Research

The Influence of Organic Matter on Soil Aggregation and Water Infiltration

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The unimpeded flow of water down through the soil is essential to agricultural production. Intensive cultivation can disrupt soil structure and restrict infiltration, which results in inefficient water and land use. In this review, the effects of organic matter on soil aggregation and water infiltration are discussed at several levels. Organic amendments (manure, plant residue, and synthetic polymers) are reported to increase soil organic matter (fulvic acids, humic acids, and polysaccharides) which binds soil particles together into aggregates. When soil structure is improved through aggregation, the resulting pore size distribution favors the downward flow of water in soil (infiltration). Mechanisms that link these components (e.g., organic amendments, polysaccharide production, aggregate formation, and increased infiltration) are suggested and management options that improve water infiltration rates are proposed.

Slow water infiltration through soil results in increased evaporation, runoff, and erosion. Drought stress caused by poor infiltration is a major problem in crop production in both the Western and Southeastern USA. In California, 20% of the irrigated land is affected by poor infiltration (LAWR, 1984). Estimated annual losses from inefficient water use range from $20/acre for irrigated pasture to $500/acre for orchards. Soils with textures ranging from clays to sandy loams can have such water penetration problems. Both cultivation practices and inherent soil properties contribute to the process of restricted infiltration. Although there is no universal solution to the problem, in certain cases, the rate of infiltration can be significantly improved with organic amendments.

Like wind and water erosion, slow water infiltration is a symptom of poor soil structure. Soil structure is the arrangement of soil particles and the pore spaces between them. The identification of organic compounds influencing soil structure is well reviewed in a number of research articles (Parr and Bertrand, 1960; Greenland, 1965; Allison, 1968; Martin, 1971; Cheshire, 1979; Tisdall and Oades, 1982; Lynch and Bragg, 1985). Because of the difficulty in defining organic matter, as well as in comparing work performed under different conditions and soils, the mechanisms by which organic additions contribute to soil structure have not always been apparent. In addition, the intimate association between the soil organic and inorganic fraction has often fallen outside the realm of conventional research.

A proposed mechanism for the generation and maintenance of adequate water infiltration depends on organic inputs (Fig. 1). These organic amendments increase the amount of soil polysaccharides. The chemical and physical properties of the polysaccharides improve soil structure through the production of stable aggregates. The result is a less restricted downward flow of water and an increased infiltration rate. Because a complete review of the four individual components is beyond the scope of this paper, Fig. 1 provides a list of selected references that more thoroughly explores each of these steps. The purpose of this review is to describe the mechanisms by which soil organic matter contributes to the improvement of soil structure and water infiltration.

SOIL ORGANIC MATTER

Soil organic matter is both the product of living matter and the source of it (Thaer, 1808). The term soil organic matter (SOM) is as much a composite of concepts, as it is of compounds (Waksman, 1938). Because SOM is a complex matrix, defying even modern analytical techniques, it has often been necessary to describe it by arbitrary separation schemes. Chemical fractionation, the classical method of describing SOM, gave rise to the terms "humic acids" and "fulvic acids." Soils are mixed with a dilute alkali solution and the solids are removed. Humic acids (HA) are a mixture of compounds that precipitate from solution when acid is added to lower the pH to 2. The organic fraction that remains in solution is defined as fulvic acids (FA). Fulvic acids have a higher proportion of carboxyl and hydroxyl functional groups and a higher percentage of O than HA. Humic acids contain a higher percentage of C and usually range between 2 000 and 100 000 molecular weight (Schnitzer, 1982; Stevenson, 1982; Greenland, 1965).

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Rather than define SOM by extraction, Jenkinson and Rayner (1977) defined it by function: decomposable plant material, resistant plant material, soil microbial biomass, physically stabilized organic matter, and chemically stabilized organic matter. The first two categories are determined by the rate of decay of plant material, whereas soil microbial biomass represents the living fraction of soil and is determined by direct microscopic counting or by chemical estimates (i.e., ATP measurements or chloroform fumigation incubation methods). Physically stabilized organic matter is that portion associated with sand, silt, and clay which is inaccessible to microbes. Chemically stabilized organic matter is believed to be derived from partially decomposed components of plants (phenylpropanoid units of lignin) and microbes (polyphenols and amino acids) which combine (through the formation of quinones) to form compounds that are resistant to further decomposition (Haider et al., 1975; Martin and Haider, 1986).

Organic Amendments

Application of organic materials to soil initiates the complex process that forms stable SOM (Kononova, 1966). The organic fraction is not only responsible for a large portion of the biological and chemical properties of soil but also has a disproportionate effect on its physical behavior. Organic matter produced off-site and applied to soil includes animal manures, food processing wastes, sewage sludges, and on a lesser scale, compost

and mulches (Brown et al., 1986; Page et al., 1983). Each organic addition to soil can improve its water-holding capacity, decrease bulk density, stabilize soil structure, and indirectly increase the water infiltration rate (Khaleel et al., 1981). Amendments vary in their degree of effectiveness. In the case of manures with a high Na content, the amendment can be detrimental to soil structure (Weil and Kroontje, 1979). Although universally recognized, the mechanism by which organic amendments improve the physical structure of soil is not completely understood (Jenny, 1980).

Synthetic Conditioners

In addition to bulk organic components, synthetic organic polymers have been evaluated and used on a limited scale for improving the physical properties of soils. The synthetic soil conditioners produced in the 1950s were expensive when applied at rates which increased aggregation. For a synthetic organic polymer to be applied at a concentration of 0.1% in soil, between 1 000 to 4 000 lb/acre of polymer must be added, depending on the desired depth of treatment. The expense of such application rates often exceeded the value of the crop. Progress has since been made in applying low rates (30 lb/acre) of polyacrylamide in irrigation water to alleviate poor infiltration at the soil surface (Mitchell, 1986). Polymers have been applied in drip irrigation systems at even lower rates to prevent soil crust formation (Shaviv et al., 1985). The new generation of soil condi-

Browning & Milan,	1944	Smith et al.,	1937
Strickling,	1950	Parker & Jenny,	1945
Miller & Kemper,	1962	McCalla,	1951
Marshall,	1963	Johnson,	1957
Baver,	1968	Quirk & Panabokke,	1962
Mortland,	1970	Greenland,	1965
Tisdall & Oades,	1982	Wischmeier & Manning,	1965
Lynch & Elliott,	1983	Weil & Kroontje,	1979
Metting & Rayburn,	1983	LAWR,	1984
Oades,	1984		

| ORGANIC AMENDMENTS | → | POLYSACCHARIDE PRODUCTION | → | AGGREGATION | → | INFILTRATION |

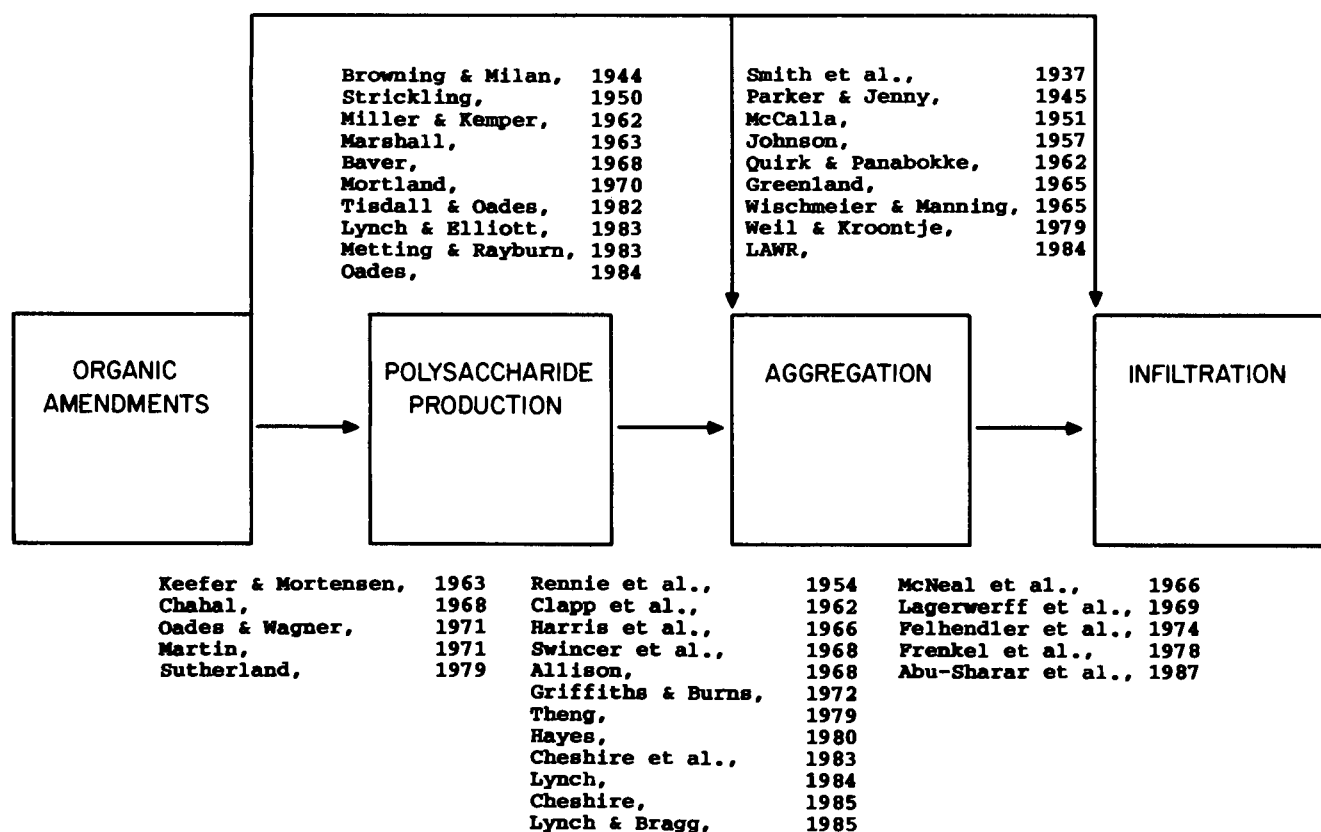| Keefer & Mortensen, | 1963 | Rennie et al., | 1954 | McNeal et al., | 1966 |
Chahal,	1968	Clapp et al.,	1962	Lagerwerff et al.,	1969
Oades & Wagner,	1971	Harris et al.,	1966	Felhendler et al.,	1974
Martin,	1971	Swincer et al.,	1968	Frenkel et al.,	1978
Sutherland,	1979	Allison,	1968	Abu-Sharar et al.,	1987
		Griffiths & Burns,	1972		
		Theng,	1979		
		Hayes,	1980		
		Cheshire et al.,	1983		
		Lynch,	1984		
		Cheshire,	1985		
		Lynch & Bragg,	1985		

Fig. 1. Selected references connecting the four major components in the process whereby organic amendments influence the infiltration rate of soil.

tioner must overcome the problems associated with the products of 30 yr ago, such as complexity of application and prohibitive costs.

Detritus

By far, plant residues and root exudates are the most abundant and least expensive organic inputs to soil. Plant residues promote microbial activity and stimulate microbial exopolymer production, which tends to stabilize soil structure (Martin and Waksman, 1940). Both fungi and polysaccharide-producing bacteria are able to produce and deposit polymeric substances which can be adsorbed to the nearby surfaces of clays (Hattori and Hattori, 1976; Stotzky, 1980; Metzger et al., 1987). Soil structure has been linked to a series of microbial pulses and biochemical pool surges. According to Monnier (1965), after fresh addition of organic material to soil, there is a flush in microbial biomass resulting in a temporary rise of microbial polysaccharides, followed by an increase in the number of stable aggregates. Organic matter's contribution to soil structure is doubtless more complex than this single linear sequence, but it does indicate the pivotal role organic residues have on soil structure. The lag time, amplitude, and effective duration of the pulses depend to a large extent on the composition of the initial organic substrate. In general, organic materials that decompose quickly, such as simple oligosaccharides and materials with a low C/N ratio, have a rapid but ephemeral effect on soil structure. Plant materials that are more resistant to decomposition require more time before they start to change soil structure, but their effect persists longer (Baver, 1968; Martin, 1971). Soil organic matter and soil structure are related, but the distinction between cause and effect is not altogether clear. Soil organic matter stabilizes soil structure while good soil structure also physically protects soil organic matter.

SOIL POLYSACCHARIDES

The associations between soil C and soil structure have been demonstrated in a number of studies. But soil structure is not solely dependent on the total amount of organic C present. It is a function of a number of factors including the composition of SOM (Strickling, 1950; Martin, 1971; Dormarr, 1983).

Polysaccharides are among the most common type of compounds that can be identified in the organic fraction of soil. Plant and microbial polysaccharides composed of homo- and heteropolymers of simple sugars contribute from 5 to 20% of the SOM (Gupta and Snowden, 1965; Cheshire, 1979). Undecomposed plant material is the most abundant source of this fixed C. Fifty to 70% of a plant is composed of cellulose and hemicellulose. Cellulose is a polymer of β-1,4 glucose units, while hemicellulose is an ill-defined composite of highly branched glycan units containing a mixture of hexose and pentose sugars. Lignin, a highly resistant heteropolycondensate comprised of a mesh of phenyl-propanoid units, is not a polysaccharide but is often associated with cellulose and is second only to cellulose in abundance in older plants.

The analysis of soil carbohydrates, which are mostly in the form of water-insoluble salts, usually involves hydrolysis and purification (Swincer et al., 1968). Because polysaccharides bind to both inorganic and other organic portions of soil (especially proteins), their yields upon extraction are poor (Cheshire, 1979). The individual concentrations of the five most common sugars in soil typically range from 0.1 to 0.6% of the SOM. The hexoses, mannose and galactose, are probably microbial in origin, while the pentoses, arabinose and xylose, are predominantly plant derivatives. Most of the glucose is thought to originate from plant cellulose and is therefore the most prevalent soil monosaccharide. These sugars form soil polysaccharides that range from disaccharides to polymers that can have molecular weights of more than a million (Cheshire, 1979). Uronic acids make up 1 to 5% of the SOM and are similar in structure to sugars except that they also possess a carboxyl (COOH) group.

Most plant polysaccharides are rapidly decomposed in well-aerated soil. As decomposition continues, there remains a quantitatively smaller but recalcitrant fraction. Martin (1971) concluded that these stabilized polysaccharides result from complexes with metals, clays, or humic acids which resist further decomposition. Plant and microbial polysaccharides rarely contain more than two or three different monosaccharides as repeating units. But more than 10 different monosaccharides found in soil hydrolysates suggest that soil polysaccharides are more complex and diverse than those derived from plants and microbes (Greenland and Oades, 1975). Martin and
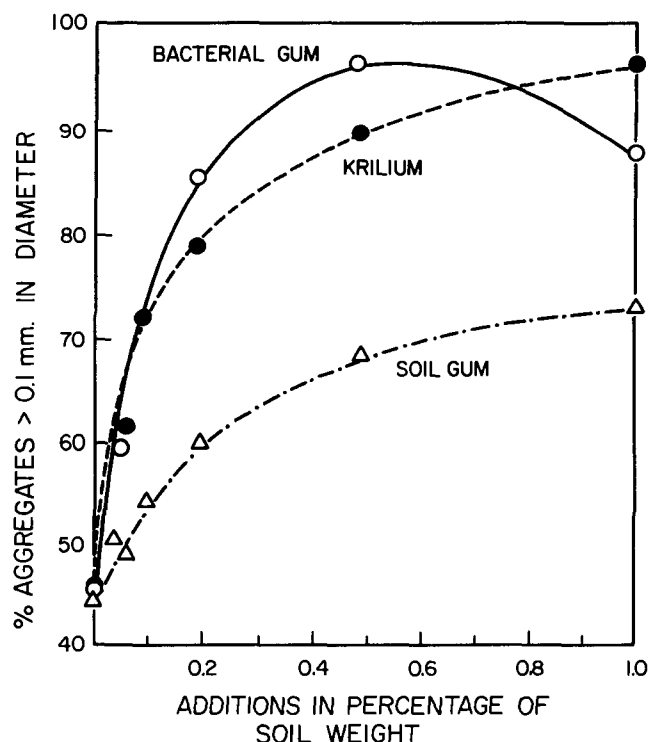

Fig. 2. The effects of bacterial gum, Krilium, and extracted soil gum in amounts equivalent to percentages of soil weight on the percentage aggregation of Spencer silt loam soil (Rennie et al., 1954). Reprinted with permission of the Soil Science Society of America.

Haider (1971) proposed that soil polysaccharides are constructed in situ from partially degraded plant and microbial polymers in a way similar to HA formation. The authors hypothesized that extracellular enzymes from lysed cells or secreted from slime-forming bacteria could combine oligosaccharides randomly into polysaccharides unique to soil.

The following describes a soil polysaccharide fraction according to function.

1. *Structural*—relatively resistant to physical and chemical degradation. It includes structural components of insects (chitin) and associated cell wall material of plants, bacteria, and fungi (i.e. cellulose, hemicellulose, gums, teichoic acids, pectin, and peptidoglycans).

2. *Extracellular*—produced by many bacteria as discrete capsules or amorphous slimes under certain environmental and substrate conditions. The highest yields are produced in pure culture when carbohydrates are present in excess and growth is limited by available N (Powell, 1979; Sutherland, 1979). Plant roots also produce exudates including mucigel, a non-diffusible polysaccharide-rich coating (Finch et al., 1971; Costerton et al., 1978; Oades, 1978; Kennedy and White, 1983).

3. *Storage*—contained within the living biomass. Upon cell death and lysis, there is a release of labile polycarbohydrates including lipopolysaccharides and starch.
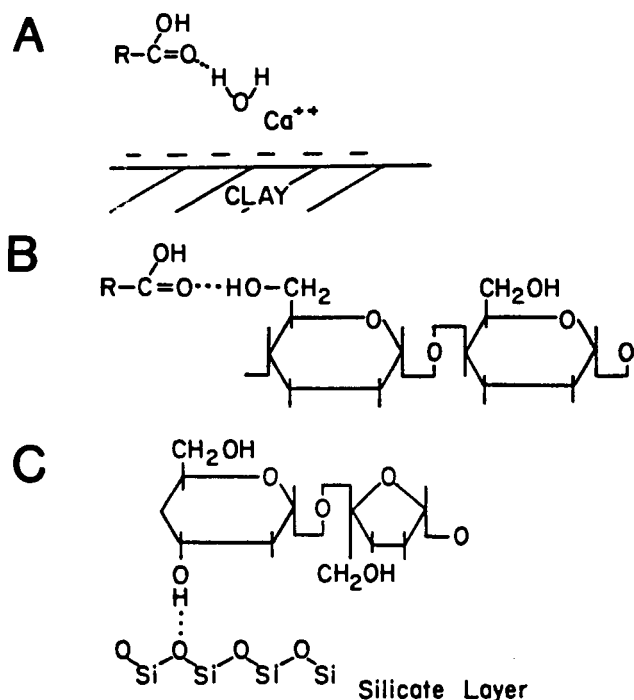

Fig. 3. Examples of hydrogen bonding. A) A carboxyl oxygen of HA forms an H-bond to a water molecule in the primary hydration shell of a cation adsorbed on the exchange complex of a clay ("water bridging"). B) A carboxyl oxygen of HA or FA attaches itself through an H-bond to one of many hydroxyl groups in a polysaccharide polymer. C) An hydroxyl H from a polysaccharide can also form a weak bridge between a polymer and the surface oxygen of a clay mineral.

4. *Chemically Stabilized*—highly diverse heteropolysaccharides closely associated with recalcitrant humic material and metals (Foster, 1981).

5. *Physically Protected*—shielded and encapsulated by clay, these polysaccharides are inaccessible to microbial degradation due to their position on the inner surfaces of aggregates.

Adhesion

The involvement of polysaccharides in soil structure is based on three main lines of evidence (Greenland et al., 1962; Cheshire, 1985). First, the addition of polysaccharides promotes the formation of stable synthetic aggregates. Microbial polysaccharides produced in pure culture can exert a marked binding effect when mixed with soil (Martin et al., 1955). Crude polysaccharide extracts from soil have been demonstrated to increase aggregation when applied to soils with poor structure. Rennie et al. (1954) reported that additions of as little as 0.02% of these carbohydrates could temporarily increase soil aggregation by approximately 50% (Fig. 2).

Secondly, periodate/tetraborate treatments destroy natural aggregates. Periodate (HIO_4) has a high degree of specificity for cleaving bonds between adjacent C atoms carrying hydroxyl groups. Subsequent addition of sodium tetraborate causes the dissolution of partially hydrolyzed polysaccharides. After both procedures there is a loss in aggregate stability in most agricultural soils (Cheshire, 1979). The persistence of a small fraction of polysaccharides in soil which have undergone such treatment may be due to entrapped carbohydrates remaining inside aggregates and thereby inaccessible to the solutions. Aggregates could similarly protect carbohydrates against enzymatic attack (Cheshire et al., 1983).

Finally, many polysaccharides posses strong adhesive properties. The strong binding activity of many nonstructural polysaccharides is related to their length and linear structure which allow them to bridge the gaps between soil particles. Their flexible nature also increases surface area contact which enhances physical and chemical binding (Martin, 1971).

Binding Behavior of Functional Groups

Several mechanisms are involved simultaneously in the sorption of organic compounds to each other and to clay minerals. These include H bonding, van der Waals forces (physical adsorption), and cation bridging. Hydrogen bonding is one form of dipole-dipole interaction that occurs when two electronegative atoms (e.g., O or N) are bridged by an H atom. These bonds are important in forming stable complexes involving large molecules but their significance in organic-clay adsorption, based primarily on infrared spectral data, is inconclusive (Harris et al., 1966; Mortland, 1970; Theng, 1979). Some examples of this form of H bridging that are intermediate in strength between ionic bonding and van der Waals attraction are illustrated in Fig. 3. The significance of such bonds depends on the strength of competing reactions as

Table 1. Mechanisms of adsorption for organic compounds in soil solutions.

Mechanism	Principal organic functional group
Cation exchange	Amines, ring NH, heterocyclic N
Protonation	Amines, heterocyclic N, carbonyl, carboxylate
Anion exchange	Carboxylate
Water bridging	Amino, carboxylate, carbonyl, alcoholic OH
Cation bridging	Carboxylate, amines, carbonyl, alcoholic OH
Ligand exchange	Carboxylate
Hydrogen bonding	Amines, carbonyl, carboxyl, phenylhydroxyl
Van der Waals interactions	Uncharged, nonpolar organic functional groups

well as the stereometric configuration of the organic molecule.

Another mechanism that can bind uncharged surfaces is the nonspecific van der Waals force. This instantaneous dipole interaction is induced between nonpolar molecules, or portions of molecules, when they are close to each other. These weak interactions are additive and therefore important for the adsorption of large polymers to each other or to clay surfaces.

Polyvalent cations can bridge negatively charged clay surfaces with anionic functional groups (e.g., FA, HA, and uronic acids) on organic polymers. This pH dependent bridging can attach organic coatings to soil particles (Morrill et al., 1982). Uncharged polar groups of polymers can also be bridged to clays by Al^{3+}, Fe^{3+}, and Ca^{2+}. This type of ion-dipole attraction is thought to be a major mechanism for the adsorption of polysaccharides. Nonpolar portions of organic polymers (e.g., alkanes) can form short range reversible adsorption to surfaces through hydrophobic (solvent-induced) bonding. Table 1 summarizes the soil adsorption behavior of organic functional groups (Sposito, 1984).

Polymer Configuration

The proportion of functional groups in a polymer also dictates the behavior of a polymer; too few functional groups can cause a large molecule to become insolable while too many cause the molecule to lose its flexibility. Soil polymers consist of groups of active sites (hydroxyl, amino, or carboxyl groups) separated by hydrophobic portions of the molecule (alkyl groups). The functional group's contribution to polymer behavior, such as solubility, can be estimated from free energy calculations. Neutral polymers (e.g., polysaccharides) tend to adopt a random coil structure unlike polyelectrolytes (e.g., HA and FA) whose configuration under similar conditions are more extended due to intramolecular anion repulsion. Ghosh and Schnitzer (1980) reported that in low pH (<2.0) or high ionic strength (>0.05 M) solution, both HA and FA behave like spherocolloids, but at intermediate pH and at lower ionic strength, the polyanions would unfurl into linear strands. In soil, the configuration and binding of organic structures will depend on the polymer, the composition of the aqueous phase, and the adsorbing surface.

Functional groups of SOM not only control clay-polymer behavior but also influence soil macrostructural characteristics. Clapp et al. (1962), reported that the abil-

ity of a rhizobial polysaccharide to form aggregates was inversely proportional to its carboxyl content. The authors suggested that the presence of the negatively charged carboxyl groups prevented the polysaccharide from establishing a close connection with the negatively charged clay, and that H-bonding between uncharged polar portions of the molecule and clay was the primary mechanism of bonding (Clapp et al., 1962; Harris et al., 1966).

Clay swelling and dispersal, a major source of aggregate instability, can be influenced by soil polymers, depending on the relative presence of negatively charged functional groups (Robinson and Page, 1950; McNeal et al., 1966). Organic polyanions can increase clay dispersion by (i) complexing with di- and trivalent metals, thereby reducing the cation concentration in solution; (ii) adsorbing onto the surfaces of clays thereby increasing the net negative charge of the colloids. Both of these mechanisms would enhance swelling by increasing the diffuse layer of cations that surround hydrated clays (Oades, 1984).

Polysaccharides can form a clay floc through a mesh of attachments. These organic bridges overcome the electrostatic repulsions without reducing the negative clay charge (Hayes, 1980). The dimensions of the organic-clay bridge can be estimated from synthetic "soil conditioners." A homopolymer such as polyvinyl alcohol or polyacrylamide with a molecular weight of a million would be about 0.0001 in. long. Therefore, a single natural coiled-polymer of similar size would rarely bind more than a few clay plates together.

There is a loss of entropy when a randomly coiled polysaccharide realigns itself to form a bridge between clay surfaces. This energy loss can be compensated for by a
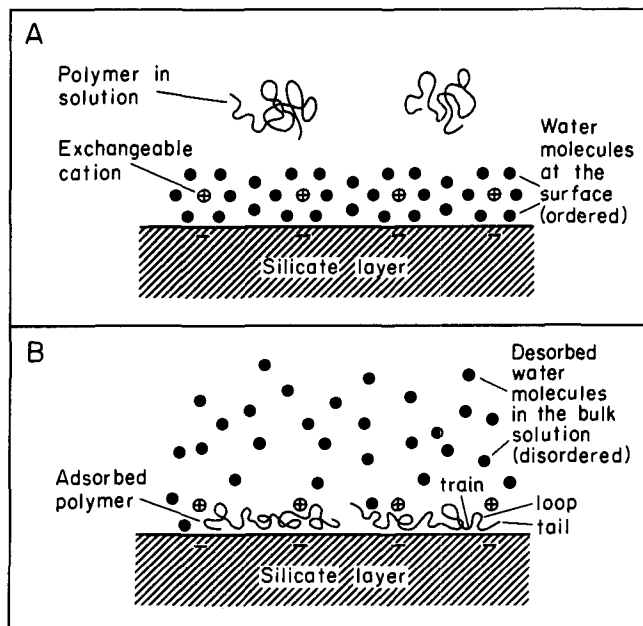

Fig. 4. Diagram illustrating the desorption of numerous water molecules from the clay surface during the adsorption of a single uncharged polymer molecule. The change in polymer conformation on adsorption is also indicated (Theng, 1979).

gain in the translational entropy of the system caused by the desorption of a greater number of water molecules (Fig. 4) (Theng, 1979). The stability of such an attachment would be enhanced if the polymer contained flexible loops that could expand during wetting and drying episodes. The number and irreversible nature of these attachments to clay surfaces tend to prevent the dissolution of adsorbed polymers.

AGGREGATION

Clay, silt, and sand are rarely present in soil as discrete entities. These primary particles are found bound together into clusters called aggregates. Aggregates normally range in size from 0.001 to 0.0001 in. Most investigators use aggregate stability as an index of soil structure and as an empirical definition of aggregation (Kemper and Rosenau, 1986; Lynch and Elliott, 1983). Although aggregation is not entirely an organic phenomenon and clays can bridge silt and sand grains together, these non-organic associations usually do not have the flexibility to remain stable under fluctuating moisture regimes.

Formation

There are few descriptive models for the formation of water-stable aggregates from primary particles (Allison, 1968). Emerson (1959) proposed that parallel clay crystals (0.0001 in.) are grouped together and behave as a unit called a domain. Organic matter stabilizes the aggregates by forming bonds between these domains and between the larger quartz particles (Emerson et al., 1986).

A mechanism for holding the similarly charged OM and clay together was suggested by Edwards and Bremner (1967). According to their model aggregates are composed of clay-polyvalent metal-organic matter complexes. The polyvalent cation serves as a cation bridge between the negatively charged clay and the exposed carboxyl groups of OM.

Another formation theory proposed that roots initiate aggregation. Root mucigel that is coated with aligned clay can become the nucleus of an aggregate. After the root dies, the aggregate would be composed of an anaerobic center containing partially degraded root and microbial material surrounded by a dense sheath of oriented clay (Payne and Norstadt, 1985).

Tisdall and Oades (1982) recognized that different binding processes are dominant at different size classes of aggretages. In the soils they studied, crumbs greater than 0.01 in. were stabilized by a network of fine roots and fungal hyphae, both of which can be disrupted by cultivation. The aggregate size class 0.01 to 0.001 in. was bound mainly by amorphous cementing agents including resistant OM. Bacterial capsules and fragments of fungal cell walls were found to bind particles between 0.001 to 0.0001 in. The less than 0.0001 in. class consisted of flocculated clay plates held together by H-bonding, van der Waals forces, and coulombic attractions. Aggregation is therefore a product of many forces including

transient mechanical binding by roots and fungal hyphae, temporary adhesive properties by products of microbial synthesis and decay, and persistent cementing action by resistent humus components which provide long-term stability (Brady, 1974).

Stabilization

According to Allison (1968), aggregation can be considered to consist of two phases, formation and stabilization. Although the processes are far from discrete and can act simultaneously, each may be influenced by different physical and chemical factors. The mechanism of stabilization depends on both the chemical nature of organic matter and on its arrangement within an aggregate. When tannic acids (high in polyphenols) and polysaccharides were mixed with soil before forming synthetic aggregates, the aggregates became unstable. But if the tannic acid was applied to the outer surface after the aggregates were formed with polysaccharides, there was a marked enhancement of stability (Griffiths and Burns, 1972). Certain synthetic polyanions are also effective soil stabilizers when added to preformed aggregates (Hayes, 1980). This synergistic effect, although speculative, suggests that polysaccharides can initiate aggregate formation by becoming encrusted with clay. The aggregates are then stabilized with an outer coating of polyphenols and polyanions. This stratified aggregate model could also account for much of the binding within, as well as the repulsion between, aggregates. The attachment of dispersive polyanions on the outer surfaces could help define aggregate boundaries (Oades, 1984). Soils contain a natural source of polyphenols and polyacids within the HA and FA fraction. Although earlier investigators found little evidence for the partitioning of organic components within an aggregate, they did not specifically look for HA, FA, or polysaccharide distribution (Kroth and Page, 1946).

An aggregate could be conceptualized as consisting of (i) "reinforced concrete," in which the polysaccharide coils correspond to the steel rods and the clay matrix to the concrete; (ii) external structural support supplied by fungal hyphae and small roots; and (iii) HA and FA as weather resistant outer covering. Although this simple analogy does not reflect the forces dominant at the smaller size scale, it does reflect the major factors involved with soil aggregate construction and stabilization (Fig. 5).

Pore Size Distribution

The degree of porosity (pore volume) determines the rate of movement of air and water into soil. Macropores favor high infiltration rates, good tilth, and adequate aeration for plant growth. The volume of these large pores increases with improved aggregation (Allison, 1973). An ideal aggregate pore distribution would include greater than 0.001 in. pores to allow for aerobic conditions and the passage of water, yet possess sufficient number of pores of 0.001 to 0.0001 in. diameter to retain

water for plant growth (Tisdall and Oades, 1982). Aggregate instability can lead to restricted flow when detached microaggregates (slaking) and clay particles (clay dispersion) are carried and lodged into pores, making them narrower or discontinuous (Lynch and Bragg, 1985; Felhendler et al., 1974). Pore structure stability is therefore necessary for the steady downward flow of water.

The initial site of structural degradation is commonly the surface aggregates. The aggregates below the air-soil interface are physically protected from those above (Lynch and Bragg, 1985). Crust formation can be attributed to many factors including raindrop impact and cultivation practices that can disrupt and expose aggregates. Soil crusts are typically composed of a 0.01 to 0.001 in. dense orientated clay seal overlying a 0.1 to 0.01 in. "washed in" layer. These surface crusts reduce infiltration by as much as 90%. When there is a physical cause for poor infiltration, such as crusting or stratified compaction, the soil requires physical amelioration (disruption) before organic additions can be effective in improving infiltration (LAWR, 1984).

INFILTRATION

Infiltration refers to downward flow of water through the soil surface. Factors that can impede water penetration include air entrapment, clay mineralogy, soil stratification, crust formation, water quality, and organic clogging of waterlogged pores (Allison, 1947; McCalla, 1951; Mitchell and Nevo, 1964; Nevo and Mitchell, 1967; Baver et al., 1972; Frankenberger et al., 1979, 1982). Because of the large number of determinants influencing infiltration, no single factor can serve as an index for predicting the infiltration behavior of a particular soil (Bouwer, 1986; Peterson and Bubenzer, 1986).

Infiltration becomes a problem when the total amount of water entering the soil over a normal irrigation period is less than that needed for plant growth in the interval between irrigation events. The frequency and type of irrigation determine whether an infiltration rate is acceptable. An intake rate of 0.05 in./h may be adequate for high frequency trickle systems but not for flood or furrow irrigation which would require a rate from 0.2 to 0.4 in./h (Peterson and Bubenzer, 1986; Bouser, 1986; LAWR, 1984).

In one of the earlier studies that looked specifically at the effect of organic additions on field infiltration rates, Parker and Jenny (1945) reported that annual incorporation of organic matter as animal manure or as a cover crop greatly increased the rate of water infiltration over that of a field that recieved only urea as a fertilizer. This and other studies indicate that a single application of a moderate to large amount of hay, straw, or barnyard manure seldom produces an effect, though repeated applications can increase the infiltration rate as seen in Fig. 6 (Smith et al., 1937).

Cultivation

Cultivation can cause a decline in organic C content through the physical disruption of aggregates which exposes previously inaccessible organic matter to enhanced bio-oxidation (Marshall, 1963; Volk and Loeppert, 1982).
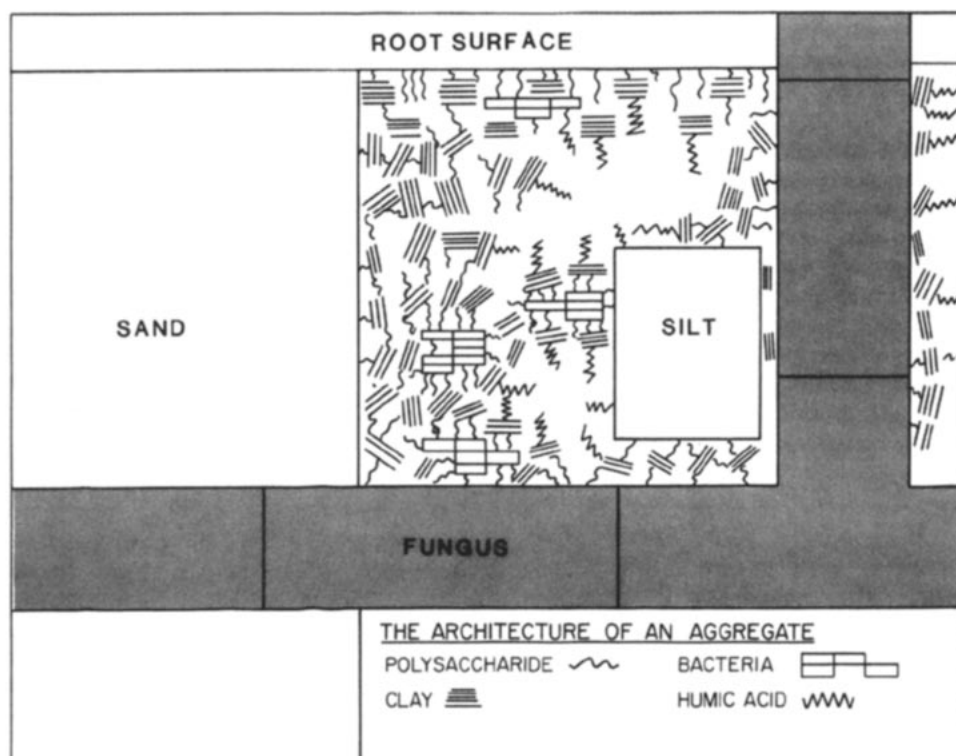

Fig. 5. A conceptual representation of the structural components of an aggregate.

A decrease in SOM is usually associated with a decrease in aggregate stability and water infiltration (Tisdall and Oades, 1982). Cultivation also removes the physical protection that plants give to the soil surface. Raindrop impact, rapid wetting, wind, and water movement all destabilize aggregates and increase dispersible clay. Burwell et al. (1968) reported that a mulch-tilled surface increased infiltration rates eight times over a bare plowed surface. The deposition of crop residues at the surface not only increases infiltration rates but also decreases water evaporation and soil erosion (Duley and Russell, 1939). The elimination of all cultivation on slowly permeable soil in conjunction with the growing of perennial crops produced a marked improvement in water penetration after 8 yr (Parker and Jenny, 1945). The authors suggested that the reason for the original low infiltration rate in these orchard soils was due to structural loss caused by cultivation and vehicle traffic.

Long-term pastures are ideal environments for aggregation. The continual plant cover of sod crops protects the soil surface, while the rhizosphere provides for both aggregate formation and stabilization (Allison, 1968). Under grasslands, soil is mechanically stabilized by a mesh of growing roots. These roots can form aggregates through differential dehydration which establishes the close contacts between clays and OM and defines the boundaries of aggregates by producing planes of weakness (Tisdall and Oades, 1982). Grass roots also produce mucigel that can either directly, or indirectly through microorganisms, supply polysaccharides for aggregation. Good distribution of OM in soil is achieved through the
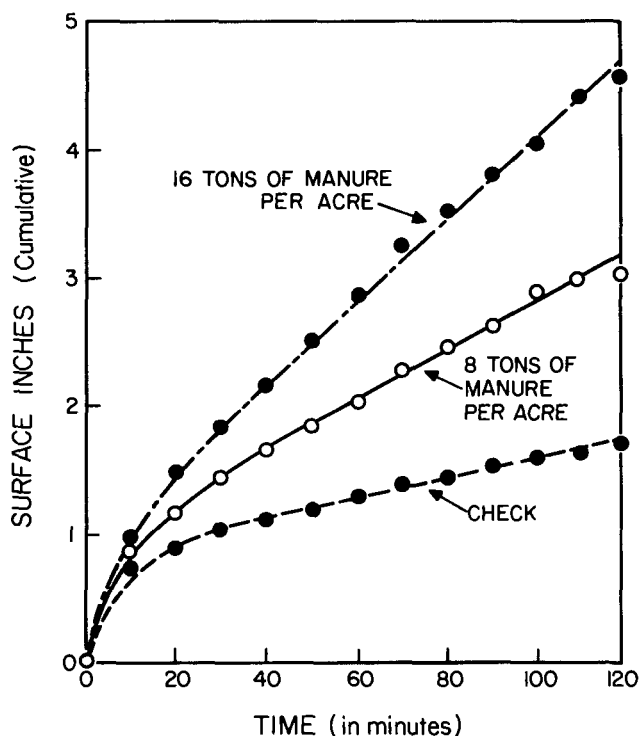

Fig. 6. Infiltration capacity in surface inches in Clarion loam (Smith et al., 1937). Reprinted with permission from the American Society of Agronomy.

fine root systems of grasses which can pump as much as 50% of their photosynthate below ground (MacRay and Mehuys, 1985).

The improvement of soil structure through aggregate stability is determined, to a large extent, by the degree to which plant growth is uninterrupted (MacRay and Mehuys, 1985). This may explain why green manuring, the turning over of a sod crop for the purpose of some agronomic improvement, rarely increases aggregate formation but often inhibits its destruction. In one field study, the stability of aggregates increased slightly after the incorporation of up to 3.4 tons/acre of alfalfa (Miller and Kemper, 1962). The effects lasted for the duration of the growing season and then diminished. Cereals were found to be similar to perennials in increasing the percentage of water-stable aggregates formed during vegetative growth, but perennials were superior in retarding the subsequent destruction of the structure following the growing season. Annuals were less effective, presumably due to their lack of stable soil cover and non-regenerative rooting structure. A grass-legume mixture was found to be the best at maintaining soil aggregation, while the least effective were cereals and root crops, which also contributed to soil and water loss (Harris et al., 1966).

Under most agroecosystems, the amount of fresh OM needed to maintain steady-state conditions exceeds the supply of available plant residues. The impact of organic inputs on aggregation appears short-lived, unless the additons are continuous or at least seasonal. An uninterrupted flow of organic matter to soil via an established rooting system that can supply both energy and structural compounds for the maintenance of soil structure is one of the reasons for the current interest in minimum tillage. Problems with overland flow on uneven surfaces have inhibited the wide scale adoption of minimum tillage on irrigated land.

SUMMARY AND RECOMMENDATIONS

Through genetic selection, modern agriculture has translocated much of the C to the more economically beneficial portion of crops. After harvesting the food and fiber from these plants, there may be less C returned to soil than is released from the oxidation of SOM. A proper allocation of fixed C is needed to balance organic export from the field with that required to preserve soil structure. Carbon that remains on site should be viewed as a necessary expense that insures a sustainable harvest. Progress in improving water intake through organic inputs has been slow because of the difficulty in measuring short-term (1-2 seasons) management effects on the variable soil properties of structure and infiltration. An integrated approach of residue management and fallow cover, in conjunction with the application of organic compounds that prevent surface crusting and enhance aggregate stability, could become an option in maintaining the structural integrity of soil. We have the potential to provide large amounts of complex natural polymers to soil from inexpensive raw materials. These polymers

could be applied to, or produced within, soil. But the industry needs a conceptual model of soil aggregation to produce polymers for improving soil structure and water infiltration.

Organic matter imparts a physical buffering capacity to a soil, and can temper the detrimental effects of human agronomic activity. A universal "infiltration loss" equation, similar in concept to the universal soil loss equation, has yet to be realized. Its development would at least quantify what is an acceptable loss of infiltration rate due to cultivation. If most cultivation practices accelerate the degradation of SOM, which in turn enhance not only the loss of soil structure but the soil itself, then it is valid to ask: Are short-term gains of enhanced productivity worth the long-term costs of soil degradation?

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