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Soil structure and management: a review

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Abstract

Soil structure exerts important influences on the edaphic conditions and the environment. It is often expressed as the degree of stability of aggregates. Aggregation results from the rearrangement, flocculation and cementation of particles. It is mediated by soil organic carbon (SOC), biota, ionic bridging, clay and carbonates. The complex interactions of these aggregants can be synergistic or disruptive to aggregation. Clay-sized particles are commonly associated with aggregation by rearrangement and flocculation, although swelling clay can disrupt aggregates. Organo-metallic compounds and cations form bridges between particles. The SOC originates from plants, animals and microorganisms, and their exudates. It enhances aggregation through the bonding of primary soil particles. The effectiveness of SOC in forming stable aggregates is related to its decomposition rate, which in turn is influenced by its physical and chemical protection from microbial action. Soil inorganic carbon (SIC) increases aggregation in arid and semi-arid environments, and the formation of secondary carbonates is influenced by the presence of SOC and Ca^{2+} and Mg^{2+}. Soil biota release CO_2 and form SOC which increase dissolution of primary carbonates while cations increase precipitation of secondary carbonates. The precipitation of (hydr)oxides, phosphates and carbonates enhances aggregation. Cations such as Si^{4+}, Fe^{3+}, Al^{3+} and Ca^{2+} stimulate the precipitation of compounds that act as bonding agents for primary particles. Roots and hyphae can enmesh particles together while realigning them and releasing organic compounds that hold particles together, a process with a positive impact on soil C sequestration. Soil structure can be significantly modified through management practices and environmental changes. Practices that increase productivity and decrease soil disruption enhance aggregation and structural development.
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Keywords: Soil aggregation; Soil structure; Aggregate dynamics; Land use management; Carbon sequestration

1. Introduction

Soil structure is a key factor in the functioning of soil, its ability to support plant and animal life, and moderate environmental quality with particular emphasis on soil carbon (C) sequestration and water quality. Aggregate stability is used as an indicator of soil structure (Six et al., 2000). Aggregation results from the rearrangement of particles, flocculation and cementation (Duiker et al., 2003). Aggregation is mediated by soil organic carbon (SOC), biota, ionic bridging, clay and carbonates. The SOC acts as a binding agent and as

a nucleus in the formation of aggregates. Biota and their organic products contribute to the development of soil structure; which in turn exert a significant control over SOC dynamics. The SOC residence time and decomposition rate are key factors influencing its effectiveness in increasing aggregation. Crystalline and amorphous metal oxides and hydroxides are important aggregants in soils. Metal ions form bridges between mineral and organo-mineral particles. Clay also acts as an aggregant, binding particles together and influencing SOC decomposition and turnover. Long-term stability of aggregates is often related to the presence of recalcitrant C (C_R) compounds and metal ions. Formation of secondary carbonates in arid and semi-arid regions is also linked to aggregate dynamics.

The decline in soil structure is increasingly seen as a form of soil degradation (Chan et al., 2003) and is often related to land use and soil/crop management practices. Soil structure influences soil water movement and retention, erosion, crusting, nutrient recycling, root penetration and crop yield. Externalities such as runoff, surface- and ground-water pollution and CO_2 emissions are influenced by soil structure. Reduction in tillage and fertilization can reduce CO_2 emissions by reducing cultivation and production inputs both of which are dependant on fossil fuels. Species biodiversity is affected by management practices; generally high-input agricultural practices decrease biodiversity while the low-input practices enhance biodiversity (Munyanziza et al., 1997; Lupwayi et al., 2001). With increases in population and urbanization, it is important to identify methods to enhance food production while maintaining environmental quality.

This review collates and synthesizes available information on soil structure and its dynamics in relation to management. The emphasis of this review is on a wide range of environmental and anthropogenic factors, and the dynamic interaction among them. Soil structure is discussed in relation to the environment, soil biological components, soil properties, and soil management practices with the intent of better understanding soil structural dynamics.

2. Soil structure

Soil structure refers to the size, shape and arrangement of solids and voids, continuity of pores and voids, their capacity to retain and transmit fluids and organic and inorganic substances, and ability to support vigorous root growth and development (Lal, 1991). Favorable soil structure and high aggregate stability are important to improving soil fertility, increasing agronomic productivity, enhancing porosity and decreasing erodibility.

2.1. Basic concepts of aggregation

Aggregates are secondary particles formed through the combination 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, pedogenic processes, microbial activities, exchangeable ions, nutrient reserves, and moisture availability (Kay, 1998). Aggregates occur in a variety of manners and sizes. These are often grouped by size: macroaggregates (>250 μm) and microaggregates (<250 μm) with these groups being further divided by size (Tisdall and Oades, 1982). Different size groups differ in properties such as binding agents and carbon and nitrogen (N) distribution.

2.2. Mechanisms of aggregation

There are several mechanisms of aggregation. Aggregates are formed in stages, with different bonding mechanisms dominating at each stage (Tisdall and Oades, 1982). Hierarchical theory of aggregation proposes that microaggregates join together to form macroaggregates and the bonds within microaggregates are stronger than the bonds between microaggregates (Edwards and Bremner, 1967). Microaggregates (<250 μm) are formed from organic molecules (OM) attached to clay (Cl) and polyvalent cations (P) to form compound particles (Cl–P–OM), which are joined with other particles (Cl–P–OM) to form macroaggregates $[(Cl–P–OM)_x]_y$ (Edwards and Bremner, 1967; Tisdall, 1996). Alternatively, macroaggregates can form around particulate organic matter (POM). As POM is decomposed and microbial exudates are released, the macroaggregate becomes more stable, the C:N ratio decreases, and microaggregates form inside. The internally formed microaggregates contain more

recalcitrant SOC pool (Plante and McGill, 2002a; Beare et al., 1994). As the more labile SOC pool is utilized and microbial activity decreases, the supply of exudates decreases and the macroaggregate loses stability, eventually disrupts and releases more stable microaggregates (Jastrow et al., 1998; Six et al., 1999).

Roots and 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 microaggregates form as bacterial colonies and their exudates form a polysaccharide 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 C in outer layers of aggregates than in aggregate interiors (Santos et al., 1997).

The precipitation of (hydr)oxides, phosphates and carbonates enhances aggregation. Cations such as Si^{4+}, Fe^{3+}, Al^{3+} and Ca^{2+} stimulate the precipitation of compounds that act as bonding agents for primary particles. Cations also form bridges between clay and SOM particles resulting in aggregation. Dissolved organic compounds (DOC) can complex with Fe^{3+} and Al^{3+} at low pHs forming mobile, organo-metallic compounds that can be precipitated elsewhere in the soil. The complexation decreases microbial access to SOC and mineralization.

It is possible that aggregates form through a combination of these processes (Fig. 1). Macroaggregates may initially form through accumulation of
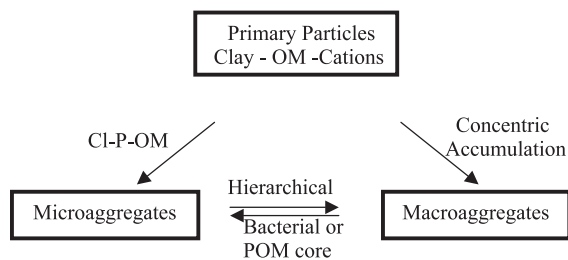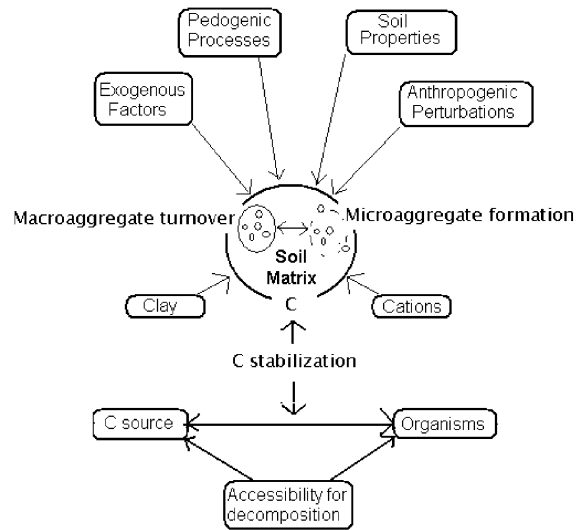

Fig. 2. Factors affecting soil aggregation.

microaggregates or around POM or bacterial cores, decomposing or breaking down later into microaggregates. Microaggregates may initially form by the progressive bonding of clay, SOM and cations, or as turnover products from macroaggregates. Primary particles can accumulate on outer layers of aggregates.

2.3. Aggregate dynamics and turnover

The on-going interactive effects of soil-forming processes, soil properties and exogenous factors such as terrain and climate establish a dynamic equilibrium in soil structure (Fig. 2). Aggregates can be disrupted by a variety of mechanisms depending on the nature of the bonding agents. The activities of soil organisms influence C retention time and turnover in soil, which in turn affect C stabilization, aggregation and turnover. Decomposition is effected by the activity of soil organisms, soil properties and environmental factors such as temperature, gaseous concentration, nutrient availability and moisture gradients (Christensen, 2001). The C:N ratio is commonly used as an indicator of SOC turnover, although for C_R and inert C (C_I) fractions, the lignin/N ratio or other more resistant compounds may be more appropriate (Vanlauwe et al., 1997). Feedback within the system suggests that

Fig. 1. Some possible scenarios of aggregation. Organic matter (OM), particulate organic matter (POM), clay (Cl), particle (P).

decomposition of SOM is affected by soil structure, through porosity, gaseous exchange and soil moisture, as well as by the physical location of C such as depth and occlusion. Turnover dynamics vary spatially within the soil and within individual aggregates as well as over time. The SOC dynamics may be slower towards the end of the growing season, resulting in slow turnover rates in macroaggregates (Plante and McGill, 2002b). Inorganic compounds, low-activity clays and C_R 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 (Schrader and Zhang, 1997). Aggregates are also susceptible to disruption by physical disturbances such as clay swelling, tillage and rainfall impact.

2.4. Pedogenic processes

Soil structural development and aggregation occur within the context of natural pedogenic processes and anthropogenic activities. The complex series of additions and losses from the soil, action of organisms and climatic effects determine soil properties. Weathering alters materials, which are translocated within soils through leaching, bioturbation, eluviation, and illuviation resulting in horizonation. Dissolved organic matter from eluvial horizons is immobilized in illuvial, B horizons (De Coninck, 1980; Guggenberger and Kaiser, 2003; Jansen et al., 2003). Precipitated materials increase binding in the B horizons.

2.5. Soil structure and plant growth

Soil structure affects plant growth by influencing root distribution and the ability to take up water and nutrients (Rampazzo et al., 1998; Pardo et al., 2000). Soil structure facilitates oxygen and water infiltration and can improve water storage (Franzluebbers, 2002). Increased water transfer through soil can reduce fertilizer retention in the soil matrix and fertilizer use efficiency in plants (Franzluebbers, 2002). Disturbance of soil structure through compaction or tillage can result in the rapid recycling of

nutrients, crusting, reduced water and air availability to roots.

2.6. Climate and exogenous factors

Climate and landscape position influence soil structure by factors such as temperature, precipitation, elevation, slope gradient, and aspect. Soil properties such as texture, mineralogy, SOC and organisms moderate the influence of the climate.

2.6.1. Climate

Climate affects soil aggregation through alterations in temperature and moisture regimes and wet–dry and freeze–thaw cycles, which can reorient particles (Singer et al., 1992) possibly resulting in improved aggregation and increased isolation of SOC within aggregates. Changes in temperature and moisture levels affect microbial and biotic 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 (Franzluebbers et al., 2001). Frigid and wet soils tend to have more unavailable SOC than warm and dry soil (Franzluebbers et al., 2001). In moist, temperate regions, aggregation is affected by freeze–thaw cycles (Dalal and Bridge, 1996).

Soils undergo continuous changes in moisture regime. Under rainfed conditions, wet–dry cycles are most commonly related to climatic factors. On a localized level, water uptake by plant roots as influenced by evapotranspiration 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 (Singer et al., 1992). Wet–dry cycles have a more positive influence in the initial stages in soils with non-swelling clays and in macroaggregates (Fig. 3). During wetting, clay particles tend to disperse and then form bridges and coatings while drying (Attou and Bruand, 1998). This leads to closer contact between particles and increased clay bridging (Singer et al., 1992). Wet–dry cycles also affect the amount of POM incorporated into aggregates (Denef et al., 2001) and porosity (Czarnes et al., 2000). Wet–
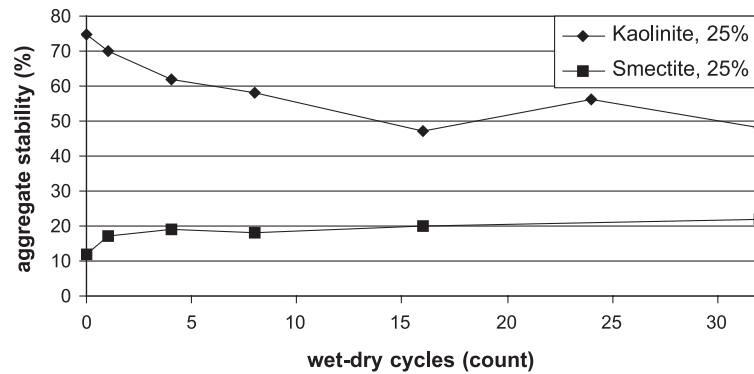
Fig. 3. Wet–dry cycles on aggregate stability for 0.5–1.0 mm aggregates with 25% kaolinite or smectite clay (redrawn from Singer et al., 1992).

dry cycles are important to aggregation in soils of arid, semi-arid and subhumid regions (Dalal and Bridge, 1996).

Arid conditions have variable effects on aggregation. Factors such as carbonates, earthworms and crusting can increase aggregate stability in arid environments (Boix-Fayos et al., 2001). While crusting reduces water infiltration, it also reduces detachment and erosion, which has a positive impact on aggregation (Amezketa, 1999). Some soils of arid regions have higher levels of aggregation and stable micro-aggregates than those in humid regions of the Mediterranean (Boix-Fayos et al., 2001). 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 cation exchange capacity (CEC) (Boix-Fayos et al., 1998).

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 (Denef et al., 2001). Dispersion or slaking caused by wet–dry cycles can be reduced by amending soils with humic substances (Piccolo et al., 1997).

2.6.2. Terrain

Geographic region, elevation, aspect and slope gradient influence vegetation and erosion. Elevation influences the rate of weathering in soils, having an indirect effect on soil structure. 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 (Boix-Fayos et al., 1998). The increased aggregate stability and vegetation feeds back to increased infiltration and reduced erosion (Boix-Fayos et al., 1998). Sloping soils are more susceptible to erosion, particularly in regions of intense rainfall. Erosion tends to preferentially 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 mineralization (Jacinthe et al., 2002a).

2.7. Soil properties

2.7.1. Soil types

Aggregation is controlled by different mechanisms in different soil types (Table 1). The rate and stability of aggregation generally increases with SOC and clay surface area and CEC. In soils low in SOC or clay concentration, aggregation may be dominated by cations, while the role of cations in aggregation may be minimal in soils with high SOC or clay concentration. In Oxisols and Ultisols Al–humus complexes and noncrystalline Al^{3+} hydroxides are predominant aggregants as these compounds are able to protect SOC from microbial decomposition and stabilize aggregation. Aridisols display high aggregate stability associated with carbonates (Boix-Fayos et al., 2001).

Table 1
Soil types and aggregation factors

Soil orders	Aggregation factors	Authors
Alfisols	SOM	Dalal and Bridge, 1996; Oades and Waters, 1991 Torn et al., 1997
Andisols	Allophane clay, non-crystalline clay	
Aridisols	SIC, carbonates and weathered clay minerals	Boix-Fayos et al., 1998; Boettinger and Southard, 1995
Entisols	SOM	Dalal and Bridge, 1996
Inceptisols	Amorphous clay	Dalal and Bridge, 1996
Oxisols	Al^{3+} and Fe^{3+} oxides	Oades and Waters, 1991; Dalal and Bridge, 1996
	Non-crystalline Al hydroxides	
	Plant roots and rhizosphere	
	Hydrophobic SOM	
Spodosols	Organo-metallic complexes	De Coninck, 1980
	Metallic hydroxides	
Ultisols	SOM	Dalal and Bridge, 1996; Zhang and Horn, 2001
	Non-crystalline sesquioxides	
Vertisols	Clay-size fractions	Leinweber et al., 1999; Dalal and Bridge, 1996
	Polycationic bridges, wet–dry cycles	

SOM, soil organic matter; SIC, soil inorganic matter.

2.7.2. Texture

Soil texture has a significant influence on aggregation. In coarse-textured soils, the SOC has a greater influence on structure; while with increasing clay content the type of clay is more important than the amount in determining aggregation (Kay, 1998). Clay concentration physically affects aggregation through swelling and dispersion. The potential of swelling-induced disaggregation is reduced at low clay levels (Attou et al., 1998). Increasing clay concentration is associated with increased SOC stabilization (Sollins et al., 1996).

2.7.3. Cation exchange capacity (CEC)

The CEC is often related to stable aggregates (Dimoyiannis et al., 1998). Aggregation is stimulated by the interaction of polycationic bridging in which the repulsive forces between negatively charged clay and/or SOC are reduced (Tisdall, 1996). Aggregates

containing polyvalent cations (Ca^{2+}, Al^{3+} and Fe^{3+}) are resistant to slaking (Tisdall, 1996).

2.7.4. Soil pH

In addition to effects on plant growth, metal ion solubility, microbial activity and clay dispersion are also influenced by soil pH (Haynes and Naidu, 1998). The negative surface charge on clay particles increases with pH increasing particle repulsion. Therefore, controlling soil pH is important in soils with dispersive clays (Chorom et al., 1994), as clay particles often flocculate at high pH values (Haynes and Naidu, 1998). Large aggregates form in soils of high pH and high carbonate concentration (Boix-Fayos et al., 2001). Lime is commonly added to soil to increase pH often resulting in increased microbial activity and crop yields, and contributing to higher SOM and increased aggregation (Haynes and Naidu, 1998).

2.7.5. Porosity

A wide range of pore sizes exists in well-aggregated soils both between and within aggregates (Dalal and Bridge, 1996). Large pores (>30 μm) include biopores, cracks and interaggregate pores. Pore space, size and amount can influence SOC and its turnover; conversely, SOC and soil texture can influence porosity (Thomsen et al., 1999). Biopores are important for improving gaseous and water diffusion influencing decomposition. Small pores can protect SOC from decomposition by limiting microbial access and through control of gas diffusivity and water availability (Dalal and Bridge, 1996; Kay, 1998; Thomsen et al., 1999, 2003). Clay dispersion, tillage, compaction and crusting can result in decreased porosity (Dalal and Bridge, 1996). In swelling soils, porosity is related to soil moisture content and swell/shrink characteristics (Kay, 1998). Tillage causes short-term increases in porosity, but long-term decreases in aggregation.

2.7.6. Soil water

Soil structure and texture influence soil water flow, availability and storage (Pachepsky and Rawls, 2003). Aggregation and interconnected pores increase bypass flow in soil; this can result in increased infiltration and reduced runoff, the movement of water deeper into the soil profile and increased leaching (Franzluebbers,

2002; Nissen and Wander, 2003). Reduced matrix flow can lead to water stress in arid conditions (Nissen and Wander, 2003).

2.8. Agents of aggregation

2.8.1. Carbon

The source of C, whether it is SOC or SIC, influences its composition and concentration in soil, which in turn influences its effectiveness in aggregation through associations with cations and soil particles. The composition of SOC reflects its decomposition rate and release of cations into soil solution as well as its ability to complex with cations in soil solution.

2.8.1.1. Soil inorganic carbon. The SIC exists in soil as primary and secondary minerals. Primary or lithogenic carbonates originate from parent rock material. Primary carbonates are the source material for the formation of secondary carbonates when they are dissolved and translocated by water with organic acids and/or CO_2 from soil and atmosphere (Fig. 4). Secondary or pedogenic carbonates form when dissolved CO_2 precipitates carbonate and bicarbonate with Ca^{2+} and Mg^{2+} from outside the system. Under conditions of decreased moisture or increased pH, cations, bicarbonate (HCO_3^-), dissolved carbonates and CO_2 can react with available cations to form secondary carbonate coatings on primary soil particles.

The effect of carbonates on structure is moderated by SOC. Increases in SOC results in increased dissolution and reprecipitation of carbonates in soil. The
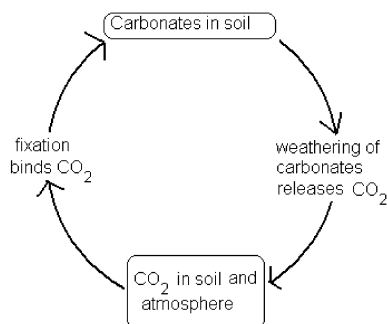

Fig. 4. Relationship between carbonates and CO_2 in the soil via weathering and fixation.

SOC increases microbial respiration and CO_2 and is a source of Ca^{2+} and Mg^{2+}. At low SOC concentration, macroaggregate stability is enhanced by carbonates (Boix-Fayos et al., 2001). High carbonate concentration enhances SOC protection, probably because of decreased SOC mineralization and increased Ca^{2+} (Clough and Skjemstad, 2000). High carbonate concentration in the silt fraction decreases aggregation, suggesting that particle size may also influence the role of carbonates in aggregation (Dimoyiannis et al., 1998). Carbonates may increase tensile strength of aggregates but decrease stability of microaggregates (Boix-Fayos et al., 2001; Schrader and Zhang, 1997). Organisms influence carbonate-mediated aggregation: earthworm activity can alter carbonate concentration, although the effects are inconsistent and may depend on earthworm species (Schrader and Zhang, 1997). Irrigation and fertility management increase SOC thereby accelerating formation of secondary carbonates in arid and semi-arid soils through the addition of carbonic and organic acids that can react with soil silicates to sequester C (Schwartzman et al., 1994) (Fig. 5).

2.8.1.2. Soil organic carbon. The SOC creates regions of heterogeneity in the soil, leading to "hot spots" of aggregation. Increased SOC is related to increased aggregation (Fig. 6). The chemical properties of SOC determine their charge and complexation capacities and influence decomposition rates which have direct effects on aggregation (Schulten and Leinweber, 2000). The aggregate binding effect of labile SOC is rapid but transient (Kay, 1998) while slower decomposing SOC has subtler effects on aggregation, but the effects may be longer lived (Martens, 2000). The isolation of the readily decomposable labile C (C_L) fraction within aggregates increases stability and durability by reducing its decomposition (Fig. 6). Increases in microbial biomass are associated with increases in aggregate stability (Haynes and Beare, 1997).

Particulate organic matter. The POM is comprised of large particles of organic matter (250–2000 μm) that exist as free POM light fraction (LF) or encrusted with soil particles, which in turn offers physical protection from decomposition (Plante and McGill, 2002a). The LF in soil is generally associated with clay and polyvalent cations to form aggregates
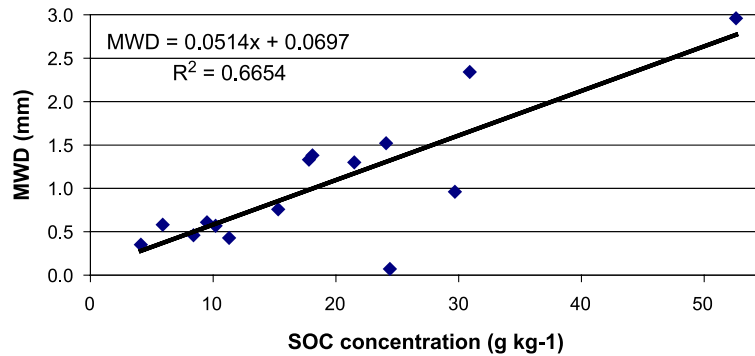
Fig. 5. SOC and MWD (redrawn from Chenu et al., 2000). SOC, soil organic carbon; MWD, mean weight diameter.

(Jastrow, 1996). The increased SOC and aggregation in no-till soils may be due to increases in LF-POM (Six et al., 1999). The POM can act as a nucleus for macroaggregate formation with material accumulating around the POM. Macroaggregates have a large concentration of low density POM (Jastrow, 1996). Within macroaggregates, the decomposition of C_L in occluded organic matter (OOM) may lead to relative enrichment of C_R. Disruption of OOM within aggregates results in the exposure of C_L, making it available for microbial decomposition (Plante and McGill, 2002a). The POM may be an important agent in binding microaggregates to form macroaggregates. As microorganisms decompose the POM, they produce extracellular polysaccharides that act as a binding agent (Jastrow, 1996).

Carbohydrates. The role of carbohydrates in improving soil structure is variable, relating to the source and nature of the carbohydrates as well as aggregate properties and environmental factors. Carbohydrates originating from plants are often coarser sized and occur in the sand fraction, while carbohydrates produced by microbial activities are finer and are present in clay and silt fractions (Schulten and Leinweber, 2000). The microbially derived carbohydrates tend to be resistant to decomposition. Reduced tillage (conservation till or no-till), manure additions and cover crops are associated with increased concentrations of carbohydrates and improved structure in soil (Shepherd et al., 2001; Debosz et al., 2002b).

Polysaccharides. Polysaccharides are readily mineralizable and act as transient binding agents
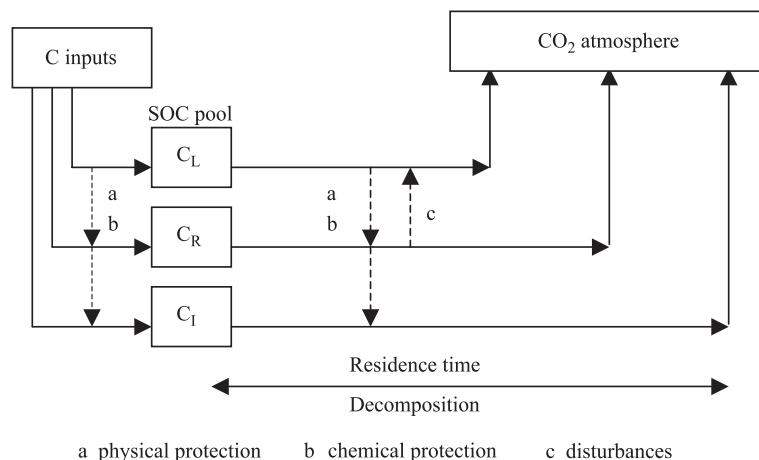

Fig. 6. SOC pool flow chart. SOC, soil organic carbon; C_I, inert carbon; C_L, labile fraction; C_R, recalcitrant C.

initiating aggregation, but may not have long-term stability (Kay, 1998; Tisdall and Oades, 1982). Polysaccharides are strongly adsorbed onto mineral surfaces, acting as ''bridges'' to bind soil particles (Kay, 1998; Martens, 2000). Polysaccharides can also form a gel-like substance that acts as a glue to bind particles into aggregates (Haynes and Beare, 1997).

Phenols. Phenolic molecules can complex with cations to form cationic bridges. Phenols and polyphenols are precursors of humic substances and increase aggregation. Lower aggregation in soils growing soybeans is attributed to low phenolic contents in the residues, and high aggregation is often associated with plants high in phenols (Martens, 2000). Phenolic acids increase aggregation interactions with microbial products (Martens, 2000).

Lignin. The low rate of lignin decomposition is considered a key factor in C turnover rates, enhancing aggregation (Palm and Rowland, 1997; Magill and Aber, 1998). Mucilage and other compounds from lignin decomposing fungus contribute to soil aggregation (Caesar-TonThat, 2002).

Lipids. In soils, lipids are often enriched in the clay fraction (Schulten and Leinweber, 2000). In some soils lipids can improve aggregate stability against slaking and dispersion, probably related to their hydrophobic nature (Dinel et al., 1997; Pare et al., 1999). The effectiveness of lipids in improving aggregate stability may be related to clay mineralogy, lipids play a more important role in bonding in illite and mixed clay soils than in kaolinite- or smectite-dominated soils (Dinel et al., 1997). Increased total extractable lipids are present in plow-till as compared to no-till soils, which generally exhibit higher levels of SOM biodegradability (Pare et al., 1999).

Humic substances. The recalcitrance of humic substances (HS) is a result of their chemical resistance and their association with the soil matrix, which offers physical protection. Tarchitzky et al. (2000) hypothesized that the distribution of HS, including fulvic acid (FA), humic acid (HA) and humin, in aggregates may reflect the initial coating of particles with HS than additional HS serving to bond particles together. The HAs can be adsorbed onto clay particles by polyvalent cations, making them especially effective in overcoming clay dispersion. The HSs can increase aggregate stability and reduce dispersion due to wet–dry cycles (Piccolo et al., 1997).

Hydrophobicity. The hydrophobicity of SOC, along with its charge properties and the interaction with soil particles, affects soil physicochemical properties including structural stability (D'Acqui et al., 1999). Hydrophobic molecules cause water repellency in soil aggregates and decrease wettability, which may result in increased cohesiveness, decreased dispersivity and reduced SOC decomposition rates. Long-term aggregate stability can be enhanced by the addition of hydrophobic organic materials such as organic wastes containing hydrophobic materials and SOC from plant types such as *Cistus* rather than *Pinus* (Ternan et al., 1996). No-till (Hallett et al., 2001) and burning (Poulenard et al., 2001) affect soil hydrophobicity. High temperature burning may result in water repellency (Poulenard et al., 2001) and increased structural stability.

2.8.2. Clay and clay mineralogy

Clay minerals influence properties that affect aggregation: surface area, CEC, charge density, dispersivity and expandability, and these in turn affect SOC decomposition rates (Dimoyiannis et al., 1998; Schulten and Leinweber, 2000). The interaction of clay, SOC and aggregates is affected by soil pH, CEC, ions (Na^+, Ca^{2+}, Mg^{2+}), all of which are related to the amount and type of clay present in the soil (Amezketa, 1999). Clay mineralogical composition is modified with soil development (Powers and Schlesinger, 2002). Low-activity clays such as kaolinite and halloysites are often present in Alfisols, Ultisols and Oxisols while high-activity clays with smectites are present in Vertisols.

Clays occur as crystalline, layered structures or as non-crystalline minerals with amorphous structure. In some soils non-crystalline clay is an important factor for aggregation, such as in volcanic soils where SOC and aggregation are associated with allophanic clay (Powers and Schlesinger, 2002). Non-crystalline clay minerals, such as allophane and imogolite, have high surface areas, and highly variable and pH-dependant charge properties that generally increase aggregation (Powers and Schlesinger, 2002). Non-expanding, crystalline clays, such as kaolinite (1:1), have low CEC and surface area, which tend to decrease aggregate stability. Kaolinite has a good flocculation capacity due to electrostatic charges between platelets and SOC. In comparison, aggregation is generally high in high-

activity clays such as smectites and other 2:1 clays, which are associated with high CEC, large surface areas and high SOC (Seta and Karathanasis, 1996; Amezketa, 1999; Schulten and Leinweber, 2000; Six et al., 2000). The expandability of smectites can disrupt aggregates during wet–dry cycles. Illitic and smectitic clays tend to decrease aggregate stability during wet–dry cycles although there are variable effects possibly due to the amount of clay and number of shrink–swell cycles (Piccolo et al., 1997; Singer et al., 1992).

Dispersivity of soil aggregates is affected by the nature of SOC and the clay type. Cations, particularly Ca^{2+} and Na^+, electrolytes and pH (Chorom et al., 1994; Haynes and Naidu, 1998) can influence clay dispersion. At high concentrations, NH_4^+ fertilizer can lead to dispersion of clay (Haynes and Naidu, 1998). The addition of gypsum to soil decreases clay dispersivity through changes in the electrolyte concentration and composition (Sumner, 1993; Baldock et al., 1994). The CEC and surface area of clay minerals, SOC and other soil properties interact to form intra-particle interactions that influence dispersivity (Nelson et al., 1999). Less reactive clays, like kaolinite, are less dispersive. The SOC and some roots can increase dispersion of clay particles while others have the opposite effect (Tisdall, 1996). Negatively charged SOC can be disruptive to aggregate structure, possibly by repelling negative charges in the soil minerals (D'Acqui et al., 1999). Differences in SOC concentrations exist between dispersive and non-dispersive clays, suggesting that decomposing organic residues may promote dispersion (Baldock et al., 1994). Less dispersive clay contains more aliphatic materials in the topsoils and carbohydrates in the subsoil. These compounds may act as 'glue' to hold particles together (Nelson et al., 1999). Easily dispersed clays contain higher concentrations of amino acids which may act as dispersants (Nelson et al., 1999).

Soils dominated by variable charge clay minerals such as 1:1 clay and oxides have higher aggregation at lower SOC levels whereas soils with mixed mineralogy clays have higher aggregation at higher SOC (Denef et al., 2002). Clay type also affects the rate of decomposition of SOM. Montmorillonite results in a rapid decomposition of SOC with the production of more low molecular weight FAs compared to kaolinite, which results in slow decomposition and more residual C and HAs (D'Acqui et al., 1998). Low pH

levels associated with chlorite may result in low decomposition rates, accounting for high C associated with these clays (Schulten and Leinweber, 2000).

2.8.3. Cations

2.8.3.1. Calcium and magnesium. Bivalent Ca^{2+} and Mg^{2+} cations improve soil structure through cationic bridging with clay particles and SOC. As previously mentioned, in arid and semi-arid conditions, Ca^{2+} and Mg^{2+} carbonates precipitate to form secondary carbonate coatings and bind primary soil particles together. Generally, Ca^{2+} is more effective than Mg^{2+} in improving soil structure (Zhang and Norton, 2002). Among bivalent cations, Ca^{2+} can inhibit clay dispersion and the associated disruption of aggregates by replacing Na^+ and Mg^{2+} in clay and aggregates, thereby adding to aggregate stability (Armstrong and Tanton, 1992).

In comparison to Ca^{2+}, Mg^{2+} may have a deleterious effect on soil aggregate stability by increasing clay dispersion (Zhang and Norton, 2002). The extent of the negative effect of Mg^{2+} compared to Ca^{2+} may depend on the type of clay and electrolyte concentration in the soil (Zhang and Norton, 2002). Further, Mg^{2+} may result in high swelling by expanding clays, resulting in disruption of aggregates.

The use of soil amendments containing Ca^{2+} and Mg^{2+}, such as lime and gypsum, can have profound effects on aggregation. Increased aggregate stability in limed soils suggests formation of strong bonding involving Ca^{2+} bridges (Chan and Heenan, 1999a).

2.8.3.2. Iron and aluminum. Polyvalent Al^{3+} and Fe^{3+} cations improve soil structure through cationic bridging and formation of organo-metallic compounds and gels (Amezketa, 1999). The solubility and mobility of these cations is pH-dependent, with higher solubility at lower pH. Aggregates containing Al^{3+} and Fe^{3+} and high-CEC clays tend to increase SOC incorporation. The interaction of Al^{3+} and Fe^{3+} with kaolinite can synergistically promote aggregation with limited impact on SOC (Six et al., 2000) while oxides and hydroxides of Al^{3+} interact synergistically with SOC and dispersible clay to improve aggregate stability (Molina et al., 2001). Both Al^{3+} and Fe^{3+} control aggregation in acidic soils with low clay and SOC contents, such as Oxisols (Oades and Waters,

1991; Barral et al., 1998). Amorphous Fe^{3+} and SOM form fine stable particles in soils with high SOC content (Barral et al., 1998). Coarse-grained particles are formed from Fe^{3+} oxides (Barral et al., 1998), which increase the tensile strength of aggregates in Oxisols and improve aggregate stability in others (Barral et al., 1998).

2.8.3.3. Phosphorus.   The effects of P on soil aggregation maybe indirect, as P availability affects shoot and root growth, and increases plant production and ground cover. The availability of P also influences colonization of arbuscular mycorrhizal fungi (AMF) (Facelli and Facelli, 2002), which affect root morphology and aggregation. Application of P as fertilizer and phosphoric acid can lead to the formation of Al^{3+} or Ca^{2+} phosphates, which act as aggregate bonding agents (Haynes and Naidu, 1998).

2.8.3.4. Sodium.   The Na^+ is a highly dispersive agent resulting directly in the breakup of aggregates and indirectly affecting aggregation through decreased plant productivity. Exchangeable Na^+ in the soil solution and at exchange sites contribute to repulsive charges that disperse clay particles. Increased dispersivity from Na^+ can break up aggregates, making SOM more available for decomposition. Sodic soils occur mostly in arid and semi-arid regions. Management practices that replace Na^+ from cation exchange sites with Ca^{2+} help to ameliorate high Na^+ and its adverse affects. Gypsum is used as a soil amendment to overcome sodicity by reducing dispersion, pH and exchangeable sodium percentage, (ESP) and increase in microbial C (C_{mic}) (Armstrong and Tanton, 1992; Batra et al., 1997). In calcareous-saline soils, the use of salt-tolerant plants improves soil physical properties due to favorable root growth and increased microbial respiration. The increase in CO_2 partial pressure in the rhizosphere increases calcium carbonate solubility that counters the adverse effects of high Na^+ (Qadir and Oster, 2002).

2.9. Biotic influences

2.9.1. Plants

2.9.1.1. Plant species.   The combined effects of the biochemical composition and amount of plant residues

returned to soils and chemicals released from plants affect the rate and stability of aggregation, and the rate of aggregate turnover. Water-stable aggregates (WSA), mean aggregate size and mean weight diameter (MWD) are correlated with biochemical composition of plant residues: phenols, lignin, proteins, monosaccharide sugars, saccharides, phenols and alkaline extractable HAs in the soil and phenolic acids such as vanillin-vanillic acid in the residue (Martens and Frankenberger, 1992; Martens, 2000). Corn (*Zea mays*) residues are high in phenols and increase aggregation compared with other crops, although continuous corn decreases microaggregates compared to corn grown in rotation (Raimbault and Vyn, 1991; Martens, 2000). Soil aggregate stability is high under continuous alfalfa (*Medicago sativa*) (Raimbault and Vyn, 1991). The low aggregation of soil cultivated to soybean is attributed to low concentration of phenols (Martens, 2000) along with low residue return to the soil.

2.9.1.2. Roots.   Plant roots and their rhizosphere have many effects on soil aggregation. Roots enmesh and realign soil particles and release exudates, which result in physical, chemical and biological alterations that influence aggregation. Aggregation tends to increase with increasing root length density, microbial associations, glomalin, and percent cover significantly affect soil aggregate stabilization (Rillig et al., 2002). Aggregate stability is greater in rhizosphere soil than in non-rhizosphere soil (Caravaca et al., 2002) due to rhizodeposition, root mass, root density, size distribution, root turnover, root length, and hyphal growth (Haynes and Beare, 1997). The rhizosphere hosts a large population of micro- and macro-organisms that contribute to SOC and aggregation. Chemically, roots enhance aggregation by releasing a variety of compounds, which have a cementing effect on soil particles. Root mucilage such as polygalacturonic acid may stabilize aggregates by increasing bond strength and decreasing wetting rate (Czarnes et al., 2000). Roots increase the wet–dry cycling of adjacent soil that can increase aggregate stability in some cases and decrease in others, possibly related to clay type (Angers and Caron, 1998). Roots can also alter the ionic and osmotic balance in the rhizosphere through nutrient uptake and rhizodeposition, which can affect aggregation.

Different root systems affect aggregation differently, relating to different root properties, exudates and func-

tions (Chan and Heenan, 1999b). Generally, extensive fibrous roots produce high levels of macroaggregation (Harris et al., 1966; Chan and Heenan, 1996). Leguminous plant roots are associated with higher microbial biomass, increased aggregation and WSA than non-legumes (Chan and Heenan, 1996; Haynes and Beare, 1997). Aggregate stability in non-legumes is related to root mass (Haynes and Beare, 1997).

2.9.2. Microorganisms

Roots, fungi and bacteria enhance aggregation by enmeshing soil particles and providing extracellular compounds that bind particles together. It is often difficult to separate the multiple effects of organisms on aggregation.

2.9.2.1. Microbial activity. The effect of aggregate size on microbial activity depends on numerous factors. In some cases, microbial activity may depend on aggregate size (Mendes et al., 1999) and in others it may not (Schutter and Dick, 2002). Bacteria are often associated with clay and polysaccharides in microaggregates, resulting in lower microbial biomass in microaggregates than macroaggregates (Tisdall and Oades, 1982; Lupwayi et al., 2001). Lower bacteria/fungi ratio in macroaggregates than microaggregates suggests that bacterial activity may dominate in microaggregation while fungal activity dominates in macroaggregate formation (Schutter and Dick, 2002; Tisdall and Oades, 1982). Increases in macroaggregates are associated with increases in fungal activities and fresh residues (Denef et al., 2001).

Microbial activity varies with aggregate size, seasons, cropping activities, management, residue quality and quantity and soil type (Schutter and Dick, 2002; Mendes et al., 1999). Microbial influence is most pronounced in sandy soils where soil microorganisms produce readily available C-source for the rapid stabilization of aggregates (Kiem and Kandeler, 1997). Fungicide treatments may lower C_{mic} in soil (Hu et al., 1995).

2.9.2.2. Fungi, arbuscular mycorrhizal fungi (AMF) and glomalin. Fungal hyphae improve aggregate stability (Ternan et al., 1996) by reorientation of clay particles, binding particles with extracellular polysaccharides, and enmeshing particles. Hyphae also enmesh microaggregates to form macroaggregates,

suggesting that aggregation increases with hyphal density (Haynes and Beare, 1997).

The AMF is one of the most important biotic influences on soil aggregation (Jastrow et al., 1998). Glomalin is a glycoprotein released from AMF. It is present in soils at high concentrations and is an important factor in stablizing aggregates, possibly due to its recalcitrant nature and high concentration in some soils (Wright and Upadhyaya, 1998; Rillig et al., 2002). Soils high in expanding clays have more total glomalin than those containing low-activity clays. It is possible that the hydrophobic, recalcitrant nature of the glomalin molecule may protect other aggregating agents (Wright and Upadhyaya, 1998). Wet–dry cycles may increase polymerization and hydrophobicity in glomalin.

2.9.3. Soil fauna

Many immature and mature insects, other arthropods, earthworms, nematodes and larger macro-organisms live in the soil and have an important influence on soil structure. They ingest and egest soil material, relocate plant material and form burrows (Amezketa, 1999). Biogenic structures formed by soil organisms such as termite mounds and casts are often protected from mineralization. The effects of these activities are variable. Macro-organisms improve aeration, porosity, infiltration, aggregate stability, litter mixing, improved N and C stabilization, C turnover and carbonate reduction and N mineralization, nutrient availability and metal mobility (Amezketa, 1999; Winsome and McColl, 1998; Brown et al., 2000). These effects can degrade soil properties by removing DOC and breaking down bonds between particles during ingestion. The dispersion is often compensated for during reformation of aggregates and egestion of C_R compounds. Ingested soil undergoes many alterations including physical realignment of clay particles and breaking of bonds within soil aggregates to alter microbial accessibility of SOC (Wolters, 2000). Feeding, mixing ejecta with soil, reworking and biosynthesis of SOC generally result in an increase in soil C_R (Wolters, 2000). Activity of soil fauna is important in the formation of organo-mineral complexes and aggregation.

2.9.3.1. Earthworms. Earthworms increase soil aggregation through biological and physicochemical changes (Brown et al., 2000). Earthworms exert

considerable direct and indirect influences on soil structure and SOC (Brown et al., 2000; Jegou et al., 2001). The impact of earthworms on aggregation varies with the species of earthworm, quality of litter and parent soil (Winsome and McColl, 1998; Schrader and Zhang, 1997). In turn, species and population of earthworm are influenced by the quality and quantity of plant material (Flegel and Schrader, 2000). Some earthworms digest soil and in the process break bonds, thereby destabilizing aggregates; however, biochemical processes stabilize aggregates (Schrader and Zhang, 1997). The reorganization of soil particles and release of enzymes by earthworms influence mineralization, water flow and microbial activities (Jegou et al., 2001). Earthworms increase SOC in casts and, to a lesser extent, in burrow-wall materials (Jegou et al., 2001). Earthworm activity increases water-stable macroaggregates, which are actually casts (Winsome and McColl, 1998).

2.9.3.2. Termites. The effect of termites on soil structure and SOC varies with species and soil. Positive (Al-Houty, 1998) and negative impacts (Fall et al., 2001) or none at all (Hyodo et al., 2001) have been reported on SOC. In most cases, ingestion of SOC and its transformation during digestion results in more stable SOC forms in termitosphere (Brauman, 2000). Termite-induced microaggregation is related to soil composition, promoted by concentrations of gibbsite and Fe-oxide in the tropics, however, not in kaolinitic soils (Schaefer, 2001).

3. Environmental impacts of soil structure

3.1. High atmospheric carbon dioxide concentrations and soil structure

The overall effect of elevated atmospheric CO_2 on soil structure is not very well understood. Enhanced atmospheric CO_2 may result in the increase in photosynthesis and ensuing increase in photosynthate, roots and microbial communities. The concurrent increases in nutrient demands may exceed the ability to meet the demands, resulting in nutrient-limited systems, increased symbiotic communities or altering the chemical composition of plant compounds, resulting in wider C/N ratio and increased lignin, tannins and phenolics, which decompose slowly (Hu et al., 1999). In environments with adequate nutrient supplies the increases in atmospheric CO_2 may result in increased SOM and aggregation, while in nutrient-limited environments the balance between availability of nutrients, plant demand and C turnover may limit the effect.

Changes in dominant species and C allocation are primary mechanisms of changes in C input and decomposition (Dukes and Hungate, 2002). Changes in plant species influence microbial population distribution and microbial compounds involved in soil structural development (Dukes and Hungate, 2002). Allocation of photosynthate to root and root exudates tends to increase SOM and microbes in the rhizosphere (Swift, 2001). Increases in C_{mic} may occur under elevated CO_2 as an indirect response to changes in plant growth (Elhottova et al., 1997; Hu et al., 1999). Increases in AMF, root length and root longevities may occur (Rillig et al., 2001). Increased levels of CO_2 have resulted in increased WSA, glomalin and AMF hyphal lengths with sorghum (Rillig et al., 2001). Increased atmospheric CO_2 may result in lower hyphal density possibly due to decreased oxygen diffusion in soils (Schack-Kirchner et al., 2000). Increased decomposition rates due to increased temperatures, moisture and microbial activity may have a greater influence on rapid turnover of SOC pool comprising plant and surface litter, than of slower fractions such as root, macro and microbial C resulting in the accumulation of SOM and higher proportion of microaggregates (Niklaus et al., 2001).

3.2. Enhancing the soil organic carbon pool

The type of soil, aggregating agents, soil management and environmental conditions interact to determine aggregation in a soil. Soil management practices that minimize disturbance maximize SOC return to the soil, optimize productivity and increase the SOC pool. Appropriate use of soil amendments such as fertilizer, lime, manure and compost can increase the SOC pool and aggregation. Sustainable agricultural practices such as mixed cropping, cover crops and crop rotations also can increase the SOC pool. Management practices that reduce decomposition rates and CO_2 emissions also help to increase the SOC storage.

4. Management for enhancing soil structure

4.1. Soil management

Soil management to increase aggregation must aim at increasing primary plant production, increasing the amount of C input into the soil, decreasing disturbances and decreasing the rate of C loss by processes such as decomposition and erosion. In this regard, improved management practices include tillage methods, residue management, amendments, soil fertility management and nutrient cycling.

4.1.1. Tillage

Tillage disrupts soil aggregates, compacts soil and disturbs plant and animal communities that contribute to aggregation and lowers SOM, CEC, nutrients, microbial activity and faunal activities that contribute to aggregation (Plante and McGill, 2002a). In comparison with plowing no-till management systems have more stable aggregates and SOC (Filho et al., 2002). Reduced tillage can result in higher macropores and biochannels that influence water movement and availability, raising concerns about water quality (Logan et al., 1991; Warkentin, 2001). In turn, this impacts leaching and loss of nutrients and chemicals in drainage and ground water. The intensity and timing of tillage determine the extent of the effect of tillage on SOC (Studdert and Echeverria, 2000).

4.1.2. Mulching and residue management

Mulches improve soil structure through a variety of methods. The addition of mulch to soil surface decreases erosion, reduces evaporation, protects against raindrop impact and increases aggregate stability (Layton et al., 1993). Mulches increase the amount of SOC pool (Duiker and Lal, 1999; Sharma and Acharya, 2000; Jacinthe et al., 2002b), modify temperature and moisture regimes and impact soil fauna. The return of plant residues to soil improves soil structure (Martens, 2000), which is related to the amount and quality of the residue.

4.1.3. Manuring

Manuring improves soil structure and MWD, increases macroaggregation and resistance to slaking but may decrease stability of soil aggregates against the dissolution and dispersive actions (Pare et al.,

1999; Whalen and Chang, 2002; Hao and Chang, 2002). The increase in SOC results in increased biological activity, which in turn results in increased porosity and the attendant decrease in bulk density (Kay, 1998). Increased microbial activity due to increases in soil C from manure applications results in increases in aggregate stability (Martens and Frankenberger, 1992). Manured soils also have high earthworm population (Hansen and Engelstad, 1999). Unmanured soils usually contain less SOC and microbial biomass, and are denser than manured soil, and aggregates are strong when dry, and weak when wet (Munkholm et al., 2002). In contrast, the manured soils have strong aggregates when wet and weak when dry. The differences between the soils when dry seem to be related to differences in concentration of dispersible clay, whereas the differences when wet are related to differences in the amount of organic binding and bonding material. Micro- and macroaggregates have higher carbohydrate levels in manured soils than in those receiving chemical fertilizers (Debosz et al., 2002a). Increased ionic concentration can be a concern in manured soil, because of increase in susceptibility to dispersion and decrease in aggregate stability. Manuring increases concentrations of Na^+, K^+ and Mg^{2+} (Haynes and Naidu, 1998; Hao and Chang, 2002). Manure applications increase dispersion of large macroaggregates (Whalen and Chang, 2002), and also affect soil pH and P availability (Whalen et al., 2000).

4.1.4. Compost

Compost additions to soil improve soil structure and lower bulk density. Composting materials can increase macroaggregation and rhizospheric aggregate stability (de Leon-Gonzalez et al., 2000; Caravaca et al., 2002). Soil properties and environmental conditions determine the impact of compost on aggregation; drought can limit the effectiveness of compost in aggregation (de Leon-Gonzalez et al., 2000). The effects of compost additions on soil structure may be short-lived although effects are generally positive on structural properties (Debosz et al., 2002b).

4.1.5. Fertilizer and nutrients

The complexities of the chemical and physical influences of fertilizers result in variable effects of

fertilization on aggregation. Fertilizer applications generally improve soil aggregation (Haynes and Naidu, 1998). However, under some conditions fertilizers may also decrease SOC concentration, reduce aggregation, and reduce microbial communities compared to manured soils. Yet, using chemical fertilizers often improves soil structure in comparison to unfertilized soils (Munkholm et al., 2002). The primary effect of improved nutrient management is on increasing plant productivity, SOC and biological activity (Haynes and Naidu, 1998). Increase in SOC by fertilizer use increases aggregation and MWD (Subbian et al., 2000). Fertilizer use also improves residue quality and quantity, but this does not necessarily increase SOC pool (Halvorson et al., 2002). Fertilizer applications alter soil pH and the electrolyte concentrations in soil, which can have adverse effects on soil structure (Haynes and Naidu, 1998). The beneficial effects of fertilizer applications generally offset any adverse affects of fertilization. Increases in plant residues and below-ground plant growth increase C_L, microbial activity and C_{mic}, which improve aggregate stability. Increases in N availability from fertilizer treatments increase the rate of decomposition in LF C_L, while further stabilizing C_I (Neff et al., 2002).

The physical and chemical effects of fertilizers are related to the type of fertilizer and soil. The use of phosphetic fertilizers enhances Al^{3+} and Ca^{2+} bonding (Haynes and Naidu, 1998). Phosphoric acid promotes soil aggregation through lowered pH, Al^{3+} mobilization and subsequent precipitation of Al phosphate as a cementing agent to form stable aggregates (Haynes and Naidu, 1998). Ammonium fertilizers can disperse clays, having an adverse effect on soil aggregation (Haynes and Naidu, 1998). The dispersive affects of NH_4^+ are temporary and diminish as NH_4^+ is nitrified to NO_3^- (Haynes and Naidu, 1998).

4.2. Crop management

Cultivation decreases total and microbial SOC pool and soil fauna but increases metabolic CO_2 (Saggar et al., 2001). Management to increase SOC and aggregation includes fertilization, grazing management, conversion from cultivation to native vegetation, inclusion of cover crops, legumes and grasses, earthworm inoculation and irrigation.

4.2.1. Crop rotations and cover crops

The aggregate dynamics vary among different crops, crop rotations and cover crops (Jarecki and Lal, 2003). The effect of different crops tends to reflect the crop chemical composition (Martens, 2000), rooting structure and ability to alter the chemical and biological properties of the soil (Chan and Heenan, 1996). These effects tend to be short-lived under conventional tillage regimes (Chan and Heenan, 1996). In some soils, rotations may not affect aggregate stability (Filho et al., 2002). Cover crops increase C input to the soil, reduce erosion, increase CEC, increase aggregate stability, increase water infiltration, and recycle nutrients. Cover crop residues may enhance microbial biomass, respiration, and N mineralization and shift microbial community (Schutter and Dick, 2002).

4.2.2. Agroforestry

The inclusion of leguminous trees in agricultural systems reduces soil erosion and improves soil productivity (Craswell et al., 1997; Buresh and Tian, 1997). Agroforestry influences SOM, which in turn influences aggregation in comparison with conventional systems (Mugendi et al., 1999; Atsivor et al., 2001).

5. Research priorities

Aggregation is correlated with root mass, root morphology, fungal mass and use of organic matter amendments such as mulch, manure and green manure. While these factors contribute to aggregation in soils, a comprehensive understanding of how this occurs is lacking. Cover crops in no-till agricultural systems offer great potential to enhance aggregation. Little is known about why some cover and agronomic crops are more effective in structural development than others. Additional information on the biochemistry and decomposition of plant residues and the interaction with soil types and environmental conditions to promote aggregation would allow for identification of more effective management practices. A better understanding of how aggregates are formed and stabilized, and how they are affected by different agricultural management and planting patterns is necessary in order to identify agricultural practices

for sustainable crop production. Primary aggregation mechanisms differ in different soil types; identification of practices to increase aggregation based on soil types and dominant development processes need to be better identified. The interaction between different SOC sources, cations and clays are important for understanding the development of stable soil structure. The role of secondary carbonate formation and SOC interactions in arid and semi-arid regions is not clear. Little is known about the impact of using insecticides and fungicides on aggregation.

Soil structure impacts water availability, nutrient uptake and leaching thereby affecting ground and surface water supplies through sedimentation and chemical contamination. It is important to develop improved practices for the judicious use of agricultural amendments to maximize their effectiveness while minimizing unintended and off-site impacts. Similarly, management practices that reduce erosion, nutrient loss and release of greenhouse gases need to be assessed.

6. Conclusions

Soil structure holds a vital, but often overlooked role in sustainable food production and the well being of society. A more holistic approach to land use and management is needed to cope with increased pressure on soil resources for sustainable food and fiber production while reducing the adverse off-site environmental impacts of agricultural practices. The impact of soil structure ranges from a global to a highly localized scale. Improved C sequestration in soil aggregates can reduce the rate of increase in CO_2 concentration in the atmosphere and associated global warming. Improved soil structure enhances nutrient recycling, water availability and biodiversity while reducing water and wind erosion, and improving surface and ground water quality.

Processes and mechanisms involved in soil aggre-gation are complex with intricate feedback mechanisms. Soil aggregation can be improved by management practices that decrease agro-ecosystem disturbances, improve soil fertility, increase organic inputs, increase plant cover, and decrease SOC decomposition rate. The SOC decomposition can be decreased in soil by isolating labile C products

within aggregates and increasing chemical protection through input of C_R compounds or transformation of C_L to C_R and C_I compounds. Soil structure can be enhanced through the use of crops and crop management practices that promote aggregation such as the use of crops with high C_R and high biomass production, the return of crop residues and incorporation of cover crops. Aggregation also tends to increase with increasing root length density; extensive fibrous roots produce highest levels of macroaggregation. Enhancing the diversity and quantity of soil flora and fauna are important in improving soil structure. Activity of soil fauna is important in the formation of organo-mineral complexes and aggregation.

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