

Managing the microbial community for soil carbon management

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Abstract

Soil carbon sequestration in agriculture may provide offsets for fossil fuel emissions. The activity and composition of the soil microbial community regulates the conversion of plant carbon into soil organic matter. Thus changes in the microbial community or its activity may provide opportunities to enhance C sequestration. Plant and soil management can directly and indirectly change the microbial community. By changing the plant-soil system, an increase in the ratio of fungal to bacterial activity increases C use efficiency thus leading to retention of plant-derived C in the soil. Direct manipulation of the plant chemistry such as alterations in plant lignin resulted in a change in soil C respired. Experiments with mycorrhizal fungi have demonstrated that increased colonization and extraradical hyphae of mycorrhizal fungi increased water-stable soil macroaggregates, as well as the amount of C retained in the soil. Suppression of mycorrhizal fungi resulted in a loss of water-stable macroaggregates and a loss of the physical protection provided by the aggregates which reduced soil C. In native systems with already high soil carbon, increases soil carbon can maybe achieved by alterations of the soil microbial community. Proper understanding of the biological mechanisms of C retention can lead to design of agricultural systems for increased soil C sequestration.

Key Words

soil carbon sequestration, microbial communities, mycorrhizal fungi, water stable aggregates

Introduction

The most important gases contributing to the atmospheric greenhouse effect are carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). Over the past several decades these gases have been increasing rapidly as a result of human activity. Nineteenth and twentieth century fossil fuel use coupled with forest clearing have increased atmospheric CO₂ levels from 260 ppm to 370 ppm (IPPC, 1995). Increasing soil C storage in agricultural systems, which have the potential to sequester 0.4 to 1.2 Gt C y⁻¹, may effectively assist in offsetting atmospheric CO₂ increases, (Lal, 2004).

The global soil C pool is 2500 Gt and can be subdivided into 1500 Gt of organic C and 950 Gt of inorganic C. This soil C pool is 3.3 times the size of atmospheric C and 4.5 times the size of biological C (Lal, 2004). This soil organic C pool is highly dynamic and influenced greatly by management practices, some of which can positively or negatively affect soil quality. Carbon dioxide is emitted from soils by the respiration of plant roots and soil microorganisms. Soil respiration is a major component of the global C cycle. Each year, soil respiration returns nearly 10 times as much CO₂ to the atmosphere as do the emissions from fossil fuel combustion. However, soil respiration is roughly balanced by the net uptake of CO₂ through plant photosynthesis. Globally, net photosynthesis and respiration amount to about 60 Pg C yr⁻¹.

About 70% of plant material entering the soil is mineralized into CO₂ in a year, with only a small fraction becoming stable soil organic matter (SOM). Carbon and N are the primary elements composing SOM, and higher amounts of soil C and N are general indicators of good soil quality (Doran et al., 1999). Land use practices that result in a net accumulation of SOM in the soil are said to be C sequestering because they result in a net removal of C from the atmosphere (Rice and Angle, 2004). For example, conservation tillage practices have been estimated to have the potential to sequester 100 to 1000 kg C ha⁻¹ yr⁻¹ for 20 to 50 years (Lal, 2004).

The inputs in SOM are primarily the result of accumulations of plant and microbially compounds that are resistant to further mineralization due to biological, chemical, or physical protection in the soil matrix. Furthermore, genetic changes in plant quality and direct or indirect manipulation of the composition and activity of soil microorganisms may lead to increases in these resistant end products and result in a greater soil C sequestration potential than traditional management practices alone.

Agricultural Management Practices that Sequester Soil C

In agricultural systems, substantial amounts of plant biomass remain in the field after harvest (including roots). From a mass balance approach, an increase in soil C can be achieved either by increasing inputs or decreasing outputs. Decreased output, or conservation of soil C, is a function of microbial activity, and physical and chemical protection (Figure 1). Soil structure plays a dominant role in controlling microbial access to organic substrates, as relatively labile material may be physically protected from decomposition by its incorporation into soil aggregates (Gregorich et al., 1989). Disturbance of aggregates, by natural (freeze-thaw, wet-dry cycles) or anthropogenic (tillage) forces increases the decomposition of the physically protected organic materials (Rice and Angle, 2004). Thus, conservation tillage practices are important for increasing soil C storage and retaining sequestered C. Tillage management practices effectively use microbial and physical controls to increase the amount of C that can be stored, or protected, by a soil.

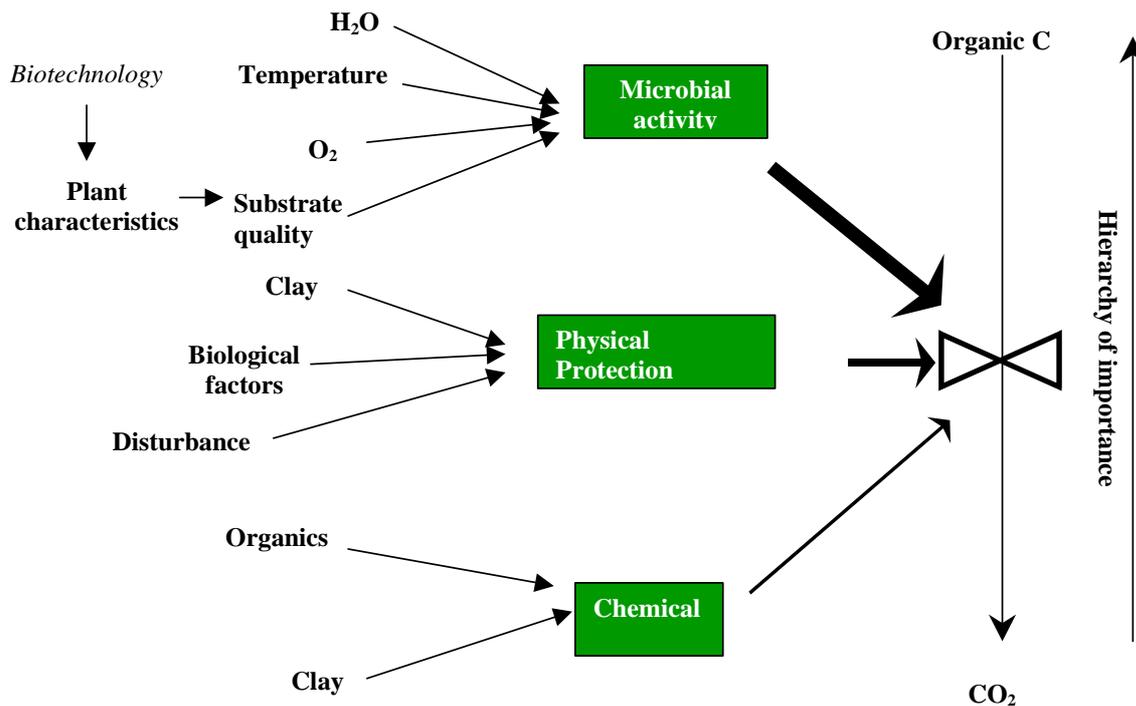


Figure 1. Factors controlling C conservation in soil. Microbial decomposition of plant residues occurs after addition to soil, but may occur at different rates and to different extents based on residue quality and other factors, including physical and chemical protection from microbial decomposition.

Long-term studies from Kansas (USA) show that no-tillage (NT) accumulated more soil C compared with tilled systems (CT) (Fabrizzzi et al., 2004), and the amount of C storage was related with the amount of precipitation on the site and crop rotation. After 37-yr, NT increased TOC and TN contents at 0-5 cm compared with CT and RT in Hays, KS, under wheat-sorghum-fallow rotation. Same results were found at Tribune, KS, (16 yr) under the same rotation. In both sites the presence of the fallow and the low precipitation of the area could explain the low C storage compared with Ashland, KS, (23 yr) and Parsons, KS, (20 yr) sites in which the increase was greater due to the high amount of precipitation received. At Parsons, KS, NT had greater TC contents at 0-5 cm, 0-15 and 0-30 cm compared with CT and RT. Data from Ashland, KS, show greater TC content under NT at 0-5 cm depth in all rotations, except for soybean/soybean rotation. Crop rotations that include wheat or sorghum promote the increase of soil C storage. More total soil C and labile soil C was found in the 250-2000 μm and $>2000 \mu\text{m}$ soil aggregate size fractions when under NT as compared to CT, indicating that the increased aggregation resulting from NT may be protecting newly added soil C (Mikha and Rice, 2004). Espinoza (2000) found higher soil C mineralization in CT than in NT systems, with values of 140 and 110 $\mu\text{g C g}^{-1} \text{ soil d}^{-1}$, respectively.

Wilson (2003) reported that suppression of arbuscular mycorrhizal (AM) fungi in native grassland resulted in a significant decrease in extraradical hyphal networks. Loss of these hyphal networks resulted in a breakdown of water-stable macroaggregates (Figure 2). A positive relationship between hyphal networks and soil C was also observed (data not shown). Therefore, AM fungal hyphae may play a major

role in the physical protection of C. Mycorrhizal fungi may also play a critical role in the stabilization of soil aggregates and the sequestration of soil C (Bearden and Peterson, 2000; Miller and Jastrow, 1992; Jastrow et al., 1998; Wright and Upadhyaya, 1998). In addition, C sequestration into the soil may be enhanced by translocation C away from the high respiratory activity around the root and into the bulk soil matrix (Kucey and Paul, 1982; Jakobsen and Rosendahl, 1989; Norton et al., 1990). Estimates of the amount of C allocated to fungal associations can be substantial, ranging from 4 to 20% of a plant's total C budget (Rygiewicz and Anderson, 1994; Tinker et al., 1994; Watkins et al., 1996).

Changes in proportion of fungi could affect C cycling. Fungi respire about 30-40% of substrate C while bacteria account for about 60%. Thus, a shift to fungi would leave more C in the soil. It is known that no tillage results in an increase in the proportion of fungi to bacterial phospholipids and this may partially explain the increase in soil C with no-tillage (Watson and Rice, 2004).

Decomposition of Plant Material and Formation of Soil Organic Matter

Plant residue is a complex mixture including soluble sugars, free amino acids, proteins, cellulose, hemicellulose, and lignin. Typical components and their percents of the whole tissue vary between plant species (Broder and Wagner, 1988) and within plant species (White et al., 2003). The residue of different plant species can decompose at different rates. Kaboneka et al. (1997) found that 48, 56, 60% of wheat straw, corn stover, or soybean stubble was mineralized during a 30 d incubation, respectively. Particular chemical structures within a biopolymer, such as aromatic rings, may also vary in recalcitrance. Martin et al. (1980) selectively labeled corn lignin by incorporating lignin building blocks coniferyl and coumaryl alcohols with ^{14}C and found that less $^{14}\text{CO}_2$ evolved when the radioactivity was located on the aromatic ring as opposed to functional or straight chain C groups.

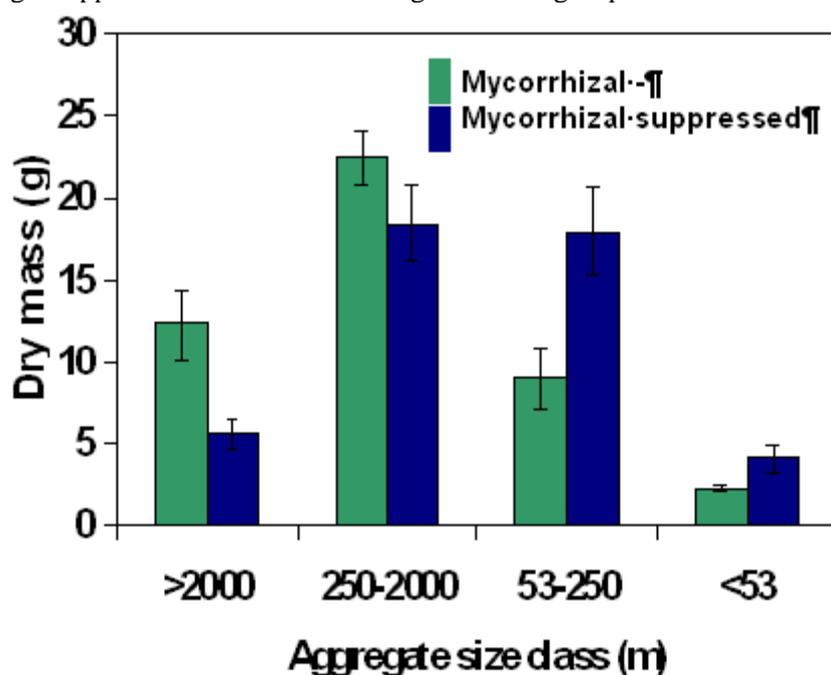


Figure 2. Aggregate distribution in mycorrhizal and mycorrhizal-suppressed tallgrass prairie in NE Kansas, USA. Suppression of mycorrhizal fungi resulted in lower proportions of macroaggregates as compared to the unsuppressed plots.

Lignin is a large polymeric structural component of cell walls of vascular plants, which is relatively indigestible by foragers (Duncan, 1996). Thus, lignin synthesis has been a major target of genetic manipulation. For example, forage digestibility was increased by down-regulation of cinnamyl alcohol dehydrogenase (CAD) in alfalfa (Baucher et al., 1999), tobacco (Halpin et al., 1994), and grain sorghum BMR-6 mutants (Pillonel et al., 1991). Down regulating these genes reduces gene expression of the enzymes required in lignin monolignol polymerization, resulting in a reduction or a change in the lignin quality or quantity in the plant. The CAD enzyme catalyses the final step in lignin precursor synthesis, which leads to altered lignin being incorporated into plant cell walls (Halpin et al., 1994). These altered lignins may be important in terms of decomposition by soil microbes and reactivity with clay minerals in

soil due to their chemical structure and properties. However, as normally plant synthesized lignin is recalcitrant in soil, over-production of plant lignin may be advantageous in terms of C-sequestration rates.

Research is being conducted to measure the decomposition of wild type (WT) and brown midrib mutant (BMR) grain sorghum residue in soil (White et al., 2004). Cross Polarization/Magic Angle Spinning ^{13}C Nuclear Magnetic Resonance confirmed changes in the plant chemical structure were present in the 145 to 160 ppm aromatic range between each WT and BMR. Wet chemical analysis indicated that the BMR residue had less acid detergent lignin than the WT residue across all varieties. Preliminary data indicate that over all cultivars, the addition of N suppressed residue mineralization from 71 to 58%, possibly indicating a greater C storage potential in soils with higher N levels. Additionally, the WT group mineralization was slower than the BMR mutants, but only with values of 63 and 66%, respectively. While small, these changes may indicate that the potential exists for biotechnology to play a role in C sequestration. Phospholipid and neutral lipid analyses (PLFA and NFLA, respectively) revealed that while there was not an increase in the total nmol of lipid due to N addition, there was a significant increase in the proportion of fungal PLFA to total PLFA when N was added with the residue. As previously mentioned, fungi can lead to increased soil C levels due to more efficient respiration as compared to bacteria.

Future Needs in Soil C Sequestration Research

Carbon as CO_2 is currently accumulating in the atmosphere at a rate of 3.5 billion tons y^{-1} as a consequence of fossil fuel use and land use change. The Intergovernmental Panel on Climate Change report (IPCC, 1995) estimated that soil C sequestration in cropland soils could remove between 40 and 80 billions tons of that C over the next century. This means that soil C sequestration could provide a temporary offset for fossil fuel emissions, thus allowing time for the development and deployment of technologies to make the carbon-free energy economy a reality by the end of the century. Information is needed to provide land managers and policy makers rates of C sequestration in soils and identify those management practices that enhance C retention. In terms of future research needs, areas which need most attention include (1) faster and better tools to assess C content and changes in the field; (2) better tools to assess protection limit of a soil, which would include microbial, chemical, and physical traits; (3) a better understanding of the belowground micro- and mesofaunal C flow rates and extents, and interactions between these two important soil communities; and (4) an enhanced understanding of aggregation and C pool fluxes during SOM formation.

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