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Commentary

Tillage and soil carbon sequestration—What do we really know?

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Abstract

It is widely believed that soil disturbance by tillage was a primary cause of the historical loss of soil organic carbon (SOC) in North America, and that substantial SOC sequestration can be accomplished by changing from conventional plowing to less intensive methods known as conservation tillage. This is based on experiments where changes in carbon storage have been estimated through soil sampling of tillage trials. However, sampling protocol may have biased the results. In essentially all cases where conservation tillage was found to sequester C, soils were only sampled to a depth of 30 cm or less, even though crop roots often extend much deeper. In the few studies where sampling extended deeper than 30 cm, conservation tillage has shown no consistent accrual of SOC, instead showing a difference in the distribution of SOC, with higher concentrations near the surface in conservation tillage and higher concentrations in deeper layers under conventional tillage. These contrasting results may be due to tillage-induced differences in thermal and physical conditions that affect root growth and distribution. Long-term, continuous gas exchange measurements have also been unable to detect C gain due to reduced tillage. Though there are other good reasons to use conservation tillage, evidence that it promotes C sequestration is not compelling.

Keywords: Carbon sequestration; Tillage; Organic matter; Sampling depth

1. Introduction

Concerns about rising atmospheric CO_2 levels have prompted considerable interest in recent years regarding the sink potential of soil organic carbon (SOC). The world's soils are estimated to contain 1500 Gt of SOC, roughly double the amount of C in the atmosphere (Schlesinger, 2000). And while that total pales in comparison to the 38,000 Gt of C contained in the world's oceans, it attracts attention because it is potentially responsive to modification. Indeed, though fossil fuel combustion has been the major cause of increasing CO_2 in the atmosphere, land modifications have been a significant contributor. Some have estimated that in United States, many soils have lost 30–50% of the C that they contained prior to cultivation (Kucharik et al., 2001).

Much of the blame for this loss of C has been assigned to the practice of plowing the soil (Reicosky, 2003), and tilled soils are viewed by many as a depleted C reservoir that can be refilled. Lal et al. (1998) estimate that United States croplands have lost 5 Gt C, an average of 36 t ha^{-1}, and suggest that much of this can be restored over a 50 year period with appropriate management. The primary practice that is mentioned is conservation tillage, broadly defined as any tillage method that leaves sufficient crop residue in place to cover at least 30% of the soil surface after planting (Lal, 2003). It has been argued that widespread adoption of conservation tillage within United States could sequester 24–40 Mt C $year^{-1}$ (Lal et al., 2003). These statistics have been projected globally to estimate that conversion of all croplands to conservation tillage could sequester 25 Gt C over the next 50 years, marking it as one of the key global

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strategies for stabilizing atmospheric CO_2 concentrations (Pacala and Socolow, 2004). This view has attained general acceptance, to the extent that some farmers now receive payments from coal-burning utilities in emissions-trading arrangements brokered through the Chicago Climate Exchange, in return for practicing conservation tillage. Payments are based on the premise that conservation tillage sequesters the equivalent of 0.5 t CO_2 acre^{-1} year^{-1}, or ~0.3 t C ha^{-1} year^{-1}. Our objective was to answer the question: how solid is the evidence for C sequestration in conservation tillage systems?

2. Soil sampling studies

The standard method for assessment of C sequestration has been soil sampling of long-term tillage trial plots. Multi-year experiments are necessary because annual changes in SOC are spatially variable and generally small relative to background SOC. A recently published review of such studies (West and Post, 2002) concluded that conversion of conventional tillage to no-till sequesters an average of 0.57 ± 0.14 t C ha^{-1} year^{-1}. No-till, in which the soil is left undisturbed from harvest to planting, is the most extreme form of conservation tillage. These numbers seem to support the generally accepted view that widespread adoption of conservation tillage, and specifically no-till, would sequester a substantial amount of C.

However, the authors also provided a table listing selected details of the experiments they reviewed, and one particular feature is a cause for concern. There were 140 treatments in which tillage was a variable, and none was sampled below 30 cm. Fig. 1 is reproduced from a classical descriptive study of plant root systems by Weaver et al. (1922) in which root systems of various crops were excavated in situ and carefully drawn. It shows the root system of a maize plant (*Zea mays* L.) near maturity; the scale is in feet, so each major division represents 30 cm. Surprisingly, none of the carbon sequestration experiments involving tillage as a variable that were surveyed by West and Post (2002) sampled below the superimposed red line. In fact, in more than half of them the maximum sampling depth was 20 cm or less.

For many plants as much as 30–50% of the C fixed in photosynthesis is initially translocated below-ground (Buyanovsky and Wagner, 1997). Some is used for structural growth of the root system, some for autotrophic respiration, and some is lost to the surrounding soil in organic form (rhizodeposition), either sloughed during root expansion or excreted in a variety of compounds. Using ^{14}C pulse labeling, Swinnen et al. (1995) found that rhizodeposition by winter wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) accounted for up to 15% of net C assimilation during the growing season. These organic C exudates may play an important nutritional role, stimulating microbial activity (Quian et al., 1997; Sanchez et al., 2002). Evidence also indicates that below-ground plant C is the major source for subsequent conversion into more stable forms of SOC. Using stable isotope fractionation, Wilts et al. (2004) estimated that the ratio of SOC derived from below-ground plant C to that derived from above-ground stover was nearly 2:1 in long-term corn plots, further emphasizing the importance of root systems in C sequestration.

Shallow sampling might be sufficient for *relative* assessments of sequestration in different tillage treatments if the fractional distribution of roots with depth were the same in each system. However, there are reasons to suspect that such may not be the case. For example, in no-till systems the soil heat flux is typically lower than in conventionally tilled fields, due to the insulating effects of surface residue

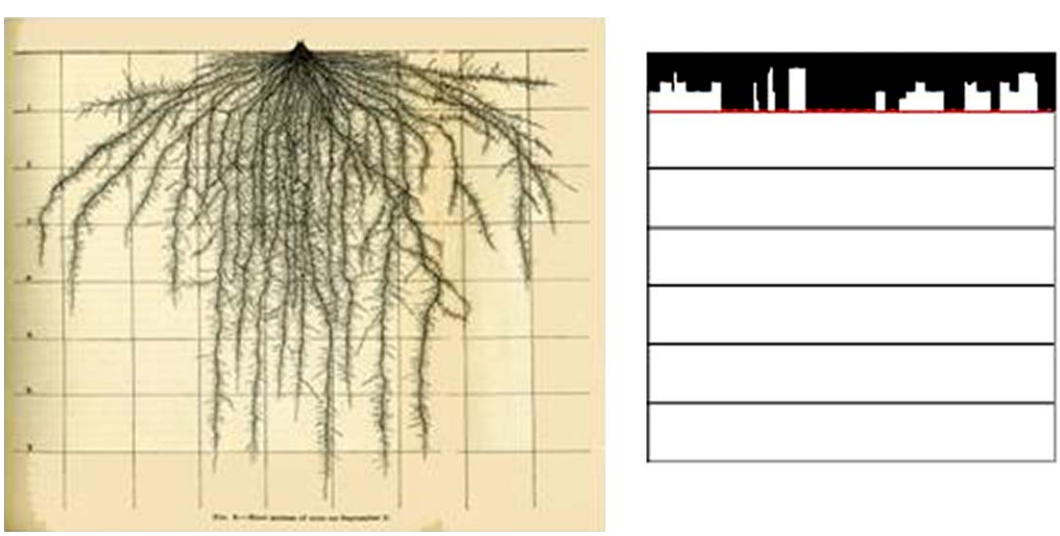

Fig. 1. The root system of a corn plant, drawn during field excavation by Weaver and colleagues, reprinted with permission of the Carnegie Institution, Washington, DC (8). The scale on the left, denoting depth below the soil surface, is in feet. The plot on the right shows the sampling depths, to the same scale, employed in 140 comparative studies of tillage impacts on soil carbon (7).

(Shen and Tanner, 1990) and an albedo that is generally higher. In combination, these features tend to make no-till soils cooler than conventionally tilled soils, especially in the early part of the growing season (Johnson and Lowery, 1985; Drury et al., 2005; Fabrizzi et al., 2005). Soil temperature in turn is one of the key factors controlling root growth, with up to 5-fold differences in root growth over temperature ranges of 4–5 °C. (Logsdon et al., 1987; Mackay and Barber, 1984). Soil strength is another factor that varies among tillage systems and affects root distribution. No-till soils have greater resistance to penetration and higher bulk density (Fabrizzi et al., 2005; Larney and Kladivko, 1989; Vyn and Raimbault, 1993), and a lower proportion of aggregates <5 mm (Larney and Kladivko, 1989), all of which discourage deeper root growth.

Intact maize and soybean (*Glycine max* (L.) Merr.) root systems from fields under different tillage systems show distinct differences in root density distribution. Qin et al. (2004) conducted a comparison of root length density of maize in plowed and no-till soils, and reported that generally root length densities were greater in no-till for the upper 5–10 cm, but greater in the plowed soil at the deeper depths. Qin et al. (2005) also examined root density distributions of winter wheat under different tillage systems, and found that no-till resulted in higher root length density in the 0–5 cm layer, but lower root length densities in deeper layers. It is sensible to expect that such differences in root distribution with depth, coupled with tillage-induced differences in the soil physical environment, might lead to systematic differences in the depth distribution of SOC.

Fortunately, there are a few recent tillage/sequestration studies in which deeper SOC sampling has been done. A survey of sequestration-related research in Canada (VandenBygaart et al., 2003), analogous to that of West and Post (2002), cites nearly 100 plot studies of the impact of conservation tillage in Canada. When the studies are segregated by sampling depth, the results are striking. In 17 experiments where the sampling depth was 30 cm or less, 37 of 45 no-till treatments (82%) reported more SOC than in the conventionally tilled control, with a mean annual SOC gain of 0.38 ± 0.72 t ha^{-1} year^{-1}; in the five experiments where the profile was sampled to a depth greater than 30 cm, a majority of the trials (35 of 51, or 69%) registered *less* SOC in the no-till treatment relative to conventional tillage, with a mean annual SOC *loss* of -0.23 ± 0.97 t ha^{-1} year^{-1}. In both cases, the standard error is so large that the mean (impact of tillage on SOC) is not significant. However, these results agree qualitatively with other studies that have shown that in soils under no-till SOC is concentrated near the surface, while in tilled soils it is distributed deeper in the profile, so that apparent SOC gains from no-till that are based only on near-surface samples disappear when deeper samples are also included (Carter, 2005; Dolan et al., 2006). Similar results were reported from a study at Rothamstead, UK more than 20 years ago by Powlson and Jenkinson (1981), who compared both SOC and microbial biomass in long-term plowed and no-till cereal plots. They found no differences in either parameter between the two treatments when they sampled to 40 cm on an equivalent depth basis (equal mass per unit area), and concluded that no-till "*has little effect on soil organic matter, other than altering its distribution in the profile*." Machado et al. (2003) reached the same conclusion following an experiment where they examined the effect of tillage on SOC in maize rotations in Brazil.

3. Gas exchange studies

Changes in soil C can in principle be inferred from continuous measurement of net ecosystem CO_2 exchange (NEE) between the land surface and the atmosphere provided other C additions or losses (e.g. harvested grain) are properly credited. The instrumentation to conduct such measurements has only recently become available, so long-term data over contrasting tillage systems are just now being assembled. These measurements are subject to their own experimental difficulties and uncertainties (Massman and Lee, 2002), and they require empirical gap-filling of time periods when conditions are unfavorable for measurement. However, a few published results exist. Baker and Griffis (2005) compared two adjacent fields, both in maize/soybean rotation, with one under conventional tillage and the other under strip tillage, a conservation tillage practice in which most of the surface is undisturbed. They found no C sequestration benefit from the conservation tillage, and both systems were apparently small net sources of C over the 2-year period. Verma et al. (2005) measured NEE for 2 years in three adjacent fields in Nebraska, all in no-till. One was in irrigated continuous maize, one in irrigated maize/soybean rotation, and the other in dryland maize. Though there were differences among systems in gross primary productivity and yield, the net carbon balance computed from NEE and yield was essentially zero for all treatments, and the authors concluded that all were either C neutral or slight sources of C.

4. Alternative explanations for SOC loss following cultivation

Because soils have lost so much C since tillage began, the idea that a reduction in tillage would sequester C seems plausible. However, this may be a case of confusing causation with correlation. The conversion of pre-settlement forests and grasslands to agriculture involved other changes beyond mechanical disturbance of the soil that may have had far more impact on SOC. Perhaps the most obvious difference between today's agricultural lands and the ecosystems that preceded them is that agriculture is dominated by annual crops, in contrast to the primarily perennial grasses and forested systems that were present prior to settlement. In annual cropping systems fields are often bare, or nearly so, for extended periods of time in the spring and fall when temperatures are well above freezing and there is substantial solar radiation (Baker and Griffis, 2005). Most maize varieties are genetically programmed to senesce approximately 100 days after germination, yet in much of United States. Corn Belt the time between last and first frost is nearly 180 days. Perennial vegetation exhibits net C assimilation for a much greater portion of this period, as Fig. 2 illustrates. The cumulative effect on SOC of annual cropping versus perennial vegetation is evident in the data collected in Russia by Mikhailova et al. (2000). They measured SOC to a depth of 2 m below native grassland, a perennial hay field, and a field planted each year to annual crops such as maize, sugar beets, and soybeans. The grassland and the hay field exhibited similar SOC throughout the profile, with a slightly lower total in the hay field, but both had substantially more SOC than the annually cropped field.

The second major alteration in cropped regions that has likely affected SOC levels has been hydrologic. The conterminous United States contained nearly 100 M ha of wetlands prior to settlement (USDA, 1987). More than half has been lost, primarily drained for conversion to farmland. The corresponding increase in aeration, and subsequent addition of nitrogen fertilizer, must certainly have had a stimulatory effect on microbial oxidation of SOC. Quantitative information on the effects of drainage on SOC stocks are scarce, but Fig. 3 provides numbers of a sort. The photograph shows an organic soil in south Florida that has subsided more than 1.5 m since it was drained for sugarcane production in 1927, a loss rate of nearly 2 cm $year^{-1}$. Assuming a bulk density for organic matter of 0.22 g cm^{-3} (Adams, 1973) and a C fraction of 0.5 g g^{-1} (Sparks, 2003) yields a rough estimate of 20 t C ha^{-1} $year^{-1}$ lost by respiration of relic SOC in these soils following drainage. This is a remarkably large C flux, but it is comparable to gas

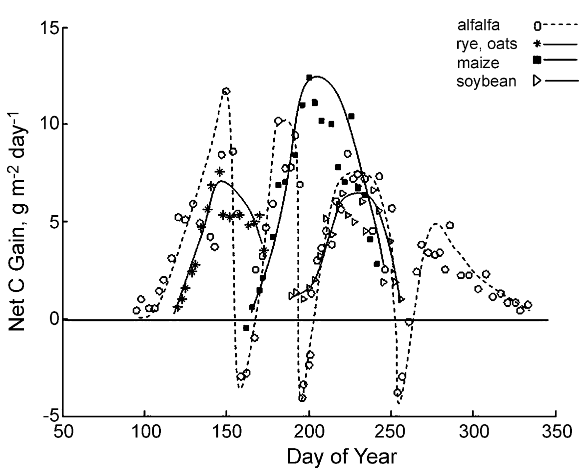

Fig. 2. Measurements of daily net carbon gain for selected crops in Minnesota. Alfalfa is the sole perennial of the group; its growing season, or C assimilation period, exceeds that of each annual crop by 100 days or more. (The three periods during the growing season when alfalfa exhibits net loss of C are periods of regrowth following hay harvest.)

Fig. 3. Subsidence of soil in Florida due to oxidation of organic matter following drainage. When the post was installed in 1923, with its base on bedrock, its top was level with the soil surface. (Photo courtesy of D. Morris, USDA-ARS, Canal Pt. FL.)

exchange measurements of respiration on drained organic soils in the Sacramento Delta in California where similar subsidence has occurred (Deverel and Rojstaczer, 1996). In the cooler climates of the midwestern United States the loss rate has doubtless been slower, but the sheer quantities of drained cropland (more than 16 M ha in OH, IN, IL, IA and MN; USDA, 1987) and the long time interval since drainage commenced suggest that drainage may have been a major factor in the frequently cited loss of 30–50% of pre-cultivation SOC across the region.

5. Conclusions

This discussion should not be construed as a defense of the plow. There are many good reasons to reduce tillage: no-till and other conservation tillage systems can protect soils against erosion (Gebhardt et al., 1985), reduce production costs (Al-Kaisi and Yin, 2004), and decrease the consumption of fossil fuels (Phillips et al., 1980). These benefits have been well documented, and are in themselves sufficient to justify the promotion of conservation tillage strategies. However, the widespread belief that conservation tillage also favors carbon sequestration may simply be an artifact of sampling methodology. There is reason to believe that the shallow sampling employed in most studies introduces a bias. Studies that have involved deeper sampling generally show no C sequestration advantage for conservation tillage, and in fact often show more C in conventionally tilled systems. Gas exchange measurements also offer little support to the notion of a consistent soil C benefit from reduced tillage.

While conservation tillage practices may ultimately be found to favor soil carbon gain, the data reported to this point are not compelling. Perhaps further research, including both long-term gas exchange measurements and deeper soil sampling, will clarify this issue. Until then it is premature to predict the C sequestration potential of agricultural systems on the basis of projected changes in tillage practices, or to stimulate such changes with policies or market instruments designed to sequester C. The risk to the scientific community is a loss of credibility that may make it more difficult to foster adoption of other land use and management practices that demonstrably mitigate rising atmospheric concentrations of greenhouse gases.

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