decadal and annual ecosystem and project-induced C sinks (mean ± SD) in the project regions**

| | Decadal ecosystem C sinks | | | | Project-induced C sink | |
|---|---|---|---|---|---|---|
| National ecological restoration projects | Biomass, Tg C | Soil, Tg C | Total, Tg C | Annual ecosystem C sink, Tg C per y | Decadal, Tg C | Annual, Tg C per y |
| Forest Protection | 479.6 ± 230.0 | 409.5 ± 386.1 | 889.1 ± 449.4 | 68.4 ± 34.6 | 181.7[*] | 14.0 |
| Grassland Conservation | 63.8 ± 2.4 | 59.9 ± 45.9 | 123.7 ± 46.0 | 15.5 ± 5.8 | 117.8 ± 47.8 | 14.7 ± 6.0 |
| North Shelter Forest fourth | 100.4 ± 18.2 | 23.82 ± 42.0 | 124.3 ± 45.8 | 12.4 ± 4.6 | 119.7 ± 49.0 | 12.0 ± 4.9 |
| Sand Control | 43.1 ± 21.0 | 9.2 ± 20.0 | 52.3 ± 29.0 | 5.2 ± 2.9 | 69.7 ± 24.4 | 7.0 ± 2.4 |
| GGP | 181.0 ± 26.1 | 89.7 ± 79.4 | 270.8 ± 83.6 | 24.6 ± 7.6 | 198.5[*] | 18.0 |
| River Shelter Forest second | 51.4 ± 10.2 | 7.4 ± 13.3 | 58.8 ± 16.7 | 5.9 ± 1.7 | 83.0 ± 38.2 | 8.3 ± 3.8 |
| Total | 919.3 ± 233.4 | 599.5 ± 399.8 | 1,519 ± 462.9 | 132.0 ± 36.3 | 770.4 ± 82.1 | 74.0 ± 8.9 |

The SD was estimated based on the variation in C accumulation and sequestration of six geological regions (as shown in Fig. 2), and the ranges of national-scale C accumulation and C sequestration for each project were acquired based on the standard variation of the biomass, soil, and total sinks and contributions to C sequestration of six geological regions (as individual independent variables), as in the flowing formula: $SD_{National} = (\Sigma SD_{Regional}^2)^{0\ 0.5}$.

[*] The estimations of project-induced C sinks for the Forest Protection (including 138.5 Tg C from the new plantings, 31.7 Tg C from biomass C retention resulted from timber reduction strategies, and 11.4 Tg C from soil C retention from soil erosion control, respectively) and GGP were partly based on statistical data and parameters from previous studies (see *Methods and Materials* and *SI Appendix, D*) and no SDs were reported here.

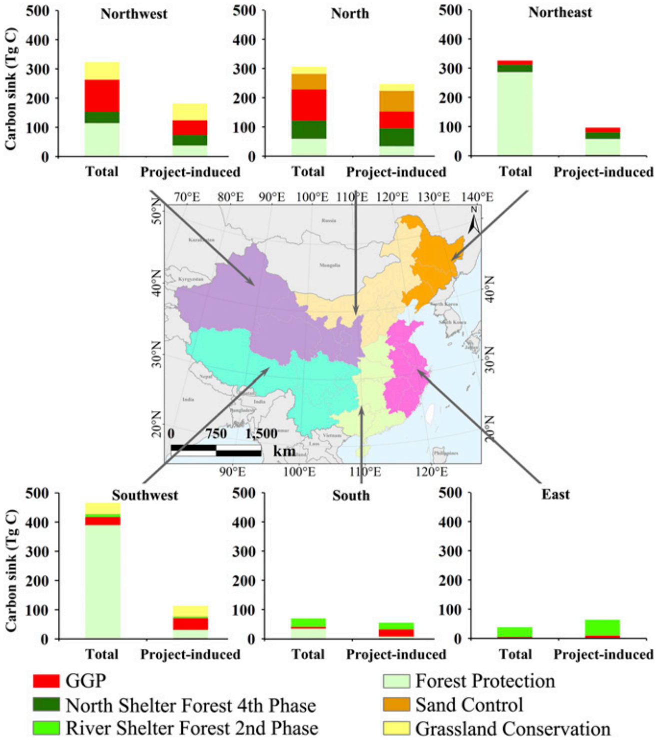

**Fig. 2.** Decadal ecosystem and project-induced C sinks in six geographical regions of China (north China, northeast China, northwest China, east China, south China, and southwest China). Detailed information is also provided in *SI Appendix, B*.

sink, followed by Forest Protection (181.7 Tg C, or 23.6%), North Shelter Forest fourth phase (119.7 Tg C, or 15.5%), and Grassland Conservation (117.8 Tg C, or 15.3%) (Table 2). These substantial project-induced C contributions were primarily attributed to the large areas of these projects (Table 1) and the considerable reduction in soil erosion resulting from afforestation (26). Other optimal management strategies, such as afforestation, timber harvest reduction, and soil erosion control under the framework of the projects, could also contribute to this C sequestration, as pointed out in previous studies (18). For example, concerning the total C sink induced by the Forest Protection, 138.5, 31.7, and 11.4 Tg C was due to new plantings, biomass C retention resulting from timber reduction policy, and soil C retention from soil erosion control, respectively (Table 2). In addition, although the projects of the Sand Control and River Shelter Forest second phase accounted for only 2.2% and 1.5% of the total project area, they contributed 69.7 (9.1%) and 83.0 Tg (10.8%) of the total project-induced C sequestration, respectively (Table 2).

The project-induced C sequestration also showed a great deal of spatial heterogeneity. More than 84% of the project-induced C sequestration occurred in north (248.4 Tg C, or 32.2%), northeast (97.7 Tg C, or 12.7%), northwest (185.2 Tg C, or 24.0%), and southwest China (118.3 Tg C, or 15.4%) (Fig. 2 and *SI Appendix, B*). Because of the relatively small project areas, the project-induced C contributions of south (56.0 Tg C, or 7.3%) and east China (64.9 Tg C, or 8.4%) were relatively small. Similarly, the proportion of the project-induced C contribution to the overall decadal ecosystem C sink differed significantly among the six project regions. In east China, the project-induced C sequestration was over two times the overall ecosystem C sequestration within the project area (Fig. 2 and *SI Appendix, B*), indicating that this region would act as a C source if without the implementation of key restoration projects. In addition, the project-induced C sequestration in north and south China accounted for nearly 80% of the overall decadal ecosystem C sink across these two regions (Fig. 2 and *SI Appendix, B*). In contrast, the project-induced C sequestration in northeast, northwest, and southwest China contributed less than 40% of the overall ecosystem C sink; these areas are relatively less affected by human disturbance and exhibit higher rates of the C sequestration.

Our findings show that the implementation of national restoration projects is the foremost factor leading to an increase of C stocks in the project regions, especially in east, north, and south China. The continued support of these projects is crucial for achieving national mitigation targets.

However, attention should be paid to the cost and possible leakage of project-induced C sequestration. To achieve the expected ecological and social benefits there will be technical, economic, and political costs. For example, the average cost of sequestering 1 ton of $CO_2$ is \$21.2 (*SI Appendix, C*), which is lower than the cost of most officially recommended industrial energy saving and emission reduction approaches in China. However, the most recent research has suggested that GHG leakage, or so-called carbon costs, may only offset up to 20% of the C sequestration (27), which is a relatively low percentage compared with mitigation measures reported in the agricultural sector (28).

**Implications.** In the Paris Agreement in 2015 China promised that by 2030 it would cap $CO_2$ emissions and increase forest volume by ∼4.5 billion $m^3$ relative to 2005 levels. Therefore, China is positioned to make significant contributions to REDD-plus (reducing emissions from deforestation and forest degradation in developing countries) through its ecological restoration projects (29, 30) and sustainable forest managements (31). The annual ecosystem C sink for all six project regions was 132 Tg C per y, which is equivalent to 50–70% of the national total annual sink from all major terrestrial ecosystems in China and could offset 9.4% of China's annual C emissions from fuel combustion during the 2000s, according to the International Energy Agency Statistics for China from 2001 to 2010 (32). Notably, most of the forests in the project regions are young and show significant potential to contribute future C sequestration (5, 33), except for the Natural Forest project, which protects a major portion of China's natural mature forests. For example, in the regions of the other four forest projects (North Shelter Forest fourth phase, River Shelter Forest second phase, GGP, and Sand Control), which began in 2000–2001, the newly planted forests were less than 10 y old in 2010. Therefore, it will be expected that the forests associated with these projects could account for significant C accumulation in the future (31). Additionally, the storage of massive amounts of C in mature forests will also contribute to the global C balance, although the C sink may gradually decrease and reach a C saturation state as the forests grow (20). However, this considerable C sequestration potential could also be regarded as an approach for buying time before C saturation occurs. Finally, our study indicates that the implementation of national ecological restoration projects could be a quantitatively important component of national climate change mitigation strategies in China and thus should be continually paid a great attention.

## Methods and Materials

**Data Sources for Estimating the C Sink.** For estimating the C sink in an ecosystem in a given project area, data on the different land-cover and vegetation types and soil C density in the region from the beginning of the project and 2010 were used. The areas of different land-cover types (i.e., $AL_{ei}$ and $AL_{si}$) were obtained from Wu et al. (34, data from 2000 and 2010) according to the reported land-cover classification (35). A dataset of C density in the ecosystems in the national ecological project regions and the reference sites was built mainly based on data presented by Tang et al. (36) by the 67 technical groups of the Ecosystem Carbon Sequestration Program. The six technical groups of the National Key Ecological Project Carbon Sequestration also provided data from other sites in typical project regions and from paired sampling in reference regions. The dataset included the spatial position of the plot, vegetation type, vegetation biomass and related C content, soil organic C content, and bulk density in various layers, to a depth of 100 cm. Biomass and soil C density values for 2010 (i.e., $CDV_{ei}$ and $CDS_{ei}$, respectively) came from the field surveys and laboratory analyses performed in the present study [as reported by Tang et al. (36), 10,033 groups of data, see *SI Appendix, D*], from a field survey conducted using the same methods and criteria by Tang et al. (36), and from the most recent peer-reviewed reports (564 groups of data, see *SI Appendix, D*). Biomass and soil C density values recorded close to 2000 (i.e., $CDV_{si}$ and $CDS_{si}$, respectively) were acquired from surveys of the published literature and peer-reviewed papers (1,653 groups of data, *SI Appendix, D*) as well as the National Forest Inventory and Soil database (for Forest Protection and River Shelter Forest). The sources for the C density data are described in detail in *SI Appendix, D*.

**Data Sources for Assessing Contribution of the Projects to C Sequestration.** For the North Shelter Forest, River Shelter Forest, Grassland Conservation, and Sand Control projects, we investigated the enhancement of the C sink resulting from human management strategies and efforts, mainly by comparing the ecosystem C stocks between the project regions and reference regions where ecological stewardship projects were not conducted in 2010. In addition to the above-mentioned data for 2010, the biomass and soil C density values ($CDB_{be}$ and $CDS_{be}$, respectively) of forests, shrublands, and grasslands were also taken from Tang et al. (36) (6,996 groups of data, *SI Appendix, D*), and additional field sampling was conducted using the same criteria employed by Tang et al. (36), producing 292 groups of data (see *SI Appendix*). AL values were obtained from Wu et al. (34) and from Landsat TM imagery (*SI Appendix, D*) and the China Forest Statistical Yearbook (37). For Forest Protection, the data for newly planted forests ($ANF_{ik}$) and the harvested volume reduction ($RHV_{kl}$) were obtained from the China Forest Statistical Yearbook (37). $CDV_{ik}$ was estimated based on the Forest Inventory of China (20, 38); the average annual rate of increase in soil retention was obtained from Ouyang et al. (4); and the topsoil organic C content ($SOC_{0\text{–}30\ cm}$) was obtained from the soil database of Shangguan et al. (39).

**Estimation of Ecosystem C Sinks in the Project Regions.** The decadal C sink is the change in the C stock from project onset to termination in the regions of the key restoration projects. Estimation of the decadal C sink was first conducted at the province scale, and the results were then summed at regional and national scales. The C sink was derived from Eq. **1**:

$$\text{C sink} = CP_e - CP_s, \qquad [1]$$

where $CP_e$ is the total C stock in the project region in 2010 and $CP_s$ is the C stock at the start of the project. $CP_e$ and $CP_s$ were estimated based on different land cover types (AL) and areas, along with the average biomass and soil C density (CDB and CDS) of each land cover type, using Eqs. **2** and **3**:

$$CP_e = \sum\left((CDB_{eik} + CDS_{eik}) * AL_{eik}\right) \qquad [2]$$

$$CP_s = \sum\left((CDB_{sik} + CDS_{sik}) * AL_{sik}\right), \qquad [3]$$

where $AL_{ei}$ and $AL_{si}$ are the areas of land cover *i* in the project region in 2010 and at the start of the project in province *k*, respectively; $CDB_{eik}$ and $CDB_{sik}$ are the average biomass C density values for land cover *i* in the project region in province *k* in the year 2010 and at the start of the project, respectively; and $CDS_{eik}$ and $CDS_{sik}$ are the average soil (0- to 100-cm layer) C density values for land cover *i* in the project region in province *k* in 2010 and at the start of the project, respectively.

During the project, the annual C sink (ASC) of each national key ecological restoration project was calculated using Eq. **4**:

$$ASC_j = \text{Carbon sink}_j / t_j, \qquad [4]$$

where $ASC_j$ is the annual C sink in the region of ecological restoration project *j*, and $t_j$ is the duration (in years) of project *j*. The value of *t* was 10 for the North Shelter Forest fourth phase, River Shelter Forest second phase, and Sand Control; 13 for Forest Protection; 11 for GGP; and 8 for Grassland Conservation (Table 1).

**Estimation of the Contribution of Project Implementation to C Sequestration.** ***Estimation of the project contributions of North and River Shelter Forests, Grassland Conservation, and Sand Control.*** If the ecological restoration projects were not implemented, ecosystem management and utilization practices would have continued as they were before the programs were designed and put into use. However, the previous management practices were quite different from those of the restoration programs, and notable differences would have been apparent during the first decade of the 21st century. For example, the North Shelter Forest and River Shelter Forest regions would exhibit substantially fewer forests and would be maintained as shrubland or grassland. Therefore, under these scenarios, the C stocks and flows in the project region ecosystems would clearly differ from their statuses under the restoration projects. The difference in C stocks between scenarios with and without ecological restoration project implementation (i.e., baseline or project scenarios) can be attributed to these projects. In this study, this difference is defined as the project contribution to C sequestration. This value was calculated using Eq. **5**:

$$\text{Project contribution} = \text{C sink}_p - \text{C sink}_b, \qquad [5]$$

where C $\text{sink}_p$ is the increase in the C stock in the project region based on the project scenario, which can also be calculated using the C sink with Eq. **6**. C $\text{sink}_b$ is the baseline increase in the C stock in the same project region (i.e., without the implementation of the national key ecological restoration projects). Based on Eq. **1**, C $\text{sink}_b$ was calculated with Eq. **7**:

$$\text{Carbon sink}_p = CP_e - CP_s \qquad [6]$$

$$\text{Carbon sink}_b = CP_{be} - CP_{bs}, \qquad [7]$$

where $CP_{be}$ is the total C stock in 2010 in the same region under the hypothetical baseline scenario (i.e., in the absence of the project scenario) and $CP_{bs}$ is the C stock at the project onset. Here, it was assumed that the C stock at the beginning of the restoration project and the C stock under the baseline scenario were equal (i.e., $CP_s$ = $CP_{bs}$). Therefore, the project contribution was estimated using the following simplified Eq. **8**:

$$\text{Project contribution} = \text{C sink}_p - \text{C sink}_b = CP_e - CP_{be}. \qquad [8]$$

Clearly, $CP_{be}$ cannot be obtained via field investigations because it occurs under the hypothetical baseline scenario. Thus, we set the reference land-cover types to be consistent with the project targets, contents, and measures (Table 1 and *SI Appendix, A*). $CP_{be}$ was estimated using Eq. **9**:

$$CP_{be} = \sum(CDB_{bek} + CDS_{bek}) * AL_{ik}, \qquad [9]$$

where $CDB_{be}$ and $CDS_{be}$ are the average biomass and soil C density (Table 1), respectively, in province *k* under the baseline scenario (be) in the year 2010. $AL_{ik}$ is the area of land cover *i* in the reference region in province *k*. For these two parameters, the C density values outside the project region were applied, but relatively high spatial similarities were present (adjacent to the project region and within the same province). Estimation was first conducted at the province scale, and the results were then summed at the regional and national scales.

***Estimation of the project contributions of Forest Protection and GGP.*** If the Forest Protection and GGP projects had not been not implemented (i.e., the baseline scenarios), the ecosystem would be in a different condition. For example, the natural forests would be further exploited, without planned reductions in harvest volumes, afforestation would be carried out in the project area, and soil erosion would continue to be serious. Furthermore, the GGP cropland in hilly areas would be maintained under cultivation, resulting in serious soil erosion. Due to difficulties in finding unprotected natural forests or hilly cropland adjacent to the project regions, the contributions of the Forest Protection and GGP projects were estimated as follows.

The project contribution of Forest Protection (Project contribution $_{FP}$) included three parts: C storage in newly planted forest biomass (CPBN), biomass C retention (BCR) resulting from harvest volume reduction, and soil C retention (SCR) due to the reduction of soil erosion resulting from the project Eq. **10**. Estimation was first conducted at the province scale, and the results were then summed at the regional and national scales:

$$\text{Project contribution}_{FP} = \sum(CPBN_k + BCR_k + SCR_k), \qquad [10]$$

where $CPBN_k$, $BCR_k$, and $SCR_k$ are the C storage in newly planted forest biomass, biomass C retention resulting from harvest volume reduction, and soil C retention due to the reduction of soil erosion in the Forest Protection project area in province k, respectively. The estimation of these contributions to C sequestration is shown in *SI Appendix, E* (formulas **S1**–**S4**).

The contribution of GGP also consisted of two components. One component was the increase in the biomass C stock because the reference scenario was croplands whose biomass C would be released into the atmosphere before the next crop was planted. The other component was SCR, due to the control of soil erosion attributed to GGP. Therefore, the contribution of GGP (Project contribution $_{\mathrm{GGP}}$) was obtained with Eq. **11**. The estimation was first conducted at the province scale, and the results were then summed at the regional and national scales:

$$\text{Project contribution}_{\mathrm{GGP}} = \sum \mathrm{CDB}_{\mathrm{ei}} * \mathrm{ALC} + \sum \mathrm{SCR}_{\mathrm{k}}, \qquad [11]$$

where $\mathrm{CDB}_{\mathrm{ei}}$ is the average biomass C density of land cover *i* that was converted from cropland in the year 2010. The estimation method for SCR due to the reduction of soil erosion resulting from the GGP project is shown in *SI Appendix, E* (formula **S5**).

**ACKNOWLEDGMENTS.** We thank Drs. Xia Zhao and Shuqing Zhao and Yafei Yuan for their constructive suggestions. This work was supported by Strategic Priority Programme of the Chinese Academy of Sciences Grants XDA05060000 and XDA05060700, National Major Research Program of China Grants 2016YFC0503403 and 2017YFA0604702, and the Youth Innovation Promotion Association, Chinese Academy of Sciences.

1. Pan Y, et al. (2011) A large and persistent carbon sink in the world's forests. *Science* 333:988–993.
2. Fang J, Chen A, Peng C, Zhao S, Ci L (2001) Changes in forest biomass carbon storage in China between 1949 and 1998. *Science* 292:2320–2322.
3. Fang J, et al. (2014) Forest biomass carbon sinks in East Asia, with special reference to the relative contributions of forest expansion and forest growth. *Glob Change Biol* 20:2019–2030.
4. Ouyang Z, et al. (2016) Improvements in ecosystem services from investments in natural capital. *Science* 352:1455–1459.
5. Hu H, Wang S, Guo Z, Xu B, Fang J (2015) The stage-classified matrix models project a significant increase in biomass carbon stocks in China's forests between 2005 and 2050. *Sci Rep* 5:11203.
6. Xu B, Guo Z, Piao S, Fang J (2010) Biomass carbon stocks in China's forests between 2000 and 2050: A prediction based on forest biomass-age relationships. *Sci China Life Sci* 53:776–783.
7. Bureau of Three North Protection Forest Construction, Ministry of Forestry (1992) The "three north" protection forest system construction of China (China Forestry Publishing House, Beijing). Chinese.
8. Houghton RA, Hackler JL (2003) Sources and sinks of carbon from land-use change in China. *Global Biogeochem Cycles* 17:1034.
9. Liu M, Tian H (2010) China's land cover and land use change from 1700 to 2005: Estimations from high-resolution satellite data and historical archives. *Global Biogeochem Cycles* 24:GB3003.
10. Zhang P, et al. (2000) China's forest policy for the 21st century. *Science* 288: 2135–2136, and erratum (2000) 289:16916.
11. Liu J, Li S, Ouyang Z, Tam C, Chen X (2008) Ecological and socioeconomic effects of China's policies for ecosystem services. *Proc Natl Acad Sci USA* 105:9477–9482.
12. Ministry of Forestry (2010) Forest resource statistics of China (2004–2008) (Ministry of Forestry, Beijing). Chinese.
13. Ministry of Forestry (2014) Forest resource report of China – The 8th national forest resources inventory (Chinese Forestry Publishing House, Beijing). Chinese.
14. Ministry of Environment Projection Chinese Academy of Sciences (2014) National ecosystem survey and assessment of China (2000-2010) (China Science Publishing House, Beijing). Chinese.
15. Wang S, et al. (2016) Reduced sediment transport in the Yellow River due to anthropogenic changes. *Nat Geosci* 9:38–41.
16. Xu W, et al. (2017) Strengthening protected areas for biodiversity and ecosystem services in China. *Proc Natl Acad Sci USA* 114:1601–1606.
17. Bonan GB (2008) Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science* 320:1444–1449.
18. Liu B, et al. (2017) Greenhouse gas emissions, carbon leakage and net carbon sequestration from afforestation. *Ying Yong Sheng Tai Xue Bao* 28:673–688.
19. Guo Z, Hu H, Li P, Li N, Fang J (2013) Spatio-temporal changes in biomass carbon sinks in China's forests from 1977 to 2008. *Sci China Life Sci* 56:661–671.
20. Zhou G, et al. (2006) Old-growth forests can accumulate carbon in soils. *Science* 314: 1417.
21. Piao S, et al. (2009) The carbon balance of terrestrial ecosystems in China. *Nature* 458: 1009–1013.
22. National Bureau of Statistics of the People's Republic of China (2011) *China Statistical Yearbook 2011* (China Statistics Press, Beijing). Chinese.
23. Liu W, et al. (2017) Human influence on the temporal dynamics and spatial distribution of forest biomass carbon in China. *Ecol Evol* 7:6220–6230.
24. Fang J, Yang Y, Ma W, Mohammat A, Shen H (2010) Ecosystem carbon stocks and their changes in China's grasslands. *Sci China Life Sci* 53:757–765.
25. Chen P, Wang X, Wang L, eds (2008) *Carbon Budget and Its Sink Promotion of Terrestrial Ecosystem in China* (Science, Beijing). Chinese.
26. Nave LE, et al. (2013) Afforestation effects on soil carbon storage in the United States: A synthesis. *Soil Sci Soc Am J* 77:1035–1047.
27. Liu B, et al. (2016) Research on greenhouse gas emissions and net carbon sequestration of "Grain for Green" Program in China. *Ying Yong Sheng Tai Xue Bao* 27: 1693–1707.
28. Lu F, et al. (2010) Net mitigation potential of straw return to Chinese cropland: Estimation with a full greenhouse gas budget model. *Ecol Appl* 20:634–647.
29. Liu T, et al. (2013) *Research on Planning Clues of Beijing-Tianjin Sand Source Control Project (2nd Phase)* (China Forestry Publishing House, Beijing). Chinese.
30. Pan Y, et al. (2010) *Research on Important Issues of the 5th Phase of the Construction of Three North Shelter Forest System* (China Forestry Publishing House, Beijing). Chinese.
31. Li SY, Huang M, Li SG (2014) REDD-plus and China's contribution. *IOP Conf Ser:Earth Environ Sci* 17:012021.
32. IEA (2012) China, People's Republic of: Indicators for 2000-2010. Available at www.iea.org/statistics/statisticssearch/report/?country=CHINA&product=indicators&year2000. Accessed November 10, 2017.
33. Li P, et al. (2016) The relative contributions of forest growth and areal expansion to forest biomass carbon. *Biogeosciences* 13:375–388.
34. Wu B, et al. (2017) *Land Cover Atlas of the People's Republic of China (1:1 000 000)* (China Map Publishing House, Beijing). Chinese.
35. Zhiyun O, et al. (2015) An ecosystem classification system based on remote sensor information in China. *Acta Ecol Sin* 35:219–226.
36. Tang Z, et al. (2018) Carbon pools in China's terrestrial ecosystems: New estimates based on an intensive field survey. *Proc Natl Acad Sci USA* 115:4021–4026.
37. State Forestry Administration (1998–2011) *China Forest Statistical Yearbook 1997-2010* (China Forestry Publishing House, Beijing). Chinese.
38. Deng L, Liu GB, Shangguan ZP (2014) Land-use conversion and changing soil carbon stocks in China's 'Grain-for-Green' Program: A synthesis. *Glob Change Biol* 20: 3544–3556.
39. Shangguan W, Dai Y, Liu B (2013) A China data set of soil properties for land surface modeling. *J Adv Model Syst* 5:212–224.