Science Bulletin 69 (2024) 2030–2033

Contents lists available at ScienceDirect

Science Bulletin

journal homepage: www.elsevier.com/locate/scib

Short Communication

Potential for soil carbon sequestration under conservation agriculture in a warming climate

Lijun Yu [a], Wen Zhang [a,b], Jingjing Liu [c], Wenjuan Sun [b,d], Qing Zhang [a,*]

[a] State Key Laboratory of Atmospheric Boundary Layer Physics and Atmospheric Chemistry, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] Anyang Meteorological Service, Anyang 455000, China
[d] State Key Laboratory of Vegetation and Environmental Change, Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China

ARTICLE INFO

Article history:
Received 12 January 2024
Received in revised form 26 February 2024
Accepted 27 February 2024
Available online 9 March 2024

Agricultural soil has numerous links with climate change. It comprises a substantial part of farming systems that are affected by climate change and can significantly impact food security [1]. An increase in the soil carbon (C) stock is associated with an increase in the crop yield. Moreover, agricultural soil remains a source for all three major greenhouse gases (GHGs), i.e., carbon dioxide (CO_2), methane and nitrous oxide, which contributes directly to climate change. In addition, enhancing soil C sequestration in agricultural land could offset GHG emissions, promote more sustainable and climate-resilient agricultural systems, and ultimately achieve C neutrality [2]. Therefore, soil C sequestration in croplands is an important part of natural climate solutions.

Croplands sequester C by balancing the loss of soil C with the sequestration of input organic C. Compared with conventional tillage, the conversion to no-till land, with a soil structure maintained by a lack of plowing over time, increases soil C accumulation [3]. Moreover, no-till practices may enhance the retention of crop residues on the soil surface and reduce the susceptibility of soil aggregates to disruption [4], resulting in benefits for the soil organic C stability. Hence, this may be a potential option for enhancing soil organic carbon (SOC) pools.

The no-till approach, the central practice of conservation agriculture, has been widely implemented as a universal soil health principle over the last few decades. However, the impact of no-till on soil C accumulation can vary in different situations. Six et al. [4] reported that SOC storage at depths of 0–30 cm increased in humid climates, while no-till adoption in dry climates resulted in C loss [4]. An investigation of temperate and tropical regions suggested that converting from conventional tillage to no-till increased SOC in the following descending order: tropical moist > tropical dry > temperate moist > temperate dry [5]. However, in cooler and/or wetter climates where the adoption of no-till decreased crop productivity and C inputs declined by more than 15%, SOC stocks decreased [6].

Despite the rapid expansion of no-till agriculture, the global distribution of potential soil C sequestration in no-till systems and consequently its overall contribution to mitigating future climate change remain unclear. Globally, the conversion of all croplands into conservation tillage could be projected to sequester a large amount of atmospheric CO_2-C over the next 50 years [2], while the potential for soil C sequestration is poorly understood in regions where no-till practices are generally beneficial for soil C accumulation relative to conventional tillage. Our previous research showed that the global patterns of soil C sequestration due to conversion to conservation agriculture are associated with extensive humidity patterns [7]. We found that in regions with humidity (HI) $\leq$ 89, SOC will most likely increase with conversion to conservation practices [7], and these regions occupy approximately 70% of the global cropland area. In contrast, in regions with HI > 89, C sequestration under conservation agriculture is lower than that achieved by local conventional tillage. In these areas, implementing conventional agriculture is more appropriate [7]. Thus, we focused on quantifying the potential for SOC sequestration if conservation agriculture practices (no-till with residue retention and crop rotation) are implemented in the recommended regions (HI $\leq$ 89) under various climate scenarios.

To this end, we first developed linear mixed models to quantify how environmental variables and agronomic practices impact SOC sequestration in arid regions (Eq. (1)) during the conventional tillage to conservation agriculture based on our primary findings and datasets from Sun et al. [7] (Tables S1 and S2 online) [7]. Then, we simulated the global SOC sequestration potential by adopting conservation agriculture for the next 50 years with projected

* Corresponding author.
E-mail address: zhangqing@mail.iap.ac.cn (Q. Zhang).

https://doi.org/10.1016/j.scib.2024.03.021

climate data derived from four global climate models (GCMs) under three representative concentration pathways (RCPs), namely, RCP2.6, RCP4.5, and RCP8.5 (Table S3 online).

$$\Delta SOC_R = A_0 \times \mathrm{MAT} + A_1 \times \mathrm{CS} + A_2 \times \mathrm{HI} + A_3 \times N_{\mathrm{input}} + \varepsilon, \quad \text{for HI} \leq 89, \tag{1}$$

where ΔSOC_R is the annual gain or loss of the SOC stock under conservation agriculture practices relative to conventional tillage, MAT is the mean annual temperature (℃), CS is the clay plus silt content (%), HI is the humidity index (mm °C^{-1}) [7], and N_{input} is the annual nitrogen fertilizer rate (kg N a^{-1}). The sources of the global input data are described in Supplementary materials 1.2 (online). Moreover, A_0, A_1, A_2, and A_3 are model parameters, and ε is a constant (Table S4 online). The stability of these parameters and the spatial representation and applicability of the observed data were evaluated via bootstrapped estimates (Fig. S1 online). Eventually, the explanation of the fixed effects on ΔSOC_R in Eq. (1) was significant ($p < 0.01$), with a small bias to the 1:1 line (Fig. S2 online). The duration of no-till is also well known as a vital factor affecting soil C sequestration. However, the duration factor was not included in the mixed effects model. Globally, there is no statistically significant relationship between changes in SOC and no-till application duration [7]. The primary reason is that the reported duration of no-till effects on SOC accumulation stabilization ranges from 25 to 30 years [8] to as long as one hundred or more years to eventually reach a new equilibrium [9], depending on climate and soil.

The simulation results showed that, globally, conservation practices are likely to cause a consistent accumulation of soil organic C to a depth of 0–30 cm under all three climate change scenarios over the 2020s–2060s (Fig. 1). There was no notable difference in soil C sequestration due to no-till among the three RCP scenarios, although soil C sequestration under RCP8.5 was slightly greater than that under RCP2.6 and RCP4.5. The projected soil C stocks fluctuated less or slightly over the 60-year period, with values of 0.37 (0.17–0.47) Mg C ha^{-1} a^{-1}, 0.38 (0.18–0.49) Mg C ha^{-1} a^{-1} and 0.38 (0.17–0.51) Mg C ha^{-1} a^{-1} under the RCP2.6, RCP4.5 and RCP8.5 scenarios, respectively (Table S5 online).

On a continental scale, soil C sequestration in the four continents of Asia, Africa, South America, and Oceania showed a positive trend from the 2020s to the 2060s (Fig. 2; Figs. S3 and S4 online; Table S5 online). Among them, cropland soils in Asia and Africa benefitted the most from conservation farming, as they received more C. A notable increase in soil C sequestration of 0.45–0.47 Mg C ha^{-1} a^{-1} was predicted in Asia under RCP2.6 (Fig. S3 online; Table S5 online) and RCP8.5 (Fig. S4 online; Table S5 online) from the 2020s to the 2060s. A similar soil C uptake of 0.43–0.47 Mg C ha^{-1} a^{-1} could occur in Africa. In contrast, cropland soils in Europe could receive C at a risk of C loss, especially under RCP2.6 and RCP4.5 (Table S5 online).

All three climate change scenarios could cause cropland expansion in areas with HI ≤ 89. The extent was projected to increase from 11.3 (×10^8 ha) in the 2020s to 11.4, 12.0, and 12.5 (×10^8 ha) in the 2060s under RCP2.6, RCP4.5, and RCP8.5, respectively (Table S9 online). The drying and drought areas of Asia, North America and Europe could increase to varying degrees, especially under RCP8.5. However, the areas in Africa, South America and Oceania experienced almost no change. Asia contributed the most to the soil C stocks, at more than 40%, while Oceania contributed the least, at only approximately 5%. Overall, our results indicated that the projected annual global rate of SOC accumulation ranges from 0.42 (0.23–0.65), 0.44 (0.24–0.69), and 0.45 (0.23–0.73) Gt C under the RCP2.6, RCP4.5, and RCP8.5 scenarios, respectively, on a global scale (Table S7 online). Graham et al. [2] reported that no-till practices without crop residue retention could increase the global soil C adoption in the top 20 cm by 0.08–0.17 Gt C a^{-1} under RCP8.5 forcing from 2015 to 2100 [2]. The positive effects of no-till with crop retention on soil C sequestration were remarkably greater than those of no-till without crop retention practices [10]. Thus, the simulation results of Graham et al. [7] were lower than those of this study.

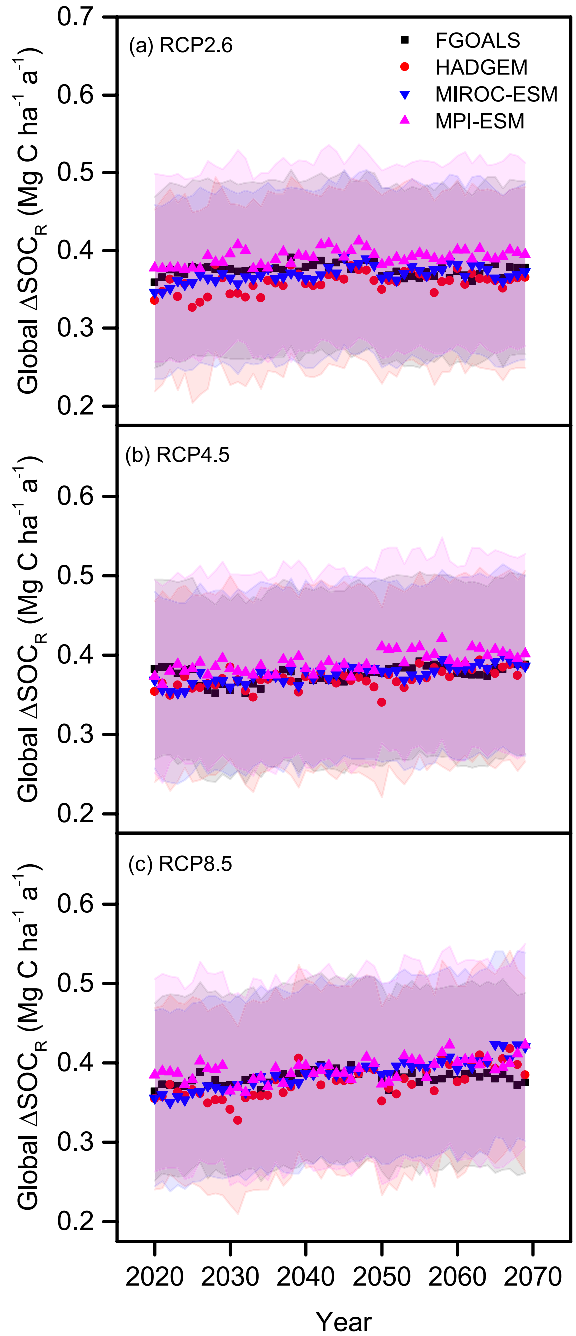

Fig. 1. Simulated changes in global ΔSOC_R under RCP2.6, RCP4.5 and RCP8.5 with different climate models. No significant differences were found between each GCM and the different RCPs.

The no-till practices in the top ten countries, which encompass the world's largest cropland area, show that India, Nigeria, Australia, Brazil, Argentina, China and the USA may experience overall C sequestration, while Canada and Russia may experience the lowest increase in SOC over the next 50 years (Figs. S5–S7 online). However, the average increase rates of soil C sequestration in Canada and Russia under RCP4.5 and RCP8.5 could be greater (Table S8 online) due to the rapid extent of cropland in the areas with HI ≤ 89 within these two countries (Table S10 online). Moreover, Ukraine could gain C at a risk of C loss (Table S6 online). The

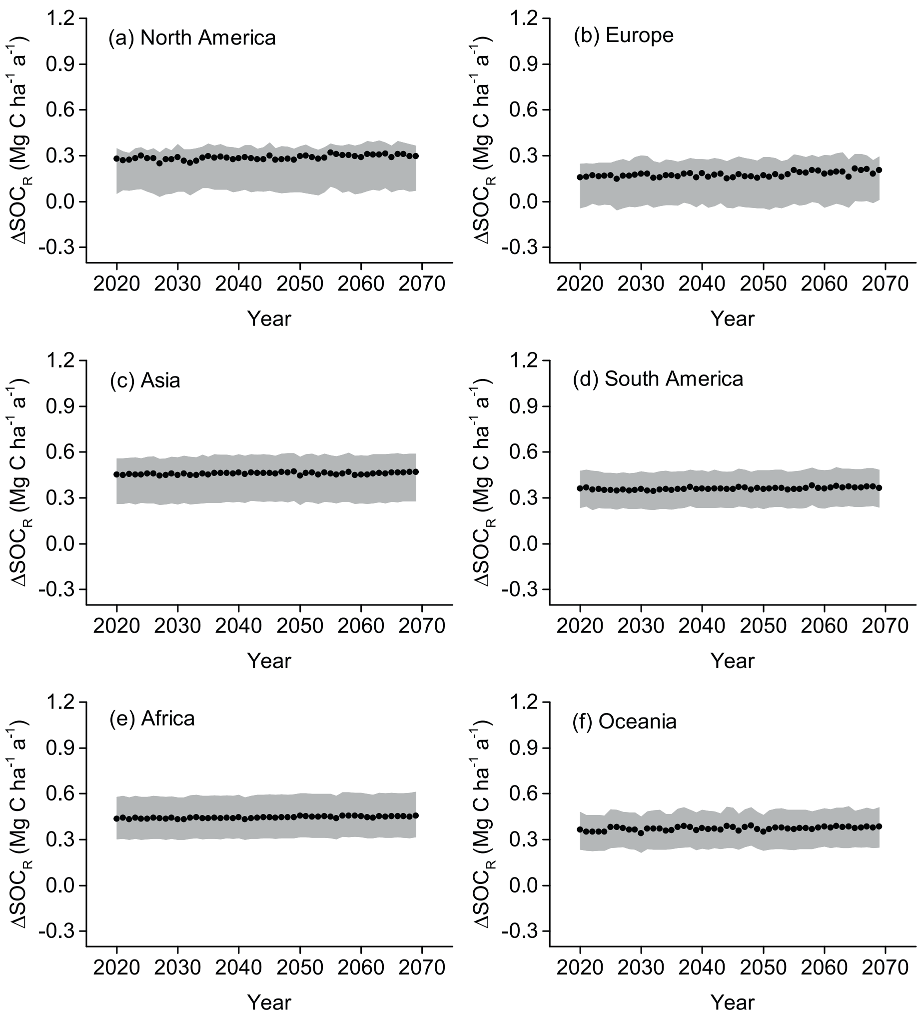

Fig. 2. Estimates of ΔSOC_R (Mg C ha^{-1} a^{-1}) on each continent under RCP4.5. The ΔSOC_R values of all continents showed significant increasing trends ($P < 0.01$) over time.

cropland soil C stocks of the ten countries accounted for approximately 58% of the global C stock. Among them, India contributed the most, at approximately 23%, while Canada and Russia contributed the least, at no more than 2%.

We first used a data-oriented approach to evaluate the potential impact of conservation practices on soil C sequestration over the next 50 years. Limited by the availability of observation and input data, the simulations were subject to high uncertainties. First, soil C saturation was not considered in this simulation. Since soil C saturation was probably reached in various systems during the periods in which the field studies occurred, it was not possible to identify a saturation year or annual sequestration rate by not reporting annual SOC changes, and the soil C saturation under no-till practices is challenging and complex due to its high dependence on the C saturation of conventional tillage [7]. Thus, the regional soil C saturation under no-till conditions remains uncertain with the existing datasets and was therefore is not considered in this study. Second, because of data availability constraints, our model did not account for the influence of the initial SOC content. Recent research has indicated that in areas experiencing drought, with a soil pH $\geq$ 7.3 and initial SOC $\leq$ 10 g kg^{-1} in China, the optimal SOC and crop yield could be achieved when conservation practices were implemented continuously for more than 10 years, with nitrogen input levels varying between 100 and 200 kg ha^{-1} [11].

Furthermore, we focused on C sequestration within the 0–30 cm layer. While changes in SOC mainly occur in the tillage layer, studies suggest that changes in deep soil C should not be ignored. In the initial years of conservation tillage, SOC decreases mainly due to an increase in surface SOC storage and a reduction in deep-layer SOC storage. However, over time, the SOC loss in no-tillage systems gradually decreases, with the net change approaching zero after 14 years [12]. Long-term field experiments have also indicated that no-till under residue incorporation, relative to plow tillage, exerts a minimal impact on soil C storage at depths of 0–50 cm [13]. Agricultural management practices are complex on a global scale, and future research should focus on the impact of long-term implementation of conservation agriculture on SOC change.

Our results are crucial for understanding the potential of soil carbon sequestration under global conservation agriculture and climate change mitigation. Achieving this potential depends on climatic conditions, socioeconomic contexts, adaptation strategies, and risk management practices. Applying these findings in practice requires collaborative initiatives among farmers, policy-makers, and stakeholders, including farmer training, gap identification, and adoption [14,15]. Further research should focus on areas at risk of both carbon loss and yield reduction to achieve a win-win outcome of SOC sequestration and enhanced agricultural productivity following adoption in the future.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

This work was supported by the National Key R&D Program of China (2022YFD1901604), and the National Natural Science Foundation of China (41901069, 42171064). We thank Drs. Pep Canadell and Tony Fischer in CSIRO, Australia for their helpful comments that led to the improvement of this paper.

Author contributions

Qing Zhang and Wen Zhang designed the research. Lijun Yu and Jingjing Liu analysed data. Lijun Yu and Wenjuan Sun prepared the manuscript.

Appendix A. Supplementary materials

Supplementary materials to this short communication can be found online at https://doi.org/10.1016/j.scib.2024.03.021.

References

[1] Cao M, Tian Y, Wu K, et al. Future land-use change and its impact on terrestrial ecosystem carbon pool evolution along the Silk Road under SDG scenarios. Sci Bull 2023;68:740–9.
[2] Graham MW, Thomas RQ, Lombardozzi DL, et al. Modest capacity of no-till farming to offset emissions over 21st century. Environ Res Lett 2021;16:054055.
[3] Briedis C, de Moraes Sá JC, Caires EF, et al. Soil organic matter pools and carbon-protection mechanisms in aggregate classes influenced by surface liming in a no-till system. Geoderma 2012;170:80–8.
[4] Six J, Bossuyt H, Degryze S, et al. A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. Soil Tillage Res 2004;79:7–31.
[5] Ogle SM, Breidt FJ, Paustian K. Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. Biogeochemistry 2005;72:87–121.
[6] Ogle SM, Swan A, Paustian K. No-till management impacts on crop productivity, carbon input and soil carbon sequestration. Agric Ecosyst Environ 2012;149:37–49.
[7] Sun W, Canadell JG, Yu L, et al. Climate drives global soil carbon sequestration and crop yield changes under conservation agriculture. Glob Change Biol 2020;26:3325–35.
[8] Alvarez R. A review of nitrogen fertilizer and conservation tillage effects on soil organic carbon storage. Soil Use Manag 2006;21:38–52.
[9] Lamb A, Green R, Bateman I, et al. The potential for land sparing to offset greenhouse gas emissions from agriculture. Nat Clim Change 2016;6:488–92.
[10] Li Y, Li Z, Cui S, et al. Microbial-derived carbon components are critical for enhancing soil organic carbon in no-tillage croplands: A global perspective. Soil Tillage Res 2021;205:104758.
[11] Lin B, Li R, Liu C, et al. Management-induced changes in soil organic carbon and related crop yield dynamics in China's cropland. Glob Change Biol 2023;29:3575–90.
[12] Cai A, Han T, Ren T, Sanderman J, et al. Declines in soil carbon storage under no tillage can be alleviated in the long run. Geoderma 2022;425:116028.
[13] Zhang X, Wang J, Feng X, et al. Effects of tillage on soil organic carbon and crop yield under straw return. Agr Ecosyst Environ 2023;354:108543.
[14] Jat ML, Chakraborty D, Ladha JK, et al. Conservation agriculture for sustainable intensification in South Asia. Nat Sustain 2020;3:336–43.
[15] Khangura R, Ferris D, Wagg C, et al. Regenerative agriculture—A literature review on the practices and mechanisms used to improve soil health. Sustainability-basel 2023;15:2338.

Lijun Yu is a postdoctoral researcher at the Institute of Atmospheric Physics, Chinese Academy of Sciences. Her research focuses on simulating the carbon cycle of terrestrial ecosystems, with a particular emphasis on the impacts of climate change and human activities on the carbon budgets of agroecosystem, forest and grassland ecosystem.

Qing Zhang is an associate professor at the Institute of Atmospheric Physics, Chinese Academy of Sciences. Her research interest involves climate change, carbon cycle, terrestrial biosphere model, focusing on field observation and the establishment, improvement, and evaluation of ecosystem models.