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OPINION

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Managing for soil carbon sequestration: Let's get realistic

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Abstract

Improved soil management is increasingly pursued to ensure food security for the world's rising global population, with the ancillary benefit of storing carbon in soils to lower the threat of climate change. While all increments to soil organic matter are laudable, we suggest caution in ascribing large, potential climate change mitigation to enhanced soil management. We find that the most promising techniques, including applications of biochar and enhanced silicate weathering, collectively are not likely to balance more than 5% of annual emissions of CO_2 from fossil fuel combustion.

KEYWORDS

biochar, carbon sequestration, climate change, silicate weathering, soil organic carbon

The long decline in the stock of soil organic matter began with the first furrow of human cultivation and is now estimated to have contributed 116 Pg of carbon (as CO_2) to the atmosphere and smaller amounts of organic carbon to marine and freshwater sediments (Sanderman, Hengl, & Fiske, 2017). Currently, losses of soil organic matter continue with the areal expansion of agriculture, especially in the Amazon basin (Assad et al., 2013; Don, Schumacher, & Freibauer, 2011). Along with methane from cattle and nitrous oxide from fertilizers, CO_2 from soils is a major agricultural by-product, changing our climate as we attempt to feed the global population of 7.6 billion people.

Minasny et al. (2017) consider the 4 per mille initiative—that is, raising the content of soil organic matter by 0.4% per year—as an optimistic and aspirational challenge to maintain and improve soil health and provide food security for the world's peoples. An ancillary benefit of this program would be to increase the removal of carbon dioxide from the atmosphere and increase its rate of storage in soil organic matter, providing a mitigation of global climate change. They suggest that this storage would "effectively offset 20%–35% of global anthropogenic greenhouse gas emissions." The proposal has been criticized on technical and political grounds, but defended vigorously by its proponents (Minasny & McBratney, 2018). Here, we argue that the potential mitigation of climate warming by improved soil management, while laudable, is likely to be very limited and is distracting to policy makers who must focus on the enormity of the climate change problem driven by fossil fuel combustion.

Soil science knows of ways to reduce the ongoing losses of soil organic matter and to reduce the emissions of greenhouse gases to the atmosphere. Unfortunately, many of these management practices produce ancillary emissions, such as CO_2 from the pumping of irrigation water and from the off-site manufacture of fertilizer (McGill, Hamilton, Millar, & Robertson, 2018; Schlesinger, 2000). Others, such as conservation tillage, reduce the emissions from agricultural machinery (West & Marland, 2002), but with only limited success in increasing the storage of carbon in soils (Powlson et al., 2014). Conversion to no-till practice on the lands under corn–soybean cropping rotation could sequester about 2% of the annual anthropogenic emissions of CO_2 emissions in the United States (Bernacchi, Hollinger, & Meyers, 2005). Decades of improved agronomy have reduced, but not eliminated, the role of agriculture as a source of CO_2 to the atmosphere (Emmel et al., 2018; West et al., 2010).

Smith et al. (2008) estimate 1.6 Pg C/year as the maximum potential for enhanced agricultural management to mitigate CO_2 emissions to the atmosphere, whereas Zomer, Bossio, Sommer, and Verchot (2017) estimate potential storage of 0.90–1.85 Pg C/year in croplands. At 2.45 Pg C/year, a recent new estimate by Lal (2018) is slightly more optimistic. A separate analysis by scientists organized by the Nature Conservancy suggests that better soil management,

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within economic constraints, might store 0.41 Pg C/year, about 16% of the technical potential and only a small fraction (~4%) of our current fossil fuel emissions (Griscom et al., 2017).

The “4 per mille” initiative was derived by dividing the current fossil fuel emissions (9 Pg C/year) by the estimated pool of organic matter in world soils (2,400 Pg C). The implication is that we could balance our annual fossil fuel emissions by incrementing the organic carbon in all soils by 0.4‰ per year. Because vast areas of land are covered by desert, which has little potential for carbon sequestration, or “northern” soils, which are destined to lose large stores of soil carbon due to climatic warming, the available land area to add 9 Pg C/year (4‰ per year) to current stocks of soil organic matter is confined to about half of the world's land surface—40% under unmanaged vegetation and 10% in cropland (Schlesinger and Bernhardt 2013).

On abandoned agricultural lands, soil organic matter can accumulate at rates of 10–30 g C m^{-2} $year^{-1}$ over decadal periods (Post & Kwon, 2000). Under intensive management, accumulations of 100–300 g C m^{-2} $year^{-1}$ have been reported in grasslands (Ryals & Silver, 2013). Long-term accumulations of soil organic matter under natural vegetation are lower, averaging about 2.4 g C m^{-2} $year^{-1}$ or 0.4 Pg C/year globally (Schlesinger, 1990; Zehetner, 2010). To replicate the effects of rising CO_2 in Earth's atmosphere, experimental manipulations of atmospheric CO_2 have resulted in only small or no net incremental accumulations of carbon in soil organic matter under forests (Jastrow et al., 2005; Lichter et al., 2008) and agriculture (Peralta & Wander, 2008; Torbert, Rogers, Prior, Schlesinger, & Runion, 1997). Under experimental or natural increases in soil temperature to replicate future conditions, agricultural and forest soils have shown large losses of soil organic matter (Bellamy, Loveland, Bradley, Lark, & Kirk, 2005; Heikkinen, Ketoja, Nuutinen, & Regina, 2013; Melillo et al., 2017).

Active management of agricultural soils may reduce the losses of soil organic matter, but full life cycle analyses for fertilized and irrigated soils seldom show net carbon sequestration (McGill et al., 2018), and manuring simply redistributes plant inputs from areas that are grazed to areas that receive amendments (Owen, Parton, & Silver, 2015). Production of nitrogen fertilizer is estimated to contribute 2%–3% of the anthropogenic additions of CO_2 to Earth's atmosphere, an amount matched by the acidification of carbonate-rich agricultural soils by nitrifying bacteria (Zamanian, Zarebanadkouki, & Kuzyakov, 2018).

Additions of biochar can result in net carbon storage, amounting to about 2% of global fossil fuel usage annually (Griscom et al., 2017), calculated as follows: Wolf et al. (2015) indicate that each year about 3.3 Pg of dry matter are generated as agricultural waste in croplands worldwide. Assuming that these residues have 45% carbon content and that 30% of the residues worldwide are gathered for pyrolysis, the amount of residues available to make biochar each year would contain 0.44 Pg of carbon, noting that in some areas it is better to leave residues for erosion control and for the maintenance of soil organic matter. If 50% of the carbon is emitted as CO_2 during pyrolysis and 50% is captured in biochar and we assume that 80% of the carbon captured in the char is stable, then about 0.18 Pg of carbon per year might be sequestered in the soil using biochar, at an estimated marginal cost of >$100/ton (Griscom et al., 2017). In an alternative analysis, Smith (2016) suggests enhanced soil carbon storage from biochar applications could store 0.7 Pg C/year, with widespread adoption.

Another recent suggestion is to add ground silicate minerals to soils to stimulate carbon sequestration via chemical weathering (Beerling et al., 2017), viz.

$$CaSiO_3 + 2CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^- + SiO_2.$$

This approach should be evaluated in light of the results from an experimental addition of 3.5 tons/ha of a calcium silicate mineral, wollastonite, to the soils at the Hubbard Brook Forest in New Hampshire (Shao et al., 2016). After 11 years, only 4.7% of the Ca had been exported, equivalent to 139 mmol/m^2, resulting in 3.4 g C m^{-2} $year^{-1}$ of carbon sequestration via HCO_3^- in runoff waters (see Supporting Information Appendix S1). This net sequestration represents a doubling of the natural rate of bicarbonate removal in runoff waters from this watershed. Globally, silicate weathering removes 0.2–0.3 Pg C/year (Hilley & Porder, 2008; Suchet & Probst, 1995) an equivalent of 2.5% of fossil fuel CO_2 emissions to the atmosphere annually. Doubling this rate by adding ground silicate rock to all soils of the world, discounted by up to 30% to account for the CO_2 emitted during the mining, crushing, and transport of silicate rock (Beerling et al., 2017, cf. Moosdorf, Renforth, & Hartman, 2014), would provide an incremental sink for about 2% of global fossil fuel emissions. Carbon sequestration by the application of wollastonite at Hubbard Brook costs about $10,000/ton of C over the 11-year period, based on recent commodity prices for wollastonite (e.g., https://www.alibaba.com/showroom/wollastonite-price.html.)—far higher than most policies proposed to stimulate carbon sequestration and higher than recent similar calculations (Strefler, Amann, Bauer, Kriegler, & Hartmann, 2018). Hartmann et al. (2013) calculated that the provision of enough silicate minerals to enhance significantly CO_2 uptake by soils would entail a huge increase in the annual transport of material commodities in world trade.

While the technical potential of various forms of C sequestration in soil is attractive, the political reality of massive soil C sequestration is far less certain or even unlikely (Poulton, Johnston, Macdonald, White, & Powlson, 2018). Presently, no coherent economic strategy has been offered that will induce millions of individual farmers to adopt and maintain prescribed practices on multidecadal time scales. When C sequestration emerges in the popular press (Barker & Pollen, 2015; Leslie, 2017; Velasquez-Manoff, 2018), it creates the dangerous impression that we can easily sequester a significant fraction of CO_2 from continuing fossil fuel emissions through better soil management. This illusion contributes to continuing political inertia, and it needs to be balanced by realistic experimental field research that is seldom part of technical soil C sequestration analyses.

In sum, while it is likely that better management of agricultural soils may enhance food production and stem the expected losses of soil organic matter under intensive agriculture, it is extremely unlikely that with better management soils can store carbon at a rate that is at all comparable to the current emissions from fossil fuel combustion. Soil carbon sequestration of 5% of current anthropogenic emissions is certainly helpful, but it represents only a small, contribution to the stabilization of CO_2 concentrations in Earth's atmosphere—a stabilization "wedge" as deemed by Pacala and Socolow (2004).

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