The Biology of Soil Compaction
(Revised & Updated)

SCIENCE

by James J. Hoorman, João Carlos de Moraes (Juca) Sá & Randall Reeder

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Editors' Note: Modified extensively from an Ohio State Extension Fact Sheet, 2009, in collaboration with Hoorman & Sá, along with the generous assistance of John Grove (soil scientist, U.Ky.), Tom Schumacher (soil scientist, SDSU), and Kris Nichols (mycorrhizae scientist, USDA-ARS).

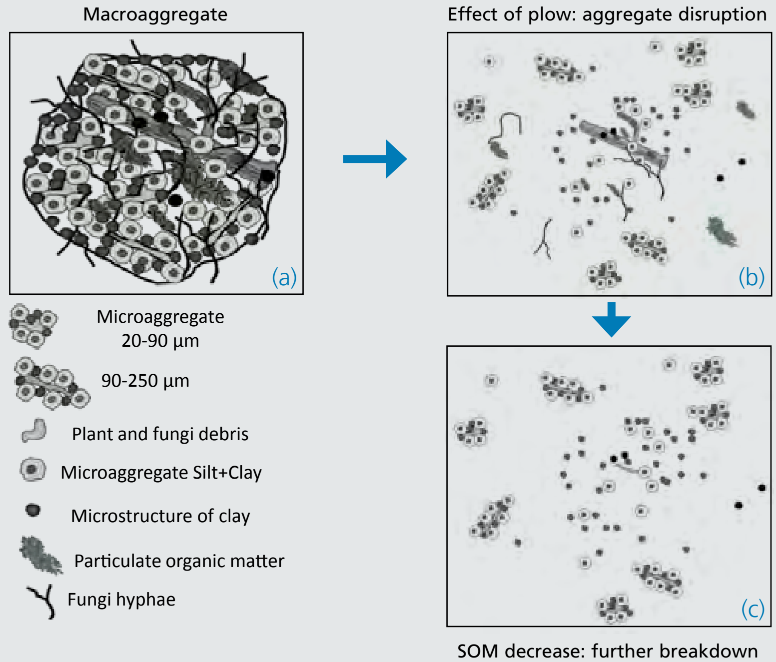

Figure 1: (a) Macro-aggregate components—schematic illustration; (b) Mechanical disturbance by tillage disrupts macro-aggregates, and exposes soil organic matter (SOM) protected within the aggregate to microbial attack; (c) loss of SOM within the aggregates (due to microbial digestion) causes destabilization of linkages in the macro-aggregate, making them vulnerable to collapse from external forces. *Macro*-aggregation gives soil most of its structure, porosity, aeration, and the ability to resist compacting forces. The smallest macro-aggregates are the size of the period at the end of this sentence, and range up to about the size of this letter 'O.' *Micro*-aggregates are smaller than the period, and some are microscopic.

Diagram source: J.C.M. (Juca) Sá.

Soil Compaction

Soil compaction is a common and constant problem on most farms that till the soil. Heavy farm machinery can create persistent subsoil compaction, even when under no-tillage management.[1] Scientists have found that compacted soils resulted in: (a) physically restricted root growth; (b) poor root-zone aeration (inadequate oxygen flow to roots); and (c) poor drainage that contributes further to poor soil aeration and to more losses of nitrogen from denitrification.[2]

Subsoil tillage has been used to alleviate compaction problems. Subsoilers (deep-rippers) are typically operated at depths of 12 to 18 inches to loosen the soil, break compaction, and increase water infiltration and aeration. Subsoiling sometimes increases crop yields but the effects may only be temporary because the soil re-compacts from rainfall as well as continued equipment traffic over wet soil. Some no-till fields never need to be subsoiled, but in other no-till fields deep tillage has increased yields, especially if equipment traffic has occurred over a large portion of the field while soils were wet. When subsoiling removes a hard pan, traffic must be controlled or compaction will re-occur. If a hard pan does not exist, equipment traffic on damp soils can create one.[3] (*Editors: Research and farmer experience across much of the USA indicate that yield increases from deep tillage are rare, and short-lived. Hard pans are primarily the result of tillage implements, and not so much from wheel traffic. And, in continuous no-till, controlled traffic [permanent tramlines] on terrain with any significant slope creates major problems, due to runoff carving rills and gullies in the permanent traffic lanes.*)[4]

The required fuel, labor, equipment, and time make subsoiling an expensive operation. If the field is sub-

1 I. Hakansson, & R.C. Reeder, 1994, Subsoil compaction by vehicles with high axle load—extent, persistence and crop response, *Soil Tillage Res.* 29: 277–304.
2 B.S. Johnson, A.E. Erickson & A.J.M. Smucker, 1986, Alleviation of compaction on a fine textured soil, ASAE Paper No. 86-1517, ASAE (St. Joseph, MI).
3 R. Reeder & D. Westermann, 2006, Soil Management Practices, in: *Environmental Benefits of Conservation on Cropland*, ed. M. Schnepf & C. Cox, Soil & Water Conserv. Soc. (Ankeny, Iowa) (pp 26–28).
4 *Tom Schumacher agrees fully with the Editors' comments and summary of the science, noting that favorable outcomes from subsoiling are usually confined to breakage of geologic or chemical hardpans (fragipans), and not those created by tillage or wheel traffic.*

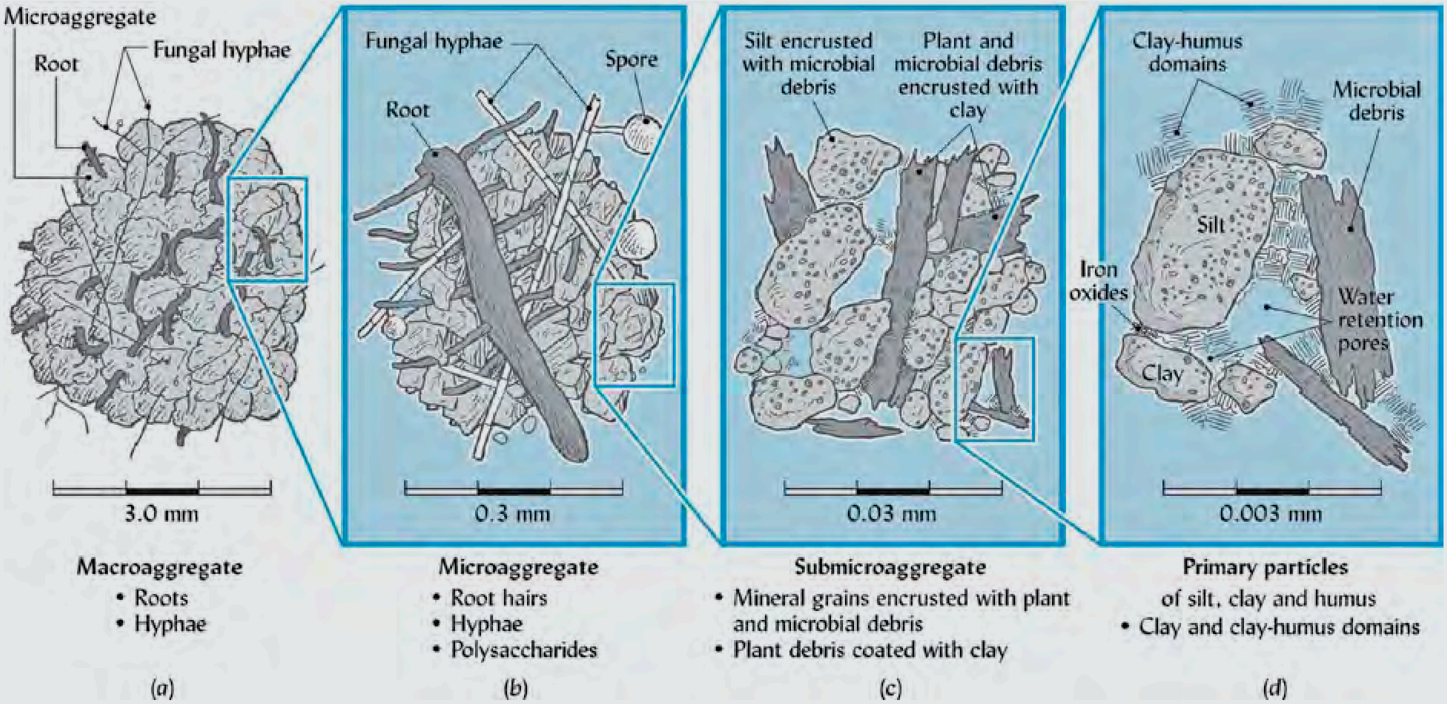

Figure 2: Peering deeper into the structure of soil aggregates. Units of measure **μ** = micrometer (millionth of a meter). Reprinted with permission from N.C. Brady & R.R. Weil, 2008, *The Nature and Properties of Soils,* 14th ed. (p 137, fig. 4.15).

soiled when it's wet, additional compaction will occur. Subsoiling dry soil (although more effective) requires even more fuel.[5] Soil texture and structure play a role in compaction. In a loamy sand with little soil structure, researchers found that soil compaction increased with time, and that cumulative rainfall accounted for 70 to 90% of surface and subsurface re-compaction, due to water movement through the soil and the force of gravity.[6] Such phenomena are less important on *well-structured* loamy and clayey soils. However, in tilled soils, compaction readily increases from the force of rain-drop impact on bare soil as well as water percolation through unstable pores and voids.

The 'root-hyphae net' holds the aggregates intact.

Crop residues (mulch) on the surface have been shown to cushion the effects of soil-compacting forces. These crop residues can be compressed, but also retain their shape once the traffic has passed. Like a sponge, the organic material then springs back to its normal shape. However, excessive traffic breaks up crop residues, and tillage accelerates decomposition of soil organic matter ('SOM': basically anything in the soil that lives or once lived, including remnants of plants, microbes, and their secretions). Low SOM levels make the soil more susceptible to compaction.[7] Crop residues *within* the soil (roots and root exudates) may be even more important than surface residues for preventing compaction.

In the last hundred years, tillage has decreased SOM levels by 60%, which means that approximately 40% of the soil organic carbon stock remains.[8] Carbon compounds provide energy for soil microbes, are a storehouse for nutrients, and help maintain nutrient cycling between plants and soil. Humus is the highly decomposed and most stable carbon type that binds individual soil particles (microscopic clays) together to form micro-aggregates. As compared to younger 'active' carbon, humus is less water soluble and isn't readily consumed by microorganisms, thus stabilizing the micro-aggregates (see Fig. 2). Humus is more resistant to tillage and microbial degradation than active carbon. Some of the more durable SOM components are centuries old.

Active carbon (plant sugars or polysaccharides; glomalin; proteins) 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 smaller aggregates into larger aggregates and stabilizes the arrangement. This is how soil porosity, water infiltra-

5 Reeder & Westermann, 2006.
6 W.J. Busscher, P.J. Bauer & J.R. Frederick, 2002, Recompaction of a coastal loamy sand after deep tillage as a function of subsequent cumulative rainfall, *Soil Tillage Res.* 68: 49–57.
7 C.S. Wortmann & P.J. Jasa, 2003, Management to Minimize and Reduce Soil Compaction, *NebGuide G896*, U. Neb.–Lincoln Extension.
8 R. Lal, 2004, Soil Carbon Sequestration Impacts on Global Climate Change and Food Security, *Science* 304: 1623–1627.

tion, aeration, and structure increase under natural vegetation and no-till systems with continuous living cover.

Aggregate Formation

Micro-aggregates are silt-sized (20 – 250 µm, or less than 0.01 inch), relatively stable, and composed of clay microstructures and microscopic bits of organic matter. *Macro*-aggregates, greater than 250 µm in size, are linked mainly by fungal hyphae, root fibers, and their glue-like secretions. These larger aggregates are less stable than micro-aggregates, but it is the macro-aggregates that give the soil structure and allow greater air flow and water infiltration. The macro-aggregation lowers bulk density (increases stable pore space) and provides most of the resistance to compacting forces. Compacted soils tend to have more micro-aggregates than macro-aggregates. (Fig. 1 & 2)

Fungi live longer than bacteria and need more stable conditions. Since fungi don't grow as well in tilled soils, fewer hyphae are produced and fewer macro-aggregates are formed.

'Glomalin' is one of the organic glues that holds aggregates together. In order for glomalin to be produced, plants and mycorrhizal fungi must co-exist: The mycorrhizal hyphae threads are allowed to enter the root, where the plant 'trades' sugars for nutrients and water from the fungus. Glomalin is an 'amino polysaccharide' or 'glycoprotein' created by combining a protein from the mycorrhizal fungus with a complex sugar (polysaccharide) from plant roots.[9] Roots exude (secrete) other organic compounds that coat soil particles. (Fig. 2 – 4)

The 'root-hyphae net' holds the aggregates intact, and clay particles partially protect the roots and hyphae from attack by microorganisms. The contribution of mycorrhizal fungi to aggregation is a process involving three simultaneous actions. First, the fungal hyphae physically entangle soil particles, meshing them together. Second, fungi physically protect the clay particles and organic debris that form micro-aggregates. Third, the plant root and fungal hyphae form glomalin that glues micro-aggregates and smaller macro-aggregates together to form larger macro-aggregates. (Fig. 4)

Photo by J.C.M. (Juca) Sá.

Figure 3: Roots, fungal hyphae, and their secretions stabilize soil aggregates and promote good soil structure, thus preventing compaction.

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 fungi, so bacteria numbers can increase rapidly in tilled soils when conditions are favorable. 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 supply of carbon food source. Since fungi do not grow as well in tilled soils, less glomalin and fewer hyphae are produced and fewer macro-aggregates are formed. **Thus, susceptibility of soils to compaction is a direct result of a biological problem: Decreased amounts of roots, hyphae, and their secretions in the soil.**

Photo by Sara Wright & Kris Nichols, USDA-ARS.

Figure 4: A microscopic view of an arbuscular mycorrhizal fungus growing on a corn root (the most prominent item in the photo). The round bodies are spores, and the threadlike filaments are hyphae of the fungus. The substance coating them is glomalin, revealed by a green dye tagged to an antibody against glomalin.

[9] S.F. Wright & A. Upadhyaya, 1996, Extraction of an abundant and unusual protein from soil and comparison with hyphal protein of arbuscular fungi, *Soil Sci*. 161: 575–586; S.F. Wright, M. Franke-Snyder, J.B. Morton & A. Upadhyaya, 1996, Time-course study and partial characterization of a protein on hyphae of arbuscular mycorrhizal fungi during active colonization of roots, *Plant & Soil* 181: 193-203; F.E. Allison, 1968, Soil aggregates—some facts and fallacies as seen by a microbiologist, *Soil Sci.* 106: 136–143.

In a typical two-year corn-soybean rotation, a significant quantity of active roots is present only a third of the time.[10] Adding cover crops after both the corn and soybeans increases the time that roots are actively growing by several months. Active roots produce more polysaccharides, which permits more hyphae and glomalin production because mycorrhizal fungus populations increase with the stable food supply.

In a corn-soybean rotation, active roots are present only 1/3 of the year. Cover crops increase the time roots are actively growing by several months.

Aggregate Loss

Surface and subsoil tillage may physically break up hard pans and soil compaction temporarily but they are not a permanent fix. First, tillage decreases mycorrhizal fungus populations. In a typical undisturbed soil, mycorrhizal hyphae are turned over (grow, age, die) every 5 to 7 days (the fungus organism may live far longer, but its finely branched absorptive hyphae must continually regrow), which provides a continuous supply of glomalin as well as more hyphae.[11] Second, tillage sharply increases oxygen flow to soil microsites,[12] thus speeding microbial decomposition of glomalin, hyphae, fine roots, and the other organic materials that create the structure needed to resist compaction. Disturbed soils have fewer fungi, more bacteria, and more micro-aggregates than macro-aggregates. Heavy equipment loads and rainfall can then push the micro-aggregates into tighter arrangements, thus decreasing the pore spaces. In other words, compacting the soil. (Fig. 5) However, macro-aggregate formation improves soil structure and its ability to resist compaction.

Cultivation of soils causes the breakdown of macro-aggregates, which are a large component of soil structure ('tilth'). Farmers who excessively till their soils[13] (e.g., repeated use of the plow, disk, sweeps) break down macro-aggregates by mechanical shattering and by allowing extra oxygen to get to the soil's microbial decomposers, thus depleting the soil of glomalin, polysaccharides, and other carbon. Greater than 90% of soil organic carbon exists as a coating on the mineral surfaces of clay, silt, and sand particles.[14] These stabilizing carbon compounds are consumed by aerobic bacteria that flourish at higher soil oxygen levels[15] (there are other bacteria that thrive when soil oxygen is extremely low). The end result is a soil composed mainly of micro-aggregates and much more prone to

Macropores act like pipes to control the rate at which oxygen reaches roots and soil microbes. Roots need oxygen. However, big influxes of oxygen result in rapid soil carbon loss because the aerobic microbes can then consume organic compounds faster.

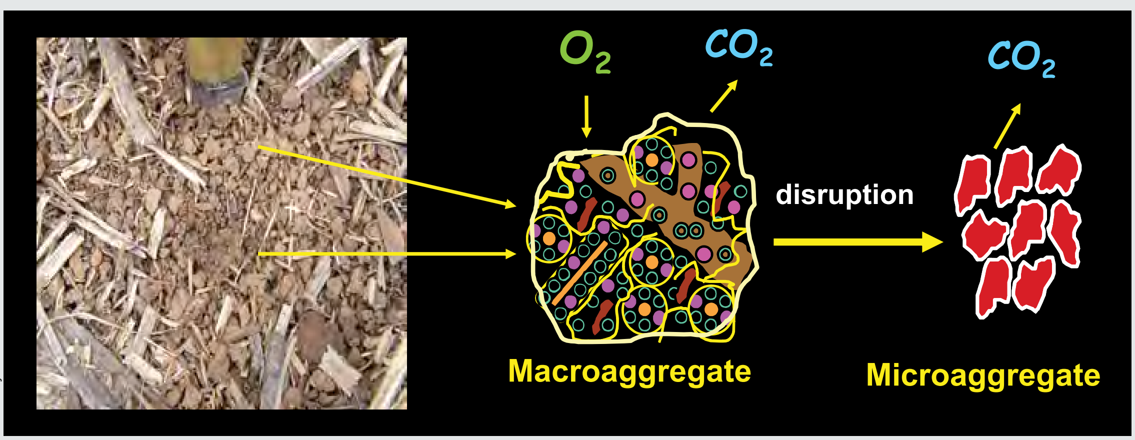

Photo by Juca Sá.

Figure 5: Tillage disrupts the macro-aggregates by physically breaking them into micro-aggregates and by exposing the organic 'glue' to bacterial digestion. Source: Juca Sá.

[10] *Editors: Unless the field has a lot of winter annual weeds.*

[11] C. Hamel & C. Plenchette, 2007, Extraradicle Arbuscular Mycorrhizal Mycelia: Shadowy Figures in the Soil, in *Mycorrhizae in Crop Production*, ed. C. Hamel & C. Plenchette, Haworth Press (hyphae die after a few days but resist decomposition and still function as a conduit in the hyphal network).

[12] *Editors: This is partly due to drying as a result of tillage—every soil aggregate has a water film surrounding it, even in the driest of field conditions. As the water films get very thin (e.g., drying by tillage), oxygen need not diffuse very far through water to reach the microbes and SOM. Oxygen diffuses 10,000 times more slowly through water than through air, so the thickness of these water films is major factor in the rate of decomposition and loss of SOM.*

[13] *Editors: In our view, virtually all tillage is 'excessive.' Unless you're installing a highway.*

[14] J.D. Jastrow & R.M. Miller, 1998, Soil aggregate stabilization and carbon sequestration: Feedbacks through organomineral associations, in: *Soil Processes and the Carbon Cycle*, ed. R. Lal et al., CRC Press (Boca Raton, FL) (pp 207–223).

[15] Tillage causes this 'mineralization' which is the release of mineral nutrients (N, P, S, etc.) and carbon from organic matter (decomposition exceeds the rate of sequestering / immobilization, a.k.a. 'tie-up').

compaction. Soils composed mainly of micro-aggregates have slower water infiltration due to a lack of stable macropores, so water tends to pond at the surface. Fields that have been excessively tilled tend to crust, seal, and compact more than no-till fields with plentiful crop residues and a living plant cover with active roots and fungi.

Agriculture that combines **a continuous living cover with continuous long-term no-till** is a system that closely mimics a natural ecosystem and **will improve soil structure and soil productivity.** A continuous or nearly continuous living cover plus continuous long-term no-till protects the soil from compaction in four major ways. *First*, the organic material on the soil surface acts like a cushion, helping to absorb the weight of heavy equipment traffic (as well as the force of planter or fertilizer openers). *Second*, plant roots create and enlarge voids and macropores in the soil so that air and water can move through the soil. These macropores act like pipes to control the rate at which oxygen reaches roots and soil microbes. The soil needs oxygen for root respiration and to support aerobic microbes in the soil (the same way we metabolize food, with carbon dioxide as by-product). However, big influxes of oxygen result in rapid soil carbon loss because the aerobic microbes can then consume organic compounds faster. *Third*, plant roots supply food for microorganisms (especially fungi) and burrowing soil fauna (e.g., earthworms) that create and maintain soil porosity by their activities. *Fourth*, roots help stabilize soil aggregates. The most stable, durable combination is where aggregates are held together by humus or old organic matter that resists decomposition. A more temporary combination is the linkage by newer plant polysaccharides and fungal glomalin, but these are more easily digested by bacteria so they need to be continually replenished to maintain or improve soil structure. This process is broken when the soil is disturbed or tilled, or lacks vegetation.[16]

Compaction is a result of macro-aggregate depletion by tillage.

Summary

Soil compaction reduces crop yields and farm profits. For years, farmers have been physically tilling and subsoiling to alleviate soil compaction. At best, tillage may temporarily reduce soil compaction but rain, gravity, and equipment traffic will re-compact it. A soil's vulnerability to compaction is largely a result of biological aspects: Living plants with active root systems, along with mycorrhizal hyphae, and the glue-like secretions of each, will significantly reduce compaction susceptibility. Year after year, this process can improve soil structure considerably and provide resistance to compacting forces. Thus, a continuous living cover and long-term no-tillage management act together to reduce soil compaction occurrence.

Tillage increases the rate at which oxygen is supplied to microsites in the soil, thus increasing aerobic bacterial populations which consume the carbon compounds that stabilize macro-aggregates. This leads to loss of soil structure. Soil compaction is the result of traffic (or the compressing forces of tillage itself) on moist soils where tillage has previously destroyed macro-aggregates. Rainfall also causes compaction where macro-aggregation has been depleted by tillage, due to flow of infiltrated water through the destabilized pores and voids, and also from raindrop impact onto barren, exposed soil.

Further reading: Tom Schumacher & Walt Riedell, 'Soil Structure Examined,' Leading Edge, *Jan. '08, pp 398-406.*

What is a clod?

Many farmers complain that their soil is cloddy and hard to work. Clods are man-made and do not usually exist in the natural world. Bricks and clay tile are made by taking wet clay from the soil, forming it, and then heating (firing) and drying the clay. When farmers do tillage, they perform the same process by exposing the 'formed' clay to sunlight, which heats and dries the soil shards until they are hard clods. Tillage also causes greater microbial decomposition of plant residues and soil organic matter which would normally keep silt and clay particles from hardening with drying. Crop residues act like sponges, absorbing water and cushioning against the force of surface traffic and raindrop impact.

Photo by Jim Hoorman.

[16] A fifth mechanism exists: On a dry-weight basis, SOM is lighter and less dense than clay and sand particles: The average bulk density of SOM is 0.3 to 0.6 g/cm^3 compared to bulk soil density of 1.4 to 1.6 g/cm^3. So gaining SOM will decrease the average soil density directly, albeit ever so slightly—since SOM is so slow to be regenerated, and most mineral soils contain only a couple percent SOM.