


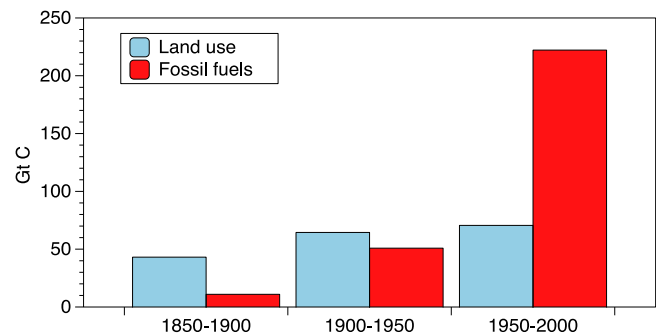
# The Pandora's box of soil carbon

Ronald Amundson<sup>a,1</sup> 

Earth scientists find themselves within an unsettling time-frame in history, where they are discovering the human impacts on the climate system while, at the same time, being under considerable societal pressure to develop ways to remediate it. Until sometime in the 20th century, the combined effects of land use—both biomass removal and soil carbon oxidation through farming—were the largest source of emissions to the atmosphere (1) (Fig. 1), and, even today, they represent roughly 10% of net emissions. Given the 133-Gt soil carbon deficit that has accrued over time (2), it is to be expected that, beginning about 20 y ago (e.g., ref. 3), proposals for repaying this carbon debt, through enhanced farming practices, began to emerge as a climate mitigation strategy. In the intervening time, more and longer-term studies have emerged, somewhat tempering the optimism for this strategy (e.g., refs. 4–6). In a significant, multidecadal research study established on the former prairie landscape of southern Wisconsin, Rui et al. (7) find that tillage and cultivar practices commonly proposed to regain soil C had minimal impacts, and that the only mechanism that began to repay the soil C debt, in the upper 30 cm, was the conversion of the plots back to permanent grassland.

The amount of carbon in soils is the balance between plant inputs and the annual loss, by microbial respiration, of CO<sub>2</sub>. In most climatically stable native systems, this balance is close to a steady state. But soils are complex biochemical systems, and the cultivation of these systems unleashes an array of unintended consequences, including the rapid decline, in less than a century, of around 50% of a soil's C. Like the mythical Pandora's box, it is, unfortunately, easier to let the C out of soil than to put it back in. The Wisconsin Integrated Cropping Systems Trial (WICST) was started in 1989 to examine how alternative cropping systems perform on the loess landscapes of this region. Included among the treatments are some of those commonly suggested for gradually replacing soil C stocks in US row-crop agriculture: minimum tillage of corn and soybean as well as organic crop rotations. Included in the initial experiment was a managed permanent grassland treatment. In 1999, three native grassland treatments were also installed (not part of the study here). The paper by Rui et al. (7) focuses on the differences between treatments after 29 y, revealing that only the permanent pasture had somewhat higher soil C (both in concentration [Fig. 2A] and mass) than the other treatments. The addition of data collected at the start of the experiment, and again in 2009 by Sanford et al. (8), reveals the sluggish nature of C change over time (Fig. 2A).

A serious problem with C sequestration efforts is knowing the local natural "limit" to soil C imposed by the local environmental boundary conditions (9). There are no datasets for uncultivated Plano soils that underlie the research site, so we do not know the original C baseline.



**Fig. 1.** Fifty-year windows of integrated C emissions from land use versus fossil fuel emissions. Data are from ref. 18.

The C contents for the experiments fall within the range of soil C found in three nearby soils sampled in 1962 by the Natural Resource Conservation Service (NRCS) (Fig. 2A), although, of course, these sites likely had approximately a century of use before sampling, and thus may represent the regional "new normal."

The slowness of the C recovery might be attributed to the challenges of capturing C while simultaneously working the land for crop or forage production. However, in a unique long-term prairie restoration study just 15 km south (near Madison, WI), soil C in a 69-y-old restored prairie remained at about 1/2 that of an adjacent prairie remnant (10). It seems that, at least in this region of Wisconsin, restoring significant amounts of preagricultural soil C is a long-term proposition.

One of the important recommendations of recent research is the need for deep soil monitoring (to a meter or more) to accurately capture the total net soil C changes under differing managements. This is needed because agricultural practices change rooting depths of plants, and also change the depth of surficial inputs (due to tillage). Rui et al. (7), unfortunately, only report total, mineral-associated, and particulate C to a depth of 30 cm. However, Sanford et al. (8) measured soil C at the WICST site to a depth of 90 cm, and found that all treatments in the WICST lost C below the upper 15 cm over the initial 20 y of the trial (Fig. 2B). Annual crops, and some of the cultivars chosen for the pasture mix, do not have the same deep rooting systems as the native grassland species, which

Author affiliations: <sup>a</sup>Department of Environmental Science, Policy and Management, University of California, Berkeley, CA 94720

Author contributions: R.A. wrote the paper.

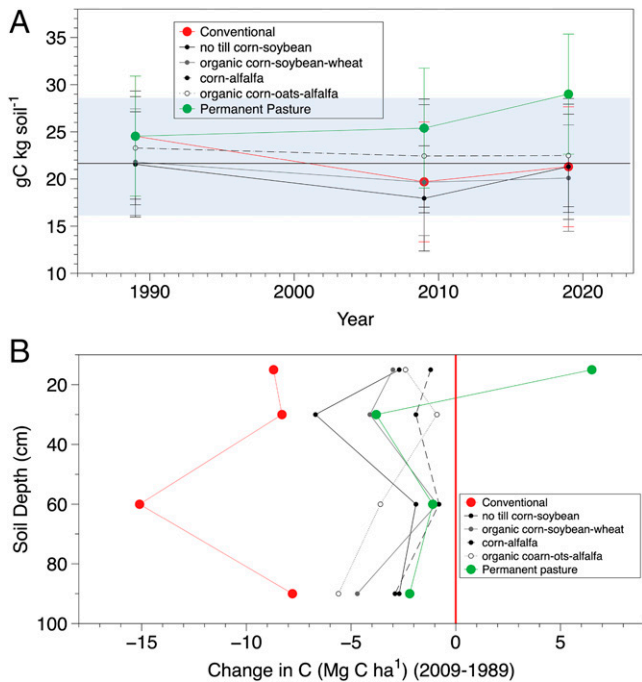
The author declares no competing interest.

Copyright © 2022 the Author(s). Published by PNAS. This article is distributed under Creative Commons Attribution-NonCommercial-NoDerivatives License 4.0 (CC BY-NC-ND).

See companion article, "Persistent soil carbon enhanced in Mollisols by well-managed grasslands but not annual grain or dairy forage cropping systems," [10.1073/pnas.2118931119](https://doi.org/10.1073/pnas.2118931119).

<sup>1</sup>Email: [earthy@berkeley.edu](mailto:earthy@berkeley.edu).

Published March 8, 2022.



**Fig. 2.** (A) The C concentration in the upper 30 cm of the six major treatments in the WICST (7, 8). An uncertainty of 26% is used, based on estimates from Sanford et al. (8). The solid line is the average of three soils sampled by the NRCS in 1962 in the vicinity of the study, and the shaded region represents the SD. (B) Change in soil profile C storage in the first 10 y of the study (data are from ref. 8).

appears to be important for deep storage. Total C inputs per year do not seem to be the sole driving force for losses, or for the slow recovery. The native prairie near Madison is reported to have an aboveground C input of  $2,710 \pm 51$  kg C·ha<sup>-1</sup>·y<sup>-1</sup> and belowground C input of  $4,880 \pm 106$  kg C·ha<sup>-1</sup>·y<sup>-1</sup>, while those of the cropping systems in the WICST are  $2,240$  kg C·ha<sup>-1</sup>·y<sup>-1</sup> to  $3,800$  kg C·ha<sup>-1</sup>·y<sup>-1</sup> and  $1,200$  kg C·ha<sup>-1</sup>·y<sup>-1</sup> to  $4,570$  kg C·ha<sup>-1</sup>·y<sup>-1</sup> for aboveground and belowground C inputs, respectively (8).

The mechanisms for the small gains in soil C in the upper 30 cm of the managed pasture treatment are investigated by Rui et al. (7), who find a higher amount of the total C associated with soil minerals, along with a higher C use efficiency by soil microbes and a greater microbial necromass production, compared to other treatments. These processes, which likely benefit from the absence of frequent physical disturbance and from the existence of perennial plants, provide hints as to how C slowly returns to perturbed soils after they regain some of their precultivation physical conditions. Indeed, we know that undisturbed soils must physically occlude (from microbes) large amounts of very labile C over thousands of years, based on the very old radiocarbon ages of the large pulse of CO<sub>2</sub> produced by microbes when the soil is first physically disturbed (11).

The challenges, and likely geographical differences, in resequencing lost soil C from agricultural lands beg the

climate mitigation question: If not soil C, what then? Prometheus, the Greek god of unintended consequences (whose spouse, in some versions of the myth, was Pandora), was likely created to explain a cascade of calamities which visited, and continue to visit, humanity as a result of its resourcefulness and innovation. The invention of farming is Promethean in scope, ambition, and consequences (12). The global net C-equivalent emissions for agriculture are roughly  $1.5$  Gt C·y<sup>-1</sup> (13), and soil C is just a part of this overall rate of emission, and a way to reduce it. There are numerous other levers that may reduce these net emissions, although every one of them is, in its own way, a difficult problem. Fossil fuel use for fertilizer production and farm management combined with emissions of N<sub>2</sub>O and CH<sub>4</sub> dominate the farm emissions ledgers (14). For example, at the WICST study site in Wisconsin, emissions of N<sub>2</sub>O from the various treatments release roughly  $300$  kg C-equivalents·ha<sup>-1</sup>·y<sup>-1</sup> to  $1,200$  kg C-equivalents·ha<sup>-1</sup>·y<sup>-1</sup> (15), rates roughly equivalent to rates of soil C sequestration deemed achievable under best management and/or regional conditions (16). Policy and incentives to decarbonize agroindustrial activities are a broad area of opportunity and need, but one that is arguably a socioeconomic problem. The large emissions of greenhouse gases from soil involve management but, ultimately, are a biological issue. Can the new era of gene editing offer opportunities to modify plant and microbial metabolic capabilities that will drive down these emissions? If so, will they be socially acceptable? Will these and other remedies, in turn, produce unintended consequences?

Whether the C sequestration trajectory of the WICST is the rule or one of the exceptions, it forces a consideration of the somewhat Sisyphean activity that soil C science has found itself enmeshed in since C sequestration for climate mitigation was first proposed more than 20 y ago. Presumably, all scientists (and planetary citizens) would love to push 133 Gt of C back into the global soil box. But this just doesn't appear to be an easy or rapid goal to accomplish. Farming is a several-millennia-old experiment, one that remains far removed from perfection. It is a complex system, subject to unexpected feedbacks—including those of a warming planet (17). A scientifically holistic approach to farming has a major opportunity to integrate differing strategies to climatically improve the system as a whole, rather than placing undue emphasis on a single component, organic C.

This underlies the challenge of transforming farming: The complexity of the problem makes it a multigenerational challenge, or even longer. The long-accrued unintended consequences resulting from incursions into complex systems might be partially reversible, but they are not instantaneous. We will continue to need to eat, and the demand for this food will increase. This requires direct use of soil. How we do this, and simultaneously transform this ancient practice, remains uncertain.

1. E. T. Sundquist, The global carbon dioxide budget. *Science* **259**, 934–941 (1993).
2. J. Sanderman, T. Hengl, G. J. Fiske, Soil carbon debt of 12,000 years of human land use. *Proc. Natl. Acad. Sci. U.S.A.* **114**, 9575–9580 (2017).
3. J. P. Bruce et al., Carbon sequestration in soils. *J. Soil Water Conserv.* **54**, 382–389 (1999).
4. C. Palm et al., Conservation agriculture and ecosystem services: An overview. *Agric. Ecosyst. Environ.* **187**, 87–105 (2014).
5. P. Poulton, J. Johnston, A. Macdonald, R. White, D. Powlson, Major limitations to achieving “4 per 1000” increases in soil organic carbon stock in temperate regions: Evidence from long-term experiments at Rothamsted Research, United Kingdom. *Glob. Change Biol.* **24**, 2563–2584 (2018).

6. D. S. Powlson *et al.*, Limited potential of no-till agriculture for climate change mitigation. *Nat. Clim. Chang.* **4**, 678–683 (2014).
7. Y. Rui *et al.*, Persistent soil carbon enhanced in Mollisols by well-managed grasslands but not annual grain or dairy forage cropping systems. *Proc. Natl. Acad. Sci. U.S.A.* **119**, 10.1073/pnas.2118931119 (2022).
8. G. R. Sanford *et al.*, Soil carbon lost from Mollisols of the North Central U.S.A. with 20 years of agricultural best management practices. *Agric. Ecosyst. Environ.* **162**, 68–76 (2012).
9. H. Jenny, *Factors of Soil Formation. A System of Quantitative Pedology* (McGraw-Hill, New York, NY, 1941).
10. C. J. Kucharik, N. J. Fayram, K. N. Cahill, A paired study of prairie carbon stocks, fluxes, and phenology: Comparing the world's oldest prairies restoration with an adjacent remnant. *Glob. Change Biol.* **12**, 122–139 (2006).
11. S. Ewing *et al.*, Role of large-scale soil structure in organic carbon turnover: Evidence from California grasslands. *J. Geophys. Res. Biogeosci.* **111**, G03012 (2006).
12. J. Diamond, Evolution, consequences and future of plant and animal domestication. *Nature* **418**, 700–707 (2002).
13. F. N. Tubiello *et al.*, The contribution of agriculture, forestry and other land use activities to global warming, 1990-2012. *Glob. Change Biol.* **21**, 2655–2660 (2015).
14. R. Amundson, Soil biogeochemistry and the global agricultural footprint. *Soil Security* **6**, 100022 (2022).
15. W. R. Osterholz, C. J. Kucharik, J. L. Hedtcke, J. L. Posner, Seasonal nitrous oxide and methane fluxes from grain- and forage-based production systems in Wisconsin, USA. *J. Environ. Qual.* **43**, 1833–1843 (2014).
16. National Academies of Sciences, Engineering, and Medicine, *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (National Academies Press, Washington, DC, 2019).
17. T. W. Crowther *et al.*, Quantifying global soil carbon losses in response to warming. *Nature* **540**, 104–108 (2016).
18. P. Friedlingstein *et al.*, Global carbon budget 2021. *Earth Syst. Sci. Data*, 10.5194/essd-2021-386 (2021).