Soil organic matter and structural stability: mechanisms and implications for management

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Summary The stability of pores and particles is essential for optimum growth of plants. Two categories of aggregates macro- ($> 250\,\mu$m) and micro- ($< 250\,\mu$m) depend on organic matter for stability against disruptive forces caused by rapid wetting. Dispersion of clay particles from microaggregates is promoted by adsorption of complexing organic acids which increase the negative charge on clays. The acids are produced by plants, bacteria and fungi. However, the dispersibility of clay in microaggregates is offset by the binding action of polysaccharides, mainly mucilages produced by bacteria, but also by plant roots and fungal hyphae. The stability of microaggregates is also enhanced by multivalent cations which act as bridges between organic colloids and clays. Macroaggregates are enmeshed by plant roots, both living and decomposing, and are thus sensitive to management, and increase in number when grasses are grown and the soil is not disturbed. Lack of root growth, *i.e.* fallow, has the opposite effect. Various implications for management of soil structure are discussed.

Introduction

Soil structure is defined as the size and arrangement of particles and pores in soils. Good structure for plant growth on loams and clays can be defined in terms of the presence of pores for the storage of water available to plants, pores for the transmission of water and air, and pores in which roots can grow (Table 1). The particle sizes associated with such pores are indicated so that we can relate pore and particle diameters. A desirable range of pore sizes for a tilled layer occurs when most of the clay fraction is flocculated into microaggregates, defined as $< 250\,\mu$m diameter, and secondly these microaggregates and other particles are bound together into macroaggregates $> 250\,\mu$m diameter. The majority of the macroaggregates should have diameters in the range 1 to 10 mm[6, 21].

The architectural arrangement described, whether natural or created by tillage, must be stable to disruption on wetting. The breakdown of macroaggregates on wetting due to entrapped air and unequal swelling

Table 1. Functional classification of soil pores and associated particles

Pore diameters (μm)	Function	Particle diameters (μm)
< 0.2	Bound water	< 2
0.2–2.5	Storage of water available to plants	2–250
25–100	Capillary conduction, aeration	250–1,000
> 100	Aeration, fast drainage root growth	> 1,000

has been termed slaking[7]. Slaking results in microaggregates from which clay particles may or may not be detached (dispersed) depending on factors described in double layer theory, and some that are not including particle size, shape, packing and the input of energy. Slaking alone is a problem and causes reduction in infiltration rate of rainfall or irrigation water, and in hydraulic conductivity. When dispersible clay is also present porosity is decreased, soil strength increased and generally unfavourable physical conditions prevail[41, 42].

Organic materials in soils influence both dispersion–flocculation phenomena and the stability of macroaggregates.

Microaggregates

Swelling and dispersion

Organic anions which form complexes with metal ions favour the dispersion of clays in a manner similar to that of Calgon and other phosphates. At least two factors are involved: a) the complexing of trivalent and divalent metal ions which reduces concentrations in solution, and a reaction with any positive sites associated with trivalent metals situated on the edges of clay lattices or on oxide surfaces, and b) the sorbed organic anions increase the negative charge on colloid surfaces thus increasing the diffuse layer of cations associated with the surfaces, favouring the dispersion of clay particles.

The influence of organic matter on the dispersion of clay has been illustrated convincingly by Gillman[12] in soils developed from basalt. Weathering of the ferromagnesian minerals has produced a soil clay rich in oxides. At depth this clay dispersed as a colloid with a net positive charge, *i.e.* the point of zero charge (PZC) of the clay was higher than the pH of the soil. Closer to the soil surface where the organic matter content was greater the PZC matched the pH of the soil and there was no water dispersible clay (Fig. 1). Within about 30 cm of the surface of the soil substantial quantities of water dispersible clay were present as the PZC was lowered below the pH of the soil by the absorption of organic materials.

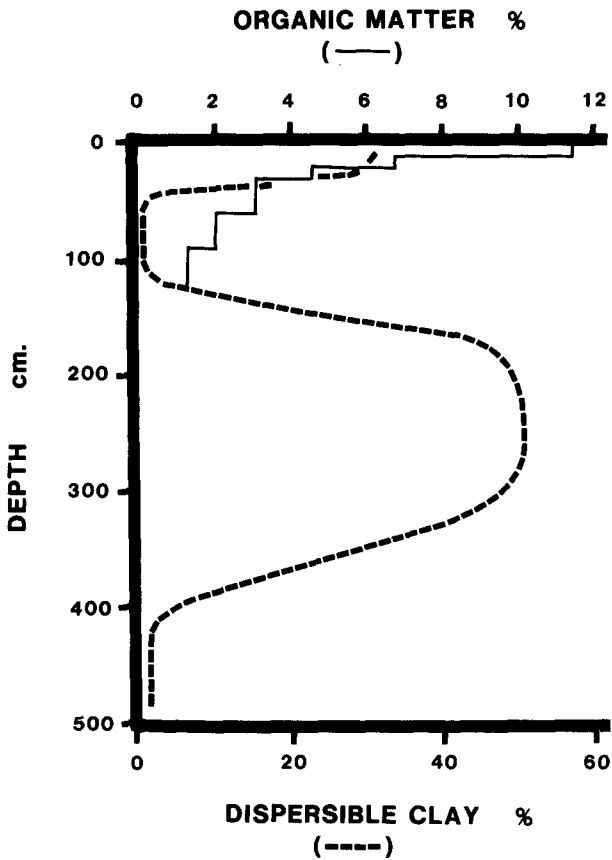The adsorbed organic materials must have been largely anionic in

Fig. 1. Organic matter content and dispersible clay (from Gillman[12]).

character. It has been shown that sorption of a range of organic anions on a soil clay to which Fe polycations had been added increased the dispersibility of the clay due to changes in the surface properties[43]. Polycations of Fe were added to a soil containing 18% clay, as determined by standard procedures, until the PZC coincided with the pH of the soil when all the clay was flocculated. To this clay a range of anions was added and the amounts of dispersible clay were determined (Fig. 2).

The anions studied were divided into four groups on the basis of their influence on dispersible clay. The effect of phosphate was predictable based on the use of various phosphates to stabilize dispersions of soil clays in the laboratory and in farm dams. The efficiency of the fulvic acid preparation was surprising because Fe-fulvate has a low stability constant. However, fulvic acid is strongly sorbed on iron oxide surfaces as carboxyl groups replace hydroxyl groups giving multiple points of contact[36]. The relative efficiencies of the other anions was
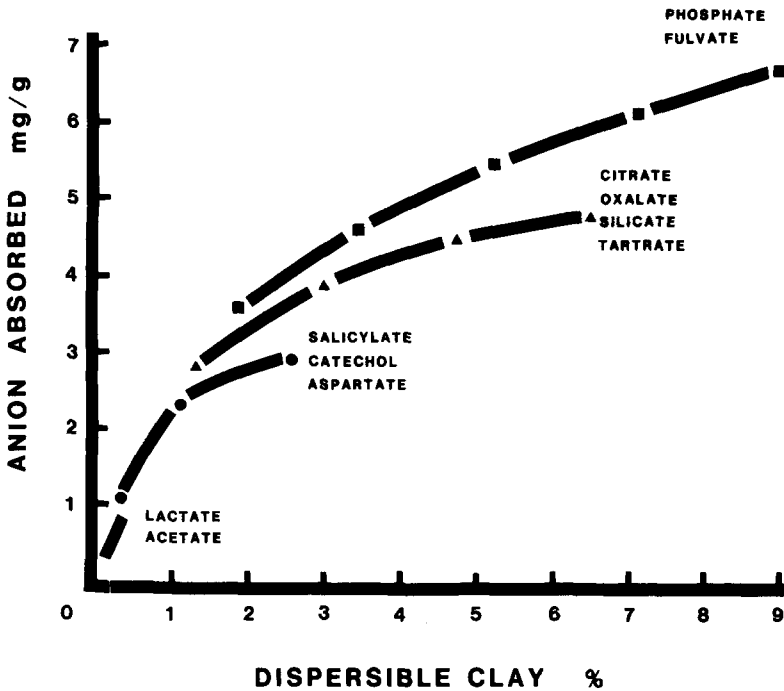
Fig. 2. The dispersion of clay by adsorption of organic anions.

related to the energy of binding of the anions to the Fe on the clay sur-
face.

The anions clearly increased the negative charge on the clay particles
as shown by the substantial negative electrophoretic mobilities for the
two groups of anions adsorbed in greatest quantity, which were also
those absorbed most strongly (Fig. 3). The increased dispersibility of
the clay caused by the adsorption of the anions increased the bulk den-
sity of the soil and decreased the water holding capacity. Simul-
taneously the modulus of rupture was increased and the friability
decreased. It would be informative to repeat this experiment in a sys-
tem where positive sites originated from Al rather than Fe.

The range of acids produced in soils has been described by Steven-
son[45]. Citric, oxalic and tartaric acids are produced by plants, bacteria
and fungi. The role of these acids, and a wide range of others, in the
process of podzolization has been described by many authors (see
Petersen[37]). The emphasis has been on the dissolution and complexing
of metals as a means of translocation of Al and Fe. However, it is likely
that acids, from simple well defined compounds through to the fulvic
acids, are involved in dispersion of clays in surface horizons and clay
transport to lower horizons (illuviation, lessivage). This dispersion of
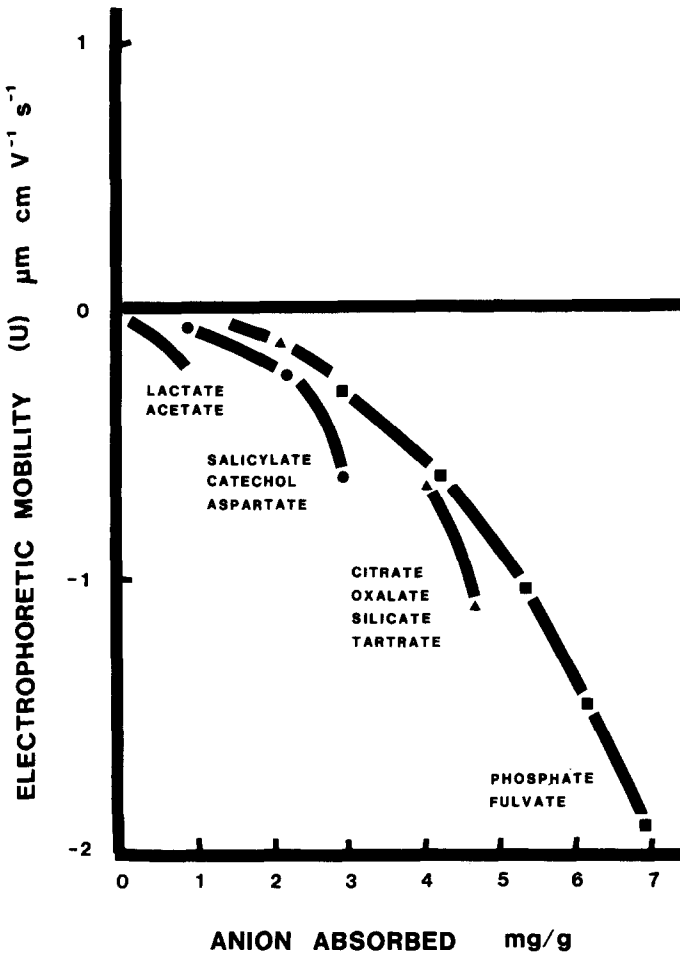clay will be important in soils with a pH of 6 ± which are leached free

Fig. 3. The influence of anion adsorption on the electrophoretic mobility of a soil clay.

of $CaCO_3$ but are not sufficiently acid for concentrations of soluble Al to be important. The soils do not need to be sodic. A range of duplex soils occupy 20 per cent of the Australian continent and many are notorious for poor physical conditions, associated with dispersible clay, which lead to surface crusts and 'hard setting' properties.

Because roots and rhizosphere organisms produce a range of acids one might predict that the living root system organisms would stimulate production of dispersible clay. Such an effect has been described by Reid and Goss[39, 39] and Reid et al.[40], particularly for maize plants during the early weeks of growth. The increased dispersion of soils after growth of maize plants for 14 to 42 days was evident if soils were maintained moist prior to analysis. The acids produced could break

organic matter − Fe. Al. Ca-clay bonds by lowering the pH and/or complexing the metal ions. Iron may also be dissolved in the rhizosphere at a low redox created by the oxygen demand of the organisms utilizing exudates from roots. Drying of the soil by plant growth or by air drying led to increased stability of soil aggregates presumably due to the increased sorption and effectiveness of organic binding agents, probably by polysaccharides which are exuded from roots in addition to the soluble exudates[30].

It is clear that as root systems mature and root hairs and roots are being decomposed continually, and the rhizosphere organisms establish themselves in root mucilage the stabilizing influences of root systems will be dominant. However, in soils which are cultivated regularly with low organic matter inputs, oxidation of organic materials will proceed at a rate which causes a gradual reduction of the organic matter content of the soil with resultant change in the composition of the residual organic matter[31]. There is an increase in the ratio of fulvic to humic acids. So the organic materials in the 'run down' soil are more soluble, more aromatic and possess more acidic functional groups per unit weight than those in a corresponding soil with 2 to 3 times the organic matter content. This loss of organic matter not only led to a substantial loss of water stable macroaggregates[52], but also a significant increase in dispersible clay probably as a result of oxidation of organic binding agents in addition to any effect of increased proportions of fulvic acids.

Flocculation and binding

The necessity to oxidise soil organic matter to determine the amount of clay in soils is well known. The standard practice during determination of inorganic particle size distributions by peroxidation of organic matter not only releases clay from microaggregates, but also releases large quantities of very fine clay, *e.g.* particle diameter ∼ 10 nm. The specific surface area of clay fractions has been increased manyfold by oxidation of organic materials (Table 2). To account for these very large increases in surface areas of fine clay fractions either the organic materials coat aggregations of clay particles and render them inaccessible to N gas when it is used to determine surface areas, or fine clay is embedded in a matrix of organic matter.

Polysaccharides

One group of natural macromolecules which have received considerable attention in the last two decades because they are important as glues in soils are the polysaccharides. Carbohydrates represent about one quarter of soil organic matter much of it being derived from plant

Table 2. Release of fine clay by peroxidation of organic matter (from Burford et al.[3]; Turchenek and Oades[54])

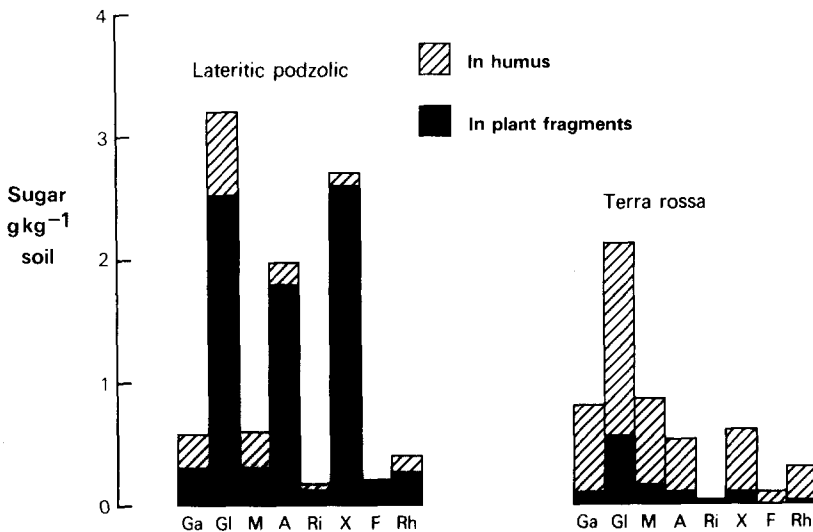| Particle diameter (μm)	Surface area m²/g	
	untreated	H₂O₂ treated
Red-brown earth; Rhodoxeralf		
<2	16	77
0.4–2.0	24	54
0.1–0.4	39	76
<0.1	32	149
Black chernozemic; Haploboroll		
0.4–2.0	24	85
0.4–2.0 < 1.8 g/cm³	7	157
0.1–0.4	44	132
<0.1	6	211
Terra rossa; Palexeralf		
<2	50	176
Krasnozem; Paleustult		
<2	54	141

Fig. 4. Aldoses in plant debris and humus in an acidic and an alkaline soil. Ga galactose; Gl glucose; M maltose; A arabinose; R ribose; X xylose; F fucose; R rhamnose.

polysaccharides in roots and plan debris. The amount of the soil carbohydrate present in macroorganic matter ($>\frac{1}{4}$ mm sieve) or separated as a 'light fraction'' by flotation or density procedures is substantial in acidic and sandy soils and much less in neutral to alkaline and clay soils (Fig. 4)[28]. These cellular plant polysaccharides are not involved directly in stabilization of soil structure. They are characterised by high proportions of pentose sugars.

The remainder of the polysaccharides in soils are mucilages associated with roots[30] or microbial mucilages[17]. Thus the rhizosphere becomes a major site for the production of mucilages, but they are also produced by organisms wherever organic debris is being decomposed. These mucilages are considered to be important glues in soils[4, 1 7, 27, 47] and evidence for this role includes correlations of aggregate stability and polysaccharide contents, the stabilization of aggregates by addition of microbial polysaccharides and polysaccharide preparations from soil, the degradation of aggregates by 'selective' oxidation of polysaccharides by periodate and recently the elegant identification of polysaccharides *in situ* in thin sections of soils[8, 9, 10, 11, 19, 20].

Recently Cheshire *et al.*[5] suggested that polysaccharides may be far more important glues than presently considered. They showed that $0.05 M$ periodate or prolonged oxidation with more dilute periodate caused further disaggregation of soils as more sugars were oxidised. However, the use of more concentrated periodate and long oxidation times raises the question of the selectivity of periodate for oxidising polysaccharides. When used on soils far more periodate is reduced than can be accounted for by oxidation of all the polysaccharides in the soil (Oades unpublished). Thus while there is no doubt that polysaccharides play a major role in binding soil aggregates determination of their precise contribution remains elusive.

Foster has indicated that the mucilages from fungi stain differently from those of bacteria. Otherwise the only guide to the origin of the mucilages in soil is the content of arabinose and xylose. Work with ^{14}C has shown that the soil microbial population synthesizes dominantly galactose, glucose and mannose and little if any arabinose and xylose, although at low temperatures yeasts produce xylose[4, 29, 35]. Plant materials contain substantial quantities or arabinose and xylose. Thus the ratio galactose + mannose/arabinose + xylose (g + m/a + x) is low (<0.5) for plant polysaccharides and high (>2.0) for microbial polysaccharides.

The composition of microbial polysaccharides is indicated in Fig. 5. Hexoses represent 70–90% of the aldoses, but equal amounts of amino compounds and uronic acids have usually been present (*e.g.* Swincer *et al.*[46]). Such complexes of macromolecules will react with clay surfaces by various mechanisms based on model systems which have been reviewed regularly (*e.g.* see Theng[49]).

The recent advances in the recognition of biological components by specific staining with heavy metals followed by transmission electron microscopy (TEM) and scanning electron microscopy (SEM) have elucidated the relation between mucilages, associated with bacterial cells,
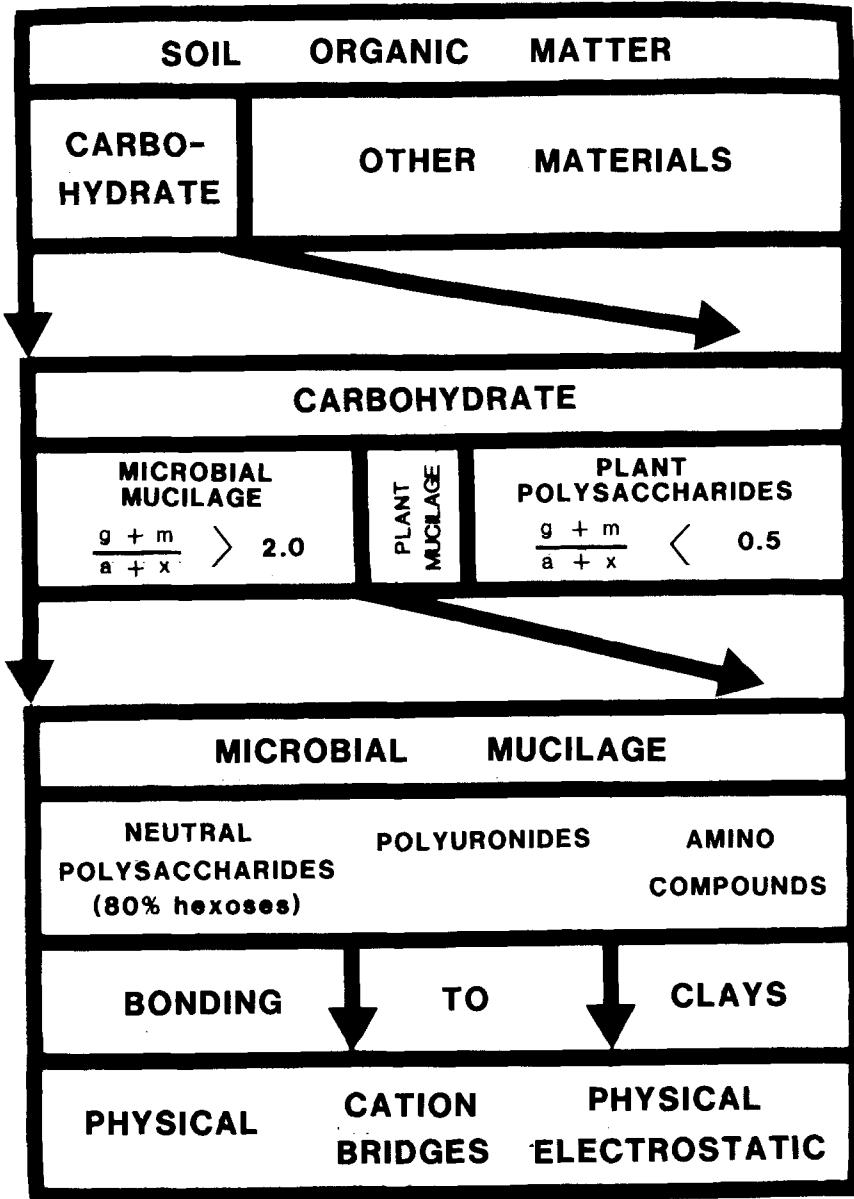
Fig. 5. Carbohydrates in soils.

fungal hyphae and the inorganic components, usually in the form of fine clay platelets[11, 19, 51]. Several important point arise from the electron microscopy

a) mucilages are produced *in situ* by roots or organisms and probably do not diffuse from the site of production. It is significant that the potential glues will be produced in pores accessible to roots and
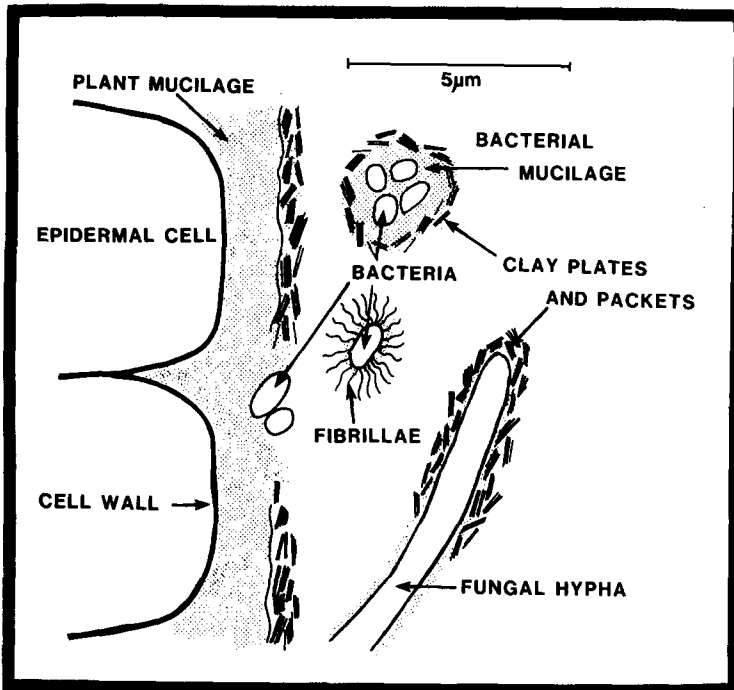
Fig. 6. Interaction of clay plates with mucilages.

organisms, *i.e.* the coarser pores from a few microns diameter upwards. These larger pores represent planes of weakness in aggregates whose stabilization is essential for structural stability.

b) polysaccharides exist as a gel or as fibrillae and do not move around in the soil as discrete polymers. The mobile component in the interaction between mucilage and clay appears to be fine clay. Dispersed fine clay will move with water in soil pores by gravity or matric suction towards roots until it contacts mucilages. The clay plates then seem to align themselves with the surface of the mucilages, encapsulating bacteria, surrounding fungal hypae or aligned parallel to roots (Fig. 6).

c) encapsulation of bacteria and associated mucilages by clay platelets and alignment of plates on mucilages indicates clearly why all the polysaccharide materials are not rapidly utilised by the microbial population. Much of the material is not physically accessible to organisms or enzymes. In addition, reaction of polysaccharides with metals inhibits degradation[27]. Thus, as Tisdall and Oades[53] described, while some of the stability of aggregates due to recently synthesised polysaccharides is transient because they are utilised by the microbial population, another part has considerable longevity. A substantial loss of organic matter

from soils can occur before the organic binding agents in microaggregates are degraded.

Cation bridges

Because clays and organic materials are polyanions they can be bridged by polyvalent cations. The cations normally considered are Ca, Mg, Al, Fe although others may be present in small amounts, *e.g.* Mn, Zn, Cu. While the divalent ions may exist as single ions with double charge which align water dipoles, Al and Fe are more likely to exist as hydrolysed species of indefinite composition and organisation, but with a net positive charge, *e.g.* polycations. The main evidence for the role of cation bridges has been based on increased disaggregation after treatments of soil with complexing agents or after treatments with acids (*e.g.* Hamblin and Greenland[15]). The complexing agents most commonly used have been pyrophosphate and acetylacetone, which is aimed particularly at Al and Fe. It has been shown consistently that pyrophosphate aids disruption of aggregates beyond that due to saturation of the system with Na. It is known to extract the more oxidised, aromatic components of the humic-fulvic system which have the most functional groups in close proximity and thus likely to complex with metal cations.[31, 55]. It also extracts some polysaccharides. The extraction of these organic polyanions is considered to be due to dispersion of the system and sequestering of polyvalent cations which have bridged clay and organic matter. The metal pyrophosphates are largely insoluble.

Pyrophosphate has been used to break cation bridges after periodate oxidation of polysaccharides[44] and caused further disaggregation. However, aggregate breakdown after sequential periodate and pyrophosphate treatments was always less than the sum of the aggregate disruptions caused by individual treatments of periodate and pyrophosphate on separate soil subsamples. The binding materials affected by both treatments could be the polysaccharides extracted by pyrophosphate and oxidized by periodate. Alternatively the common materials may involve the substantial polyuronide fraction. The pyrophosphate treatment gives no indications of the metals involved in the bridging effect.

Acetylacetone in aqueous and organic solvents has been examined as a means of breaking Al and Fe bridges between clays and organics[13, 14, 15, 16]. The limited results of the latter authors indicate that aqueous acetylacetone may be more efficient in extracting Al and Fe from organic materials. However, Giovannini and Sequi[13, 14] showed that acetylacetone in benzene led to a substantial decrease in the water stability of aggregates in five soils. They envisaged organic matter as a

network in which the junctions of the network were held together by Al and Fe. When the Al and Fe were removed wetting caused degradation of the net.

While pyrophosphate and acetylacetone may displace some organics from the surfaces of Al and Fe hydroxides, neither complexing agent is likely to displace polyanionic materials from oxide surfaces or from associations with highly disordered minerals. There are a number of good correlations between organic matter and disordered Al and Fe compounds[55]. Thus the influence of Al and Fe as bridges is probably underestimated.

Microorganism – clay interactions

Various sorptive interactions between soil particles and microorganisms have been reviewed by Marshall[26] who considered implications for the microorganisms rather than aggregation. More recently[2] the adhesion of microorganisms to surfaces has been described including the fundamental forces of interaction between organisms and surface and the implications for the organisms involved and the surfaces acting as adsorbent.

The soil microflora can be regarded as aquatic and it is reasonable to regard bacterial cells as part of the colloidal system that exists in soil. The fact that microorganisms are not readily leached or washed out from soils indicates that they are attached to either clay or humic materials and will be involved in dispersion–flocculation reactions which occur along with the other colloidal materials present. The cells are on average, larger than clay particles, they are ionogenic and in many cases amphoteric due largely to carboxyl and amino groups. Most microbial cells possess a net negative charge at the pH of the soil. It is therefore intriguing to consider how such negatively charged bioparticles approach clay surfaces sufficiently closely to be adsorbed. Organisms appear to offer at least two mechanisms to attach themselves firmly to clay surfaces: the first is the production of fibrillae which may extend up to tens of nm from the wall of the organisms to contact a nearby surface, the second is the production of a slime or mucilage which is dominantly polysaccharide in nature. While there is less information available for fungi many hyphal walls contain similar compounds to bacteria and similar properties could be assumed. Tisdall and Oades[51] presented some evidence that clay platelets were attached to fungal hyphae by means of a polysaccharide mucilage.

Several workers have shown that a substantial proportion of the soil biomass lives on or near the surfaces of aggregates, and while some can
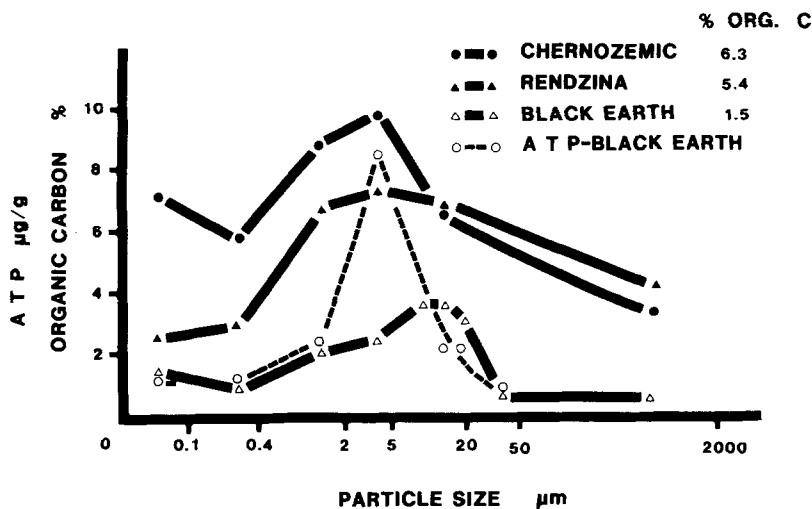
Fig. 7. Enrichment of carbon in aggregates in the silt fraction of calcareous soils.

be washed off by various procedures such as centrifugal washing, most remain with the inorganic fraction. When the aggregates are disrupted the microbial biomass is found in association with smaller particles particularly those from 1 to 20 μm equivalent spherical diameter, a proportion of which survive limited treatment with ultrasound. This appears to be particularly important in calcareous clay soils where organic materials and microorganisms accumulate in silt size particles resistant to dispersion by ultrasound[33, 48, 56]. Recently Ahmed[1] confirmed that substantial portions of the ATP in soil resided in the silt fraction. Furthermore, during the early stages of decomposition of glucose in soil substantial portions of the biomass (according to ATP) were present in a fine clay fraction. Subsequently there was a shift to larger particle sizes presumably as the organisms interacted with clay to form silt sized aggregates[1]. It is clear that the biomass which represents only several percent of the organic matter cannot account for the stability of all the aggregates in the silt fraction (Fig. 7) but that generations of bacteria have interacted with clay in a similar fashion forming a pool of stable aggregates enriched in carbon, nitrogen and also organic phosphorus[22, 23, 24, 34]. The fact that an accumulation of organic matter in silt fractions does not occur in leached acidic soils may reflect a much lower bacterial population, and/or perhaps a lack of calcium to bind organisms, residues of organisms and clay particles into silt sized aggregates.

Plate 1. Grass roots in black cracking clay.

Macroaggregates

Given sufficient quantities of mucilage or humic materials associated with metal ions spread uniformly through the soil, there is no reason why large aggregates cannot be stabilized. However, it seems that the production of a uniform matrix of organic materials is rare and slaking causes production of particles $100 \pm \mu$m diameter. This is presumably a result of the bonds within the microaggregate being strong compared with those between the aggregates because of a discontinuous organic matrix caused initially by an uneven distribution of microorganisms.

However, it is clear that resistance to slaking is associated with larger pieces of organic debris from roots litter and fungi, or faecal pellets and worm casts, or from the network of living roots and hyphae.

The association of roots and hyphae with macroaggregates especially those > 2 mm diameter has been discussed by Tisdall and Oades[53]. The roots form a mesh with strands of diameter 10μm upwards. These roots have grown in the coarser pores and are thus distributed around larger aggregates (Plate 1). Hyphae particularly the VA mycorrhiza can be regarded as an extension of this root system developing mycelia with hyphal diameters up to 10μm throughout finer pore systems and around smaller aggregates (Plate 2). The fibrillae and flagellae of microorganisms are another order of magnitude smaller and can occupy pores between clay packets and particles, *i.e.* stabilizing microaggregates.

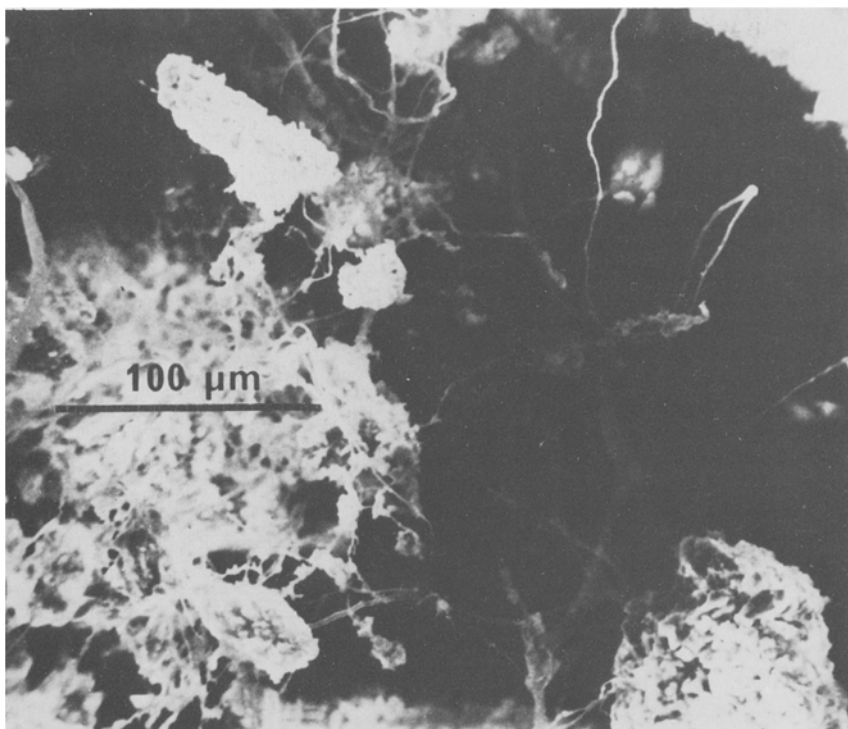The complex chemistry of roots and hyphae renders them resistant

Plate 2. Scanning electron micrograph of soil particles entangled by fungal hyphae.

to chemical treatments, and the binding effect of the fungal hyphae, in particular, is not influenced by either periodate or pyrophosphate (Carter and Oades unpublished; Tisdall[50]).

The roots and associated hyphae have been described as temporary binding agents[53] because they do not persist for more than a year or so. Thus unless they are being replaced annually the binding effects disappear and the number of water stable macroaggregates declines. A bare fallow is notorious as the most deleterious management treatment with respect to soil structure.

As the roots and hyphae decompose the fragments become the centre of a water stable macroaggregate. Mucilages produced during decomposition of the organic fragment interact with clay which begins to encrust the organic fragment, eventually to an extent where the degradation of the organic material is retarded. The final product is a microaggregate bound by a matrix of humic materials and mucilages. This is a stage which exhibits considerable stability in the field unless there are chemical stresses which aid dispersion, e.g. exchangeable Na or severe mechanical stresses, e.g. raindrop impact.

Soil fauna

The influence of fauna on soil has been reviewed by Hole[18] and space does not permit an expansive treatment here, but a short statement is warranted.

Well aggregated soils always appear to contain a substantial population of both macro- and mesofauna. Whether the fauna are responsible for the porosity or whether suitable pores offer an optimal habitat for the fauna is a circular argument. Examination of calcareous soils under grassland indicates that surface layers are almost entirely materials 'casted' by earthworms or faecal pellets of other fauna including Collembola and mites. It is well known that regular cultivation decimates the numbers of macrofauna and it has been shown that certain herbicides have a similar effect on the Collembola and mites[25]. Very few approaches to management have considered the soil fauna, but stimulation rather than destruction of faunal populations may offer economical approahces to structural improvement, *e.g.* during stubble mulching or for improving infiltration rates from production of biopores.

Implications for management

Macroaggregation

In those soils where organic matter is the major binding agent macroaggregation is controlled by management. In general, numbers of macroaggregates can be increased by addition of decomposable organic materials. The best distribution of organic materials and mixing with the inorganic colloids is through root systems particularly the fine, bushy and extensive root systems of grasses. Limited data indicate that the stabilization of macroaggregates under grasses is maximal if the grass is cut at intervals which are long enough to allow root systems to recover. In this manner maximum death and growth of the root system is obtained, which will result in maximum organic inputs to the soil. Periods of bare fallow have the opposite effect. The proportion of a rotation which needs to be in grassland will depend on the soil and climate and will need to be determined for each situation.

The soil fauna will multiply given sufficient time, perhaps several seasons, with little soil disturbance. Addition of litter in appropriate circumstances will accelerate the recovery of the fauna, particularly earthworms. Infiltration of water has been increased manyfold by such treatments, but it is not applicable to broad scale farming.

Microaggregation

Microaggregation is not so sensitive to management. Therefore it is more difficult to improve microaggregation by normal farming practices although systems which conserve organic matter will slowly improve the number of microaggregates.

The pool of mucilages in the soil reflect an equilibrium between production by plants and organisms and degradation by subsequent microbial populations. Thus to maintain a large pool, stimulation of root growth is essential as this will give the best distribution of plant mucilage and energy source for microorganisms. Because grasses produce some 50% of their photosynthate below ground they are generally regarded as the most efficient 'structural improvers'. Alternatively, additions of organic matter will serve the same effect.

It seems unlikely that Al or Fe will be added to soils to stimulate bridging between organic materials and clays even though polycations of Al and Fe flocculate clays most efficiently[32]. However, the beneficial effects of maintaining a significant concentration of Ca in soil solution deserve examination. Gypsum can be used to supply sufficient Ca to flocculate colloids but unless large quantities are added the effect is only transient and it is not known if the high concentration of Ca for several years has any effect on the stability of polysaccharides, the production of Ca bridges between humic mateials and clays or on the stimulation of the soil microflora and fauna. Perhaps the long term effects of liming on soil structure should be reappraised.

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