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Managing Soil Structure Under Rainfed Conditions

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Abstract

This paper reviews concepts, of factors that determine, and ways of managing soil structure Soil structure per se provides nothing that is essential for crop growth, but it provides the framework within which all soil processes operate. It is difficult to measure and for characterizations of management practice effects key processes or controlling properties should be measured Soil structure is determined by basic soil constituents (particle size, clay type, bonding materials and soluble and exchangeable cations) interacting with environmental factors (mainly wetting and drying), biological factors, and management inputs. In the semi-arid tropics water often limits crop growth Various options for managing soil structure to optimise rainfall use efficiency, to reduce risks of crop losses and to reduce erosion are discussed

Introduction

Soil structure *per se* provides nothing that is essential for plant growth. However, it does provide a frame work within which physical, chemical and biological processes operate. These processes, mainly operating within the pore system defined by the framework, influence the suitability of a soil as a medium for plant growth and how it responds to environmental factors and farmer inputs. The key physical processes influenced by soil structure are infiltration, water redistribution and storage, drainage, soil erosion by wind and water, exchange of gases with the atmosphere, flow of heat, and movement of nutrients Chemical processes include those involved in the carbon and nitrogen cycles within the soil, and oxidation and reduction Biological processes include seed germination and seedling emergence, root growth and function, and the activity of soil flora and fauna.

While soil has an inherent range of structure due to its fundamental constituents, soil structure is subject to change and it can be 'managed' by aiding beneficial processes and by slowing harmful processes. The aim of soil structure management should be to manipulate the factors that influence soil structure so that agronomically beneficial processes are kept in a favorable range. One approach is to specify a range of value within which soil structural

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properties are maintained by management practices (Tisdall and Adem, 1987) However, the necessary soil measurements and managements inputs required to adjust the properties (see Cockroft and Tisdall, 1978) are seldom possible in high risk, low input farming particularly in the marginal soil and climatic environments common in the semi arid tropics (SAT) Soil structure management is usually only a priority concern when some aspect initiates major yield loss or seriously increases risks of yield loss

In this paper we briefly examine concepts of and some of the key factors that determine, soil structure and consider some options for management

What is Soil Structure?

Definitions vary according to the interests of the observer Farmers use terms such as 'friable', 'puggy', 'snuffy', 'cloddy' 'powdery, 'soapy', etc , to describe soil structure Pedologists have developed more formalised, but still qualitative descriptions of soil structure Soil Survey Staff (1951) classified macrostructure observable in the soil profile on the basis of shape, size, arrangement, distinctness and durability of the visible peds Unfortunately pedological description of macrostructure, may be weakly expressed in soil-plant relation, (Ayres *et al* , 1973) Kubiena (1938) considered that macroscopic soil structure depended on the arrangement of two major components of the micro-fabric a skeleton of immobile mineral grains and a plasma of mobile, highly active smaller particles Descriptions of microstructure have been further developed (Brewer 1964, 1979)

There have been many comprehensive definitions of soil structure Recently Dexter (1988) proposed 'the spatial heterogeneity of the different components or properties of soil Almost 50 years earlier Nikiforoff (1941) proposed 'an arrangement of soil material into aggregates in which the primary particles of such material are held together by ties stronger than ties between adjacent aggregates This definition embodies two key concepts - differentiation in terms of the distributions of solid and non-solid phases in the soil matrix, and the stability of this differentiated arrangement Fox and Teakle (1963) emphasised the importance of voids as the key element of soil structure an aspect discussed in more detail by Greenland (1979) and Dexter (1988)

Edaphologists have listed many attributes that should or should not be evident in "good" soil structure These include offer little resistance to root penetration, permit rapid infiltration, resist erosion, provide adequate aeration, enable easy workability and incorporation of crop residues, provide stable traction for farm implements (all from Slipher, 1932), provide good seed-soil contact (Nash and Baligar, 1974), absence of crusting (Arndt, 1965), and afford adequate anchorage of plants (Harris *et al* , 1966)

How can we measure soil structure?

The difficulty with all the definitions mentioned so far is that they are qualitative Structure must be quantified to measure change due to management practices and to relate a particular response in soil structure to a yield response Perhaps the most common question asked of soil physicists is - 'how can I measure soil structure?' The problem is that soil structure is not capable of being expressed by any single measurement or number (Cole, 1939). There have nevertheless been many attempts to find a single valued function that would express soil structure, e.g., flow of gases (Buehrer, 1932), pore characteristics (Currie, 1961), flow of water (Childs *et al.*, 1957), and moisture characteristics (Childs, 1940, 1942). As pointed out by Hillel (1980) 'such approaches give an indirect character-izations of one attribute of soil structure and are best specific to the purpose for which they were devised and at worst arbitrary'.

Agronomically important processes in soils usually occur in the pores within the soil. The extent, continuity and stability of pores is difficult to measure, (however, see Moran *et al.*, 1988), but dependent processes can be measured. The approach we recommend is to select the key agronomic or physical processes of interest and judge responses to treatments from measurements that directly indicate or are very closely related to the process under field conditions. Thus the response of treatments designed to improve water entry under rain should be judged by measuring infiltration under actual rain or simulated rain rather than measuring (say) bulk density or aggregate stability to immersion.

The Key Factors Determining Soil Structure

There are a number of fundamental soil factors and mechanisms that operate in soils to determine structure:

i) Particle size distribution
ii) The nature of the clay fraction
iii) Interparticle bonding mechanisms
iv) Exchangeable cations and electrolyte concentration
v) Wetting and drying

Particle size effects

Because particle size in soils have a basic influence on many soil processes (McHenry and Russell 1943; Peterson 1946; Salter *et al.*, 1966; McIntyre 1979; and Shaw and Thorburn 1985) there have been several attempts to model the role of particle size in soil structure. Michurin (1965) proposed uniform spherical particles (and aggregations) packed in a close-faced hexagonal array. The first order of this model may be useful for some soils with single grain structure, but it does not apply to aggregated soils (Smith, 1978). Because soils are made up of a range of particle sizes, multi-size packing models developed for industrial materials (Furnas 1931; and Westman and Hugill 1930) may be more appropriate. Bodman and Constantin (1965) proposed a binary matrix model where coarse and fine matrices consisting of spherical components were packed (each at maximum density) in such a way that particle interactions and boun- dary effects were negligible. The matrix concept was used to indicate compositions in which each size class predominantly influenced packing properties.

Smith *et al.* (1978) examined a range of soils for evidence of binary matrix packing. Clay size material was regarded as the fine component and all material coarser than clay as the coarse component. In dry aggregates formed from puddles pastes they found a bilinear trend in void ratio as clay content increased. The best fit for both regression lines gave minimum void ratio at 48.8% clay (Figure 1) while the model predicted minimum void ratio at 28% clay. The deviations were

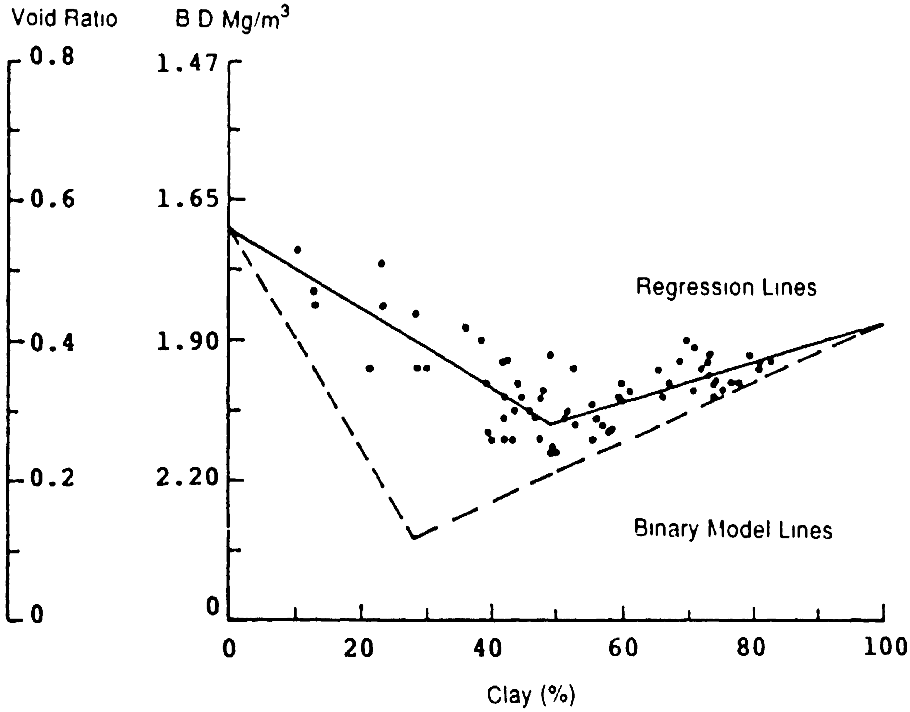

Figure 1. Void ratio and bulk density of dry remoulded aggregates versus clay percentage (Smith et al. 1978)

attributed to interaction between the two matrices. When these aggregates were wet gently and dried (3 times) mean weight diameter plotted against clay content formed a trilinear pattern (Figure 2) They proposed a semi-quantitative matrix packing model defining three structural regions·

1. ***0 to 35% clay*** — an expanded coarse matrix in which coarse grains are progressively separated by oriented clay, but the geometry of which is fixed by the spatial distribution of the coarse grains The oriented clay reduces packing density and acts as a binder to increase aggregate size.

2 ***35% to 50% clay*** — a region where coarse and fine matrices coexist and where expansion of the coarse matrix is complete Interstices are progressively filled with clay Clay is less oriented and sand grains initiate failures (Coughlan *et al*, 1978a) which define aggregates

3 ***> 50% clay*** — where the fine matrix exists and envelopes coarse particles The frequency of sand grain initiated failures decreases, hence aggregate size increases

Coughlan *et al*. (1978b) also found for mixtures of clay and fine sand that the transition from coarse to fine matrix dominance occurred at about 40% clay

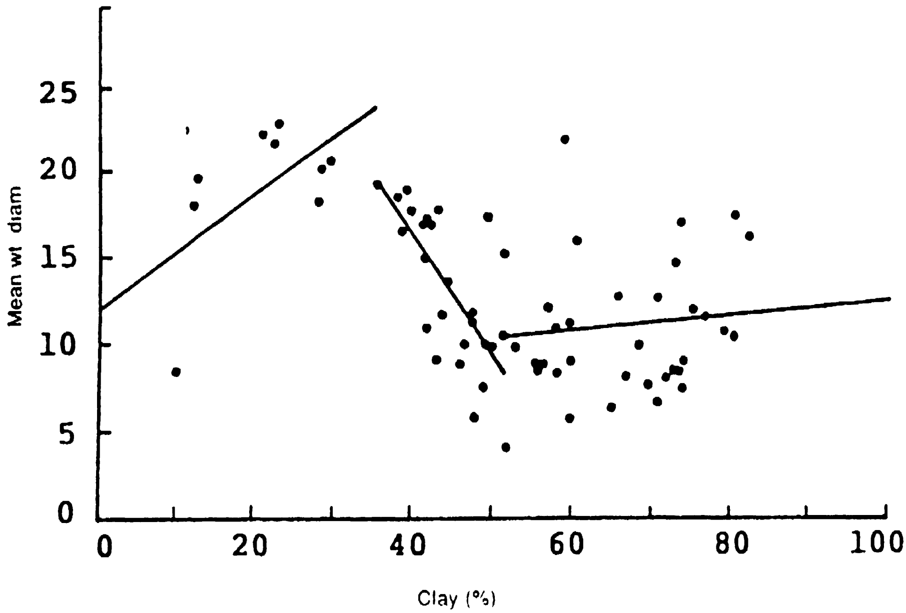

Figure 2. *Mean wt. dia. of wet and dried (3 cycles) remoulded aggregates versus clay percentage, regression lines are for <35%, 35-51.3% and > 51.3% clay.*

These statistical relationships give an insight into the fundamental role of clay content across a range of soil types. However, better quantitative models are needed to predict agronomically important parameters from basic soil analytical data. Gupta and Larsen (1979) using the sphere packing models of Staple (1975) sub-divided particles between 0.002 mm and 2mm into 9 size ranges and calculated minimum and random packing bulk densities. Gupta and Larsen (1982) used a similar approach to calculate bulk density of mixtures of aggregates. A difficulty with soil-particles-as-spheres models is selection of the packing density to be used for each size fraction and the size scale and prehistory of the sample being tested (Bodman and Constantin 1965; Gupta and Larsen 1979; and Panayiotopoulos and Mullins, 1985). Arya and Paris (1981) assumed that each size range packed as spheres, at the measured bulk density of the soil sample. This model gave quite good predictions of soil moisture characteristics for some of the rigid, non-aggregated soils tested. The deviation for some of the soils tested by Arya and Paris highlights the difficulties in applying particle size based models to the more complicated case of aggregated soils. These models may be quite useful for prediction of the 'textural porosity' of Fies and Stengel (1981), but they are as yet unable to account for the porosity associated with matrix interaction and aggregation

The nature of the clay fraction

There are three common families of layer silicate clay minerals-kaolinites, smectites and illites Kaolinitic clays tend to be formed under warm climates with conditions favouring leaching of bases (Russell 1973) Cation exchange capacity (CEC) is normally less than 100 mmol (+)/kg and surface area 10 to 20m^2/g Because of relatively low CEC, koalinites are considered 'inactive ' clays. Smectitic clays tend to be formed under warm climates where leaching is poor They are dominant in cracking clay soils and present in many soils The distance between the basic layer units is affected by exchangeable cations, electrolyte concentration, and mechanical energy inputs, hence the term 'expanding lattice clays' is sometimes used for these minerals. Smectites have a CEC of 800-1200 mmol(+)/kg and a surface area of around 800m^2/g They are considered as 'highly active' because of the relatively high CEC Illitic clays resemble smectitic clays, but layers are bonded by non-exchangeable potassium The value of CEC for illites is 100 to 300 mmol(+)/kg, but may be higher in some soil types

The behaviour of clay is influenced by exchangeable cations, electrolyte concentration and various bonding agents, but there are some general differences in the effect of clay type on soil structure. For example Emerson (1964) found kaolinite aggregates crumbled on wetting whereas smectite aggregates did not, smectite aggregates were less dense than kaolinite aggregates (Coughlan *et al.*, 1978b), the rate of wetting of soil aggregates increased with CEC (Coughlan 1979, 1984), and the water content required for mechanical disruption increased with CEC (Coughlan *et al*. 1973) When the clay minerals present in a soil are not known, clay mineral activity can be inferred from the soil CEC/clay content ratio This approach attributes all CEC to the clay fraction and serious errors can occur if soil CEC is low and the charge is associated with organic matter or other active components Soil CEC itself can be a guide to soil structure related properties. Shaw and Yule (1978) found useful relations between soil CEC and the upper and lower limits of available water for a range of Queensland soils Also Yule and Ritchie (1980) found CEC in Texas Vertisols was linked with the volume of stable pores which drained near saturation.

Interparticle bonding mechanisms.

There are various qualitative models of bonding mechanisms within soil aggregates These models serve to illustrate the way in which various particle sizes, orders of aggregation and bonding mechanisms operate, (e.g., Emerson, 1959 1977, Quirk and Panabokke, 1962; Quirk and Aylmore, 1971; Greenland, 1979, Warkentin, 1982; Tisdall and Oades, 1982, and Dexter, 1988). No bonding model is appropriate for all soils and formulating a qualitative model agreeing with the spectrum of experimental results is quite difficult (Quirk 1978, 1979; and Edward and Bremner, 1967). The first order of bonding is between clay particles. The location of clay with respect to coarse grains and the orientation around, and bonding to coarse grains can profoundly effect soil structure (Mullins and Panayiotopoulos 1984, and Mullins *et al.*, 1987).

Some 15 interparticle bonding mechanisms are listed by Harris *et al* (1966) (see also Greenland *et al* 1962 Edward and Bremner 1967 Emerson 1977 and Tisdall and Oades 1982) These include a range of natural organic compounds exchangeable cations microbial filaments or fragments synthetic soil conditioners, oxides carbonates, and silicates

Exchangeable cations and electrolyte concentration

The type of exchangeable cations and the concentration of electrolyte in the soil solution determine whether particles tend to coalesce (flocculation) or to repel each other (dispersion) The composition of the exchangeable cations is closely related to the composition of the electrolyte Exchange is instantaneous, but when amendments are added to soil to modify soil structure the initial response is usually attributed to the increased electrolyte concentration (Loveday, 1976) Despite the widely recognised threshold concentration concept introduced by Quirk and Schofield (1955), electrolyte concentration, although frequently determined for soil salinity appraisal, is seldom used as a guide to soil structure The test described by Rengasamy *et al* (1987) does take it into account

Exchangeable sodium is well known as a dispersive agent harmful to soil structure It is monovalent and has high hydration energy and will cause clay particles (if not restrained by electrolyte concentration or bonding mechanisms) to disperse in saturated soil (Emerson 1956) Sodic soils are impermeable when wet and strong and dense when dry Microstructure is more homogeneous because dispersed clay acts as a filler and binder There have been many attempts to define critical threshold levels above which exchangeable sodium adversely affects soil structure An exchangeable sodium percentage (ESP) of 15 as proposed by Richards (1954) is widely used However for Australian soils an ESP of 4 6 seems more appropriate (Loveday and Pyle 1973 Northcote and Skene 1972 and McIntyre, 1979) Many factors influence the effect of exchange- able sodium and it is likely that quite low levels affect in other soils (McIntyre 1979) Some farmers on the Darling Downs in South Queensland have claimed a worthwhile response to gypsum on soils with ESP in the range 3 to 6 Also, Coughlan and Loch (1984) found a significant positive correlation between dry aggregate size (which is linked with seedling emergence, Yule *et al*, 1976) and ESP in the ESP range 0 4 to 6 4 for a range of Queensland Vertisols

Clay type conditions the effect of exchangeable sodium Coughlan and Loch (1984) in a study of 26 cracking clay soils found that if soils were divided into groups on the basis of the CEC/clay content ratio i e < 0 5 to 0 8 and >0 8, the proportion of dry aggregates 5 mm increased with decreasing clay activity, but within each group this aggregate size index increased with increasing ESP

Exchangeable magnesium is usually equated with exchangeable calcium in terms of beneficial effects on soil structure, e g , calculation of the sodium adsorption ratio (Richards 1954) However, in Australia, exchangeable magnesium is commonly suspected to reinforce the dispersive effects of exchangeable sodium in illitic soils (Emerson and Bakker, 1973, and Emerson 1983)

Wetting and drying and structural stability

The forces holding water in soil have a major influence on soil structure. Croney and Coleman (1954) showed that if a puddled clay was put through a series of wetting and drying cycles it developed structure stable to wetting, due to states of minimum energy, associated with particle arrangements and bonding brought about by the surface tension of the drying water film. Hence drying tends to be a structure building process. However, Utomo and Dexter (1982) found that the effect of wetting and drying on the water stability of red-brown earth aggregates depended on soil history.

Aggregate definition in cracking clay soils is due to propagation of failures in the drying water film. Many Vertisols undergo a process known as 'selfmulching' whereby a loose layer of dry aggregates forms in the surface due to wetting and drying. Coughlan (1984) concluded that soils with a strong 'selfmulching' capacity tended to have relatively higher exchangeable Ca/Mg ratio, aggregate porosity, CEC, and swell-shrink capacity. These soils were also more likely to slake on wetting (although slaking is not synonymous with selfmulching), and did not disperse readily. Emerson (1964) found kaolinite slaked readily but kaolinitic soils do not generally selfmulch (see Shiel *et al.*, 1987 for an exception), showing that slaking upon wetting is not the major mechanism. Towner (1988) found that balls formed from moulded pastes of kaolin and 1 mm diameter glass beads did not crack on drying, whereas mixtures with larger bead sizes did. This shows the importance of drying in creating failures in the clay matrix.

There are two processes in wet soils that also influence structure-slaking, and breakdown under raindrop impact.

Slaking

Quirk and Panabokke (1962) found that relatively rapid wetting (at 2 cm tension) caused incipient failure within aggregates from cultivated soil, but not in aggregates from virgin soil. These failures defined discrete aggregates when the original aggregates were placed in water, that is, the failures were no longer incipient when water tension was removed. Studies of aggregate breakdown due to rapid wetting (slaking) have shown that the explosive effect of entrapped air is the main cause (Robinson and Page 1950; and Emerson, 1964) and that initial water content is important (Collis-George and Lal 1971). The rate of wetting may be an intrinsic soil property determined by internal microstructure and degree of hydrophobicity or by changes upon raindrop impact of an outer layer which acts as a throttle (Coughlan, 1984). Bonding mechanisms that distribute stresses through the matrix (possibly associated with heterogeneous distribution of organic matter) can prevent slaking (Quirk and Panabokke 1962). Coughlan (1979) found size of water stable aggregates was a function of wetting rate which was partially an intrinsic soil property.

The agronomic effects of slaking in field soils varies. It is commonly seen as a harmful, structure degrading process in soils in New South Wales (see Collis-George and Laryea, 1971) where it reduces infiltration, but Smith and McShane (1981) found it could be used to break up large intractable clods. Collis-George and Greene (1979) considered that the size and arrangement of aggregates in, as well as the thickness of the slaked layer, influenced infiltration.

Breakdown under raindrop impact

In the system of classification of soils based on coherence of immersed aggregates, proposed by Emerson (1967), spontaneous dispersion is one criterion. that aggregates be reduced to clay size separates to adversely effect soil structure. The proportion of material <0.125 mm in the soil surface has been found to be inversely linked with infiltration rate under simulated rain (Loch and Foley 1987; and Glanville and Smith 1988)

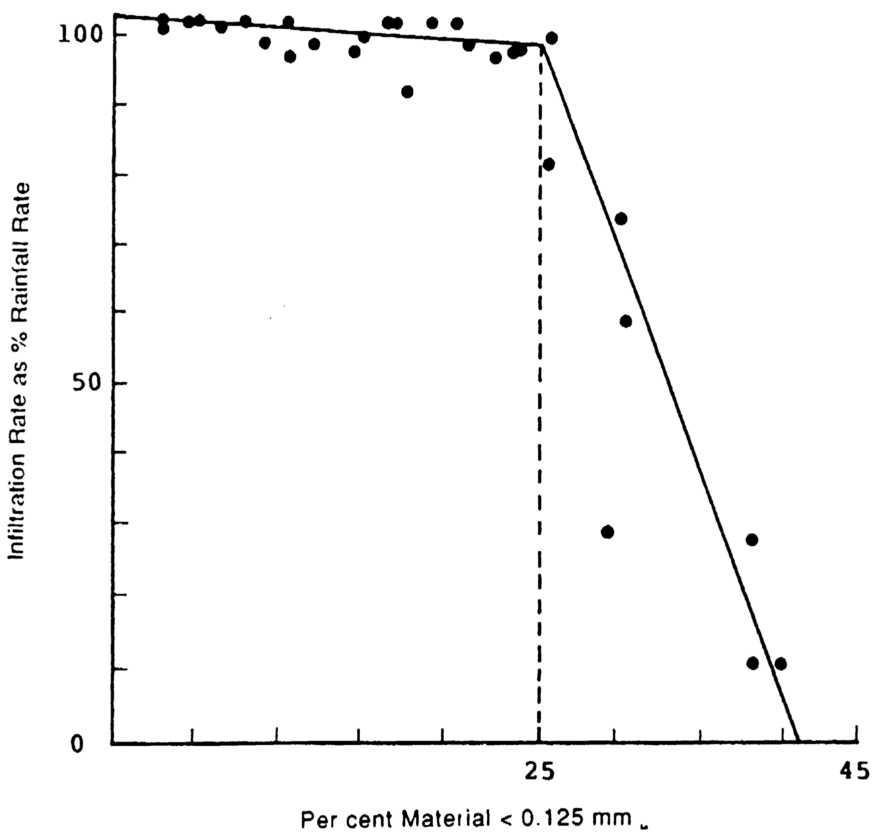

Figure 3. *Relation between infiltration rate under simulated rain and % material <0.125 mm in the 0.1 cm layer, for four Queensland soils (bare and covered) (Glanville and Smith, 1988).*

Very few Queensland Vertisols show spontaneous dispersion. However, in the field many of these soils have structural problems attributed to aggregate breakdown and (some) clay dispersion due to raindrop impact. It is not necessary (Figures 3 and 4). But the critical size ranges have not been identified, bearing out the suggestion by Dexter (1988) for more studies of structure in the range < 0.1 mm. Most laboratory tests on aggregate stability do not relate to conditions under

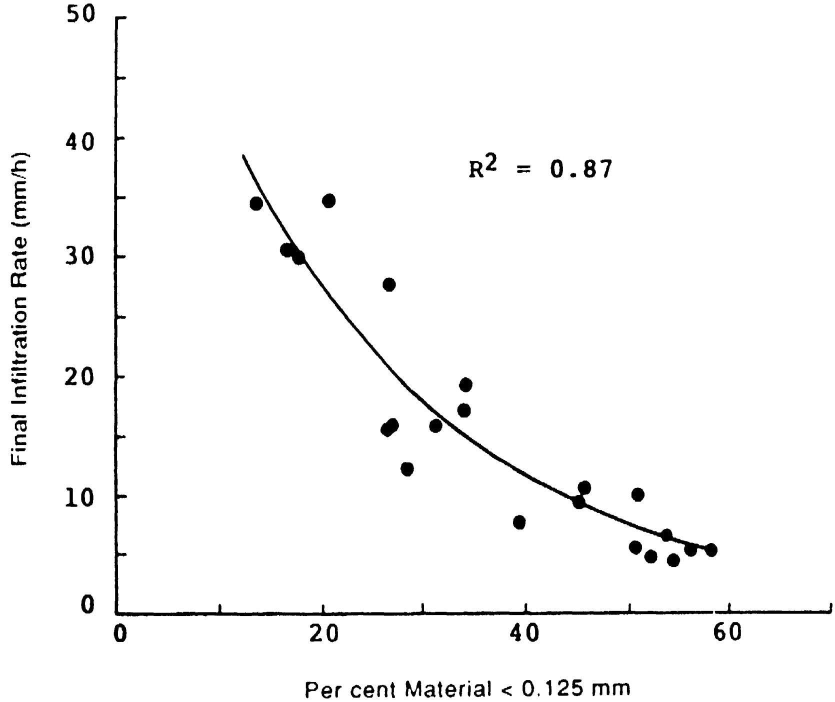

Figure 4. *Relation between final infiltration rate under simulated rain and % material <0.125 mm in the 0.1 cm layer, for a range of Queensland soils (Loch and Foley, 1987).*

rain in the field (Coughlan *et al.*, 1978a; and Loch and Smith 1985). However, the proportion of dispersed clay after end-over-end shaking of a dilute soil suspension has been linked (positively) with dry aggregate size in the field (Coughlan 1984) and (negatively) with saturated hydraulic conductivity in laboratory tests (Cook and So, 1987).

There is a particular water content above which clay in a given soil (Emerson, 1977) will disperse with input of energy. There is also a particular water content at which aggregates can be disrupted by the input of energy. This has been termed the disruptive moisture content (DMC) (Coughlan *et al.*, 1973). The relation between these two water contents has not been examined. If the DMC is seldom exceeded, problems due to aggregate disruption and (probably) to clay dispersion should not arise. Soils with more active clays have higher DMC. Factors that influence water content in the surface of field soils include rainfall intensity, infiltration rate, surface cover and the initial water deficit.

Approaches to Managing Soil Structure in the Field

Interest in managing soil structure usually arises because one or more physical processes are judged to have adverse impacts on crop yield, production efficiency (e.g., rainfall use efficiency), degree of risk (e.g., waterlogging, moisture stress or poor crop establishment) or costs and convenience of farming (e.g., tillage required for seedbed preparation). Where poor soil structure is alleged to restrict yield it is wise to carry out an experiment to rule out the effect of major plant growth limiting factors, such as nutrients, diseases etc, and to collect data on physical processes (e.g., McNee *et al.*, 1982). In cases where a diagnosis has to be made with limited data, constraints should be clearly identified, that is, if the problem is moisture stress, is it due to surface sealing, a throttle within the profile, low water holding capacity of the soil, or to restrictions to root growth making water inaccessible; if the problem is poor crop establishment, is it due to poor germination (seed viability, cloddy or dry seedbed, or insect damage) or to failure to emerge (mechanical impedance, insect damage, or disease)? The correct management decisions can only be made if the constraint is clearly understood. Preferably, the processes involved should be quantified so that particular crop yield results can be explained.

Options for soil structure management

Available options can be classified in the following three groups:

(1) Options to protect soil structure

- (a) from environmental factors
- (b) from compaction by foot or wheel traffic

(2) Options for short term changes in soil structure

- (a) plant root systems
- (b) surface configurations
- (c) tillage
- (d) compaction

(3) Options for long term changes in soil structure

- (a) particle size
- (b) organic amendments
- (c) soil conditioners
- (d) crop rotations
- (e) inorganic amendments

Protection from environmental factors

Water availability commonly limits crop growth in the (SAT). Rains are seasonal and intense rains often fall on bare soil. Runoff losses are high and soil erosion degrades the soil resource. Surface sealing due to rain drop impact is a problem accentuating low water storage capability on many soils. Sealing destroys void continuity because the soil particle bonding mechanisms break down under drop impact and particles are rearranged (McIntyre, 1958). Sealing has been found to be directly related to cumulative kinetic energy or rain (Morin *et al.*, 1981; and Hoogmoed and Stroosnijder, 1984) and to the amount of material <0.25 mm in the surface (Loch and Foley 1987; and Glanville and Smith 1988). The most effective way to prevent surface sealing is to protect the soil from raindrop impact by some form of cover. This can take the form of a standing crop, standing or mulched crop residues, or a sand or gravel mulch. Crop establishment early in the rainy season is important (Charreau and Fauck, 1970), and can be improved by mulching (Vijayalakshmi, 1987). When stones are available for use as protection they are more effective if placed on, rather than buried within, the soil surface (Poesen,

1986) Further research is needed on the use of stones, a freely available resource on many SAT soils.

In many farming systems in the SAT crop residues are used for fodder or fuel. There is some evidence that relatively low rates of soil cover can be effective in preventing runoff and soil loss. For example, Freebairn and Wockner (1986) found that on Queensland Vertisols 20% cover (wheat residue) reduced sediment concentration in runoff by up to 4 fold (Figure 5). More research is needed to determine the benefits obtainable from, and the best ways of using, small amounts of crop residues. On an Alfisol at ICRISAT, 5 t/ha of groundnut hulls reduced runoff and soil loss (ICRISAT 1986). Mulch may have effects even when a crop is present. Sinclair (1987) found 6 t/ha of rice straw mulch on tied ridges reduced puddling and ponding in tied ridges under pearl millet. At ICRISAT in the 1988 rainy season it was found that 5 t/ha of rice straw spread between rows of pearl millet reduced runoff from a flat land surface (1.6% slope). Joshi (1987) found a FYM mulch placed over seed rows increased emergence. Jones and Wild (1975, p 213) consider that for best effects on physical properties crop residues must be incorporated either by tillage or soil fauna. Crop yield may be reduced if nutrients are tied up during decomposition (for example, ICRISAT 1988, P 295). Mulches, apart from protecting the soil surface from raindrop impact, and extremes of temperature, may encourage termites, earthworms etc, which would improve pore structure under the mulch. McCown (1987) advocates a "no till" pasture ley system in which crops are sown into mulch - in this case the mulch reduced soil temperature and soil strength and increased emergence. Mulches also reduce the rate of evaporation, but the worth of this effect depends on the distribution of rainfall.

Some Vertisols seal under rain (Smith *et al.*, 1984), but if runoff can recharge the subsoil via gross cracks, surface sealing may actually improve the effective storage of rainfall. Management should aim to keep cracks open to the surface. The broad bed and furrow (BBF) system used at ICRISAT as part of improved technology for Vertisols is a good example. Gross cracks are generally located in the furrow, which is usually clear of loose soil, trash etc., at the start of the wet season. This system also provides crop cover during the rainy season which not only protects the soil, but increases the likelihood of cracks being available to store runoff. The combined advantages are shown in Table 1.

Table 1

Effect of double cropping and BBF surface configurations on runoff and soil loss from a Vertisol, ICRISAT Center, 1977 to 1984.

	Runoff (mm)	Proportion of rain (%)	Soil loss (t/ha)
Improved double cropping on BBF	130	14	1.5
Traditional post-rainy season crop on flat land	227	25	6.4

Source: ICRISAT (1985)

Cover (such as crop or residue) that shades the soil will increase size of aggregates in the surface of Vertisols (Srivastava *et al.*, 1987). This could be a disadvantage if "selfmulching" is desired to produce a fine tilth, but Loch and Coughlan (1984) attributed improved water entry in zero-till stubble retained

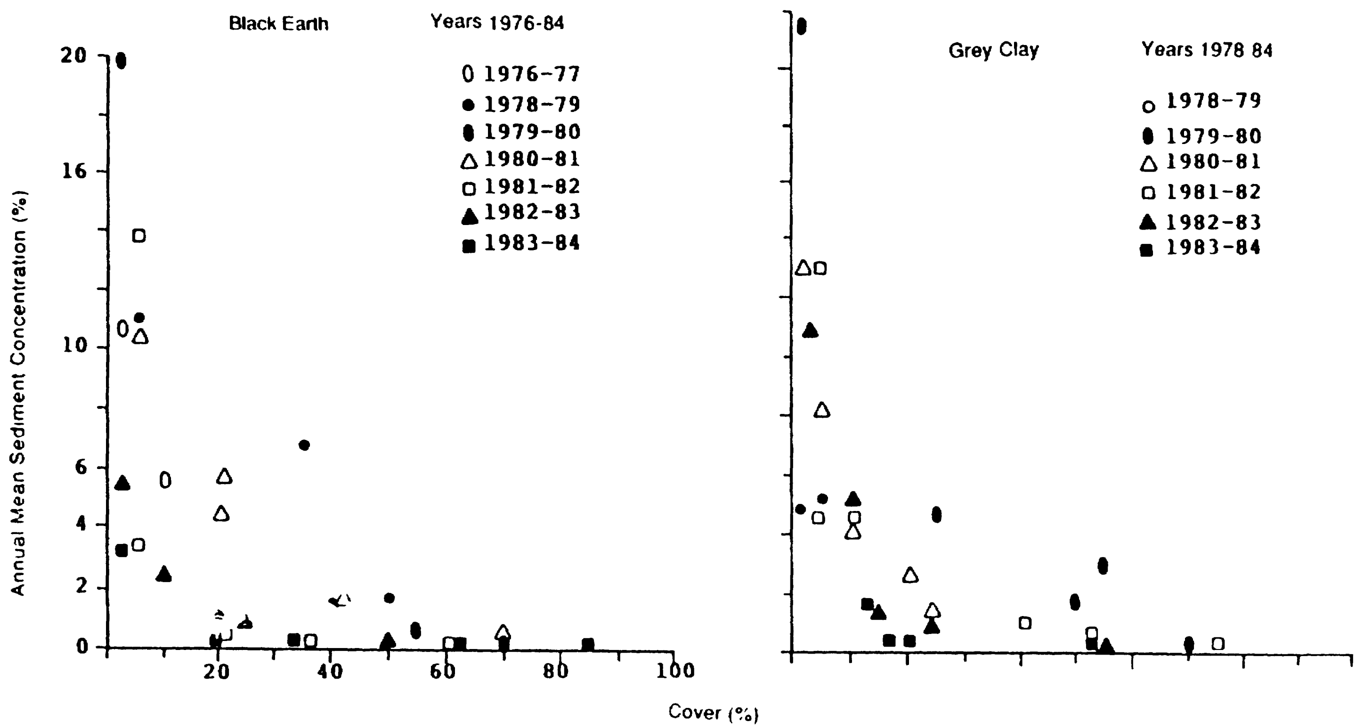

Figure 5. *Annual mean sediment concentration of runoff versus cover for a black earth and a grey clay soil on the Darling Downs, Queensland. (Freebairn and Wockner, 1986).*

treatments, partly to larger and more continuous pores, formed as a result of slower drying in the surface.

Prevention of compaction

Compaction under heavy machinery is a serious problem in the agriculture of developed countries (McGarry, 1987). Resource poor farmers use only light implements, but compaction may occur if operations are carried out on wet soil. Srivastava *et. al.*, (1987) found that human trampling on the raised beds of the BBF system, during harvest of the rainy season crop, increased cloddiness and impaired establishment of the subsequent crop. They considered that trampling should follow the furrow where, if compaction increased the width of cracks, it could improve water storage.

Crop root systems

Crop roots can affect structure by binding and compressing aggregates, by creating continuous voids, and by causing heterogeneous stress distribution on drying. Lowland rice is well known for its ability to produce a temporary fine granular surface due to transpirative drying of clay soils (Smith and McShane, 1981). Crops or pasture grasses with a fine fibrous root system would have similar effects on soil structure, but will only be grown if economic. On cracking clay soils, gross cracks tend to form midway between plants, especially if sown in rows (Swartz, 1966). This probably helps to locate cracks in the furrow of the BBF system where they assist water entry and are less likely to damage crop root systems.

Exudates from roots, as well as the root remains, can help to stabilise aggregates and pores. If sequential crops are sown in precisely the same place, seedbed preparation for the following crop, and root penetration, may benefit from soil structure changes brought about by root systems. The combination of continuous voids created by roots and the stability given by organic remains of the root should offer considerable advantages for root penetration in zero or reduced tillage practices.

Surface configurations

Where waterlogging is likely, surface configurations can be used to provide surface drainage. Various linear configurations have been tested at ICRISAT. On Vertisols the BBF system, usually on 0.4 to 0.8% slope, is preferred because it is stable and not easily overtopped. However, on Alfisols the BBF system increased runoff (Table 2).

Table 2

Effect of surface configuration on runoff and soil loss on an Alfisol, ICRISAT Center 1981-1985.

	Runoff (mm)	Soil loss (t/ha/yr)
BBF, 0.4% slope	276	3.06
Flat on grade, 0.4% slope	152	1.60
SE	±21.2	± 0.213

Source. ICRISAT (1986)

Hegde *et al.* (1987) also found linear configurations did not improve water retention or crop yield on an Alfisol, but low gradient furrows could be useful to reduce erosion. However, furrow length and slope is important (Jones and Wild, 1975). Linear surface configurations (for example, a ridge and furrow system) can also be valuable aids to reduce wind erosion. If runoff must be induced for water conservation purposes, a combination of linear configurations, compaction and surface sealing can be used (Laing, 1978; and Ben-Hur *et al.*, 1986). However, where *in-situ* storage is desired, configurations can be designed to maximise detention storage, e.g., surface pits or basins (Rawitz *et al.*, 1983) or tied ridges (Lawes, 1966). These must be carefully designed so as not to aggravate runoff and erosion by cascade collapse. Jones and Wild (1975 p. 186) discuss the fact that while tied ridges increases yield in dry years they can reduce yield in wet years.

Tillage

Excessive tillage can be harmful to soil structure by oxidising organic matter, discouraging soil fauna, and pulverising the larger aggregates that define large pores (e.g., Charreau and Nicou 1971; Larsen and Osborne 1982; Charriere, 1984; Abbott *et al.*, 1979; and Adem *et al.*, 1984). There is, therefore, a need to think carefully about the reasons for tillage and to ensure that it is timely (as there is an optimum water content range to avoid compaction, smearing or excessive cloddiness; Gupta and Larsen, 1982), and efficient in terms of the objectives and resources (Willcocks, 1981; 1984; 1987; Boone, 1988; and Rawitz *et al.*, 1983). Tillage should aim to harmonise with natural processes in the soil. Where possible, the effects of wetting and drying should be utilised. An example of this is the preparation of seedbeds on Vertisols. In the improved ICRISAT technology, the primary tillage for preparation of the seedbed for the crop to be sown in the following rainy season starts soon after the harvest of the previous crop. This tillage aims to promote and take advantage of effects of wetting and drying in the occasional dry season rains. Similarly shallow tillage of Alfisols in the dry season is recommended to improve water intake and assist with seedbed preparation in the rainy season (e.g., Charreau and Nicou, 1971; Hedge *et al.*, 1987, Vijayalakshmi, 1987; and Perrier, 1987).

Increasing the depth of tillage may improve yield if there is a root restricting layer or an impermeable layer below the normal plowing depth and seasonal conditions are favourable (e.g., Vittal *et al.*, 1983). However, there should be a clear target layer and the implement should be suited to work at that depth.

Compaction to improve soil structure

In some cases there are benefits from increasing soil bulk density. Examples are to stabilise and strengthen ridges made in sandy soil to reduce wind and water erosion (Joshi, 1987) and to improve crop establishment when seedbed conditions are unfavourable (Radford, 1986). In some excessively permeable soils of Tamil Nadu compaction with a heavy roller soon after rain, increased yield (of maize, groundnut, tomato and sorghum) by 18-20% and the effect lasted for 2 years (TNAU, 1985).

Particle size distribution

Silt from small reservoirs (tanks) is commonly used to topdress soils in India. Benefits come at least partly from plant nutrients. In Andhra Pradesh, clay soils are sometimes added to Alfisols to reduce water holding capacity permeability. Subbarami Reddy *et al.* (1985) found that the yield of maize, wheat and sorghum crops increased for five years if clay content was increased by 5%. An increase of 1% had no worthwhile effect. Coarse sand is also added to some soils and it can only have a physical effect. It may act as a mulch to slow evaporation or to improve to water entry. Sachan and Smith (1989) found that increasing coarse sand content from 85 to 95% reduced runoff (averaged over 1987 and 1988) from 35% to 8.5%. Nagaraja Rao *et al.*, (1977) found that adding 30% coarse sand to the surface of an Alfisol more than doubled germination of pearl millet (*Pennisetum glaucum*). Subbarami Reddy *et al.* (1985) obtained similar results. Top dressing clay soils with coarse sand would improve the effectiveness of storage of light falls of rain because only a relatively small quantity of water is needed to wet coarse sand. The difficulty with this option is that it is costly because relatively large quantities of sand must be added to have any impact. An inverting tillage to mix clay into the surface will improve physical properties in some soils (e.g., Brown *et al.*, 1985). In other cases noninverting tillage over a long period can increase yield by increasing the sand content of the immediate surface (Pathak *et al.*, 1985).

Organic amendments

Organic amendments such as FYM, or crop residues are commonly added to soil to improve both physical and chemical characteristics. Changes in soil structure due to additions of organic matter are expected to be due to increased soil cohesion, reduced wettability, reduced swelling, and reduced dispersion. It is difficult to separate crop responses due to nutritional aspects from responses due to physical changes (e.g., Subbarami Reddy *et al.*, 1985). Whether from FYM or crop residues, the effects on soil structure are usually ascribed to polysaccharides (Quirk, 1979) which can be relatively short lived in soils. Even large applications of FYM can be oxidised quickly in tropical soils. In a study at ICRISAT, the addition of 5 t/ha of FYM annually to an Alfisol over 8 years had no significant effect on total organic carbon or on visible structural features (K.L. Sahrawat, ICRISAT, personal communication, 1987). The type of organic matter present and its distribution within the soil may be an important factor. Organic amendments would be expected to have less effect in cracking clay soils because the powerful effects of clay content and clay type largely determine structural behaviour (Coughlan, 1984). Green manure crop are unlikely to be practicable or worthwhile under rainfed conditions in the SAT.

Soil conditioners

Soil conditioners are usually synthetic polymers that form bonds between soil particles. A variety of materials is available (see for example SSSA 1975) and although several are effective at relatively low concentrations, their high cost means they are likely to be economic only for special purposes or strategic applications. They are usually applied to aggregates that have been preformed into a preferred size distribution. Quirk and Williams (1974) proposed stabilising particular pore size classes within aggregates. A different type of conditioning is to make a layer of aggregates at the soil surface water repellant by applying chemicals such as organosilicones (see Hillel, 1980, p. 115). If soil conditioners are used it is essential that the treated layer be carefully managed to prevent dilution or inversion (Oades, 1976).

Crop rotation

In the SAT, the main benefits from annual crop rotations are expected to come from increased nitrogen availability to crops following a legume phase or from breaking disease or pest cycles (e.g., Clarke and Russell, 1977). However, if a ley pasture phase can be rotated with arable cropping, soil structure may be improved. Species with finely branched ot systems are more likely to modify soil structure (e.g., Clarke *et al.*, 1967), but Low (1955) reports that in some cases legumes gave better results. Tisdall and Oades (1979) found that ryegrass gave greater aggregate stability than white clover; they attributed this to higher populations of vesicular arbuscular mycorrhiza on the grass roots. It may take some years for a pasture phase to impact on soil structure. Low (1955) suggests 50 years on clay soils and 5-10 years on sandy soils in England. In Australia, Greacen (1958) identified weak aggregates due to short term (2-3 yrs) pasture and stronger aggregates formed under longer term pastures on red-brown earth ›ils. Greenland *et al.* (1962) considered that pastures need to exceed 4 years for strong aggregation on a similar loam soil. Quirk (1979) suggested that the stronger aggregates are bonded by organic compounds other than polysaccharides. Greenland *et al.* (1962) also show that a period of bare fallow results in weaker aggregates than a wheat monoculture. This is probably because tillage for weed control destroys organic matter. Experiments are at present underway at ICRISAT to study the effect of *Stylosanthes hamata*. *Cenchrus ciliaris* and perennial pigeonpea (*Cajanus cajan*), alone or in combination, on soil physical properties.

Inorganic amendments

The inorganic amendment most likely to be used in rainfed conditions is gypsum (calcium sulphate) available as a byproduct of fertiliser (phosphogypsum) or hydro-fluoric acid manufacture, or from mines. Although gypsum is sometimes used as a source of nutrients (calcium or sulphur), when applied as an amendment the aim is to change soil structure. By increasing the electrolyte concentration and supplying calcium to replace exchangeable sodium, it prevents spontaneous dispersion, restricts swelling, and causes flocculation if clay is dispersed mechanically.

Several methods have been used to predict gypsum responsiveness of soils. Some are based on the theoretical amount needed to reduce ESP to a particular level. Usually it is possible to get a response at a much lower application rate because of the electrolyte effect (Loveday, 1974, 1976; and So and McKenzie, 1984) and tests which evaluate dispersive tendencies in relation to electrolyte concentration (Rengasamy *et al.*, 1987; and Cook and So, 1987) are more likely to be reliable. However, because many factors affect the response to gypsum in the field (the soil factors that affect soil structure, the crop type and cultural methods, and the nature and sequence of rainfall events), it is unreasonable to expect a laboratory test to predict the economic worth of gypsum. Field indications of responsive soils include: excessively cloddy seedbeds, narrow moisture range for tillage, extreme range in soil moisture over short vertical distance in the soil, surface sealing and turbid runoff, clods rounded by raindrop impact, sand "wash" on the soil surface, and clay "curls" left in depressions. Because gypsum is expen- sive (usually due to freight costs and the high rates used) small test strip appli- cations should be used so that the farmer can judge the worth of the response under his management practices. Farmers are often impressed by intangible benefits (convenience responses) such as easier tillage, easier weed control, and longer duration of optimum tillage conditions, which are not matched by yield responses. The residual effects depend on how quickly gypsum is dissolved and leached, and what proportion of ESP is replaced. Rates used for wheat soils in Australia range from 1 to 5 t/ha. So and McKenzie (1984) found a rate of 2.5 t/ha was most economical for wheat production on a Vertisol in New South Wales. The effect was due to increased water storage in the subsoil as a result of increased hydraulic conductivity in surface layers (see also Sharma, 1971). Calcium or sulphur in gypsum (or the small amounts of phos- phorus in phosphogypsum) may increase crop yield when gypsum is applied to soils deficient in these elements. Fertilisers should be applied separately as a control to prove the response to gypsum is due to soil physical, rather than to nutritional effects. In some soils better crop growth due to the soil physical effects of gypsum can induce nutrient deficiencies because soil water is no longer limiting (Smith *et al.*, 1985).

Conclusion

Soil structure has two important influences on productivity of soils. Firstly, by influencing the components of the soil water balance it has a significant impact on rainfall use efficiency. Secondly, by influ- encing the extent of runoff and erodibility of soil it determines trends in soil fertility over the long term. Soil structure also has an important bearing on how easy it is for farmers to establish successful crops and the degree of risk of crop losses. The factors and processes that determine the structure of particular soils need to be understood and manipulated to create and maintain a pore structure suitable for physical processes. Farming under rainfed conditions always involves risks from the weather. Soil structure directly affects, and is directly affected by, the soil response to particular weather events. The success and economic worth of practices aimed to manage soil structure are also at risk from the weather. These risks plus the fact that rainfed farming is generally low input farming, imposes a constraint on what can be done to manage soil structure (Mullins *et. al.*, 1987). Decisions on options must be made taking probabilities of weather events into account where possible. Tillage, because of its direct, albeit temporary effects, is presently preferred by farmers - although it degrades the soil resource in the long term. Science faces a major challenge to develop farming systems that preserve the soil and yet are economically attractive to the resource poor farmer. The various resour- ces and options available to manage soil structure need to be applied strategically in terms of both timeliness and spatial distribution. Adaptation of the zonal tillage concept (Larsen, 1963; and Willcocks, 1981) to resource inputs may have an important place in soil structure management in the SAT.

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