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# THE BIOLOGY OF SOIL COMPACTION

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Soil compaction is a common and constant problem on most farms that till the soil. Heavy farm machinery can create persistent subsoil compaction (Hakansson and Reeder, 1994). Johnson et al. (1986) found that compacted soils resulted in: (a) restricted root growth; (b) poor root zone aeration; and (c) poor drainage that results in less soil aeration, less oxygen in the root zone, and more losses of nitrogen from denitrification.

Subsoil tillage has been used to alleviate compaction problems. Subsoilers are typically operated at depths of 12 to 18 inches to loosen the soil, alleviate compaction, and increase water infiltration and aeration. Subsoiling usually increases crop yields but the effects may only be temporary as the soil re-compacts due to equipment traffic. Some no-till fields never need to be subsoiled, but in other no-till fields deep tillage has increased yields especially if equipment traffic is random. When subsoiling removes a hard pan, traffic must be controlled or compaction will reoccur. If a hard pan does not exist, equipment traffic generally will create one (Reeder and Westermann, 2006).

If the soil is subsoiled when the soil is wet, additional compaction may occur. In a loamy sand, Busscher et al. (2002) found that soil compaction increased with time, and cumulative rainfall accounted for 70 to 90 percent of the re-compaction due to water filtering through the soil and the force of gravity. The fuel, labor, equipment, and time to subsoil makes it an expensive operation. Subsoiling in dry conditions requires even more fuel (Reeder and Westermann, 2006). Two other factors that impact soil compaction are rainfall impact and gravity. In soils that have been tilled, both the velocity of the raindrop impact on bare soil and natural gravity combine to compact soils.

Low organic matter levels make the soil more susceptible to soil compaction. Organic residues on the soil surface have been shown to cushion the effects of soil compaction. Surface organic residues have the ability to be compressed but they also retain their shape and structure once the traffic has passed. Like a sponge, the organic matter is compressed and then springs back to its normal shape. However, excessive traffic will break up organic residues, and tillage accelerates the decomposition of organic matter. Organic residues in the soil profile may be even more important than surface organic residues. Organic matter (plant debris and residues) attached to soil particles (especially clay particles) keeps soil particles from compacting. Organic matter binds microaggregates and macroaggregates in the soil. Low organic matter levels make the soil more susceptible to soil compaction (Wortman and Jasa, 2003).

In the last hundred years, tillage has decreased soil organic levels by 60 percent, which means that approximately 40 percent soil organic carbon stocks are remaining (International Panel on Climate Change, 1996; Lal, 2004). Carbon provides energy for soil microbes, is a storehouse for nutrients, and keeps nutrients recycling within the soil. Humus or old carbon (>1,000 years old) is the most stable carbon and binds micro soil particles together to form microaggregates. Humus is non-water soluble so it stabilizes microaggregates and is not readily consumed by microorganisms. Humus is more resistant to tillage and degradation than active carbon.

Active carbon (plant sugars or polysaccharides, glomalin) is consumed by microbes for energy. Active carbon is reduced with tillage but is stabilized under natural vegetation and no-till systems using a continuous living cover. Active carbon is part of the glue that binds microaggregates into macroaggregates and insulates the macroaggregate from oxygen. Soil porosity, water infiltration, soil aeration, and soil structure increase under natural vegetation and no-till systems with continuous living cover. Increased soil macroaggregation improves soil structure and lowers bulk density, keeping the soil particles from compacting.

## Microaggregates and Macroaggregate Formation

Microaggregates are 20–250 µm in size and are composed of clay microstructures, silt-size microaggregates, particulate organic matter, plant and fungus debris, and mycorrhizal fungus hyphae: these particles are stable in size. Roots and microbes combine microaggregates in the soil to form macroaggregates. Macroaggregates are linked mainly by fungi hyphae, roots fibers, and polysaccharides and are less stable than microaggregates. Macroaggregates are greater than 250 µm in size and give soil its structure and allow air and water infiltration. Compacted soils tend to have more microaggregates than macroaggregates. See the microaggregate-macroaggregate model (Figure 1) and the macroaggregate model and hierarchy (Figure 2).

Glomalin acts like a glue to cement microaggregates together to form macroaggregates and improve soil structure. Glomalin initially coats the plant roots and then coats soil particles. Glomalin is an amino polysaccharide or glycoprotein created by combining a protein from the mycorrhizal fungus with sugar from plant root exudates (Allison, 1968). The fungal *"root-hyphae-net"* holds the aggregates intact and clay particles protect the roots and hyphae from attack by microorganisms. Roots also create other polysaccharide exudates to coat soil particles (see Figures 2 and 3).

The contribution of mycorrhizal fungi to aggregation is a simultaneous process involving three steps. First, the fungus hyphae form an entanglement with primary soil particles, organizing and bringing them together. Second, fungi physically protect the clay particles and the organic debris that form microaggregates. Third, the plant root and fungus hyphae form glomalin and glue microaggregates and some smaller macroaggregates together to form larger macroaggregates (see Figure 4).

In order for glomalin to be produced, plants and mycorrhizal fungus must exist in the soil together. Glomalin needs to be continually produced because it is readily consumed by bacteria and other microorganisms in the soil. Bacteria thrive in tilled soils because they are more hardy and smaller than fungus, so bacteria numbers increase in tilled soils. Fungi live longer and need more stable conditions to survive. Fungi grow better under no-till soil conditions with a continuous living cover and a constant source of carbon. Since fungi do not grow as well in tilled soils, less glomalin is produced and fewer macroaggregates are formed. Fewer macroaggregates is associated with poor soil structure and compaction. **Thus, soil compaction is a biological problem related to decreased production of polysaccharides and glomalin in the soil. Soil compaction is due to a lack of living roots and mycorrhizal fungus in the soil.**

## Microaggregates-Macroaggregates Model

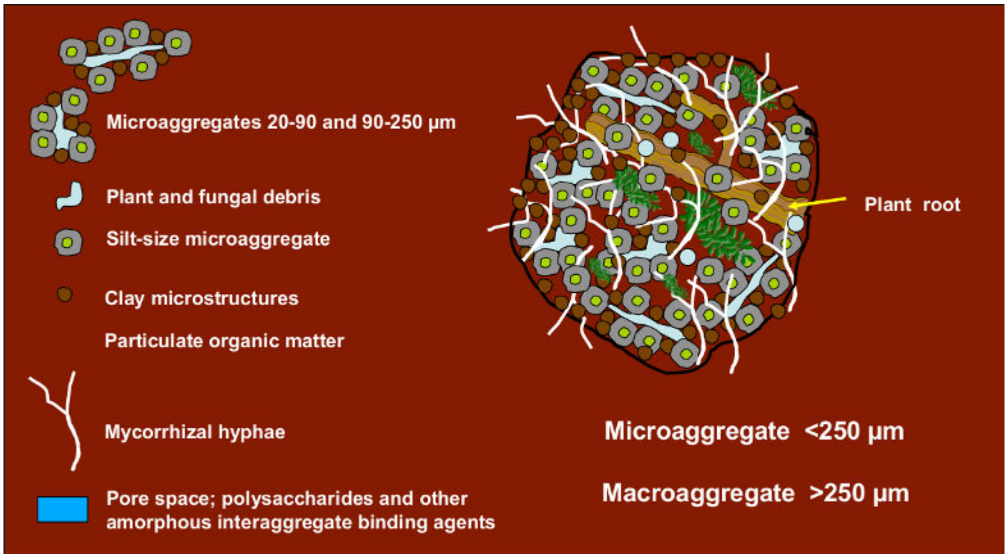


*Figure 1. Dr. Charles Rice presentation adapted from Jastrow and Miller, 1997.*

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## Macroaggregate Model and Hierarchy

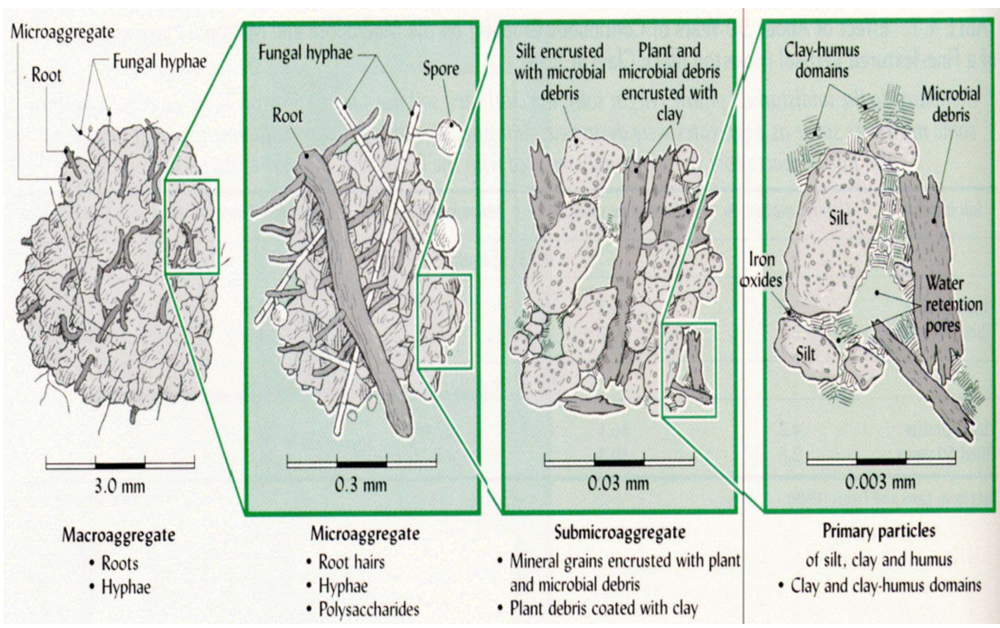


*Figure 2. From Tisdall & Oades, 1982.*

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*Figure 3. Roots, fungi hyphae, and polysaccharides stabilize soil macroaggregates and promote good soil structure. From Dr. João de Moraes Sá.*

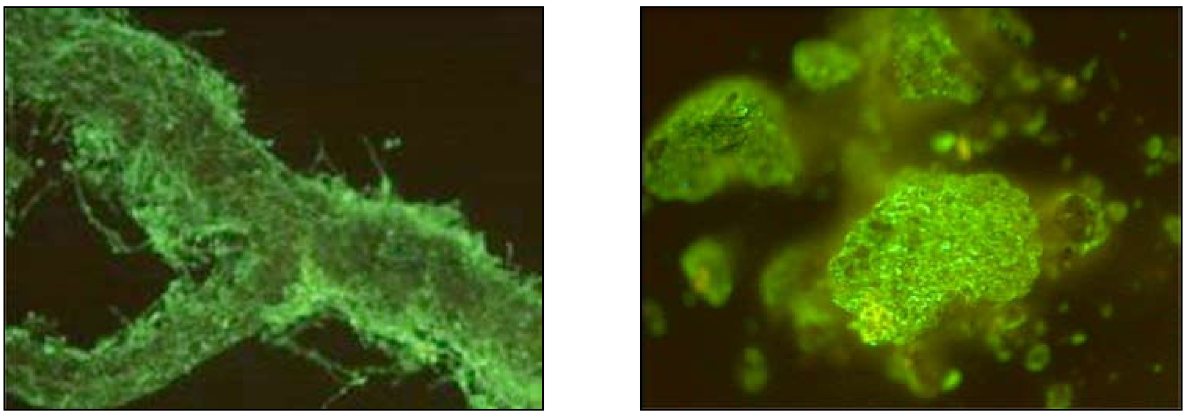

*Figure 4. Glomalin surrounding a root heavily infected with mycorrhizal fungi and soil macroaggregates surrounded by glomalin. Photos by Dr. Sara Wright, USDA-ARS.*

In a typical corn-soybean rotation, active roots are present only a third of the time. Adding cover crops between the corn and soybean crops increases the presence of active living roots to 85 to 90 percent of the time. Active roots produce more amino polysaccharides and glomalin because mycorrhizal fungus populations increase due to a stable food supply.

Surface and subsoil tillage may physically break up hard pans and soil compaction temporarily but they are not a permanent fix. Tillage increases the oxygen content of soils and decreases glomalin and amino polysaccharide production by reducing plant root exudates and mycorrhizal fungus populations. Soil compaction is a result of the lack of active roots producing polysaccharides and root exudates, and a lack of mycorrhizal fungus producing glomalin. In a typical undisturbed soil, fungal hyphae are turned over every 5 to 7 days and the glomalin in the fungal hyphae is decomposed and continually coats the soil particles. Disturbed soils have less fungus, more bacteria, and more microaggregates than macroaggregates. Heavy equipment loads push the microaggregates together so that they can chemically bind together, compacting the soil. Macroaggregate formation improves soil structure so that soil compaction may be minimized. Thus, soil compaction has a biological component (see Figure 5).

## Oxidation and Release of $CO_2$

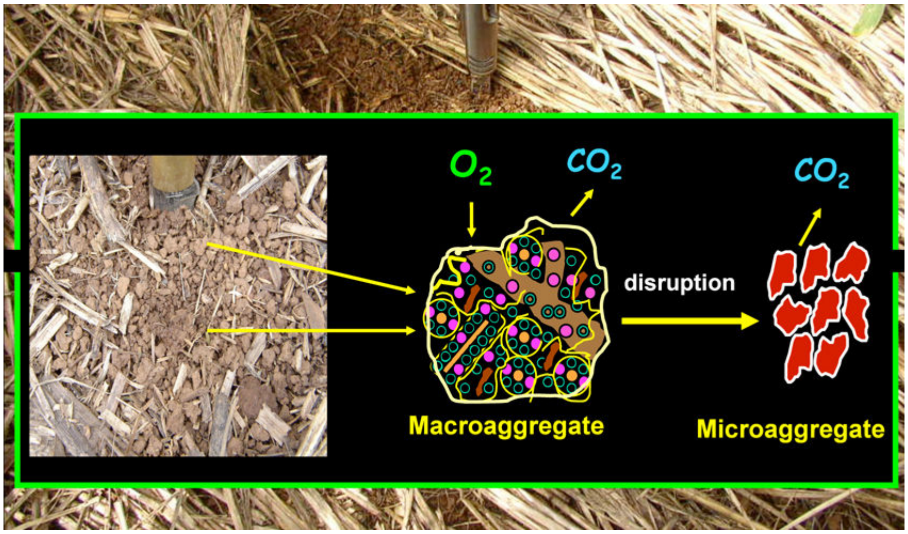


*Figure 5. Tillage disrupts the macroaggregates and breaks them into microaggregates by letting in oxygen and releasing carbon dioxide. From Dr. João de Moraes Sá.*

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Cultivation of soils, heavy rains, and oxygen promotes the breakdown of macroaggregates, which give soil structure and soil tilth. Farmers who excessively till their soils (for example, heavy disking or plowing) break down the soil structure by breaking up the macroaggregates, injecting oxygen into the soil, and depleting the soil of glomalin and polysaccharides and a loss of carbon. Greater than 90 percent of the carbon in soil is associated with the mineral fraction (Jastrow and Miller, 1997). Glomalin and polysaccharides are consumed by flourishing bacteria populations that thrive on high oxygen levels in the soil and the release of nutrients in organic matter from the tillage. The end result is a soil composed of mainly microaggregates and cloddy compacted soils. Soils composed mainly of microaggregates prevent water infiltration due to the lack of macropores in the soil, so water tends to pond on the soil surface. Farm fields that have been excessively tilled tend to crust, seal, and compact more than no-till fields with surface crop residues and a living crop with active roots to promote fungal growth and glomalin production.

An agricultural system that combines a **continuous living cover (cover crops) with continuous long-term no-till** is a system that closely mimics a natural system and should restore soil structure and soil productivity. A continuous living cover plus continuous long-term no-till protects the soil from compaction in five major ways. **First**, the soil surface acts like a sponge to help adsorb the weight of heavy equipment traffic. **Second**, plant roots create voids and macropores in the soil so that air and water can move through the soil. Roots act like a biological valve to control the amount of oxygen that enters the soil. The soil needs oxygen for root respiration and to support aerobic microbes in the soil. However, too much soil oxygen results in excessive carbon loss from the aerobic microbes consuming the active carbon. **Third**, plant roots supply food for microorganisms (especially fungus) and burrowing soil fauna that also keep the soil from compacting. **Fourth**, organic residues left behind by the decaying plants, animals, and microbes are lighter and less dense than clay, silt, and sand particles. The average bulk density of soil organic matter is 0.3 to 0.6 $kg/m^3$ compared to soil density of 1.4 to 1.6 $kg/m^3$. So adding organic residues to the soil decreases the average soil density. **Fifth**, soil compaction is reduced by combining microaggregates into macroaggregates in the soil. Microaggregate soil particles (clay, silt, particulate organic matter) are held together by humus or old organic matter residues, which are resistant to decomposition, but microaggregates tend to compact in the soil under heavy equipment loads. Polysaccharides and glomalin weakly combine microaggregates into macroaggregates but this process is broken down once the soil is disturbed or tilled.

## Summary

Soil compaction reduces crop yields and farm profits. For years, farmers have been physically tilling and subsoiling the soil to reduce soil compaction. At best, tillage may temporarily reduce soil compaction but rain, gravity, and equipment traffic compact the soil. Soil compaction has a biological component and the root cause of soil compaction is a lack of actively growing plants and active roots in the soil. A continuous living cover plus long-term continuous no-till reduce soil compaction in five ways. Organic residues on the soil surface cushion the soil from heavy equipment. Plant roots create voids and macropores in the soil for air and water movement. Plant roots act like a biological valve to control the amount of oxygen in the soil to preserve soil organic matter. Plant roots supply food for soil microbes and soil fauna. Residual organic soil residues (plants, roots, microbes) are lighter and less dense than soil particles.

Soil compaction is reduced by the formation of macroaggregates in the soil. Microaggregate soil particles (clay, silt, particulate organic matter) are held together by humus or old organic matter residues and are resistant to decomposition. Macroaggregates form by combing microaggregates together with root exudates like polysaccharides and glomalin (sugars from plants and protein from mycorrhizal fungus). Polysaccharides from plants and glomalin from fungus weakly hold the microaggregates together but are consumed by bacteria so they need to be continually reproduced in the soil to improve soil structure. Tillage and subsoiling increases the oxygen content in soils, increasing bacteria populations, which consume the active carbon needed to stabilize macroaggregates, leading to the destruction of soil structure. Soil compaction is a direct result of tillage, which destroys the active organic matter and a lack of living roots and microbes in the soil. Heavy equipment loads push soil microaggregates together so that they chemically bind together, resulting in soil compaction.

## What is a clod?

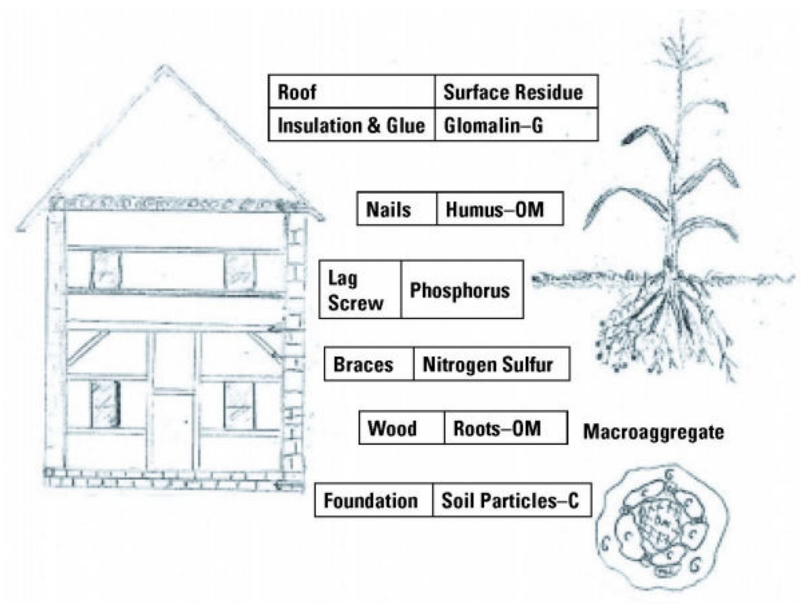
Many farmers complain that their soil is cloddy and hard to work. Clods are manmade and do not usually exist in the natural world. Bricks and clay tile are formed by taking wet clay from the soil, and heating and drying the clay. When farmers till the soil, they perform the same process by exposing the clay to sunlight, heating and drying the clay until it gets hard and turns into a clod. Tillage also oxidizes the soil and results in increased microbial decomposition of organic residues. Organic residues keep clay particles from chemically binding. Clay soils that remain protected by organic residues and stay moist resist turning into clods because the moisture and organic residues keep the clay particles physically separated.

*Organic residues act like sponges, absorbing water and soil nutrients, cushioning soil particles. Clods act like bricks, resisting water absorption and making soils hard and compacted. Photo by Jim Hoorman.*

## *Building Soil Structure*

Building soil structure is like building a house. Mother Nature is the architect and plants and microbes are the carpenters. Every house needs to start out with a good foundation like bricks *(clay, sand, silt)* and cement *(cations like Ca++, K+).* When a house is framed, various sized wood timbers, rafters, and planks are used to create rooms (represented by the various sized roots in the soil). Wood and roots give the house and the soil structure, creating space where the inhabitants (plants, microbes, and soil fauna) can live.

Wood in a house is held together by various sized nails *(humus)* and lag screws *(phosphate* attaches organic residues to clay particles). A house has braces to add stability *(nitrogen* and *sulfur* provide stability to organic residues) and a roof to control the temperature and moisture. In the soil, a deep layer of surface residues controls oxygen and regulates water infiltration and runoff. A roof insulates the house and regulates the temperature just like surface residue on the soil surface keeps the soil temperature in a comfortable range for the inhabitants *(microbes* and *plant roots)*. Houses need insulation and glue to keep the house together. Root exudates form polysaccharides and glomalin (formed with *mycorrhizal fungus)* to insulate the soil particles and keep the soil macroaggregates glued together. If the roof on a house is destroyed, moisture and cold air can enter the house and rot out the wood and dissolve the glues.




*Building Soil Structure Is Like Building a House. Diagram by James J. Hoorman. Illustrated by Danita Lazenby.*

In the soil, organic matter decomposes very quickly when tillage, excess oxygen, and moisture either break down the glues *(polysaccharides* and *glomalin)* or are easily consumed by flourishing bacteria populations. Excess oxygen in the soil (from tillage) stimulates bacteria populations to grow and they consume the polysaccharides as a food source, destroying the soil structure. With tillage, macroaggregates become microaggregates and the soil becomes compacted.

As every homeowner knows, houses need regular maintenance. In the soil, the roots and the microbes (especially *fungus)* are the carpenters that maintain their house, continually producing the glues *(polysaccharides* and *glomalin)* that hold the house together. Regular tillage acts like a tornado or a hurricane, destroying the structural integrity of the house and killing off the inhabitants. Tillage oxidizes the organic matter in the soil, destroying the roots and the active organic matter, causing the soil structure to crumble and compact. If you remove wood supports and glue in a house, the house becomes unstable just like the soil does when you remove the active living roots and active organic residues (polysaccharides). Wood beams in a coal mine stabilize the coal mine tunnel like active living roots and healthy microbial communities give the soil structure to prevent soil compaction. Active roots and macroaggregates give soil porosity to move air and water through the soil in macropores. In an ideal soil, 50 to 60 percent of the soil volume is porous while in a degraded compacted soil, soil porosity may be reduced to 30 to 40 percent of the total soil volume. Compacted soil is like a decaying house turning to a pile of bricks, cement, and rubble.

## Five Ways Soil Organic Matter Resists Soil Compaction

1. Surface residue resists compaction. Acts like a sponge to absorb weight and water.

2. Organic residues are less dense (0.3-0.6 g/cm$^3$) than soil particles (1.4-1.6 g/cm$^3$).
3. Roots create voids and spaces for air and water.
4. Roots act like a biological valve to control oxygen in the soil.
5. Roots supply exudates to glue soil particles together to form macroaggregates and supply food for microbes.

## References


- Allison, F.E. "Soil aggregates—some facts and fallacies as seen by microbiologist." *Soil Sci. 106* (1968): 136–143.
- Busscher, W.J., P.J. Bauer, & J.R. Frederick. "Recompaction of a coastal loamy sand after deep tillage as a function of subsequent cumulative rainfall." *Soil and Tillage Research 68* (2002): 49–57.
- Hakansson, I., & R.C. Reeder. "Subsoil compaction by vehicles with high axle load-extent, persistence and crop response." *Soil and Tillage Research 29* (2–3) (1994): 277–304.
- Jastrow, J.D., & Miller, R.M. "Soil aggregate stabilization and carbon sequestration: Feedbacks through organomineral associations." In *Soil Processes and the Carbon Cycle* (ed. R. Lal et al.), pp. 207–223. Boca Raton, FL: CRC Press, 1997.
- Johnson, B.S., A.E. Erickson, & A.J.M. Smucker. *Alleviation of compaction on a fine textured soil* ASAE Paper No. 86-1517. St. Joseph, MI: ASAE, 1986.
- Lal, R. "Soil Carbon Sequestration impacts on global climate change and food security." *Sci. 304* (2004): 1623–1627.
- Reeder, R., & Westermann, D. (2006). Soil Management Practices. In M. Schnepf & C. Cox (Eds.), *Environmental Benefits of Conservation on Cropland: The Status of Our Knowledge (*Ch. 1, pp. 26–28). Ankeny, IA: Soil and Water Conservation Society.
- Tisdall, J.M., & J.M. Oades. Organic matter and water stable aggregates in soil. *J. of Soil Science. 33* (1982)*:* 141–163.
- Dr. João Carlos de Moraes Sá. (2008). *Biological interactions with aggregate formation & carbon cycle in the terrestrial environment* [PowerPoint presentations].
- Wortman, C., & P. Jasa. 2003. Management to Minimize and Reduce Soil Compaction. NebGuide G896. Lincoln, NE: University of Nebraska–Lincoln Extension.
- Wright, S.F., & Upadhyaya, A. "Extraction of an abundant and unusual protein from soil and comparison with hyphael protein of arbuscular fungi during active colonization of root." *Plant Sci. 181* (1996): 193–203.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