Geoderma, 56 (1993) 377–400
Elsevier Science Publishers B.V., Amsterdam

The role of biology in the formation, stabilization and degradation of soil structure

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(Accepted October 14, 1992)

ABSTRACT

Oades, J.M., 1993. The role of biology in the formation, stabilization and degradation of soil structure. In: L. Brussaard and M.J. Kooistra (Editors), Int. Workshop on Methods of Research on Soil Structure/Soil Biota Interrelationships. Geoderma, 56: 377–400.

Soil structure is defined as the arrangement of particles and associated pores in soils across the size range from nanometres to centimetres. Biologic influences can be demonstrated in the formation and stabilization of aggregates but it is necessary to distinguish clearly between those forces or agencies which create aggregations of particles and those which stabilize or degrade such aggregations.

The formation of soil structure involves the physical forces of shrinking and swelling created by changes in water status of soils, freezing and thawing, tillage, or by movement of the larger biota in soils. Expansive properties of soils are controlled by the clay content. Thus changes of structural organisation are minimal in sands and maximal in clays. Plant roots, earthworms and other macrofauna large enough to move soil particles create pores recognisable by cylindrical shapes and smooth curved surfaces. Various visual and microscopic techniques aided by dyes are available to demonstrate the extent of biovoids in soils.

Biology plays a major role in stabilization of soil structure. The major factors vary depending on the scale of soil structure. At larger scales plant roots and associated hyphae can be seen to enmesh soil particles by acting as a "sticky string bag". At the microscale the influence of mucilages from roots, hyphae, bacteria and fauna such as earthworms can be shown by a range of microscopic techniques to be involved in stabilizing smaller aggregates and the linings of biopores. Techniques include optical and fluorescence microscopy, scanning electron microscopy including EDAX, transmission electron microscopy using heavy metals or other electron dense staining techniques for specific chemical compounds, and computer aided tomography. The microscopic techniques can be used on individual aggregates, stabilized soils, sections or separates of soils.

Both microflora and fauna are involved in the degradation of stabilizing agents. Fauna may comminute roots and hyphae which stabilized larger aggregates and microorganisms utilize mucilaginous stabilizing agents as an energy source resulting in a slow breakdown of structural stability. Such effects can be established by combinations of studies of aggregation including microscopy. Further destruction of structure is caused by tillage and compaction by vehicles and animals.

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0016-7061/93/$06.00

INTRODUCTION

The role of biology in the formation and stabilization of soil structure is being recognised increasingly by scientists and there is growing interest in managing soil biota to develop desirable soil structure and to minimise the use of machinery for production of tilths and optimum seed beds.

Soil structure has been defined simply as the arrangement of particles and pores in soils. To this definition must be added the stability of the structure or architecture of the soil because structure is not static and changes with water content and other agencies of stress which may be applied to the system. Structure needs to be defined across nine orders of magnitude (Waters and Oades, 1991) but descriptions at any one scale need to be integrated into the properties of the whole soil otherwise the scientific endeavours will have little value in the field. Similarly the size range of soil biota which influences soil structure is enormous, from soil microorganisms and their biopolymers, through arthopods and Collembola to moles, rodents and wombats, to large plants such as trees.

There is a good deal of confusion in the literature with respect to the formation of aggregates and pores, and their stabilization. In many cases a particular structure is formed by one process and stabilized by another. Sometimes the formation and stabilization occur simultaneously but often formation precedes stabilization. In this review the simple definitions in Table 1 will be followed.

The major forces involved in the formation of structure are the physical forces created by wetting and drying which increase with the clay content of soils. However, roots and the larger soil organisms also create soil structures in both direct and indirect manners. The major role for biology is in the stabilization of soil structure, although in some undisturbed soils faecal pellets may dominate the upper horizons.

The greatest influence on soil structure—both creation and destruction, but rarely stabilization—is caused by tillage, by traffic and by hooved animals.

In this review an attempt is made to discuss those techniques which allow

TABLE 1

Definitions used in this review

Soil structure	the arrangement of particles and pores
Structural stability	the stability of a particular arrangement to internal and external stresses
Formation	of an arrangement of particles and pores
Stabilization	of an arrangement of particles and pores by organic or inorganic materials
Degradation	a detrimental change in structure for, e.g., aeration, water movement, root growth, etc.

structural features in soils created by biological and physical factors to be recognised, and where possible quantified so that biota can be managed to produce an optimum stable soil structure *for crop production.*

FORMATION OF SOIL STRUCTURE IN SANDS, LOAMS AND CLAYS

Before discussing biology and structural features we need to establish a few basic principles with respect to modern views of soil structure. We need to consider sands, loams and clays separately, particularly if we wish to compare biotic and abiotic influences on structure.

Soil structure as defined in the introduction is a broader concept than aggregation and includes aggregation. Particles in a soil may be single-grain mineral particles, e.g., quartz, or aggregations of single-grain particles into compound particles which are generally referred to as aggregates or peds. Other terms such a granules or crumbs have implications for porosity and strength. A sand has structure because it has a pore size distribution created by the size and the packing of sand grains. This structure can be changed by altering the packing of the sand grains by tillage or compaction or rearrangement by soil animals. The structure is not altered significantly by drying and wetting cycles because the shrink–swell capacity is virtually zero. Binding of sand grains together will thus depend on biological factors.

In loams the cohesive nature of clays and the shrink–swell capacity associated with colloidal particles creates aggregates during drying and wetting cycles. The existence of an aggregate infers that the cohesive forces between the particles within an aggregate are greater than those between the aggregates. In situ the aggregates may be separated by voids or are defined by planes of weakness which may not be obvious unless the system is stressed mechanically. This can occur internally due to drying and wetting or externally by tillage. The greater the clay content, the greater the shrink–swell capacity and the more vigorous the cycles of structural formation during dry–wet cycles. Plants play a major role in structural development of loams because they influence the rate, extent and spatial development of the drying phase. Root systems also play a major role in stabilization of the structure created. Soil fauna also create aggregates as faecal pellets and both biotic and abiotic factors are important in loams (Table 2).

Maximum development of aggregation occurs in smectite-rich clays in Vertisols and Mollisols. In Australia some clay soils exhibit the desirable structural feature of "self mulching". This involves the development of a friable, granular soil structure in the top few centimetres of soil after only a few drying and wetting cycles. Even a severely puddled soil will regenerate this desirable structure after two or three wet–dry cycles. Attempts to quantify this property have been described by Grant and Blackmore (1991). In such clay-rich soils the creation of structure is dominated by the behaviour of the clays and as far

TABLE 2

Biotic and abiotic influences on soil structure

	Sand[a] (< 15% clay)	Loam[a] (15–35% clay)	Clay[a] (> 35% clay)
Shrink–swell capacity	Minimum	Important	Maximum →
Abiotic aggregate formation	Minimum	Important	Maximum →
Biotic influences	Aggregate stabilization and degradation	Aggregate stabilization and degradation	Minimal (biopores?)

[a] Determined by the coefficient of linear extensibility?

as the top few centimetres of these soils are concerned biological factors are not important for either structural formation or stabilization. Similar tilth-mellowing processes are utilized by farmers in northern latitudes by exposure of soils to freeze–thaw cycles.

The precise definitions of sand, loam and clay will cause a good deal of discussion. Pedologists will use clay contents. Heinonen (1982) and Horn (1990) have suggested that at least 15% clay is needed for the abiotic development of aggregation in soils especially those which have been compacted. Thirty to 35% clay is the content usually required for the textural definition of clay. However, the precise clay content as determined by the classical procedure is not important and a measure of shrink–swell capacity such as the coefficient of linear extensibility (COLE) would be a more useful parameter to differentiate between sands, loams and clays for the purpose of structural studies.

The importance of biology in structural formation is greatest in soils with low shrink–swell capacity and minimal in self-mulching clays. Biology plays a major role in stabilization of soil structure in sands and loams, providing sodicity is excluded. A basic assumption is that the soil undergoes drying–wetting cycles. If not, the biotic factors may be relatively more important.

ABIOTIC FORMATION OF SOIL STRUCTURE

In sands any clay present will be drawn into interstices between larger mineral particles by water menisci as the soil is dried. This may create aggregation of clay particles in the micron range. Whether or not these new aggregates remain stable when the soil is rewetted will depend on the severity of drying, the shape and packing of the particles and the electrolyte environment. In loams the cohesive behaviour of the clays becomes a dominant factor. On drying shrinkage occurs and creates tensile stresses which will eventually lead

to the development of cracks along planes of weakness thus creating aggregates. The development of desiccation cracks in a "uniform" soil has been illustrated by Dexter (1988), see Fig. 1.

The distances between cracks is controlled by the distribution of planes of weakness and is crucial to the development of soil structure. Cracks will appear where the soil has low tensile strength which is where the soil is wettest. One factor controlling cracking patterns is thus the uniformity, or lack of it, during drying. The drying of surface soils is often controlled by plant roots and major biopores which serve as sinks for water. Within the root zone the soil is dried and shrinkage causes cracks to appear in wetter regions not yet influenced by water uptake from the roots. This explains the common observation of cracks running between and parallel to plant rows of cereals and maize. Under plants not sown in rows, e.g., pastures, the even distribution of roots will cause smaller more frequent cracks with no specific orientation. The result is a well-aggregated granular soil to the depth of maximum root development.

One consequence of structural formation by shrink–swell processes is the tendency for smaller denser aggregates to be formed. It has been claimed that both roots and earthworms have aided compaction during their passage through soils but since an impedance of 3 MPa limits root growth by ~80%

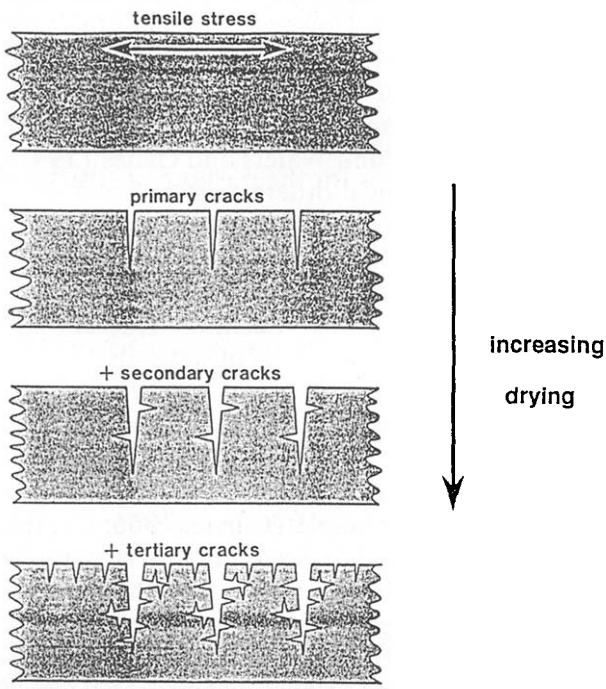

Fig. 1. Development of soil structure by shrinkage on drying (after Dexter, 1988).

(Greacen, 1981) and the forces exerted by earthworms are unlikely to exceed 0.2 MPa (McKenzie and Dexter, 1988) the biologic effects are unlikely to be significant except in very wet soils.

Methods for assessing soil structure do not usually differentiate between biotic and abiotic factors responsible for creating structure. A range of methods are available with an interesting mix of approaches by pedologists and physicists, with more recent influences by biologists. A concise overview of methods is available with a physicists bias in the review by Dexter (1988).

AGGREGATE HIERARCHY AND THE EXCLUSION PRINCIPLE

Aggregation in loams and clays leads to concepts which can help in determining the importance of the biologic cycle and organic materials in soil structure and its stability. One concept is that of aggregate hierarchy. Aggregation of a range of different soil particles of different sizes could occur such that large aggregates contained all soil components in a completely random fashion. The large aggregate would have no planes of weakness so that when it disintegrated all the elementary single grain particles including clay plates and crystals would be released immediately. A simple approach to such a phenomenon would be an aggregate formed by the drying of a strongly sodic soil with no biologic inputs. When stressed by rewetting the clay would swell and disperse and all larger particles would fall apart. However, this tends to be the exception and more commonly large aggregates disintegrate under stress to yield smaller aggregates. This process may be repeated several times before the soil is broken down to its textural constituents. This concept of aggregate hierarchy has been described by Kay (1990) and Waters and Oades (1991) in the figure indicating that several hierarchical orders exist in some soils, e.g., clay microstructures represent a first order measured in terms of microns. A second hierarchical order was termed microaggregate, $\sim 100\ \mu m$ in diameter, and a third order, macroaggregate with diameters of several millimetres. Larger aggregates were termed clods (tens of centimetres) and are generally regarded as an undesirable result of cultivation of wet soils.

The concept of aggregate hierarchy is illustrated in Fig. 2 which shows a small group of ten small particles which form an aggregate because they are in relatively close contact. The secondary aggregates are themselves grouped to form a tertiary compound particle and so on. One consequence of this aggregate hierarchy is the porosity exclusion principle (Currie, 1966; Dexter, 1988) which shows that smaller aggregates should have the lowest porosity and the greatest contact between particles. Thus the tensile strength of smaller aggregates will be greater than that of larger aggregates (Braunack et al., 1979; Hadas, 1987). Such aggregates in the soil will disintegrate in a stepwise fashion and not catastrophically. Oades and Waters (1992) demonstrated aggregate hierarchy in a Mollisol and Alfisol but not in an Oxisol. The hierarchy

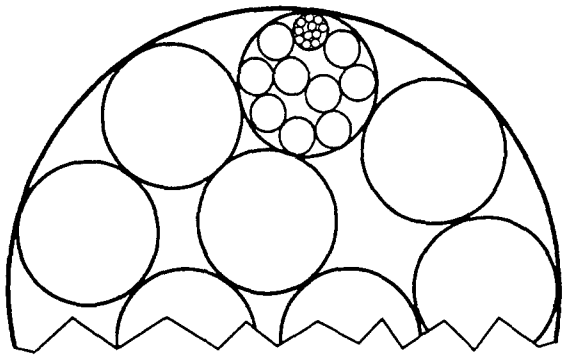

Fig. 2. The concept of aggregate hierarchy.

was considered to be due to root systems and was exhibited to the fullest extent in a Mollisol which had been under prairie grassland for hundreds of years. The structure of the Oxisol was stabilized by oxides as well as organic materials and hierarchy was not demonstrated in this soil which was very stable but eventually broke down to release clay and silt with no obvious intermediate stages.

In an ideal soil aggregate hierarchy would occur in even steps as illustrated in Fig. 2 and the morphology of the aggregates of each hierarchical order would be similar at different scales. In this situation the fractal approach to soil structure as described by Bartoli et al. (1991) and Young and Crawford (1991) should prove useful. Bartoli et al. suggested that self similarity did exist in silty and sandy soils. Where root systems are involved in stabilizing aggregates in loams and clays aggregate hierarchy appears to exist, but the stabilization by the biological agencies is of particular sizes of aggregates which have different morphology as well as scale. One might speculate at this stage that aggregate hierarchy exists in soils as a legacy from a long history of exploration by roots, particularly from grasses, and that it will not apply to very young soils such as the polders, or perhaps to soils where inorganic cements are dominant, e.g., Oxisols.

BIOTIC FORMATION OF SOIL STRUCTURE

Structure can be formed by the creation of aggregates or pores. The formation can be direct as when larger fauna ingest soil and produce excreta in the form of casts or pellets and the formation of biopores by roots, earthworms, termites, ants, spiders and the larvae of various beetles and moths. In general the mesofauna are not considered important in the formation of structure in arable soils because they are too small to move most soil particles. The best quantitative data available are those of Didden (1990) who showed that about

one third of enchytraeid worms studied in Dutch soils contained mineral grains. However, calculations indicated that it would take at least 100 years for these small worms to turnover 1% of the 0–40 cm layer. However, the mesofauna in conjunction with the larger fauna could well be beneficial in enhancing and stabilizing the pores in which they live. This may also be true of mites and Collembola which rely on earthworm channels for descent into the soil with the onset of drying (Malinda et al., 1982).

In general the mammals which burrow in soil do not have beneficial effects especially in arable soils and usually create problems such as in dam walls. For the activities of animals in soils the review of Hole (1981) should be consulted.

The biotic influence on formation of soil structure can be indirect such as the impact of root systems on drying in loams and clays. Roots grow mainly in wet soils with low tensile strengths and even then prefer to grow in pores rather than through aggregates. The root system dries the soil and it is of interest to compare the potential drying of the soil by dicotyledenous plants compared with monocotyledenous plants such as grasses. The latter have numerous fine roots which dry the soil at countless sites thus creating many non-oriented cracks which give rise to the beautifully granular, crumb structure associated with old grassland soils, e.g., Mollisols before cultivation. It is difficult to separate the biotic and abiotic effects in loams and clays and there are few quantitative data on the role of roots in forming soil structure. The subject is complicated because roots may form and stabilize structure simultaneously. Unfortunately there have been few experiments which aimed to define the most beneficial plants with respect to structure formation and stabilization. Those which have, indicate that productive grasses are most efficient, e.g., Tisdall and Oades (1982) and Grevers and De Jong (1988). A challenge for sustainable agriculture is to identify those plants which are most efficient in forming stable soil structure and to incorporate them into economic rotational management systems.

THE DEVELOPMENT OF BIOPORES

The larger biopores in soils are made by roots and earthworms and are usually cylindrical and very long.

It has been claimed that roots of annual plants can exert pressures up to 9 MPa but they do not grow under such conditions. However, larger roots, e.g., tap roots of dicotyledons and tree roots exert greater radial pressures as they expand their diameters. Certain plants, e.g., jack pines are noted for their ability to penetrate strong soils. Annual plants have a lesser ability to penetrate strong soil, but even so plants with tap roots have capabilities to penetrate strong layers to depth. The old root channels then become a thoroughfare for new roots. Large root channels can be recognised by a lining of resistant

bark, infillings of the remnants of the root decomposition and often soil materials from upper horizons, as well as new roots. Successive generations of tree roots may follow the same channels, often through rocks, for many years. The surfaces of old root channels may be sites for crystallization of gypsum and calcium carbonate and in poorly drained soils old root channels show staining of iron oxides as the iron solubilized by reduction and acidity in the rhizosphere is oxidised and precipitated. Root channels are recognised by observation and the various techniques available for investigating biopores.

A review on soil fauna and soil structure was recently compiled by Lee and Foster (1992) including a section on earthworm burrows from which the following summary is drawn. The burrows are constructed by exertion of radial pressures to enlarge the burrow diameter or by moistening the soil with saliva and then ingesting it. The pressures developed are less than 0.2 MPa. Thus earthworms require a structured soil in which pores can be widened during the construction of the burrow or a wet soil in which burrows are created by ingestion and casting of soil materials. Burrows are generally of two forms. Those of anecic species which are semipermanent individual systems with mainly vertical channels and those of endogeic species which burrow continuously producing horizontally oriented extensive linked networks. When earthworms are plentiful, their burrows are large enough to dominate the macroporosity in soils and play a major role in water infiltration and gaseous exchange. Water infiltration may be increased tenfold and sometimes considerably more in soils with high populations of earthworms compared with soils with few earthworms.

Earthworm burrows are recognised by their cylindrical shape, size and length. The burrow walls like the walls of rhizopores are often coated with oriented clay, humic materials, calcium carbonate and iron oxides.

METHODS FOR INVESTIGATION OF BIOPORES

A range of techniques is available to study biopores to extend what can be seen in vertical and horizontal sections of soils. Volumes and shapes of biopores can be obtained by pouring liquids into the pore systems to produce "casts" from which the soil materials can be washed away.

Various materials have been used as listed below:

latex	Garner (1953)
polyethylene	Willoughby and Walsh (1972)
polyester epoxy resins	Jongerius and Heintzbergen (1975)
paraffin wax	Dexter (1976)
plaster of Paris	Fitzpatrick et al. (1985)

In most cases the impregnated samples have been sectioned by sawing and smoothed depending on the scale at which they will be studied. The sections

have then been examined optically and microscopically, photographed and subjected to various forms of image analysis which enables the classification of soil pores based on size, shape and orientation. To obtain the three-dimensional arrangement of pores by serial sectioning is very time consuming. Predicting structure in three dimensions from two-dimensional measurements, i.e., stereology, is a developing area of soil structural characterization (Ringrose-Voase and Bullock, 1984; Kretzschmar and Monestiez, 1987; Ringrose Voase and Nortcliff, 1987) as is the application of computer aided tomography to soil structural studies (Phogat and Aylmore, 1989).

Biopores have also been studied using dyes to study both infiltration rates and to observe the flow pathways of liquids in sections of the soil. This is an excellent technique to determine preferred pathways of water flow through soil systems in the field, but has limitations at small scales (Murphy et al., 1977a, b; Omoti and Wild, 1979; Kooistra et al., 1985).

The soil "peel" method has also proved useful in studying biopores. The method involves pouring a resin onto a soil surface which can be cut vertically or horizontally in the soil. When the resin has set and has been reinforced, if necessary, it can be peeled off bringing with it a soil surface fractured along planes of weakness. This surface can be viewed to count pores and to approximate their sizes and shapes and to a limited extent their continuity (Plas and Slager, 1964; Bouma and Hole, 1965; Smettem and Collis-George, 1985).

Rogaar and Boswinkel (1978) derived the three-dimensional arrangement of earthworm tunnels using binocular microscopy and X-ray stereo-radiography. Radiographs of 5 mm thick sections were developed into drafted interpretations of an earthworm chamber.

Other large voids in soils of semiarid and arid regions are made by ants and termites. Both ants and termites construct burrows and galleries which are often very extensive both laterally and vertically to the extent that they influence the hydrologic cycle. Their impact on soils is great in small areas where they build nests and mounds. Their impact on aggregation is not known but is likely to be limited. For information the reader is referred to Lee and Wood (1971), Lobry de Bruyn and Conacher (1990) and Lee and Foster (1992).

THE DEVELOPMENT OF AGGREGATES

Two main types of aggregates are formed by soil fauna: earthworm casts and faecal pellets.

Earthworm casts

Earthworms may ingest substantial quantities of soil materials which are then cast on the surface or in earthworm burrows. For temperate pastures and grasslands Lee (1985) estimated that on average earthworms cast 40–50 t

$ha^{-1}yr^{-1}$ on the surface which represents 3 to 4 mm. More material is cast below the surface. Greater activity may occur in some soils in the tropics and in warm temperate climates.

Earthworm casts are characteristically spherical or ovoid pellets from 1 to 10 mm in diameter depending on species and age, or paste-like slurries which are still rounded in form. There are numerous reports on the importance of earthworm casts (Lee, 1985; Lee and Foster 1992). In some soils the top 10 or 20 cm of soil is entirely casted material. It is also clear that earthworm casts can be more stable than other soil aggregates (e.g. Monnier and Jeanson, 1964; Van Rhee, 1977; and others). For example casts have been shown (a) to withstand 5 to 54 times more kinetic energy from raindrop impact before disintegration compared with soil aggregates (De Vleescheuwer and Lal, 1981), and (b) to contain more water stable aggregates (Lal and Akinvemi, 1983) and to have greater tensile strength than soil aggregates (McKenzie and Dexter, 1987). In all instances where earthworm casts have been dried before measurements were made they have been shown to be stronger and more stable than soil aggregates. Drying of earthworm modexi causes substantial shrinkage and hence problems with measurements of bulk density and porosity. It is reported several times that earthworm casts have lower bulk densities and higher porosities than non-casted aggregates. If this fact can be confirmed it raises two interesting questions. The first concerns the greater strength of aggregates with lower bulk densities and higher porosities. In most soil aggregates the reverse is true as outlined in the porosity exclusion principle. Two explanations can be offered. One is the greater content of clay and silt in casts compared to non-casted soil aggregates. The second explanation concerns the mixing of all soil particles in the gut of the earthworm (Lee and Foster, 1992), to produce dispersed clay (Shipitalo and Protz, 1988; Marinissen and Dexter, 1990). The thorough mixing and presence of dispersed clay may improve surface contact between particles and eliminate larger pores which would serve as planes of weakness in non-casted soil aggregates.

Generally casts or modexi are recognised by their shape based on their roundness or sphericity, and when fresh, lack of rugosity. Quantitative morphological studies of aggregates are now possible. We have the possibility to do this in the field by simple comparative tests or to make more sophisticated and quantitative mathematical descriptions using computers and image analysis.

A range of authors have commented that it was easy to recognise earthworm casts without describing the criteria involved. Descriptive classifications have been developed by Barratt (1969) where the size of "pelleted" materials and their shapes such as cylindrical or obvate were described. She used other terms such as rugose and spongey. Bal (1973), who introduced the term modexi for faunal excrements, suggested five morphological criteria: spherical, elliptical, cylindrical, platey and mitoid (threadlike). For rela-

tively fresh earthworm casts this system would be a useful basis for description and classification of modexi but is difficult to apply to casts during stages of degradation.

The problem becomes that of recognising sphericity or roundness. A first approach could be to take a chart of standard comparison shapes such as those used in field handbooks (e.g. McDonald et al., 1990). Simple rating of aggregates against such a chart would readily allow the shapes and curvatures of modexi to be recognised and quantified at whatever scale was appropriate.

More sophisticated approaches to quantifying the shapes of aggregates have been described by Dexter (1985) who concluded that the most sensitive single value measurement was the shortest aspect ratio. This is the ratio of the shortest to the longest diameters through the centroid. Radius spectra and curvature (Fig. 3) gave the most comprehensive information on shape. These methods have been applied to earthworm casts by McKenzie and Dexter (1987). Casts were photographed and tracings made of cast shape. The tracings of aggregate outlines were scanned by a TV camera connected to a digitizer and computer to determine the centre of the aggregate which was then divided into quadrants for further scanning.

From the digitized outlines three simple ratio methods were calculated and two mathematical spectral analyses made, a radius spectrum and a curvature spectrum. Both spectra allowed quantitative assessments of the greater roundness of modexi compared with other soil aggregates.

Further approaches to recognition and quantitative assessment of earthworm casts could be based on measurements of sphericity, roundness and rugosity. It is possible now to do this with software programs and PCs. Further work is needed on bulk density as a means of separating casts from other aggregates.

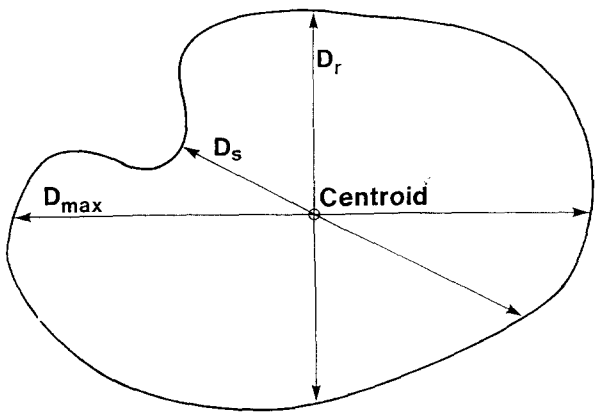

Fig. 3. Aggregate outline for description of shape (McKenzie, 1988). D_{max} = maximum diameter, D_s = smallest diameter, D_r = diameter at right angles to D_{max} through the centroid.

It is possible that such techniques with other more conventional approaches to aggregation may allow the relative importance of grass root systems and earthworms to be determined. For example Blanchart et al. (1989) claimed earthworms to be more important in forming aggregates in shrub savannas than grasses. Stewart et al. (1980) presented data indicating that earthworms were responsible for producing more aggregates than ryegrass. New Zealand experiences have indicated synergy between grasses and earthworms. In the presence of earthworms the beneficial effects of grass root systems was extended to a greater depth (Lee, 1985). It may well be that earthworms could be the major formers of soil aggregates in soils which are not subjected to severe wet–dry cycles and that grass root systems are the dominant formers of aggregates, through severe multi-point drying in soils with wet–dry cycles.

Faecal pellets

The smaller fauna do not play a major role in moving soil particles nor ingesting mineral materials but in certain environments such as forest soils, microarthropods, dominated by mites and Collembola are sufficiently active to influence structure by production of faecal pellets. The majority are saprophytic and produce faecal pellets which are mixtures of plant debris and humic materials. The pellets are usually < 1 mm diameter and can be recognised under the SEM by their roundness and smooth surface. With time they become densely colonized by fungi. In thin section viewed by TEM faecal pellets are readily recognised by the presence of densely packed bacterial cells (Lee and Foster, 1992).

THE STABILIZATION OF AGGREGATES

There are some soils in which structure is stabilized by inorganic materials such as oxides of aluminium and iron. This occurs in Oxisols and the biologic cycle although still performing the same role as in other soils is not the only stabilizing agent. In such soils it is not so important to maintain large organic inputs through the primary producers for soil structure. However, in tropical environments the very stable Oxisols may lose structural stability suddenly and catastrophically, as has occurred in some soils used for sugar cane production.

In most other soils biota play the major role in stabilizing structure especially in sands and loams.

For optimum aggregate stabilization there are three major requirements. Perhaps the most important is the photosynthetic input to the soil by the primary producers. This is the source of energy which drives the biologic cycle and there is no doubt that when the energy input is decreased by exploitive

management practices structural stabilization decreases creating a decline in what is normally considered to be desirable soil structure. This basic consideration is often forgotten in studies of soil structure because the inputs to soils are very difficult to measure and research workers are usually focused on specific mechanisms or organisms. The methodology involves long-term trials and development of models, e.g., the Rothamsted model (Jenkinson et al.,1991) and the Century model (Paustin et al., 1992) and the use of ^{13}C and ^{14}C as tracers to determine the cycling of carbon after inputs into soil by plants (e.g. Ladd et al., 1985). However, these approaches do not tell us how to recognise biologically stabilized structure.

A second major factor in structural stabilization is the form and distribution of the photosynthetic products added to soils. Are they added to the surface as litter, as large roots, distributed in numerous fine roots as in grasses, or in fact exuded from roots?

The third factor to consider is whether there are good conditions in the soil for roots, earthworms and other fauna so that structural stabilization is optimised.

In our quest for production we often limit carbon inputs to soil, we create external stresses and severely restrict growth of roots, animals, cryptogams and fungi.

Stabilization in sands

Stabilization of aggregates of sand particles involves the growth of higher plants, fungi and bacteria in the pore system between grains. The sand grains are then held together by (a) colonies of organisms and their mucilages (microbial aggregates), (b) roots and hyphae (root microbial aggregates) and (c) metabolic products from the decomposition of fragments of higher plants (Forster, 1979, 1990). The shape of the three types of aggregates were distinctive. Those stabilized by bacteria were spherical while those associated with roots, hyphae and plant fragments tended to have one long axis (Fig. 4). The absence of clays allows a straightforward development of stabilization not complicated by abiotic factors.

Stabilization in loams

The association of stable aggregation with grass was established long before the process was studied by scientists but we are now beginning to understand some of the mechanisms of the stabilization of aggregates by root systems, particularly the root systems of grasses (Tisdall and Oades, 1982; Oades, 1984, 1987).

In the Australian environment pastures are the only form of management which has been demonstrated to increase the organic matter status of soils

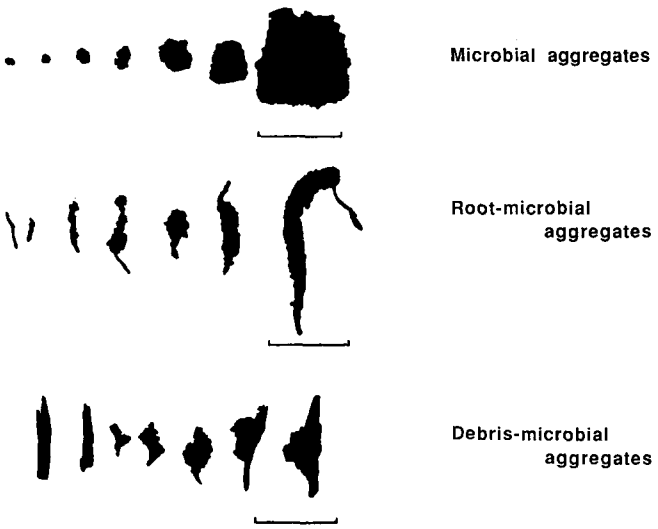

Fig. 4. Aggregate stabilization in sands (after Forster, 1990). Bar = 10 mm.

(Russell and Clarke, 1977). There is a positive correlation between the organic matter content of the soil and aggregation (Tisdall and Oades, 1982). Such correlations have been obtained by workers round the world. As stated earlier the grass root systems both form aggregates and stabilize aggregates simultaneously and it is not easy to separate the processes. In the absence of plants (long fallows) the wet–dry cycles continue, albeit not as vigorously as under pasture, and the stability of larger aggregates is lost. The difference is the lack of a growing root system with hyphae and rhizosphere so that even if aggregates are formed by tillage or internal stresses they are not stable to subsequent stresses. The methods involved in studies of aggregation and stabilization by root systems depend on long-term experimental trials containing rotations of plants or crops of interest, or farmers paddocks with reliable histories. The long-term effects of the root sysems can then be studied using the various measurements of soil structure described by Dexter (1988). Observations can be made in the field on undisturbed soil samples and on separates of aggregates by the naked eye, by optical and electron microscopy, etc.

Another approach is to grow plants under controlled environments to study the formation of stable aggregates by root systems (e.g. Tisdall and Oades, 1979). To date, various plants have been compared which confirm that monocotyledenous plants are superior to dicotyledenous plants in stabilizing aggregates and that grasses are better than cereals. What is required is a systematic approach to determine the most efficient species for sands, silts and clays with controlled wet–dry cycles or under optimum water relations with and without earthworms and other fauna.

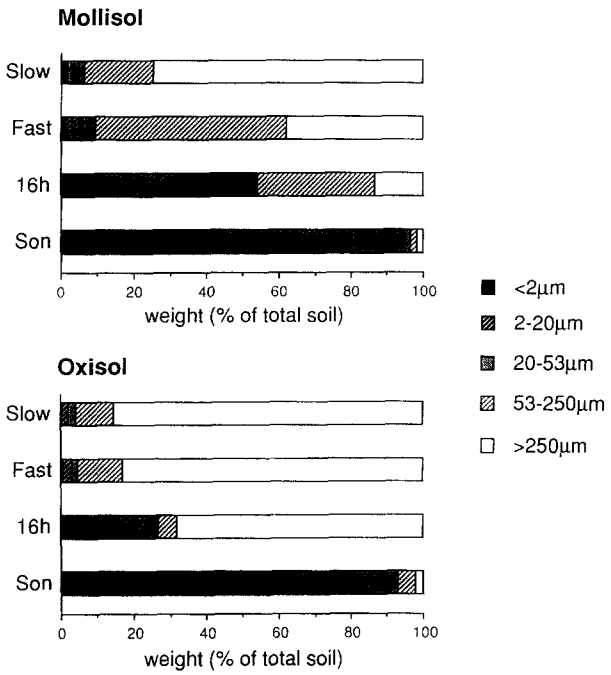

Fig. 5. Progressive disruption of aggregates from a Mollisol and Oxisol (Oades and Waters, 1991).

Methods for studying roots in soils and aggregates include root washing techniques either manually on sieves, or by using water jets to stir and disrupt soils to float off fine particles and roots so the roots may be sieved. Roots can be weighed or lengths measured by the method of Tennant (1975) or by image analysis procedures. There are problems with severity of washing and loss of root hairs. Similar procedures on a smaller scale can be used to measure the length of fungal hyphae in soil. The procedure of Tennant then requires the use of a microscope. For both roots and hyphae there are problems with separating living from dead. The use of various dyes can help in this respect.

For the study of intact aggregates SEM is the method of choice because the depth of field of binocular microscopes is limited. The SEM with EDAX can be used for identification of both inorganic and organic particles based on elemental analysis including heavy metal binding by organic materials. Recently in our studies of mechanisms for the stability of microaggregates and macroaggregates to establish whether or not aggregate hierarchy existed in soils we used a range of disaggregation procedures from gentle to vigorous followed by conventional characterization including SEM aided by EDAX and backscattered electrons (Waters and Oades, 1991; Oades and Waters,

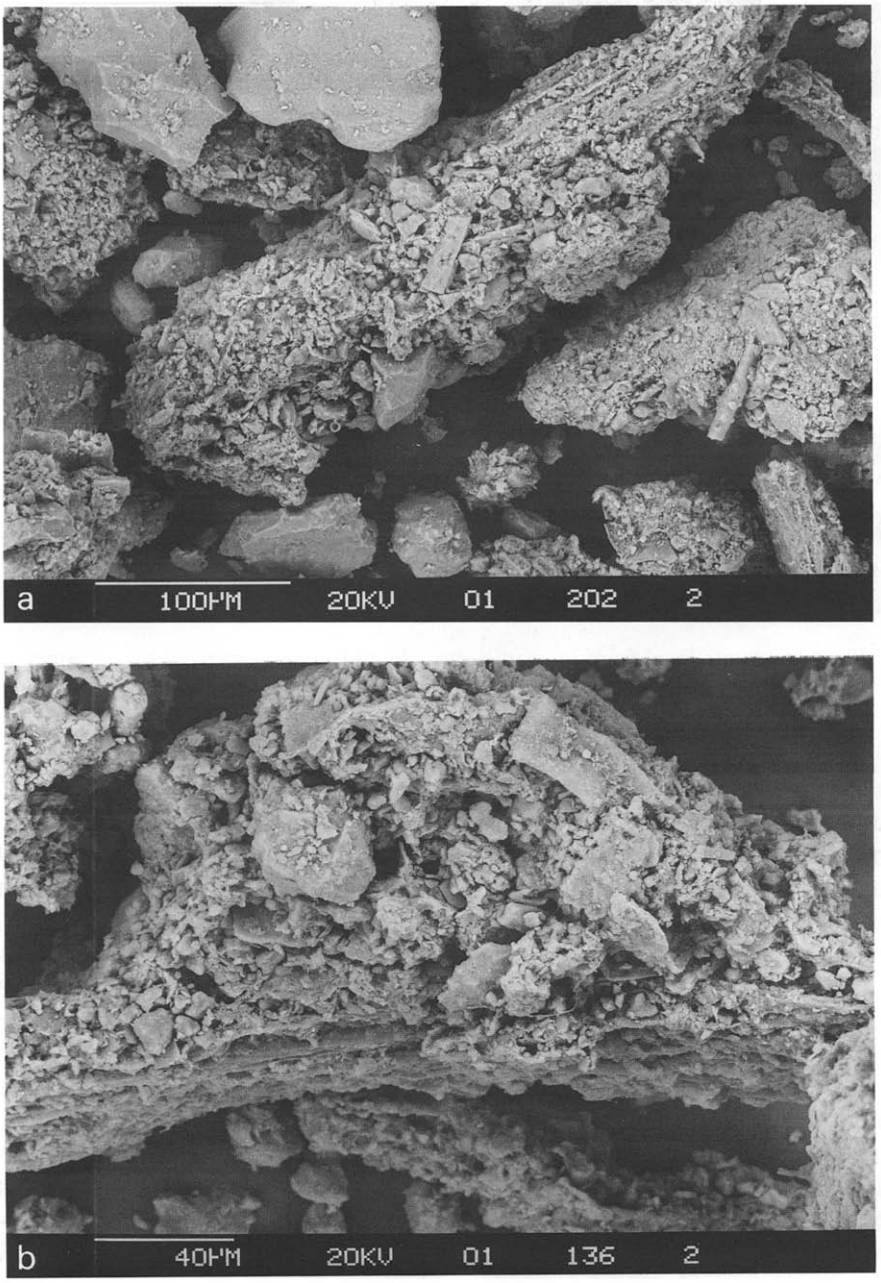

Fig. 6. SEM of encrusted plant fragments in aggregates of diameter 90–250 μm (reproduced with permission).

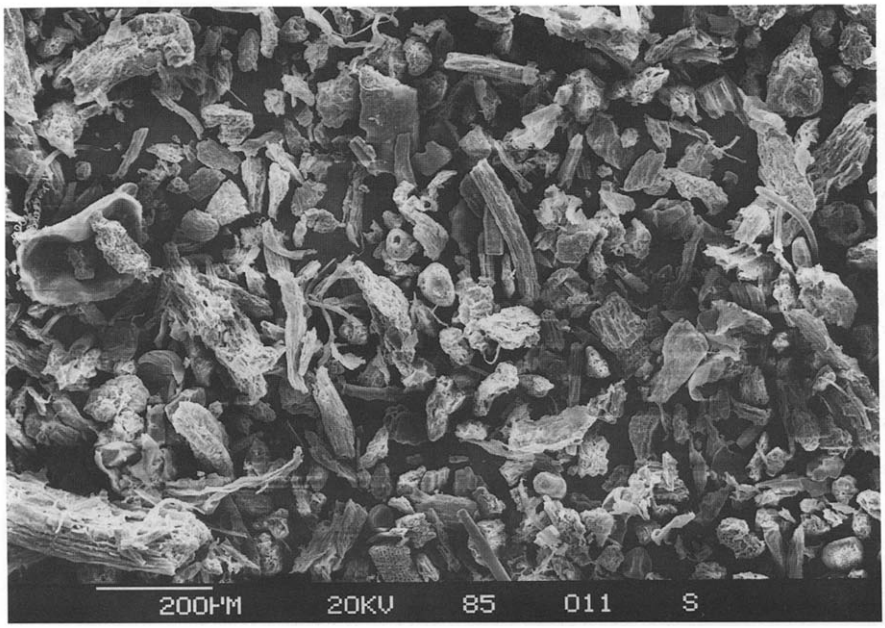

Fig. 7. Plant fragments freed from inorganic crusts by ultrasonic dispersion of aggregates of diameter 90–250 µm (reproduced with permission).

1992). The following summary outlines one approach to establishing the role of biology in aggregate stability.

The 0–10 cm horizons of a Mollisol and an Oxisol were subjected to slow wetting, fast wetting, mechanical shaking, and ultrasonic dispersion followed by fractionation into sizes from 2 mm to <2 µm (Fig. 5). The disaggregation patterns showed clearly that the Mollisol disintegrated in a stepwise fashion. Larger aggregates broke down to smaller aggregates before any significant release of fine particles. For the Mollisol fast wetting disrupted aggregates >250 µm, the shaking disrupted aggregates ~ 100 µm in diameter while ultrasonic energy disrupted aggregates 2–20 µm in diameter. This aggregate hierarchy was described by Tisdall and Oades (1982) and has been shown to exist in North American Mollisols (Elliott, 1986; Miller and Jastrow, 1990). It does not apply to all soils, for example, the Oxisol was shown to be very stable but when it was disrupted fine particles resulted and no step-wise breakdown was evident. Possible reasons for the stability of the microaggregates were illustrated by SEM of the particle size fractions released by the various disaggregation procedures. The SEM work showed clearly that many aggregates 100–200 µm in diameter had cores of plant debris. Some were completely coated with inorganic crusts but retained elongate shapes with length to width ratios greater than 2 (Fig. 6). When such aggregates were disrupted by ultrasonic energy obvious plant fragments were obtained by density separations

(Fig. 7). Smaller aggregates contained a few last remnants of plant debris or cavities left when the remnants had been completely utilized by microorganisms. The smaller aggregates were more spherical. Again as in Forster (1990) width to length ratios proved quite useful for identifying aggregates which owed their existence to remnants of plant debris.

Below 20 μm the SEM showed evidence of clay microstructure as illustrated by Oades (1987) but biologic features could not easily be found. The hierarchy is thought to be due to the stabilization of macroaggregates by roots and hyphae in the form of "sticky string bags". When the root systems die and are degraded, elongate aggregates of plant debris encrusted by inorganics result. The protection offered to the plant debris by the crusts slows down the decomposition of the debris and the microaggregates persist for perhaps hundreds of years. Such a concept should not apply to very young soils which have not had the chance to grow grass roots for long periods, e.g., young polders as indicated by Kooistra (1991).

Stabilization at scales below ~ 20 μm

The role of microorganisms and their metabolic products in soil structure has been reviewed many times. Various experimental procedures have been used to show that microorganisms, when supplied suitable substrates, will stabilize aggregates through filamentous structures, extruded biopolymers and particularly, extracellular polysaccharides (Burns and Davies, 1986). However, our concepts of the role of microorganisms in stabilizing aggregates at scales of 20 μm or less have improved over the last 10 years by studies of micromorphology using light and electron microscopy. The methods have been applied mainly to stabilized thin sections and surfaces but also to natural surfaces of aggregates. Sample preparations are crucial if the observations are to be made on unchanged biological materials with respect to shrinkage. Specialised techniques based on variations on apolar liquid replacement have been developed for drying samples without shrinkage . Staining procedures for roots, organisms and specific biopolymers have also been developed. These involve application of histochemical procedures using specific binding of heavy metals, including gold-coated lectins. The various submicroscopic techniques available for studying the preparations have been described by Bisdom et al. (1990). Applications of micromorphology to soils to study structure and biota including quantitation of the results by image analysis have been described by Kooistra (1991).

Histochemical techniques to study biota and biopolymers in situ in soils have been developed by Foster in a series of papers over the last decade (e.g. Foster and Martin, 1981; Foster et al., 1983; Foster, 1986, 1988).

The preparation of samples to examine the detailed arrangement of organisms, biopolymers and inorganic materials in aggregates contains some art

with the science. The brief summary is gleaned from a series of Foster's papers. The preparation involves three major processes: physical stabilization to prevent movement of components during subsequent treatments, chemical stabilization to prevent loss of soluble components during various solvent exchange drying procedures, and staining with heavy metals to detect specific biopolymers. The latter reaction usually involves binding of the metal by a specific functional group.

The soils have been fixed by enclosure in agar or gelatin and chemically fixed with organic aldehydes such a glutaraldehyde, formaldehyde and acrolein or lanthanum hydroxide followed by osmium tetroxide. Tertiary butyl alcohol has been used for dehydration followed by embedding in Spurr's resin. The samples were viewed directly or sectioned using ultramicrotomy and diamond knives. The preparation of ultrathin sections of real soils remains a very expensive procedure because sand grains ruin diamond knives.

Osmium tetroxide reacts with phenolic hydroxyls, alkyl groups and sulfhydryl groups. Ruthenium red and lanthanum hydroxide enables detection of acidic polysaccharides in slimes and mucilages. Detection of neutral polysaccharides required more specialised treatments in which formaldehyde was used for fixation and postfixation by OsO_4 was omitted. Neutral polysaccharides were treated with periodic acid to convert 1,2 diglycol groups to aldehydes which then react with silver methenamine or thiosemicarbazide and silver proteinate. Further details and recipes can be found in Foster's papers particularly Foster and Martin (1981) and Foster (1988).

STRUCTURAL DEGRADATION

The term structural degradation assumes a change from an optimal structure to something less desirable for particular purposes. The same agencies may produce good structure and then go on to produce poor structure by the same mechanisms. For example wet–dry cycles will help to break down (mellow) a cloddy soil to a more desirable aggregate size for crop production. In the absence of a biological influence, i.e., no vegetation and associated organisms further wet–dry cycles will continue the disaggregation processes and may ultimately lead to complete incoherence of textural units.

The breakdown of aggregates is accelerated by cultivation, especially if the cultivation takes place when the soil is too wet, or too dry, i.e., the water content is distant from the plastic limit. Breakdown of the aggregates and the corresponding pores occurs according to the exclusion principle. Thus the larger aggregates breakdown first and it is the coarser pores responsible for drainage and aeration ($> 30\ \mu m$) which disappear first. In a soil which has been under pasture the degradation is initially very rapid with a major decline in structure, as measured by hydraulic properties or aggregate stability in the first few years. It seems as though this initial rapid decline occurs as the root

systems are comminuted and the "sticky string bag" is disintegrated, The rate of decline in macroaggregation or macroporosity after a pasture is ploughed is thus very similar to the decomposition curve for plant materials added to soils and can be predicted based on mean annual temperatures (Ladd et al., 1985). Further structural degradation will then continue if cultivation persists and the input of carbon to the soil is limited. Eventually the microaggregates will also be disintegrated and the soil becomes very vulnerable to compaction and erosion.

Cultivation destroys the continuity of biopores by cutting them off at plough depth. Such pores will not then transmit free water. Cultivation disturbs the habitat of larger organisms and decreases their numbers.

Changes in soil structure below 20 μm are very slow. For example clay microstructure in soils is stable and is a characteristic of soils which is not likely to be influenced by management practices.

CONCLUSIONS

We now have available a range of techniques to measure soil structure at various scales. The techniques measure particles or pores or are based on transmissive properties for water.

There is a great need to apply these techniques to soils in the field where the history of soil management is well known. This requires the development of field tests, supported by laboratory work, otherwise there is a danger that there will be no links between field and laboratory.

Secondly we need the field data quickly so we cannot afford to use sophisticated laboratory procedures to obtain all our structural data.

There is a need to develop cooperative and multidiscliplinary approaches to problems in soil structure. Again this will take time and requires a focus on soil structure and management and not on a particular disciplinary approach.

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