Soil Structure and the Physical Fertility of Soil

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Key Points

- The physical properties of soil are at least as important as the chemical properties in determining fertility.
- The quality of soil structure is measured by the capacity of the soil particles to clump together or aggregate.
- Aggregation is influenced by soil organic carbon (SOC), soil biology/microbiology, chemical reactivity and the presence of clay.
- Agricultural practices that decrease soil disruption can enhance aggregation and soil structural development.
- The promotion of beneficial soil structure can have a positive impact on the sequestration of carbon in soil.

“Good soil structure is vital for sustainable agriculture. It regulates soil erosion and gaseous exchange rates, the movement and storage of water, soil temperature, respiration and development, nutrient cycling, resistance to structural degradation, and supports biological activity. It also promotes germination, emergence, crop yields, grain quality and soil health”

From: Simply Sustainable Soils.

Summary

Soil structure is the arrangement and organisation of the particles and substances that constitute soil. It exercises important influences on the broad characteristics of soil and the way soil performs its vital environmental functions. It is the capacity of the primary particles
of soil to form the clumps and clods more formally known as aggregates. The formation of these aggregates result from the combination of complex interactions mediated by soil organic carbon (SOC), soil biology, chemical reactivity and the presence or absence of clay and carbonate particles. The complex interactions of these components can either promote or inhibit aggregation. Clay particles are often associated with having a positive effect on aggregation though swelling clay can be disruptive. The SOC originating from plants, animals and microorganisms enhances aggregation through the bonding of soil particles. Plant roots and the hyphae (branching, root-like structures) of fungi can enmesh particles together while realigning them and releasing organic compounds that hold particles together. Soil structure can be significantly modified through management practices and environmental changes. Agricultural practices that decrease soil disruption can enhance aggregation and structural development.

Analysis

Soil Structure Defined

The structural properties of soil are at least as important as soil chemical and biological properties in determining soil fertility. Soil structure is defined as the manner in which the primary soil particles (sand, silt and clay) are combined and arranged with other solid soil components to form clumps or aggregates. The size, shape and arrangement of these soil solids and the spaces between them influences the soil’s capacity to retain and transmit air, water, organic and inorganic substances, and its ability to support root growth and development. The structure of soil influences greatly its ability to sustain life and perform other vital soil functions such as carbon, water and nutrient cycling. Management of soil structure and aggregate stability are important to maintain and improve soil productiveness, enhance porosity, decrease erosion and increase agricultural productivity.

A decline in soil structure is increasingly seen as a form of soil degradation. It is often related to land use and crop management practices. Soil Structure is also strongly affected by changes in climate and biological activity. It affects the retention and transmission of water and air in the soil as well as the mechanical properties of the soil. Soil structural properties tend to be more difficult to measure than soil chemical properties and even biological properties. As a result, reliable data for many Australian soils is lacking.

Basic concepts of aggregation

Aggregates are formed through the attachment of mineral particles with organic and inorganic substances. The complex dynamics of aggregation are the result of the interaction of many factors, including the environment, soil management factors, plant influences and soil properties such as mineral composition, texture, SOC concentration, soil forming processes, microbial activities, chemistry, nutrient reserves, and moisture availability. Aggregates occur in a variety of manners and sizes. These are often grouped by size: macro-aggregates (greater than 250 micrometres) and micro-aggregates (less than 250 micrometres) with these groups being further divided by size. Different size groups differ in properties such as binding agents and carbon and nitrogen distribution.
How aggregates are formed

Aggregates are formed in stages and can be formed in different ways. In the initial stages, micro-aggregates are formed from molecules attached to clay, which are joined with other particles to form macro-aggregates. Alternatively, macro-aggregates can form around particles of organic matter. As the organic matter is decomposed and microbial bi-products are released, the macro-aggregate becomes more stable. Roots and fungi hyphae enmesh and release organic compounds that act as glue to hold particles together. Particles can be rearranged during enmeshment, while wet–dry cycles help to stabilize the aggregates. Bacterial micro-aggregates form as bacterial colonies release fluids that form a capsule around which clay particles are aligned and pulled in by drying and shrinkage. The clay shell forms a protective coating for the bacterial colony inhibiting decomposition of the SOC inside. Concentric theory of aggregation suggests that external layers are concentrically built upon the external surface of the aggregate, with younger carbon in outer layers of aggregates than in aggregate interiors.

![Figure 1. A diagrammatic representation of well-structured and poorly structured soils. Source: Victorian Department of Agriculture.](image)

Aggregates can form through a combination of processes. Macro-aggregates may initially form through accumulation of micro-aggregates or around organic matter particles or bacterial colonies, decomposing later into micro-aggregates. Micro-aggregates may initially form by the progressive bonding of clay and SOC, or as turnover products from macro-aggregates. Primary particles can accumulate on outer layers of aggregates.

Aggregate dynamics and turnover

The on-going interactive effects of soil-forming processes, soil properties and external factors such as terrain and climate, establish a dynamic equilibrium in soil structure.
Aggregates can be disrupted by a variety of mechanisms depending on the nature of the bonding agents. The activities of soil microorganisms influence carbon retention time and turnover in soil, which in turn affect carbon stabilisation, aggregation and cycling. This decomposition is effected by the activity of soil organisms, soil properties and environmental factors such as temperature, gaseous concentration, nutrient availability and moisture levels. Feedback within the system suggests decomposition of SOM is affected by soil structure, through porosity, gaseous exchange and soil moisture, as well as by the physical location of carbon such as its depth. The turnover of SOC may be slower towards the end of the growing season, resulting in slow turnover rates in macro-aggregates. Inorganic compounds, low-activity clays and stable carbon bonding agents are generally resistant to breakdown. The mobilization and precipitation of substances can promote the dissolution and breakdown of aggregates as well as the formation of new aggregates. Ingestion by soil fauna can disrupt aggregates, although it generally increases aggregate stability. Aggregates are also susceptible to disruption by physical disturbances such as clay swelling, tillage and rainfall impact.

Figure 2. Example of soil macro-aggregates.

Soil structure and plant growth

Soil structure affects plant growth by influencing root distribution and the ability to take up water and nutrients. Soil structure facilitates oxygen and water infiltration and can improve water storage. Increased water transfer through soil can reduce fertilizer retention in the soil matrix and fertilizer use efficiency in plants. Disturbance of soil structure through
compaction or tillage can result in the rapid recycling of nutrients, crusting (the hardening of the soil surface layer) reduced water and air availability to roots.

**Climate and landscape factors**

Climate and topography influence soil structure through factors such as temperature, precipitation, elevation, slope gradient and directional aspect. Soil properties such as texture, mineralogy, SOC and organisms interact and moderate the influence of the climate.

**Climate** affects soil aggregation through alterations in temperature and moisture regimes and wet–dry and freeze–thaw cycles, which can reorient particles possibly resulting in improved aggregation and increased isolation of SOC within aggregates. Changes in temperature and moisture levels affect microbial and biological activity, which alter decomposition rates. The relationship between temperature and decomposition is highly variable due to the influence of a variety of other factors. Warmer temperatures result in higher respiration and biological activity in soil, while lower temperatures result in higher standing stock of SOC. Frozen and wet soils tend to have more unavailable SOC than warm and dry soil. In moist, temperate regions, aggregation is affected by the freeze–thaw cycles.

Soils undergo continuous changes in moisture content. Under rain-fed conditions, wet and dry cycles are most commonly related to climatic factors. On a local level, water uptake by plant roots can lead to drying in the root zone. Soil moisture and wet–dry cycles have a variable effect on aggregation. Wet–dry cycles can disrupt aggregation in swelling clays. As clay particles swell they separate from other particles, decreasing aggregate stability. Wet–dry cycles have a more positive influence in the initial stages in soils with non-swelling clays and in macro-aggregates. During wetting, clay particles tend to disperse and then form bridges and coatings while drying. This leads to closer contact between particles and increased clay bridging. Wet–dry cycles also affect the amount of organic material incorporated into aggregates and porosity. Wet–dry cycles are important to aggregation in soils of arid, semi-arid and subhumid regions.

Arid conditions have variable effects on aggregation. Factors such as carbonates, earthworms and crusting, can increase aggregate stability in arid environments. While crusting reduces water infiltration, it also reduces detachment and erosion, which has a positive impact on aggregation. Some soils of arid regions have higher levels of aggregation and stable micro-aggregates than those in humid regions of Mediterranean climate zones. Decrease in soil moisture and the ensuing reduced vegetation can result in decreased structural development and aggregation and increased erosion. Decreased aggregate stability may be due to increased erosion and runoff resulting in lower SOC, clay content, and chemical reactivity.

Temperature and moisture regimes can be modified by management practices such as irrigation, cover cropping, and mulching. Conventional tillage increases exposure to air, sun, and wind. Management practices moderate the impact of wet–dry cycles, no-till soils experience less intense wet–dry cycles due to protection by surface residue. Dispersion or slaking caused by wet–dry cycles can be reduced by amending soils with humic substances.
Landscape and terrain features such as elevation, directional orientation and slope gradient influence vegetation and erosion. Elevation influences the rate of weathering in soils, having an indirect effect on soil structure. For example, north-facing slopes in the Mediterranean soils have higher aggregation than south-facing slopes, perhaps due to vegetative differences caused by differences in micro-climate. The increased aggregate stability and vegetation feeds back to increased infiltration and reduced erosion. Sloping soils are more susceptible to erosion, particularly in regions of intense rainfall. Erosion tends to remove low density or light particles including clay and SOC that are two of the primary bonding agents in aggregation. Erosion of SOC may also increase the rate of chemical decomposition.

Management for Enhancing Soil Structure

The management of soil to improve its structure has the potential to increase primary plant production, increase the amount of carbon deposited into soil and to decrease the rate of carbon loss through decomposition and erosion. Accordingly, soil management practices that can contribute to improving soil structure include:

- **Tillage.** Tillage disrupts soil aggregates, compacts soil and disturbs plant and animal communities that contribute to aggregation. It lowers SOM, nutrients, microbial activity and faunal activities that contribute to aggregation. In comparison with ploughing, no-till management systems have more stable aggregates and SOC. Reduced tillage can result in more pores and channels that influence water movement, availability and quality. In turn, this influences the loss of nutrients and chemical drainage into ground water.

- **Mulching and residue management.** Mulches improve soil structure in a variety of ways. The addition of mulch to soil surface decreases erosion, reduces evaporation, protects against raindrop impact and increases aggregate stability. Mulches increase the SOC pool, modify temperature and moisture regimes and impact soil fauna.

- **Manuring.** Manuring improves soil structure and density, increases aggregation and resistance to slaking but may decrease stability of soil aggregates against the dissolution and dispersive actions. The increase in SOC results in increased biological activity, which in turn results in increased porosity and the attendant decrease in bulk density. Increased microbial activity due to increases in soil carbon from manure applications results in increases in aggregate stability. Manured soils also have high earthworm population. Unmanured soils usually contain less SOC and microbes, and are denser than manured soil.

- **Compost.** The application of compost to soil improves structure and lowers bulk density. Composting materials can increase aggregation and aggregate stability. Environmental conditions such as drought can limit the effectiveness of compost. The effects of compost additions on soil structure may be short-lived although outcomes are generally positive.
• **Fertiliser and nutrients.** The complexities of the chemical and physical influences of fertilisers result in variable effects on aggregation. Fertiliser applications generally improve soil aggregation; however, under some conditions fertilisers may also decrease SOC concentration, reduce aggregation, and reduce microbial communities when compared to manured soils. When applied correctly, fertiliser will improved nutrient management, increasing plant productivity, increase SOC and promote biological activity. These effects, will intern, increases aggregation and improves density.

**Conclusion**

Soil structure holds a vital, but often overlooked role in sustainable food production and the well-being of the environment. Changes in soil structure can have manifest consequences locally and globally. It can impact the vigour and yield of individual plants and also the planetary carbon, nitrogen and water cycles. Improving soil structure may even have the potential to assist in moderating the effects of climate change through the sequestration of greenhouse gasses in the soil. Future research that recognises the essentially interrelated nature of the three components of soil fertility: the chemical, biological and structural, may provide the foundation for continued, sustainable agriculture and assist in addressing fundamental, environmental challenges.

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