How much can soil organic matter realistically be increased with cropping management in California?

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Introduction

Soil organic carbon (SOC) is one of the most important characteristics of soils that results from the interplay of biogeochemical processes promoted through net primary producers, soil biomass and soil mineralogy. The stabilization of SOC with reactive minerals, particularly clays and short range order and metal oxide minerals, provides for a stable matrix that supports soil structure, increases moisture holding capacity and a source of nutrients for crops. The importance of SOC to support food and fiber production cannot be understated. The outcome of different management practices to support SOC sequestration with the aim of improving soil health and productivity and to mitigate carbon dioxide (CO_2) emissions from land use change and fossil C combustion has become a hot topic in both soil science and policy areas.

Since the Green Revolution and before, the intensity of cropping and soil management has increased considerably. The increase in agronomic management intensity has resulted in soil organic carbon (SOC) loss of up to 50% (Bebi and Brar 2009). Overall, fossil fuel use to support intensification and the long-term conversion of extensive areas of virgin land to agriculture have led to agriculture systems being net contributors to changing the atmospheric composition and climate (Falkowski et al., 2000).

Management to Sequester Carbon

The general consensus on the carbon (C) balance of agricultural land is that SOC loss has dominated as a result of agricultural intensification. The initial loss of SOC was attributed to the "plow effect" where soil disturbance from tillage exposed protected SOC, particularly occluded within aggregates. Other factors discussed or documented in the literature include, 1.) A reduction in crop species diversity, often a monoculture such as grain crops, that reduced the complexity of soil inputs 2.) a reduction in manure return as farmers specialized in crops and eliminated or reduced herd sizes, 3.) increased winter fallow as fertilizers reduced the need for cover crops, 4.) winter fallow lead to soil erosion, 5.) excess use of nitrogen (N) fertilizers that increased the mineralization of SOC, 6.) removal of crop residues for animal feed and fuel, resulting in less C inputs, and 7.) open field burning as a residue management practice. All of these and other factors contributed to considerable SOC losses from the plow layer of surface soils (0–30 cm) and in many cases deeper (Fig. 1).

The importance of SOC to soil productivity has long been recognized (Jenny 1941; Allison 1973). Numerous studies and observations have concluded that restoring SOC can increase crop yields (Lal 2007). Cropping and soil management practices such as reduced or no till, cover crops, diverse crop rotations, manure inputs, etc., can increase SOC (Qiao et al. 2014; Lal 2004; Lal 2010). However, in a study on arable crops in Europe, restoring SOC did not necessarily increase crop yields, given sufficient nutrients to support productivity from fertilizer inputs

(Hijbeek et al. 2017). The general consensus among soil scientists is that increasing SOC is an important component of increasing soil health and in reversing the global warming potential of agricultural systems.

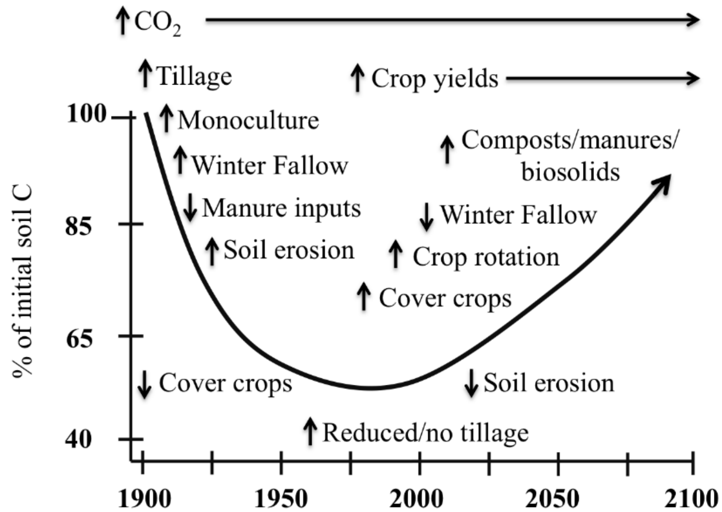

Figure 1. The effect of management practices, rising CO_2 and improved crop yields on the degradation of SOC and the effect of management practices to support SOC sequestration is shown since 1950 and projected to 2100.

Animal Manures Sequester SOC

The Rothamsted Experiment, started in 1849, showed the annual application of 35 Mg ha^{-1} of animal manure for 140 years steadily increased SOC (Jenkinson 1991). Numerous studies have shown the positive effects of animal manure on SOC sequestration. This is particularly evident in China, where decadal long-term experiments show the use of animal manure increases SOC and crop yields (Pan et al. 2009). Poudel et al. (2001a), showed the use of composted poultry manure annually significantly increased SOC in California.

On average, the availability of animal manure for crop production satisfies only 10% of crop N needs globally (Conant et al. 2013). Therefore, fertilizer N will continue to be used to support crop production. Human waste in the form of biosolids may also have the same positive effect on SOC sequestration than does animal manure. Silva et al. (2013), showed that the one time application of 100 Mg ha^{-1} of iron stabilized biosolids to open cast mine land in Brazil where topsoil was removed exposing the C horizon resulted in SOC sequestration 3 to 4 times higher than the original savannah. The use of biosolids has similar effects to animal manure in promoting SOC sequestration and should be considered as an important nutrient source to enhance soil productivity to sustain crop production in the future.

Conservation tillage impact on SOC sequestration

Conservation tillage incorporates a range of residue management and no till or reduced tillage practices. Many studies on conservation tillage systems show the majority of sequestered SOC occurs in the shallow zero to 15 cm soil depth. Studies comparing tillage treatments to depths greater than 30 cm often find no difference in SOC sequestration potential (Horwath et al. 2002). In an overview of conservation agriculture practices and associated ecosystem services, Palm et al. (2014) found that of more than 100 studies, about half reported SOC sequestration rates greater in tilled than no-tilled systems. Powlson et al. (2014), concluded that no-till systems have limited potential for climate change mitigation, primarily due to limited SOC sequestration potential. However, they also concluded that the accumulation of SOC at the soil surface in no-till systems improves soil properties, such as water infiltration and crop growth. The stratification of SOC in no-till systems is a positive ecosystem service that likely overshadows differences in soil C sequestration potential between tillage management.

Cover crops and crop rotation effects on SOC

In many ways, planting cover crops and diverse crop rotations have similar outcomes, most notably sequestering SOC (Poudel 2001). The use of cover crops provides soil surface cover during fallow periods, reducing erosion potential. Cover crops also provide valuable ecosystem services, such as increased water infiltration (Mailipalli et al. 2012), increase nutrient retention, reduced need for chemical N inputs, suppress weeds and increase soil microbial biomass (Drinkwater et al. 1998). For these reasons, cover crops are an essential soil management practice to promote soil health by increasing SOC and retaining and increasing the availability of N.

Potential to sequester SOC

Interest in using soils to sequester SOC through management with the goal of offsetting anthropogenic carbon emissions started in the 1990s (Barnwell et al. 1992). As a result, the potential for soil management to sequester SOC has been since extensively studied over the last three decades. The recent 4 per thousand (4PT) initiative, promoted by the United Nations General Assembly at the 21st Conference of Parties (COP21) held in Paris in 2015, is an integrated effort to promote SOC sequestration as a solution to offset fossil carbon emissions. The 4PT initiative contends that a small increase in soil C in agriculture, grasslands and forests would increase crop and fiber production while contributing to offsetting global carbon emissions.

Agriculture soil represents an important opportunity to sequester SOC. Agricultural soils are unique in the level of disturbance imparted upon them as a result of inputs and soil management practices. As a result, degraded agricultural soils have a larger potential sequester SOC. The average lower limit and upper limit for agricultural SOC sequestration is 0.14 and 0.38 Mg g C ha^{-1} y^{-1} (Minasny et al. 2017). Re-sequestering atmospheric CO_2 back to SOC could mitigate fossil C emissions to the atmosphere. The estimate of GHG emissions in the 4PT initiative is based on 8.9 Gt of fossil carbon emissions annually. Global SOC stocks to 2 m in depth are estimated to be 2,400 Gt (Batjes 1996). Therefore the ratio of 8.9 Gt soil C to 2,400 global SOC results in the value 0.4% or 4 per mil or thousand. This could limit global warming to an increase of 1.5° C as set forth in the COP21 by mitigating annual GHG emissions.

The average SOC content per hectare is estimated to be 161 t (Minasny et al. 2017). Assuming that the SOC sequestration rates of the 4PT initiative can be achieved, the average global rate would need to be 0.6 t C ha^{-1} y^{-1}. This value falls within the above the range of potential SOC sequestration mentioned above for agricultural land. The 4PT initiative value of 0.6 t C ha^{-1} y^{-1} is an average value, suggesting that actual SOC sequestration amounts would be higher or lower depending on soil type and region.

There are reasons to suspect that reported potential SOC sequestration values have been overestimated. Most reported values are done on research facilities where management practices are often done year in and year out consistently. For example, the same crop rotation or management practices are implemented for decades without consideration of economic constraints that often confront farmers. For example, a decadal project performed at the University of California Davis from 1988 two 2000 on the transition from conventional to low input/ organic agricultural practices determined that low input system (a hybrid between conventional and organic agriculture systems) increased SOC with annual winter cover crops and reduced chemical inputs (fertilizers and pesticides) (Poudel et al. 2001). The low input system had greater than 97% system N use efficiency and the highest crop yields, however was not economically viable compared to the conventional system with no cover crops and chemical inputs. Mitchell et al., (2107), in a long-term study found that the use of cover crops and no-till in the San Joaquin Valley achieved SOC sequestration comparable to the upper rate mentioned in the previous paragraph. These examples demonstrates that researchers can develop appropriate solutions towards climate friendly agricultural systems, but their practical application is constrained by not addressing the farmer's economic situation. However, Singer (2003), found in comparing 125 archive soil samples over a 60 year period in California that intensively managed and irrigated systems have increased in SOC on average from 1.06 to 1.34% likely reflecting increases in crop productivity and total residue inputs overtime. For these reasons, California farmers have the potential to sequester SOC using demonstrated soil management practices.

Nitrogen is required to sequester SOC

SOC sequestration cannot occur in the absence of N. The C to N ratio of stable SOC ranges from 8 to 12. The SOC sequestration rate promoted in the 4PT initiative would require an additional 100 Tg N y^{-1} assuming a soil C to N ratio of 12 (van Groenigen et al. 2017).

Fertilizer N inputs have increased overtime resulting in increased food production. The inefficient use of N in cereal crops suggest that residual N maybe available for SOC sequestration. However, less than 7% of applied fertilizer N is available to subsequent crops suggesting the N is likely lost from the system via leaching, runoff and gaseous routes (Ladha et al. 2005). After 40 years of synthetic fertilizer N applications that exceeded grain N removal by 60 to 190% at the longest continuous corn experiments at the Morrow Plots in Illinois, a net decline in SOC was observed (Khan et al. 2007). In addition, it was also found that soil N was depleted in the Morrow Plot despite the excess N inputs (Mulvaney et al. 2009).

Conclusion

The role of soils in mitigating climate change through SOC sequestration has been studied extensively for the last three decades. Many of the soil management practices discussed here have been shown to significantly increase SOC sequestration. Most of these results have been obtained from carefully planned studies at research institutions and less so on farmer fields. As suggested, this may overestimate SOC sequestration due to a omitting economic constraints that farmers are confronted with as well as not addressing the variability in management practices and soils resources that effect SOC. However, both research plots and farmer data show there is potential to sequester SOC in California to improve soil health.

Soils will play a major role in mitigating climate change, however the expectations to mitigate fossil C emissions set forth in the 4PT initiative maybe overly optimistic. Despite this optimism, the goal of SOC sequestration is of paramount importance and independent of the expectations of the 4PT. The benefits of promoting SOC sequestration range from maintaining or increasing crop productivity and supporting vital ecosystem services and should be supported through initiatives to promote soil health.

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