Correction

OPINION

Correction for "Opinion: Soil carbon sequestration is an elusive climate mitigation tool," by Ronald Amundson and Léopold Biardeau, which was first published November 13, 2018; 10.1073/pnas.1815901115 (*Proc. Natl. Acad. Sci. U.S.A.* **115**, 11652–11656).

The authors note that, on page 11652, left column, line 9, "10 Gt CO_2" should instead appear as "10 Gt C." The online version has been corrected.

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CORRECTION

OPINION

Soil carbon sequestration is an elusive climate mitigation tool

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The need to stabilize the greenhouse gas concentrations of the atmosphere is the great environmental challenge of this century. To control these concentrations, humanity can reduce fossil fuel emissions and/or identify mechanisms to remove greenhouse gases once they have been emitted. The scope of the problem is challenging because of the size of the fluxes involved. Presently, industry, transportation, and domestic use emits nearly 10 Gt C to the atmosphere annually, and there is no immediate hope for a drastic reversal of these rates of emission (1). Thus, sequestration of atmospheric carbon dioxide as organic carbon in the biosphere attracts attention as an alternate way to help stem the rate of greenhouse gas growth and associated changes in our climate.

For nearly 2 decades, researchers in the soil science community have studied and estimated the potential of sequestering carbon in soil organic matter (2, 3). The premise is inherently rational: nearly 10,000 years of cultivated agriculture has reduced global soil carbon by 116 Gt (4), an amount equivalent to more than a decade of the present rates of industrial emissions. Through changed agricultural techniques, it is proposed, much of this carbon can be restored to domesticated soils and thus serve as a significant tool to mitigate climate change, providing a wider timeframe

Some soil researchers have suggested that altered agricultural techniques can help restore much carbon to domesticated soils, thus helping mitigate climate change. But cultural and scientific challenges suggest that this proposition is overly optimistic and inherently flawed. Image courtesy of ScienceSource/Jerry Irwin.

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for society to decarbonize. Unfortunately, both cultural and scientific challenges suggest that this proposal is overly optimistic and inherently flawed.

Nevertheless, this long and relatively well-funded (5) area of research recently gained novel international exposure because of the unveiling of the French "4 per mille" initiative (6), signed by more than 100 nations at the 21st Conference of the Parties in Paris. According to the French 4 per mille web site:

> If we increase by 4 ‰ (0.4%) a year the quantity of carbon contained in soils, we can halt the annual increase in CO_2 in the atmosphere, which is a major contributor to the greenhouse effect and climate change.

This is indeed physically true—if it can be done. But is it politically and economically possible? The questions surrounding implementation are mostly ignored, or at best are superficially considered, in the scientific and popular press that has followed the announcement of the 4 per mille initiative (7, 8). To be clear, for the 4 per mille initiative to achieve its full objective, it must be implemented immediately on all lands on Earth, and the practices must be sustained without change for decades. This commitment must be achieved in light of the fact that there are 570 million farms globally with an estimated 3 billion rural practitioners who manage these farms (9). Although some researchers have used the French goal simply as an aspirational target and focused on lesser gains as acceptable goals, even these smaller targets also will require support from private landowners.

As we outline below, cultural, economic, and physical barriers mean that soils face dim prospects as major carbon sinks. The problem begins with researcher's sometimes poor understanding of their stakeholders and a lack of appreciation or acknowledgment about the complexity of policy implementation. The discussion here centers on the United States, the area for which we have data and research to inform this discussion. Undoubtedly, social and political differences between nations will mean that potential barriers may indeed be different elsewhere. However, this only further underscores the complexities impeding the implementation of soil carbon sequestration on a global scale.

Science and the Stakeholders

Human value systems are shaped, in part, by our intimate interactions with our families and communities (10). Farmers are among the most conservative people in the United States (11), a value system which places significant importance on personal independence (as opposed to social or societal support programs) and a high regard for authority (as opposed to egalitarian views of authority and a propensity for shared decision making). Many farmers, even those who practice innovative conservation methods, are suspicious of, and even hostile to, environmentally motivated academics and the perceived government intervention that will follow with any environmental initiatives. Many additionally reject the reality that humans are causing climate change (12) and that fossil fuel is inherently a problematic energy source. In a recent California survey of farmers, their greatest concern about climate change was increased government regulations rather than any other perceived climate impact on their operation or production (13). In particular, farmers are skeptical of nonfarmer experts, who are inexperienced or unaware of the economic and regulatory challenges that they face (14).

Academic environmental scientists are largely the value-system opposites of their rural stakeholders. They may fail to recognize that they are inherently viewed with suspicion by the people they may wish to influence. Although farm advisors, who may be members of the local community, may help lower these cultural barriers over environmental policies, the advocacy of "best management practices" by researchers concerned largely with carbon sequestration may have little to offer farmers in dynamic and challenging economic landscapes. It is far more important for researchers to understand people, rather than soil, in the difficult process of communicating environmental risk (15), an activity in which most researchers lack the required expertise.

Who are the stakeholders who actively manage US farmland? In 2012, nearly 40% of the farmland in the United States was operated by renters (Fig. 1). Renters may have less financial incentive to invest in conservation programs that have long-term payoffs or benefits (16–18). Ownership of the land is diverse, and owners may be absentee. By 2030, it is projected that women over the age of 60 will own 75% of the transferred land in the United States (19). Older landowners may see little reason to invest in long-term management strategies (18). Offsite or urban landowners may fail to understand or have any immediate interest in conservation programs that are discussed below.

Cultural, economic, and physical barriers mean that soils face dim prospects as major carbon sinks.

Given the landownership tapestry of US farmland, it is not surprising that adoption of present US government programs related to soil health (which have accessory carbon sequestration benefits) are extremely low: only 2 to 5% of croplands in the United States receive funds under the two largest conservation programs (Fig. 1) (21). In addition to philosophical and economic barriers, farms exceeding $900,000 in income are excluded from receiving conservation support for some programs. The cost of capturing carbon via these existing Natural Resources Conservation Service (NRCS) programs is presently estimated to range between $32 and $442 per ton of CO_2, with an average of $183 per ton (16), although the programs provide other intended environmental benefits.

Policy and Economic Challenges

A significant expansion of carbon sequestration in US farmlands is inhibited by (*i*) large transaction costs

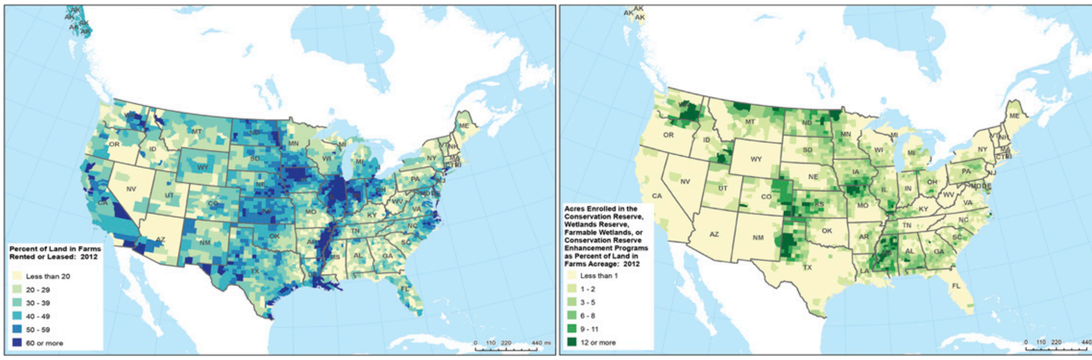

Fig. 1. A map of the percentage of farms operated by renters in the United States (*Left*) and one depicting the percentage of land enrolled in government conservation programs. Data from 2012, taken from ref. 20. Image courtesy of USDA/NASS.

including farmer-based research and planning, as well as associated farm-based investments in new equipment, infrastructure, labor, and management; (*ii*) limits of soil carbon–sequestration science, because the verification of carbon sequestration under various managements is difficult and expensive; (*iii*) a lack of technical assistance to farmers because there is insufficient NRCS staffing to engage and assist farmers in adopting the present conservation programs that are offered (16); and (*iv*) farmer resistance to the intrusion of privacy and government regulations. Additionally, only approximately 2% of farmland is available for sale in a given year (20). We are unaware of any large-scale parcel-level studies evaluating whether farmland prices accurately reflect improvements in soil quality, and it is, thus, unclear whether conservation adaptation translates into higher property values.

These barriers to the implementation of presently offered conservation programs exist in one of the richest nations on Earth, underscoring the challenges that will likely occur in less developed or prosperous nations. Yet, the challenges of landowner/manager buy-in are only tangentially addressed in papers that largely focus on technical potential (8). In cases in which policy options are listed, some are inherently politically problematic (22). Simply, there has not been a research effort focused on the cultural and policy complexities of soil carbon sequestration that matches the level of the effort that has been made on the technical issues. These social science challenges, particularly in the United States, are as challenging as the physical science side of the climate problem itself.

Physical Boundaries

We will not, here, exhaustively review the large body of literature on the physical processes of soil C sequestration under different management techniques. Instead, our goal is to address the issues commonly under-discussed in these projections. One of these is climate change itself. Anthropogenic warming sets in motion a positive feedback loop with soil carbon, which is converted to carbon dioxide by soil microbes responding to increasing temperature (23). There is great concern about the magnitude of this feedback on soils of the northern latitudes (24), but the same physical impacts will be felt by farmland soils. Soil–climate feedback will reduce the magnitude of the maximum sequestration potential of all soils by an uncertain amount (25).

Zomer et al. (26) have estimated that, over the next 20 years, with the full adaptation of best practices, 18 to 37 Gt C could be technically sequestered (a factor of three to six less than the total loss through historical agriculture discussed above). As for soil carbon sources, land clearing is reported to release carbon at about the same rate (26), whereas global soil warming may cause a feedback release of between 100 and 600 Gt (23). These estimates are uncertain in value but not sign. They underscore where monetary and political effort might be most effectively directed to avert serious climate change: reduce the rate of land clearing and rapidly transition from fossil fuel emissions, both of which will help avert a largely uncontrollable feedback in the global soil carbon system.

Mitigation Versus Adaptation

We fully agree with soil carbon sequestration advocates that any carbon sequestered is a good thing, and soils can indeed regain some carbon. However, the promotion of this method to significantly alleviate our carbon dioxide imbalance is somewhat irresponsible and has political implications. The suggestion that soil carbon sequestration may be a "bridge" serves only as a reason to yet further delay action (27).

Pursuing soil carbon as a climate-mitigation strategy could have an impact on scientific credibility. By not fully considering the barriers that inhibit implementation, some in the soil science community may be committing to an unachievable goal. More than a decade ago, Smith et al. (28) clearly stated this:

> Given the recognized biological, economic, social, political and institutional constraints on the implementation of soil carbon sequestration measures, the scale of carbon sequestration in agriculture will rely more upon overcoming these constraints than upon filling in gaps in our scientific and technical knowledge.

They noted there is a large gap between the maximum physical potential and that achievable in a

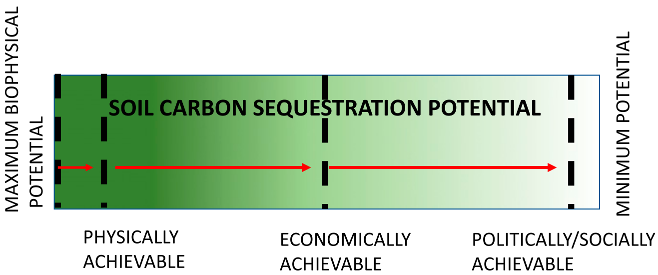

Fig. 2. **An illustration of the various impediments to maximum versus achievable soil carbon sequestration due to physical and socioeconomic controls. Modified from ref. 29, © 2004 Scientific Committee on Problems of the Environment (SCOPE), with permission by Island Press, Washington, DC.**

complex society (Fig. 2). The present status of soil carbon sequestration a decade later seems unchanged, given a lack of significant progress in the related social science issues and the ever-changing political climate in the nation.

Although soils are seemingly unlikely to help us remediate climate change, they are almost essential for us to survive it. In the soil–climate research arena, the current emphasis on carbon sequestration as the primary goal—with ancillary improvements in water management, soil erosion, and food security—seems almost inverted in its prioritization. Better soil carbon management is best placed within a framework of a multifaceted effort to further improve farming methods in this century. The scientific opportunity, and societal challenge, for soil science is leading research that adapts soils and agriculture to a rapidly changing climate, allowing them to continue to produce food in a changing world. However, even this research will be subject to cultural and political scrutiny.

Recognizing that many farmers are concerned about "weather" much more than climate change (12, 13) will help researchers—and scientific extension specialists—frame approaches that are more readily adaptable and acceptable. If some carbon is sequestered in this effort, so much the better. But it should not drive our soil research agenda. As researchers, we may speak of "climate-smart soils" (22) centered on their greenhouse gas balances. But for farmers, we might be much more successful to frame the problem as "weather-proofing soils," with an enhanced ability to store water, recycle nutrients, and produce new types of crops in a changing, growing environment. The wins in the win–win situation of soil carbon sequestration should likely be reversed and the goals of our present research reevaluated to achieve maximum societal impact.

1 Jackson RB, et al. (2017) Warning signs for stabilizing CO_2 emissions. *Environ Res Lett* 12:110202.
2 Lal R (1999) Soil management and restoration for C sequestration to mitigate the accelerated greenhouse effect. *Prog Environ Sci* 1:307–326.
3 Lal R (2001) Potential of desertification control to sequester carbon and mitigate the greenhouse effect. *Clim Change* 15:35–72.
4 Sanderman J, Hengl T, Fiske GJ (2017) Soil carbon debt of 12,000 years of human land use. *Proc Natl Acad Sci USA* 114:9575–9580.
5 US Department of Energy (2016) ARPA-E Announces $70 Million in Funding for New Programs to Power Transportation and Store Carbon in Soil. Available at https://www.energy.gov/articles/arpa-e-announces-70-million-funding-new-programs-power-transportation-and-store-carbon-soil. Accessed September 15, 2018.
6 4p1000 "4 Per 1000" Initiative. Available at https://www.4p1000.org. Accessed September 15, 2018.
7 Lal R (2016) Beyond COP 21: Potential and challenges of the "4 per Thousand" initiative. *J Soil Water Conserv* 71:20A–25A.
8 Minasny B, et al. (2017) Soil carbon 4 per mille. *Geoderma* 292:59–86.
9 FAO (2014) The state of food and agriculture in 2014: In brief. Available at www.fao.org/3/a-i4036e.pdf. Accessed July 15, 2018.
10 Mooney C (2012) *The Republican Brain: The Science of Why They Deny Science—and Reality* (Wiley, New York), p 327.
11 Verdant Labs (2016) Democratic vs. Republican Occupations. Available at verdantlabs.com/politics_of_professions/index.html. Accessed September 15, 2018.
12 Rejesus RM, Mutuc-Hensley M, Mitchell PD, Coble KH, Knight TO (2013) U.S. agricultural producer perceptions of climate change. *J Agric Appl Econ* 45:701–718.
13 Jackson L, et al. (2012) Adaptation Strategies for Agricultural Sustainability in Yolo County, California. (California Energy Commission, Sacramento, CA). Publ No CEC-500-2012-032.
14 Tabuchi H January 28, 2017) In America's heartland, discussing climate change without saying "climate change." *NY Times*. Available at https://www.nytimes.com/2017/01/28/business/energy-environment/navigating-climate-change-in-americas-heartland.html. Accessed September 15, 2018.
15 Kahan D (2010) Fixing the communications failure. *Nature* 463:296–297.
16 Biardeau L, Crebbin-Coates R, Keerati R, Litke S, Rodríguez H (2016) Soil Health and Carbon Sequestration in US Croplands: A Policy Analysis. Available at https://food.berkeley.edu/wp-content/uploads/2016/05/GSPPCarbon_03052016_FINAL.pdf. Accessed September 15, 2018.
17 Carolan MS (2005) Barriers to the adoption of sustainable agriculture on rented land: An examination of contesting social fields. *Rural Sociol* 70:387–413.
18 Feathersteon AM, Goodwin BK (1993) Factors influencing a farmer's decision to invest in long-term conservation improvements. *Land Econ* 69:67–81.
19 Petrzelka P, Sorenson A (2014) *Women Non-Operating Landowners: Overcoming Barriers to Increasing Conservation on Leased Farmland Preliminary Report* (American Farmland Trust, DeKalb, IL).

20 Nickerson CJ, Zhang W (2013) Modeling the determinants of farmland values in the United States. *The Oxford Handbook of Land Economics*, eds Duke J, Wu J (Oxford Univ Press, London), pp 111–138.
21 United States Department of Agriculture (2012) Ag Census Web Maps. Available at https://www.agcensus.usda.gov/Publications/2012/Online_Resources/Ag_Census_Web_Maps. Accessed September 18, 2018.
22 Paustian K, et al. (2016) Climate-smart soils. *Nature* 532:49–57.
23 Amundson R, et al. (2015) Soil science. Soil and human security in the 21st century. *Science* 348:1261071.
24 Koven CD, Hugelius G, Lawrence DM, Wieder WR (2017) Higher climatological temperature sensitivity of soil carbon in cold than warm climates. *Nat Clim Change* 7:817–822.
25 Meersmans J, et al. (2016) Future C loss in mid-latitude mineral soils: Climate change exceeds land use mitigation potential in France. *Sci Rep* 6:35798 10.1038/srep35798.
26 Zomer RJ, Bossio DA, Sommer R, Verchot LV (2017) Global sequestration potential of increased organic carbon in cropland soils. *Sci Rep* 7:15554.
27 Anderson K (2015) Duality in climate science. *Nat Geosci* 8:898–900.
28 Smith P, et al. (2005) Carbon sequestration potential in European croplands has been overestimated. *Glob Change Biol* 11:2153–2163.
29 Field CB, Raupach MR, eds (2004) *The Global Carbon Cycle: Integrating Humans, Climate and the Natural Word* (Island Press, Washington, DC).