AMBIO
DOI 10.1007/s13280-014-0518-7

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

PERSPECTIVE

Carbon Sequestration Function of Check-Dams: A Case Study of the Loess Plateau in China

Yafeng Wang, Liding Chen, Yang Gao, Shuai Wang, Yihe Lü, Bojie Fu

Received: 19 November 2013 / Revised: 13 February 2014 / Accepted: 13 March 2014

Abstract Check-dams are the most common structures for controlling soil erosion in the Loess Plateau. However, the effect of check-dams on carbon sequestration, along with sediment transport and deposition, has not been assessed over large areas. In this study, we evaluated the carbon sequestration function of check-dams in the Loess Plateau. The results indicate that there were approximately 11 000 check-dams distributed in the Loess Plateau, with an estimate of the amount of sediment of 21×10^9 m^3 and a soil organic carbon storage amount of 0.945 Pg. Our study reveals that check-dams in the Loess Plateau not only conserve soil and water but also sequester carbon.

Keywords Check-dam · Carbon sequestration · Sediments · Soil erosion · Loess Plateau · Ecosystem services

INTRODUCTION

Soil erosion plays an important role in the global carbon (C) cycle (Berhe et al. 2007; Van Oost et al. 2008). Recent studies indicated that soil erosion and deposition acted as a C sink globally (Harden et al. 2008; Van Oost et al. 2008). It was estimated that soil erosion and subsequent sedimentation on land can sequester 1 Pg C $year^{-1}$ globally (Stallard 1998; Smith et al. 2001). Berhe et al. (2007) estimated that the worldwide erosion deposition induced a terrestrial C sink of 0.72 Pg C $year^{-1}$. Check-dams, which are widely used to trap sediments in areas with high soil erosion, can also act as a carbon sink; however, only a few assessments of carbon sequestration by check-dams have been performed (Li et al. 2007; Cao 2008). Therefore, this lack of evaluations makes estimates of the C sequestration by erosion and subsequent deposition in check-dams difficult (Liu et al. 2011b).

Check-dams are the most widespread but unique structures for conserving soil and water in the Loess Plateau, a region characterized by its complex geomorphology and considerable soil erosion and sediment yield. The Loess Plateau covers an area of 640 000 km^2 in the upper and middle reaches of the China's Yellow River. Over 60 % of the land is susceptible to soil and water losses, and the soil of this region is known as the "most highly erodible soil on earth" (Laflen et al. 2000). The Loess Mesa Ravine Region and the Loess Hill Ravine Region in combination cover 30 % of the Loess Plateau and exhibit some of the most severe soil and water losses in the world (Laflen et al. 2000). Erosion in the two regions is occurring at a rate of 5000–10 000 tons km^{-2} $year^{-1}$, with the rate increasing to up to 20 000–30 000 tons km^{-2} $year^{-1}$ in some extreme years (Miao et al. 2010, 2011, 2012). Carbon sequestration due to soil erosion and sedimentation resulting from the development of check-dams, however, has rarely been quantified. Therefore, the main objective of the current study was to evaluate the effect of check-dams on the soil carbon dynamics and carbon stock based on an overall assessment of the check-dam development in the Loess Plateau.

CHECK-DAM DEVELOPMENT IN THE LOESS PLATEAU

A check-dam can be defined as a dam constructed across a drainage channel to mitigate and reduce soil erosion. It can be made of various materials, including woods, boulders, and concrete blocks. Designing check-dam systems requires estimates for (1) preferred dam sites, (2) the number of dams required and their heights for sediment retention and flood control, and (3) the optimal sequence and interval for dam construction.

Published online: 03 April 2014

Check-dam development and utilization have a long history in China. By making use of the local geography and climate, the people of the Loess Plateau of China skillfully invented the check-dam system in gullies several centuries ago to retain sediments and to form farmland. For example, check-dams at the Kanghe Gou watershed of Fen-xi County, built in the Ming Dynasty 400 years ago, are still in good condition. As one of the primary measures to conserve water and soil, the check-dam project has been given great emphasis ever since the founding of the People's Republic of China in 1949. By 2002, approximately 113 500 check-dams had been built, creating 3200 km^2 of farmland with high productivity. Thus, the check-dam system is the most important and well-known project in China to conserve soil and water. The Chinese Ministry of Water Resources stated that 163 300 additional check-dams will be built in the Loess Plateau by 2020 (CMWR 2003).

CARBON SEQUESTRATION IN A CHECK-DAM

The sediments trapped by check-dams can potentially serve as natural archives for reconstructing the environmental history of soil erosion at a given location. Sediments are one of the most efficient indicators for revealing the function of modern ecosystems and landscapes (Dearing et al. 2008). Sediment deposits contain reallocated carbon (Poch et al. 2006), and they play a significant role in carbon sequestration in the agro-ecosystems of the Loess Plateau (Cao et al. 2009, 2010a, b). Mobilization of terrestrial C due to erosion could have a measurable impact on the global C cycle, but quantitative assessments of the magnitude and direction of that impact are sparse (Liu et al. 2011a; Yuan et al. 2012; Zhao et al. 2013; Zhou et al. 2013). Berhe et al. (2007) reported that up to 70 % of the SOC in eroded soil could be decomposed during transport and deposition.

Soil erosion, with the accompanying sediment transport and deposition, provides insight into environmental change. Sediment fingerprinting has proven to be an effective means to track sediment movement within a check-dam in terms of the source type and the spatial origin (Walling 2005). The fingerprint properties in check-dams should be (1) measurable in the sources as well as in the stream sediment, (2) representative of a particular source, and (3) conservative between sediment generation and delivery (Liu et al. 2003). One of the various pathways by which carbon is lost from the Loess Plateau is through the sediments. Soil erosion affects the SOC dynamics by (1) redistribution within a watershed or transport outside of its boundaries and (2) altering the SOC mineralization processes in disturbed sediment (Gregorich et al. 1998). Hence, there are two possible ways by which soil erosion and deposition in check-dams may impact C sequestration. Burial and subsequent accumulations of SOC in depositional sites occur in check-dams. According to Jacinthe et al. (2004), the organic carbon content in sediments and eroded material was over twice that of the original soils; the same authors estimated that 5.7 Pg SOC is removed annually by water erosion in terrestrial ecosystems. Erosion–deposition-induced potential C burial in the check-dams might increase when soil erosion is intensified by human disturbances. Mechanistically, soil erosion creates a C sink in the global C cycle through C burial by eroding SOC off site and depositing it into check-dams. The strength of this C sink is related to the erosion rate, the replenish rate of the eroded materials, and the fraction of eroded C that eventually is protected from decomposition (Stallard 1998; Liu et al. 2003; Lal 2004; Van Oost et al. 2007). Some SOC-enriched sediment is redistributed over the check-dams, while others are deposited in the depression sites and transported into aquatic ecosystems.

DISTRIBUTION AND CARBON STOCK OF CHECK-DAMS IN THE LOESS PLATEAU

As shown in Fig. 1, over 85 % of the check-dams are located in the middle of the Loess Plateau region, near the middle reaches of Yellow River, and belong to the source area of high and coarse sediment in the Loess Plateau. In total, there are approximately 110 000 dam blocks existing in the Loess Plateau region, storing 21×10^9 m^3 of sediment. The distributions of check-dams in the Loess Plateau are as follows: Shaanxi (36 816), Shanxi (37 820), Gansu (6630), Inner Mongolia (17 819), Ningxia (4936), Qinghai (3877), and Henan (4147). The Shaanxi, Shanxi, and Mongolia Provinces have nearly 9 million dams, accounting for 82.5 % of the total dams in the Loess Plateau region (CMWR 2003). In the middle of Loess Plateau region, there is more intensified agriculture and a large population compared to the other locations. Therefore, most of the check-dams were built in this region to improve agricultural production and develop the economy (Cao 2011; Cao et al. 2011).

Table 1 shows the different soil organic carbon contents measured in the check-dams of the Loess Plateau area. Soil Organic Carbon sequestration for the check-dams in Loess Plateau was estimated by using spatial calculations according to sediments volume and average soil organic carbon contents. According to existing research, the bulk density of check-dam sediment is on average 1.36 kg m^{-3}, and the amount of sediments is over 21×10^9 m^{-3} in the Loess Plateau (Bao 2008). Because the average of the organic carbon content in the Loess Plateau is approximately 3.31 g kg^{-1}, the soil organic storage in check-dams in the Loess Plateau could reach 0.945 Pg (1 Pg = 10^{15} g), which accounts for 18–24 % of the total carbon storage of

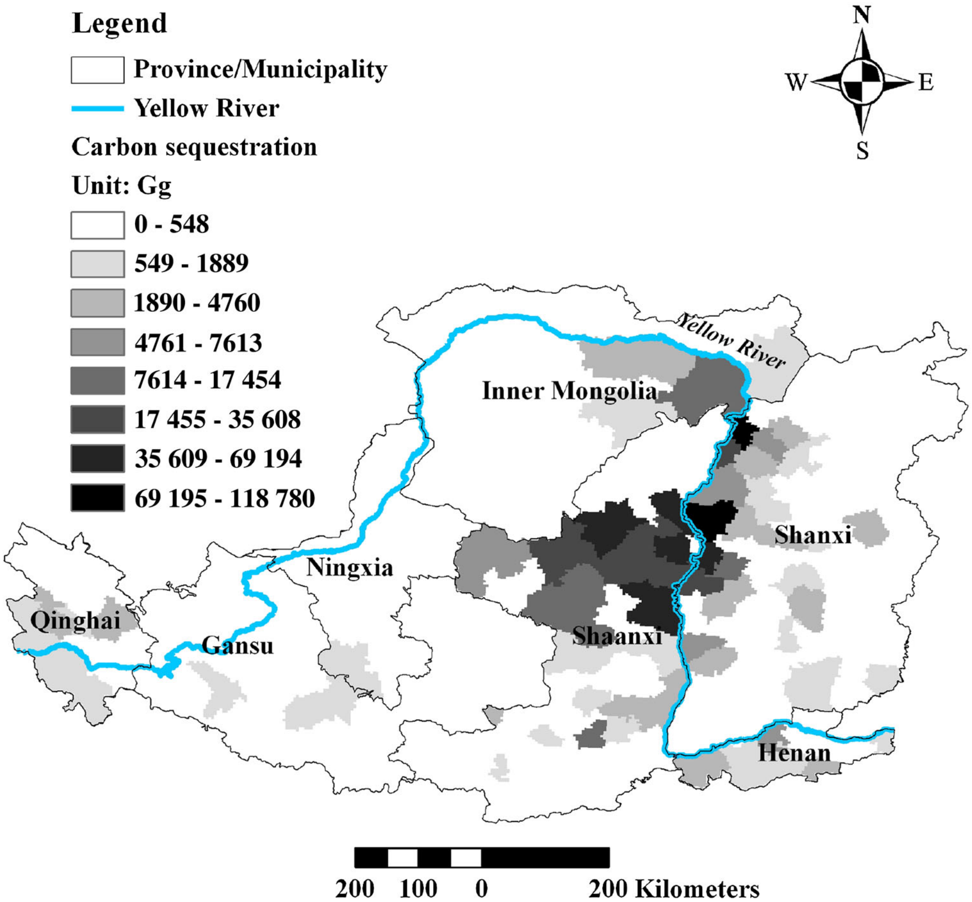

Fig. 1 Carbon storage distribution in the check-dams in the Loess Plateau (1 Gg = 10^9 g)

Table 1 The organic carbon content in different check-dam sediments in the Loess Plateau

	Location	*N*	Organic carbon (g kg^{-1})			
			Low	High	Average	SE
1	Nianzhuang (Li and Bai 2003)	12	1.51	13.60	3.66	2.09
2	Yan'an (Bao 2008)	20	2.64	4.05	3.07	0.84
3	An'sai (Li et al. 2007)	84	2.03	4.30	3.20	0.59

forest vegetation in China (Zhao and Zhou 2006). We mapped the extent of the depositional soils in the Loess Plateau areas with high organic carbon sequestration (Fig. 2). In the Loess Plateau region, the organic carbon transport and storage were basically linked to the solid phase by erosion events, depending on the rainfall. Given the high C storage in check-dams, the accelerated erosion of soils may drastically increase the C accumulation at the depositional sites. Furthermore, the eroded area would lose a considerable amount of soil organic carbon, depending on the depth of soil truncated by erosion due to the check-dams. Thus, it is important to study the effects of accelerated erosion on the soil organic carbon storage in the check-dams of the Loess Plateau.

CONCLUSIONS AND PERSPECTIVES

The check-dams in the Loess Plateau of China are excellent examples of efforts to prevent land from soil degradation and transform barren lands into agricultural areas. The use of check-dams is so popular in China that over 100 000 check-dams have been built in the past 50 years. The check-dams control erosion and deposition within the channels. Bank gully erosion mobilizing high amounts of sediment is recognized as one of the major processes involved in land degradation. The amount of sediment retained by these check-dams has been found to be the largest among all other measures, and high crop yields have been obtained in the deposited dam-lands because of the plentiful moisture and nutrients (Fig. 3). By 2002, 3200 km^2 of dam croplands had been created (CMWR 2003). According to the monitoring data from the Suide Soil and Water Conservation Experiment Station of the

Yellow River Conservancy Commission, the soil water content in dam cropland is 1.86 times of that in slope cropland. The food production in dam cropland is 2–3 times higher than that in terrace cropland, and 6–10 times higher than that in slope cropland (CMWR 2003). Accordingly, check-dam as hydro-engineering approach

Fig. 2 Check-dam views in the Loess Plateau by Google Earth

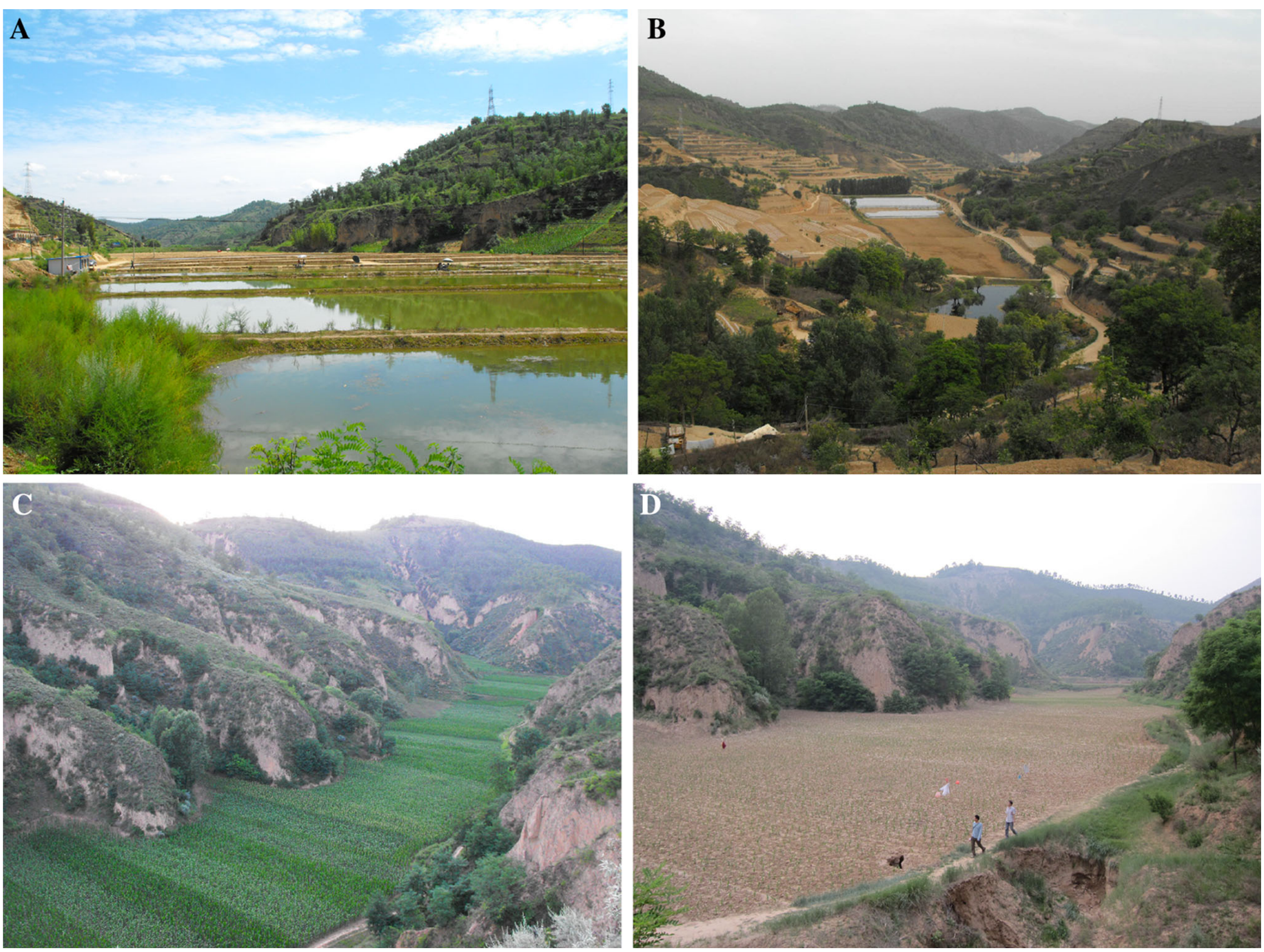

Fig. 3 Different functions of check-dams in the Loess Plateau (**a** Fishpond; **b** Green houses for vegetables; **c**, **d** High yield farmland)

for soil erosion control has actually brought about services for environmental conservation and human welfare in the Loess Plateau of China.

Check-dam sediments could be an important indicator of environmental change and its effect on soil erosion and may provide a multi-proxy record of soil erosion evolution at the local scale in the middle reach of the Yellow River. There are wide distributions of temporal and spatial check-dams in the Loess Plateau, and sediments from these dams could be collected to study the development of soil erosion in a semi-arid area on a regional scale. The dam can also alleviate erosion by slowing the flow velocity of the sediment-laden water, by clarifying the sediment-laden fluid stored in the reservoir, and by capturing sediments for the dam-land, to protect the dam-land from erosion. The gullies could auto-stabilize themselves after the check-dams were built. In conclusion, the use of check-dams is the most effective way to conserve soil, water, and carbon in the Loess Plateau. More studies are required to understand the fate of the eroded carbon and the relationships with the rainfall characteristics due to the crucial role of erosion in the check-dams in the Loess Plateau areas.

This study suggests that the check-dam associated soil and water conservation measures implemented in the Loess Plateau tended to facilitate synergies on carbon sequestration, soil conservation, grain production, and other ecosystem services. These synergies are important goals that ecosystem management tries to reach in the future.

Acknowledgments This work was supported by the National Natural Science Foundation of China (No. 40901098 and 41230745) and the CAS/SAFEA International Partnership Program for Creative Research Teams of "Ecosystem Processes and Services." We thank Geoffrey Hart (Montréal, Canada) for editing an early version of this paper.

REFERENCES

Bao, Y.X. 2008. *The Characteristics and evolution of soil nitrogen in Damland and Terrace in Loess Hilly region*. Xi'an, China: Northwest Agriculture Forestry University Press (in Chinese with English Abstract).

Berhe, A.A., J. Harte, and J.W. Harden. 2007. The significance of the erosion-induced terrestrial carbon sink. *BioScience* 57: 337–346.

Cao, S.X. 2008. Impact of spatial and temporal scales on afforestation effects: Response to comment on "Why Large-Scale Afforestation Efforts in China Have Failed to Solve the Desertification Problem". *Environmental Science and Technology* 42: 7724–7725.

Cao, S.X. 2011. Impact of China's large-scale ecological restoration program on the environment and society in Arid and Semiarid Areas of China: Achievements, problems, synthesis, and applications. *Critical Reviews in Environmental Science and Technology* 41: 317–335.

Cao, S.X., L. Chen, and X.X. Yu. 2009. Impact of China's Grain for Green Project on the landscape of vulnerable arid and semi-arid agricultural regions: A case study in northern Shaanxi Province. *Journal of Applied Ecology* 46: 536–543.

Cao, S.X., G.S. Wang, and L. Chen. 2010a. Questionable value of planting thirsty trees in dry regions. *Nature* 465: 31–31.

Cao, S.X., G.S. Wang, and L. Chen. 2010b. Assessing effects of afforestation projects in China Reply. *Nature* 466: 315–315.

Cao, S.X., L. Chen, D. Shankman, C.M. Wang, X.B. Wang, and H. Zhang. 2011. Excessive reliance on afforestation in China's arid and semi-arid regions: Lessons in ecological restoration. *Earth-Science Reviews* 104: 240–245.

CMWR. 2003. Programming for check dams in the Loess Plateau. Ministry of Water Resource of P.R. China. Report.

Dearing, J., R. Jones, J. Shen, X. Yang, J. Boyle, G. Foster, D. Crook, and M. Elvin. 2008. Using multiple archives to understand past and present climate–human–environment interactions: The lake Erhai catchment, Yunnan Province, China. *Journal of Paleolimnology* 40: 3–31.

Gregorich, E.G., K.J. Greer, D.W. Anderson, and B.C. Liang. 1998. Carbon distribution and losses: Erosion and deposition effects. *Soil and Tillage Research* 47: 291–302.

Harden, J.W., A.A. Berhe, M. Torn, J. Harte, S. Liu, and R.F. Stallard. 2008. Soil erosion: Data say C sink. *Science* 320: 178–179.

Jacinthe, P.A., R. Lal, L.B. Owens, and D.L. Hothem. 2004. Transport of labile carbon in runoff as affected by land use and rainfall characteristics. *Soil and Tillage Research* 77: 111–123.

Laflen, J.M., J.L. Tian, and C.H. Huang. 2000. *Soil erosion and dryland farming*. Baco Raton, FL: CRC Press.

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. *Science* 34: 1623–1627.

Li, G.X., Z.B. Li, and X. Wei. 2007. Two key physical characteristics indexes of farmland sediment for check dams in Loess Plateau. *Research of Soil and Water Conservation* 14: 218–221.

Li, Y., and L.Y. Bai. 2003. Variations of sediment and organic carbon storage by check-dams of Chinese Loess Plateau. *Journal of Soil and Water Conservation* 17: 1–5 (in Chinese).

Liu, S.G., N. Bliss, E. Sundquist, and T.G. Huntington. 2003. Modeling carbon dynamics in vegetation and soil under the impact of soil erosion and deposition. *Global Biogeochemical Cycles* 17: 1074.

Liu, S.G., Z.X. Tan, Z.P. Li, S.Q. Zhao, and W.P. Yuan. 2011a. Are soils of Iowa USA currently a carbon sink or source? Simulated changes in SOC stock from 1972 to 2007. *Agriculture, Ecosystems & Environment* 140: 106–112.

Liu, S., B. Bond-Lamberty, J.A. Hicke, R. Vargas, S. Zhao, J. Chen, S.L. Edburg, Y. Hu et al. 2011b. Simulating the impacts of disturbances on forest carbon cycling in North America: Processes, data, models, and challenges. *Journal of Geophysical Research-Biogeosciences* 116.

Miao, C.Y., J.R. Ni, and A.G.L. Borthwick. 2010. Recent changes of water discharge and sediment load in the Yellow River basin, China. *Progress in Physical Geography* 34: 541–561.

Miao, C.Y., J.R. Ni, A.G.L. Borthwick, and L. Yang. 2011. A preliminary estimate of human and natural contributions to the changes in water discharge and sediment load in the Yellow River. *Global and Planetary Change* 76: 196–205.

Miao, C.Y., W. Shi, X.H. Chen, and L. Yang. 2012. Spatio-temporal variability of streamflow in the Yellow River: possible causes and implications. *Hydrological Sciences Journal (Journal Des Sciences Hydrologiques)* 57: 1355–1367.

Poch, R.M., J.W. Hopmans, J.W. Six, D.E. Rolston, and J.L. McIntyre. 2006. Considerations of a field-scale soil carbon budget for furrow irrigation. *Agriculture, Ecosystems & Environment* 113: 391–398.

Smith, S.V., W.H. Renwick, R.W. Buddemeier, and C.J. Crossland. 2001. Methane oxidation in a peatland core. *Global Biogeochemical Cycles* 15: 697–707.

Stallard, R.F. 1998. Terrestrial sedimentation and the carbon cycling: Coupling weathering and erosion to carbon burial. *Global Biogeochemical Cycles* 12: 231–257.

Van Oost, K., J. Six, G. Govers, T.A. Quine, and S. Gryze. 2008. Response to "Soil erosion: A carbon sink or source?". *Science* 319: 1042.

Van Oost, K., T.A. Quine, G. Govers, S. De Gryze, J. Six, J.W. Harden, J.C. Ritchie, G.W. McCarty, et al. 2007. The impact of agricultural soil erosion on the global carbon cycle. *Science* 318: 626–629.

Walling, D.E. 2005. Tracing suspended sediment sources in catchments and river systems. *Science of the Total Environment* 344: 159–184.

Yuan, W.P., S.L. Liang, S.G. Liu, E.S. Weng, Y.Q. Luo, D. Hollinger, and H.C. Zhang. 2012. Improving model parameter estimation using coupling relationships between vegetation production and ecosystem respiration. *Ecological Modelling* 240: 29–40.

Zhao, M., and G.S. Zhou. 2006. Carbon storage of forest vegetation in China and its relationship with climatic factors. *Climatic Change* 74: 175–189.

Zhao, S.Q., S.G. Liu, T. Sohl, C. Young, and J. Werner. 2013. Land use and carbon dynamics in the southeastern United States from 1992 to 2050. *Environmental Research Letters* 8: 044022.

Zhou, D.C., S.G. Liu, J. Oeding, and S.Q. Zhao. 2013. Forest cutting and impacts on carbon in the eastern United States. *Scientific Reports* 3: 3547.

AUTHOR BIOGRAPHIES

Yafeng Wang has a PhD in Ecology and he works as a Associate Professor in the State Key Lab of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, CAS. His research focuses on carbon cycling and ecosystem services.
Address: State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, PO Box 2871, Beijing 100085, China.
Address: SKLLQG, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710075, China.
e-mail: yfwang@rcees.ac.cn

Liding Chen is a Professor of Landscape Ecology in the State Key Lab of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, CAS. His research focuses on landscape pattern and ecological process.
Address: State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, PO Box 2871, Beijing 100085, China.
e-mail: liding@rcees.ac.cn

Yang Gao has a PhD in Environmental Engineering and he works as a Associate Professor in Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, CAS. His main interests are forest hydrology, environmental physics, and carbon cycling.
Address: Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China.
e-mail: gaoyang0898@163.com

Shuai Wang has a PhD in Ecology and he works as a Senior Researcher in the State Key Lab of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, CAS. His main interests are forest hydrology.
Address: State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, PO Box 2871, Beijing 100085, China.
e-mail: shuaiwang@rcees.ac.cn

Yihe Lü is a Professor of Landscape Ecology in the State Key Lab of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, CAS. His research focuses on landscape pattern and ecological restoration.
Address: State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, PO Box 2871, Beijing 100085, China.
e-mail: lyh@rcees.ac.cn

Bojie Fu (✉) is a Professor of Landscape Ecology in the State Key Lab of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, CAS. His research focuses on landscape pattern and ecological process.
Address: State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, PO Box 2871, Beijing 100085, China.
e-mail: bfu@rcees.ac.cn