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. 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.

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.

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

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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.
soiled when it's wet, additional compaction will occur. Subsoiling dry soil (although more effective) requires even more fuel.\textsuperscript{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.\textsuperscript{6} Such phenomena are less important on well-structured loamy and clayey soils. However, in tilled soils, compaction readily increases from the force of raindrop impact on bare soil as well as water percolation through unstable pores and voids.

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.\textsuperscript{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.\textsuperscript{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-

\textsuperscript{5} Reeder & Westermann, 2006.
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)

‘Glomalin’ is one of the organic glues that holds aggregates together. In order for glomalin to be produced, plants and mycorrhizal fungi must coexist. 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)

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.

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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.

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 soils13 (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 levels15 (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

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10 Editors: Unless the field has a lot of winter annual weeds.
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.
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 macro pores, 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 macro pores in the soil so that air and water can move through the soil. These macro pores 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

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.


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/cm³ compared to bulk soil density of 1.4 to 1.6 g/cm³. 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.