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Declines in soil carbon storage under no tillage can be alleviated in the long run

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A R T I C L E I N F O

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A B S T R A C T

Improved management of agricultural soils plays a critical role in mitigating climate change. We studied the temporal effects of the adoption of no-tillage (NT) management, often touted as an important carbon sequestration strategy, on soil organic carbon (SOC) storage in surface and subsurface soil layers by performing a meta-analysis of 1061 pairs of published experimental data comparing NT and conventional tillage (CT). In the early years of adoption, NT increased surface (0–10 cm) SOC storage compared to CT but reduced it in deeper layers leading to a decrease of SOC in the entire soil profile. These NT-driven SOC losses diminished over time and the net change was approaching zero at 14 years. Our findings demonstrate that NT is not a simple guaranteed solution for drawing down atmospheric CO_2 and regenerating the lost SOC in cropping soils globally and highlight the importance of long-term NT for the recovery of initial SOC losses.

Mitigating global greenhouse gas (GHG) emissions and climate change is a grand challenge to mankind. Agriculture is the second-largest source of GHGs with annual GHG emissions of 9.3 Gt CO_2 equivalent (Tubiello and Conchedda, 2021). The historical carbon (C) loss from global cropping soils has not only contributed to increased GHG emissions and ongoing climate change but also threatened food production and worsened water quality, biodiversity, and many other ecosystem services (Sanderman et al., 2017). Whether agricultural technological innovations and conservation-based management shifts can reverse this trend remains highly uncertain.

No-tillage (NT) farming is a major agricultural development in the last few decades and has been widely promoted as a universal soil health principle. NT can potentially save costs, reduce fossil fuel consumption, soil erosion, and other negative impacts on soil health caused by tillage practices, and slow soil C turnover (Kan et al., 2021). The effect of NT is mainly achieved by technological innovations such as NT planters and a combination of genetically-modified seeds and agrochemicals. Despite numerous studies that have reported SOC sequestration achieved by NT, whether it is a reliable SOC sequestration strategy globally, in the long run, remains highly contentious (Cusser et al., 2020; Powlson et al., 2014).

Accurate assessment of SOC sequestration under NT requires long-term monitoring of SOC changes of the entire soil profile, rather than merely the surface layers, where most existing research has focused on and increases in SOC storage were usually reported (Powlson et al., 2014). Studies on SOC storage that explored deeper soil layers, despite the scarcity of numbers, often indicate an opposite trend. The reasons for the vertical discrepancies are unclear, but may be due to the absence of mixing topsoil layers which receive most of the carbon inputs to the soil with deeper, soil carbon depleted layers, which usually occurs in tilled soils. This points to a great uncertainty of the actual SOC sequestration potential by NT. In addition, despite the highly variable duration of NT

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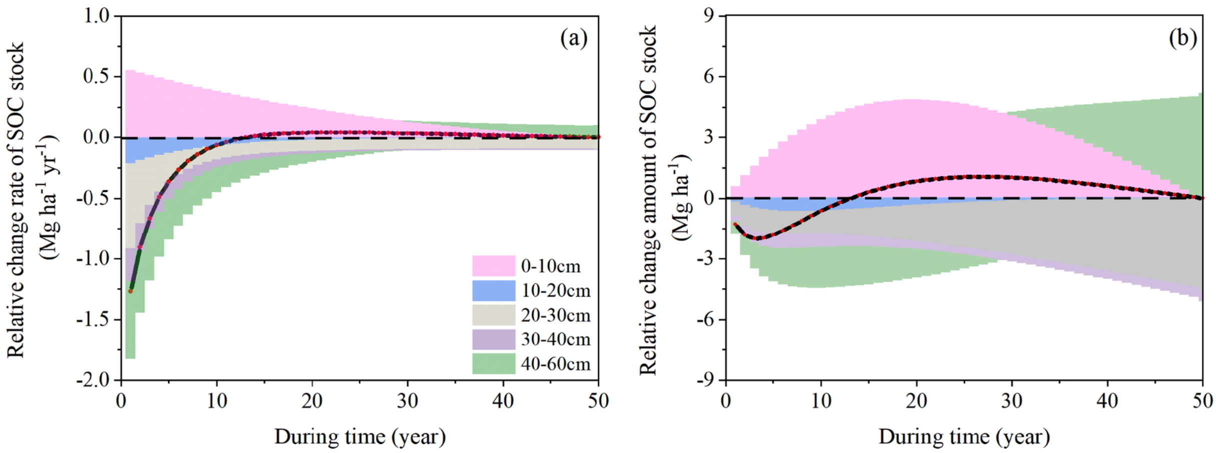

Fig. 1. The effect of no-tillage on the relative change rate (a) and relative change amount (b) soil organic carbon (SOC) storage compared with conventional tillage.

vs. CT comparisons in existing literature, spanning from 1 to 50 years, a comprehensive analysis of the temporal patterns of SOC changes under NT in the entire soil profile is lacking, limiting our ability to inform current policies regarding climate change mitigation.

Here we conducted a meta-analysis, drawing data from published studies around the world that investigated SOC sequestration under NT vs. CT (1061 paired comparisons from 144 studies). We assessed the time series of relative changes of SOC sequestration (NT vs. CT) of individual layers and the entire soil profile (Supplementary). NT increased SOC storage at the soil surface (0–10 cm, 3.47 Mg ha^{-1}) relative to CT but reduced it in deeper soil layers (10–60 cm,) ranging from −0.28 to −2.29 Mg ha^{-1}, resulting in slightly reduced total SOC storage in the entire soil profile (−0.24 Mg ha^{-1}) compared with CT (Supplementary Fig. 4). No difference in SOC storage was found between NT and CT below 60 cm. These results suggested that the increase and decrease in SOC storage due to NT should be considered simultaneously to properly assess the soil carbon sequestration effect of NT (Supplementary Fig. 5). Critically, the relative SOC increases in the surface soil and decreases at depth under NT relative to CT diminished over time (Supplementary Fig. 6), indicating that NT-driven SOC changes diminished over time. As a result, the net SOC sequestration of the 0–60 cm soil profile was approaching zero when the experimental duration was 14 years (Fig. 1).

These results clearly demonstrate that SOC sequestration under NT was limited to the surface soil and was only visible in the early years of adoption. When deeper soil layers were accounted for, NT led to decreases in SOC storage in the entire soil profile compared with CT, although these decreases were alleviated over time. After 14 years, the variations of entire soil profile SOC changes under NT stayed in a narrow range (0 Mg ha^{-1} to 1.07 Mg ha^{-1}). These results suggest that long-term effects of NT on SOC sequestration may not be significant and sequestration estimates based on surface soil data only, such as IPCC emission factors and output from widely used agro-ecosystem carbon models such as Daycent and DNDC, usually only accounting for 0 to 15 or 20 cm depth, are misleading (Lu et al., 2009).

SOC storage is regulated interactively by plant C inputs, soil microbial activity, and soil mineral matrix, with climate exerting first-order controls on biological activity. Although the underlying mechanisms of SOC dynamics under NT are inherently complex, a combination of changes in physical, chemical, and biological related kinetic processes may have contributed to the observed patterns (Bai et al., 2019). Increases in SOC storage at the surface and decreases at depth following the adoption of NT were not necessarily surprising, due to slower incorporation of crop residue into the deeper soil layers under NT (Six et al., 2004). The possible increased soil compaction and stratification due to NT may limit root growth and the amount of plant C inputs into deeper soil layers (Martínez et al., 2008). NT may be reducing C accumulation at depth by influencing on the dominant flow, heat conduction and soil biodiversity. SOC storage of soil layers > 60 cm was not significantly affected by tillage treatments since this is below the plough layer. The SOC changes at 0–10 and 10–60 cm soil layers, however, regulated by the above-mentioned processes, will eventually reach a new equilibrium controlled by climate and edaphic conditions. This is supported by the fact that mean annual precipitation, together with initial SOC concentration, were the most influential variables on the effect of NT on SOC storage among eight selected variables (Supplementary Fig. 7). Higher mean annual precipitation and lower initial SOC concentration were more beneficial for SOC sequestration under NT compared with CT, suggesting potential targeted areas where NT can lead to best outcomes of SOC sequestration at regional scales (Sun et al., 2020).

Our analysis provides strong evidence that NT has limited benefits in atmospheric CO_2 drawdown and SOC sequestration. While the adoption of NT has important soil health and agronomic benefits, including reducing soil erosion and runoff, improving soil structure and water retention, and reducing fuel and labor costs, NT alone should not be promoted as a panacea for climate change mitigation.

Data availability statement

All data related to this manuscript are available from the Dryad Digital Repository: https://figshare.com/s/2ce3ca0f7446f9efc4d8.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2022.116028.

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