THE ROLE OF MICROAGGREGATION IN PHYSICAL EDAPHOLOGY

by

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Dedicated to my late mother, Ekillia.
You took me to school on my very first day.
How I wish you were here today!

DECLARATION

I hereby declare that this thesis has been composed by myself, that it has not been accepted in any previous application for a degree, that the work of which it is a record of has been done by myself, and that all quotations have been distinguished by quotation marks and the sources of information specifically acknowledged.

Peter W. Mtakwa,
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SUMMARY

Soil type and the previous history of cultivation can both affect soil strength. I characterized soil strength by measuring tensile strength and penetration resistance (PR) as a function of matric potential (the strength characteristics). It was expected that microaggregation should allow the soil to fail easily along failure planes in between the microaggregates. Five Tanzanian soil types were compared ranging from a hardsetting Paleustalf at one extreme of strength behaviour, through a Paleudoll, Paleudalf and a Paleustult, to a strongly microaggregated Orthox expected to be at the weak end of the scale. At each site soils that had a history of 7 or more years of cultivation and cropping were compared with newly cultivated soils. The Orthox and Paleustult had the best PR characteristic for ease of root growth and the Paleustalf had the worst characteristic which suggested that it would not permit root growth at matric suctions exceeding 100 kPa. The Orthox also had much the most favourable tensile strength characteristic. At air dryness (100 MPa suction), the previously uncultivated and previously cultivated Orthox topsoils had 3 and 9 times less tensile (and compressive) strength, respectively, than the corresponding Paleustalf topsoils. For three of the soils (Orthox, Paleudoll and Paleustult) a previous history of cultivation was found to have significantly and substantially reduced the tensile strength of the topsoil at any given matric suction compared to the newly cultivated soil.

A study was made of techniques for quantifying microaggregation. The limitations of current techniques are discussed and a scheme for determining microaggregation *sensu stricto* is proposed. This scheme avoids the assumption that water-stable slaked soil fragments are necessarily microaggregates.

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INTRODUCTION

The timing of cultivation and sowing, and the rate of crop root growth can all be limited by high soil strength. These problems are particularly important in the subhumid and semi-arid tropics where crop growth is limited by the length of the rainy season. Since soil strength varies with water content, it is necessary to determine the soil 'strength-characteristic' in order to estimate the importance of this problem. The strength-characteristic is the relationship between soil strength and matric potential or water content. This characteristic varies with soil type and the state of the soil. Thus cultivation usually changes the strength characteristic of the topsoil although this may return to the original state if the soil slumps after rainfall. Most research shows that soils that have a long history of cultivation are stronger at any given matric potential than similar soils in a virgin or uncultivated state. This is usually attributed to the reduction in soil organic matter concentration that often accompanies cultivation and cropping (Ley *et al.*, 1989).

Alfisols, oxisols and ultisols are the most widespread soil types in the tropics. Many tropical alfisols are hardsetting or can become hardsetting after they have been cultivated for some time, which means they are too hard to cultivate or to permit sowing in the dry season. Hardsetting soils are also likely to restrict root growth whenever the soil starts to dry (Mullins *et al.*, 1987; 1990), and can prevent emergence if the soil surface dries before the shoot has emerged (Weaich *et al.*, 1992). In contrast, oxisols and ultisols may be microaggregated which can be expected to confer more favourable physical properties including a better strength characteristic. However, it is not clear if the benefits of microaggregation can withstand the effects of repeated cultivation or if such soils will progressively lose their favourable strength characteristics.

Soil strength cannot be described by a single parameter. Shear and tensile strength mainly determine soil response to cultivation implements. In this thesis I have used tensile strength-characteristics of soils as a guide to their ease of cultivation at any given matric potential. I could equally well have chosen to measure shear strength. However, since the tensile and shear strength usually vary in a similar way (Ley *et al.*, 1989), it is often unnecessary to measure both in order to obtain an estimate of ease of cultivation at different matric potentials.

Penetration resistance (PR) determines root response to mechanical impedance in the absence of structural pathways that allow roots to bypass the bulk of the soil. PR is a complex function of many strength-related properties (Greacen *et al.*, 1968; Taylor, 1974; Glinski and Lipiec, 1990). I have measured it directly since this is simpler than trying to predict it from other strength parameters. Root growth is greatly reduced or completely halted in soil at a PR of between 3 and 6 MPa (Bengough and Mullins, 1990). Smaller PR values of 1 MPa or less can reduce the rate of root growth to less than 50% of its unimpeded rate, and the PR-characteristic can also be used in modelling root growth response in soil whose PR is increasing during drying (Tsegaye and Mullins, 1993).

The aims of this work were to study the influence of soil type on soil tensile strength- and PR-characteristics, and to discover what effect a period of 7 to 10 years of cultivation had on these strength characteristics. Continuously cultivated and previously uncultivated plots on five contrasting soils in Tanzania were investigated. The soil types ranged from a hardsetting Paleustalf (at Ismani) at one extreme of strength behaviour, through a Paleudoll (at Magamba), Paleudalf (at Mbimba) and Paleustult (at Ukwile), to a strongly microaggregated Orthox (at Sao Hill) at the other extreme.

An additional objective was to study the factors responsible for microaggregation and techniques that might be used to detect or quantify microaggregation in soils.

The literature review in Chapter 1 describes the various definitions of microaggregation used in the literature, the occurrence of microaggregated soils worldwide, the origin and formation of microaggregates and their effect on physical edaphology.

Chapter 2 describes the materials and methods used in determining the various parameters related to the soil strength-characteristics as well as techniques for quantifying microaggregation.

The results obtained in this study are presented and briefly discussed in Chapter 3. In Chapter 4 these results are discussed further and a scheme for quantifying microaggregation is proposed. Furthermore, Chapter 4 suggests where the present results can be used and future research needs in soil microaggregation studies.

In Chapter 5 I have summarized the major findings of and conclusions drawn from the present study.

CHAPTER 1

LITERATURE REVIEW

Microaggregated soils, such as some Oxisols and oxic families of Alfisols, Ultisols and Inceptisols are expected to be easier to dry-cultivate and may impose less restriction on seedling emergence and root growth than soils that are not microaggregated. This chapter reviews: definitions of microaggregation and the occurrence, origin, stability with time, mode of formation and management of microaggregated soils.

1.1 Definitions of microaggregation

Definitions of microaggregation are based on whether the microaggregates were produced by sieving (either dry sieving or wet sieving or both) or they were observed in their natural state. Edwards and Bremner (1967) defined microaggregates as aggregates with a diameter of < 250 µm. These microaggregates were derived from the breakdown of macroaggregates (> 250 µm diameter) on wetting due to entrapped air and unequal swelling in a process known as 'slaking' (Emerson, 1977). According to Oades (1984):

> "Slaking results in microaggregates from which clay particles may or may not be detached (dispersed) depending on factors described in double layer theory, and some that are not including particle size, shape, packing and the input of energy."

Collis-George and Lal (1971) stated that small particles resulting from slaking that are themselves composed of ultimate particles have been termed microaggregates. Defined in this way, microaggregates can be equated to water-stable aggregates (< 250 μm). Kolodny and Joffe (1939) and Kolodny and Neal (1941) related microaggregation to the degree of dispersion. They (Kolodny and Neal, 1941) determined the percentage of particles that were microaggregated as:

$$\text{\% Microaggregated} = \frac{\text{\% of particles} < 40\ \mu\text{m microaggregated into elements} > 40\ \mu\text{m}}{\text{\% of particles of diam.} < 40\ \mu\text{m (determined by particle size analysis)}}$$

The authors explained that the term 'microaggregated' was used because wet-sieving of their soil indicated no water-stable aggregates > 250 μm.

Determination of microaggregation by wet-sieving has been carried out by many other workers (*e.g.* Collis-George and Lal, 1970; Ahn, 1979; Nvaka and Voronova, 1980; Tisdall and Oades, 1982; Sparling and Cheshire, 1985; Elliott, 1986; Gupta and Germida, 1988; Seech and Beauchamp, 1988; Pini and Guidi, 1989; Piccolo and Mbagwu, 1990; Van Gestel *et al.*, 1991). Defining microaggregation based on wet-sieving may be suitable for the northern temperate zone where soils commonly contain aggregates larger than 1000 μm but in the tropics this is often not the case. In much of tropical Africa, for example in the clayey residual soils, the clay component in the subsoils consists largely of microaggregates that range in size from 30 μm to 1000 μm but without aggregation at the larger scale (Trapnell and Webster, 1986).

The microaggregates in the tropical soils discussed by Trapnell and Webster (1986) cannot be seen by the unaided eye. A powerful hand lens or a low power microscope is needed. In addition, their presence is readily detected from the mealy feel of the moist soil when lightly handled (Trapnell and Webster, 1986). Such soils become more clayey in texture with kneading. In Australia such soils have been referred to as 'friable clays' (Butler *et al.*, 1942) or 'subplastic soils' (Butler, 1955; Brewer and Blackmore, 1956; McIntyre, 1976). In Africa and elsewhere microaggregated soils have also been called 'pseudosands' because they become more clayey in texture with continued kneading (Charreau and Fauck, 1970; Charreau and Nicou, 1971; Moura and Buol, 1972; Ahn, 1979). Moura and Buol (1972) reported that the clay content of an Oxisol in Brazil increased from 40 to 83 percent after removal of iron oxide. For an Ultisol in Kenya, Ahn (1979) reported an increase in clay content from 20.5 to 58.4 percent on the top 0-8 cm (increased from 0.8 to 83.4 percent in the 190 cm depth) when two parallel particle size analyses were carried out: without and with a dispersant, respectively. The clay content of the Oxisol from Ghana increased from 7.7 to 45.2 percent on the top 0-5 cm and from 6.2 to 68.5 percent at 145 cm depth (Ahn, 1979).

Arocena and Pawluk (1991), however, use the term pseudosands to refer to fine sand and silt particles aggregated together by dark isotropic material composed of organic matter, Fe, Al, Si and low amounts of K and Ti.

Based on their appearance microaggregates have also been called 'micropeds' (Beaudou, 1972; Benayas *et al.*, 1974; Muller, 1977;

Stoops and Buol, 1985), or, simply as 'microstructure' (Buol and Eswaran, 1978). Chauvel *et al.* (1978) used the term 'micronodules' to describe what Trapnell and Webster (1986) called microaggregates of the order of 100 µm, including small grains of quartz.

Microaggregates have been observed not only by using hand lenses and low power microscopes (Trapnell and Webster, 1986) but also in thin sections (*e.g.* Chauvel *et al.*, 1978; Federoff and Aurousseau, 1981) and with a Scanning Electron Microscope with a magnification of 30 to 10000 times (Benayas *et al.*, 1974).

Although Edwards and Bremner (1967) define microaggregates as < 250 µm aggregates, microaggregated soils such as the 'fragmental soils' described by Trapnell and Webster (1986) have microaggregates from 30 to 1500 µm in size.

It is possible that other authors have not found larger 'microaggregates' because they have not looked for them since, in many cases workers choose to use sieving or sedimentation only to estimate a preselected size range of microaggregates. Thus one problem in the definition of microaggregates is whether to define them by size (and exclude anything larger) or to define them according to some process by which they may be detected (such as wet sieving). In this thesis, since I am concerned with the effect that microaggregation has on the strength properties of tropical soils, it is convenient to adopt the size range of 10 - 1500 µm quoted by Trapnell and Webster (1986).

1.2 Occurrence

Microaggregated soils have been reported in both the temperate and tropical zones. Table 1.1 lists some of their reported locations. The methods used to determine microaggregation and, also, the description of the observed microaggregates are aimed at enabling the reader to judge whether the microaggregates are as they occur naturally or are water-stable fragments.

1.3 Origin and formation of microaggregates

Based on Edwards and Bremner's (1967) definition of microaggregates, it is evident that microaggregation is a product of slaking which is the first step in the degradation of soil structure (Collis-George and Lal, 1971). Edwards and Bremner (1967) asserted that the basic structural units in soils of high base status are fine sand- and silt-size microaggregates (mostly < 250 µm diameter).

Organo-mineral associations have been reported to act as binding agents particularly in the aggregates with a diameter < 250 µm (Edwards and Bremner, 1967; Hamblin, 1977; Turchenek and Oades, 1978). Edwards and Bremner (1967) proposed a theory (based on a Mollisol) that depicts microaggregate formation as a solid-phase reaction involving linkage of electrically neutral clay minerals and organic matter particles by polyvalent metals on exchange sites. Below are the conclusions on the 'Microaggregate Theory' advanced by Edwards and Bremner (1967):

"1. The basic structural units in soils of high base status are sand- and silt-size microaggregates (mostly < 250 µm diameter) consisting largely of clay-polyvalent metal-organic matter

Table 1.1 Occurrence of microaggregatsd soils and the methods used for microaggregation identification.

Location	Soil type	Method of determination; description	Reference
Australia (mostly the drier south-eastern Australia: Riverina)	'Red earths', 'red-brown earths, and 'the red ones' (mallee soils)	Kneading; *subplastic soils*. Subplasticity ranked into: *(i)* Subplastic (SP) I *(ii)* SP II and *(iii)* SP III according to classes of texture change over several minutes of kneading.	Taylor & Hooper, 1938; van Dijk, 1958; Churchward, 1963; Beattie, 1970; Collis-George & Lal, 1970; McIntyre, 1976; Hubble et *al*., 1983; van Gestel *et al*., 1991.
Brazil, Madagascar, Malaysia and Zaire	Oxisols	Thin section and Scanning Electron Microscope (SEM); *microaggregates*.	Buol & Eswaran, 1978.
Canada (Saskatchewan)	Mollisol (Chestnut)	Dispersion; *water-stable aggregates*.	Edwards & Bremner, 1967.
Canada	Mollisol	Dry-sieving; *stable microaggregates*.	Gupta & Germida, 1988.
Canada	Alfisol	Dry-sieving; *stable microaggregates*.	Seech & Beauchamp, 1988.
Canary Islands (Tenerife Island)	Inceptisol (Andosol)	SEM; *rounded micropeds*.	Benayas *et al*., 1974.
Canary Islands:			
Tenerife Island	Inceptisol	SEM;	Fedoroff & Rodriguez, 1978.
La Palma	Inceptisol	SEM;	
Central African Republic	Oxisol (Ferrallitic soil)	Thin section; *microped*.	Beaudou, 1972.
Central Cameroon	Oxisol	Thin section; *micronodules*.	Muller, 1977.

Table 1.1 (Contd.)

Location	Soil type	Method of determination; description	Reference
East and Central Africa (Malawi, Kenya, Tanzania, Zaire and Zambia)	Oxisols, Alfisols (*i.e.* Ferrallitic and Ferruginous tropical soils)	Hand lens and low-power microscopy; *microaggregates* 10-1500 μm diameter; Classes: *(i) Fragmental* *(ii)* Intermediate (*meso granular)* *(iii) Microgranular* soils	Trapnell & Webster, 1986.
France	Inceptisols	Thin section; *microfragments* (70-100 μm) *microgranular aggregates.*	Aurousseau, 1978; Fedoroff & & Aurousseau, 1981; Aurousseau *et al.*, 1985.
Ghana, Kenya	Oxisol, Ultisols	Two parallel particle size distribution analyses: *(i)* with and *(ii)* without a dispersing agent; *pseudosand.*	Ahn, 1979.
India (Mysore Plateau)	Alfisol? (Ferruginous)	Wet-sieving; *water-stable microaggregates* < 50 μm.	Rengasamy & Krishna Murti, 1978.
Italy	('PC', 'UD' & 'PT')	Light Laser Scattering; *water-stable aggregates.*	Pini & Guidi, 1989.
Italy	Inceptisol	Dry-sieving; *stable microaggregates* (250 μm - 50 μm).	Piccolo & Mbagwu, 1990.
Ivory Coast	Oxisol	Thin section; *microaggregates* 50 - 100 μm diameter.	Verheye & Stoops, 1975.

Table 1.1 (Contd.)

Location	Soil type	Method of determination; description	Reference
Nigeria	Alfisol/Oxisol (Tropical ferruginous); Vertisol	Dispersion; *water-stable aggregates.*	Nvaka & Voronova, 1980.
Scotland	Inceptisol, Spodosol	Dispersion; *water-stable aggregates, microaggregates.*	Sparling & Cheshire, 1985.
Senegal (middle Casamance)	Oxisol	Thin section; *micronodules.*	Chauvel *et al.*, 1978.
Senegal (Sefa Casamance)	Oxisol	Thin section; *pseudosand.*	Charreau & Fauck, 1970; Charreau & Nicou, 1971.
U.S.A.: New Jersey	'Sandy loam'	Dispersion; *water-stable aggregates.*	Kolodny & Joffe, 1939; Kolodny & Neal, 1941.
U.S.A.: Nebraska	Mollisol	Wet-sieving; *water-stable aggregates.*	Elliott, 1986.
Zambia (former Northern Rhodesia)	Oxisols	Visual, hand lens and low-power microscopy; *'massive' appearance, mealy feel;* aggregates about 50 ïm diameter discerned.	Trapnell, 1957; Webster, 1965.

complexes which may be represented as $[(C\text{-}P\text{-}OM)_x]_y$, where C = clay mineral particle, P = polyvalent metal (*e.g.* Ca, Al, Fe), OM = organo-metallic complex (humified organic matter complexed with polyvalent metals), $(C\text{-}P\text{-}OM)_x$ and C-P-OM represent compound particles of clay size (< 2 μm), and *x* and *y* are finite whole numbers with limits dictated by primary clay particles.

2. The bonds linking the C-P-OM particles into larger $(C\text{-}P\text{-}OM)_x$ and $[(C\text{-}P\text{-}OM)_x]_y$ units are readily ruptured by sonic (or ultrasonic) vibration and can be disrupted by mild shaking treatments if interparticle bonds are weakened in some manner (*e.g.* by substitution of Na for some of the polyvalent metals in these units).

3. The stable microaggregates postulated are formed by a mechanism which is largely a reversal of the process that occurs when soil particles are dispersed by vibration or water shaking. The reversal process can be represented as follows (D = Dispersion, A = Aggregation):

$$[(C\text{-}P\text{-}OM)_x]_y \underset{A}{\overset{D}{\rightleftharpoons}} y(C\text{-}P\text{-}OM)_x \underset{A}{\overset{D}{\rightleftharpoons}} xy(C\text{-}P\text{-}OM)."$$

Edwards and Bremner (1967) concede that the concepts are oversimplified and that other linkages, such as C-P-C, OM-P-OM *etc.* are likely to contribute to aggregation in most soils. Giovannini and Sequi (1976*a*; *b*) selectively extracted Al and Fe from some Italian soils. They postulated that Al and Fe were involved in the linkages (Edwards and Bremner, 1967) which result to the formation and stability of soil microaggregates.

The theory proposed by Edwards and Bremner (1967) is of limited application to tropical soils most of which are of low base status. In the Philippines, Briones and Veracion (1965) reported that the stability of a Philippine 'red soil' increased linearly with clay content up to 50 percent clay, implying that clay is important for binding microaggregates. Elsewhere, Ahn (1979) concluded that since hydrogen peroxide destroys all or nearly all humus, the surviving aggregation in his test was not due to organic matter binding but represented a more intrinsic quality of the mineral soil. He did his test on an Oxisol and three Ultisols. However, Tisdall and Oades (1982) maintained that the water-stability of microaggregates depends on what they called 'persistent' organic binding agents and appears to be a characteristic of the soil, but they agree with Ahn (1979) that the microaggregation is independent of management. Piccolo and Mbagwu (1990) argued that humic substances are the predominant binding agents of microaggregates (< 250 µm diameter) in Inceptisols in Italy. Chaney and Swift (1986) have suggested that humic materials associated with amorphous iron, aluminium and aluminosilicates are the persistent binding agents of microaggregates.

The role of roots and mycorrhiza in the formation of stable aggregates in a Mollisol and Alfisol was suggested by Miller and Jastrow (1990). Dormaar and Foster (1991) examined by transmission electron microscopy the initial genesis of compound particles in the size range 2 - 20 µm. They reported that microaggregates were formed by the fusion of attapulgite-coated bacteria colonies and cell remnants. The aggregates thus formed persisted after the death of the bacteria (Dormaar and Foster, 1991). Many workers (e.g. Elliott, 1986; Gupta and Germida, 1988) have reported the presence of more microaggregates in cultivated than in grassland soils. Buol and Eswaran (1978) asserted that microaggregation is better developed in the more weathered material and better expressed in the ustic moisture regime.

Tisdall and Oades (1982) proposed a hierarchical model of soil structure formation. They suggested that microbial polysaccharides and polysaccharides associated with roots and the microbial biomass in the rhizosphere are involved in the binding of soil microaggregates.

In the Riverina area of south eastern Australia, the property of subplasticity (microaggregation) has been associated with materials described as parna, a calcareous aeolian clay (Butler, 1956; Butler and Hutton, 1956). Brewer and Blackmore (1976) reported positive correlations between subplasticity, strongly oriented clay, dithionite-soluble iron oxide and stability of aggregates. However, Norrish and Tiller (1976) suggested that organic matter may be more important than free iron oxide in forming stable aggregates. Blackmore (1976) contended that the subplastic behaviour of Australian soils arises from some form of cementation between clay particles and between groups of particles. He reported that there was no unequivocal indication of whether increasing subplasticity reflected more cement or stronger cement or a combination of both. Further, Blackmore (1976) reported that there was no evidence of an actual material cement at all, only evidence of physical effects consistent with the presence of a cement. Sherwood

(1967) studied similar soils and suggested that the cement is silica, a possibility accepted by Blackmore (1976).

In Africa, Trapnell and Webster (1986) note that the precise origins and modes of formation of microaggregated structures are not known. They have described parent materials and climates in which some of the microaggregated soils are found. Muller (1977) distinguishes five genetic types of micropeds, namely: network-, ferritic-, zoogenetic-, relict-, and complex-micropeds, and describes how they seem to have developed.

Faunal origin at least for some microaggregated soils is suggested by Trapnell and Webster (1986). They suggest that present and past termite activity may have helped the development of microgranular soils. Topsoil passes through the gut of humus-feeding termites, subsoil is carried upwards by mound-building species and may be cemented with saliva or faecal material, either for mound-building or for the lining of underground passages or for making covered runways on the surface (Lee and Wood, 1971; Pomeroy, 1976; Wielemaker, 1984). Bagine (1984) reported that termites translocated soil at a rate equivalent to one tonne soil per hectare per year in an arid area in northern Kenya. Assuming a bulk density of 1 Mg m^{-3}, this corresponds to approximately 0.1 mm soil depth per year. In the Canary Islands, Benayas et *al*. (1974) reported very intense biological activity and many faecal pellets.

1.4 Effect of microaggregation on soil physical properties, and its persistence with time

Microaggregated tropical soils are claimed to have good acceptance and storage of water, low runoff and relatively low liability to erosion in relation to slope (Ahn, 1979). Piccolo and Mbagwu (1990) also suggested that the 250 - 20 µm fraction may play an important part in limiting soil erosion by water since this fraction is stable against rapid wetting and agricultural practices (Tisdall and Oades, 1982). Gumbs and Warkentin (1975) studied the effect of aggregate size on the amount of water retained at suctions greater than 80 kPa. They found no difference in water retained by aggregates ranging in size from 200 - 400 µm, 840 to 1000 µm and 2000 to 2300 µm diameter. However, Chibber (1964) using stabilized aggregates, reported that the 200 to 1000 µm range had the highest water holding capacity compared to larger sizes.

Nvaka and Voronova (1980) found that ferruginous soils formed on the weathering products of basalt in Nigeria had highly water-stable macroaggregates and microaggregates, and a favourable ratio between aggregate and inter aggregate porosity. They (Nvaka and Voronova, 1980) reported further that the aggregates of these microaggregated soils were loosely packed and bulk density was low. In Zambia, Lenvain and Pauwelyn (1988) studied the physical properties of two oxic Alfisols, one with features resembling those of a hardsetting soil (McDonald *et al.*, 1984), the other with features comparable to a microaggregated soil (Trapnell and Webster, 1986). The 'microaggregated' soil (soil with good physical conditions) had lower bulk density (1.50 Mg m^{-3} at both 10 and 30 cm depths) compared to the 'hardsetting' one (1.71 and 1.76 Mg m^{-3}, respectively at 10 cm and 30 cm depth). Lenvain and Pauwelyn further reported that the available water capacity (θ at pF2-pF3) was 142 mm m^{-1} and 108 mm m^{-1} for the microaggregated and hardsetting soil, respectively. The 'microaggregated' soil had a ten times greater hydraulic conductivity ($K_{unsat.}$) at θ = 0.25 cm^{-3} (0.001 mm h^{-1} for the 'hardsetting' soil and 0.01 mm h^{-1} for the 'microaggregated' soil, respectively). The subsoils of both soil types had better hydrodynamics than the topsoils, implying structural degradation of the top soil (Lenvain and Pauwelyn, 1988). In a Mysore clay loam soil in India, however, Rengasamy and Krishna Murti (1978) reported that hydraulic conductivity was negatively related to clay content and microaggregation.

Microaggregates are useful in minimizing evaporation from the soil which can be very important in the semi-arid regions (Braunack and Dexter, 1989). Hillel and Hadas (1972) reported that under uniform evaporative conditions, minimum water losses occurred from beds containing aggregates with a diameter of 500 - 1000 µm. Under non-isothermic conditions, Hadas (1975) found that beds with aggregates from 500 - 2000 µm diameter gave minimum water losses. Kimball (1973) reported that under field conditions minimum evaporative loss occurred through beds of 1000 µm diameter aggregates.

Hardly any work on the persistence of microaggregation under continuous cultivation has been reported apart from the general observation (*e.g.* by Rengasamy and Krishna Murti, 1978; Tisdall and Oades, 1982) that microaggregates are stable to rapid wetting and agricultural practices. This aspect needs more detailed research.

1.5 Management of microaggregated soils

Because microaggregation is not very sensitive to management (Tisdall and Oades, 1982), it is difficult to create it by normal farming practices. However, systems which conserve organic matter may slowly increase the proportion of microaggregates (Oades, 1984). Based on results from a study of microaggregates from soils that had been amended for several years with pig slurry, cattle slurry and sewage sludge, Piccolo and Mbagwu (1990) concluded that a close relationship exists between aggregate stability and high molecular weight humic substances. They suggested that additions to the soil of organic materials containing high molecular weight constituents would represent a useful management practice to improve aggregate stability. Mbagwu and Bazoffi (1988) also reported that addition of cattle wastes resulted into a positive influence in the stability of microaggregates in three soils in Italy.

1.6 Comments

1. In the literature there is no single clear definition of microaggregation or microaggregated soils. Even the term 'pseudosands' appears to carry a different connotation when used, for example, in Canada (Arocena and Pawluk, 1991) and in Africa (Ahn, 1979). There is, therefore, an urgent need to produce a standard definition of microaggregation.

2. It is clear that in some microaggregated soils inorganic materials are responsible for microaggregation whereas in others organic matter or organo-mineral complexes are responsible. It is probably worth distinguishing between the

two sources of microaggregation. It is also important to better study the role of biological processes in microaggregate formation and stability.

3. Depending on the circumstances, a number of mechanisms for microaggregate formation are possible.

4. The water-stability of soil fragments should not be taken in isolation as an indication of the existence of soil microaggregates.

CHAPTER 2

MATERIALS AND METHODS

2.1 Site details

Five sites, covering soils ranging from strongly microaggregated to ones that are hardsetting, were selected in the southern highlands of Tanzania (Iringa and Mbeya Regions). Sites were selected based on field observation of soil microstructure using a handlens, laboratory examination with a binocular microscope and considerations of accessibility and the degree of experimental control. Soils considered were only those in the 4 regions within the research mandate of the Uyole Agricultural Centre (U.A.C.). The location of the 5 sites within Tanzania are shown in Figure 2.1. Table 2.1 shows the general characteristics of the soils at these sites. The soils selected are representative of many soils in the southern highlands and the soils in the four biggest grain producing regions in Tanzania: Iringa, Mbeya, Rukwa and Ruvuma Regions. The following sections describe the details of each site.

At each site two areas (treatments) were selected representing soil that was under permanent cultivation and had been for some time and soil that had never been cultivated or for which there was no record of cultivation in the past 7 or more years. An attempt was made to ensure that, apart from the treatments, the paired soils were otherwise similar (*e.g.* in texture). The distance between the two treatments at Ismani was about 20m while at Magamba, Mbimba, Sao Hill and Ukwile the two treatments were about 20m, 50m, 40m and 500m apart, respectively. For convenience these treatments are hereafter

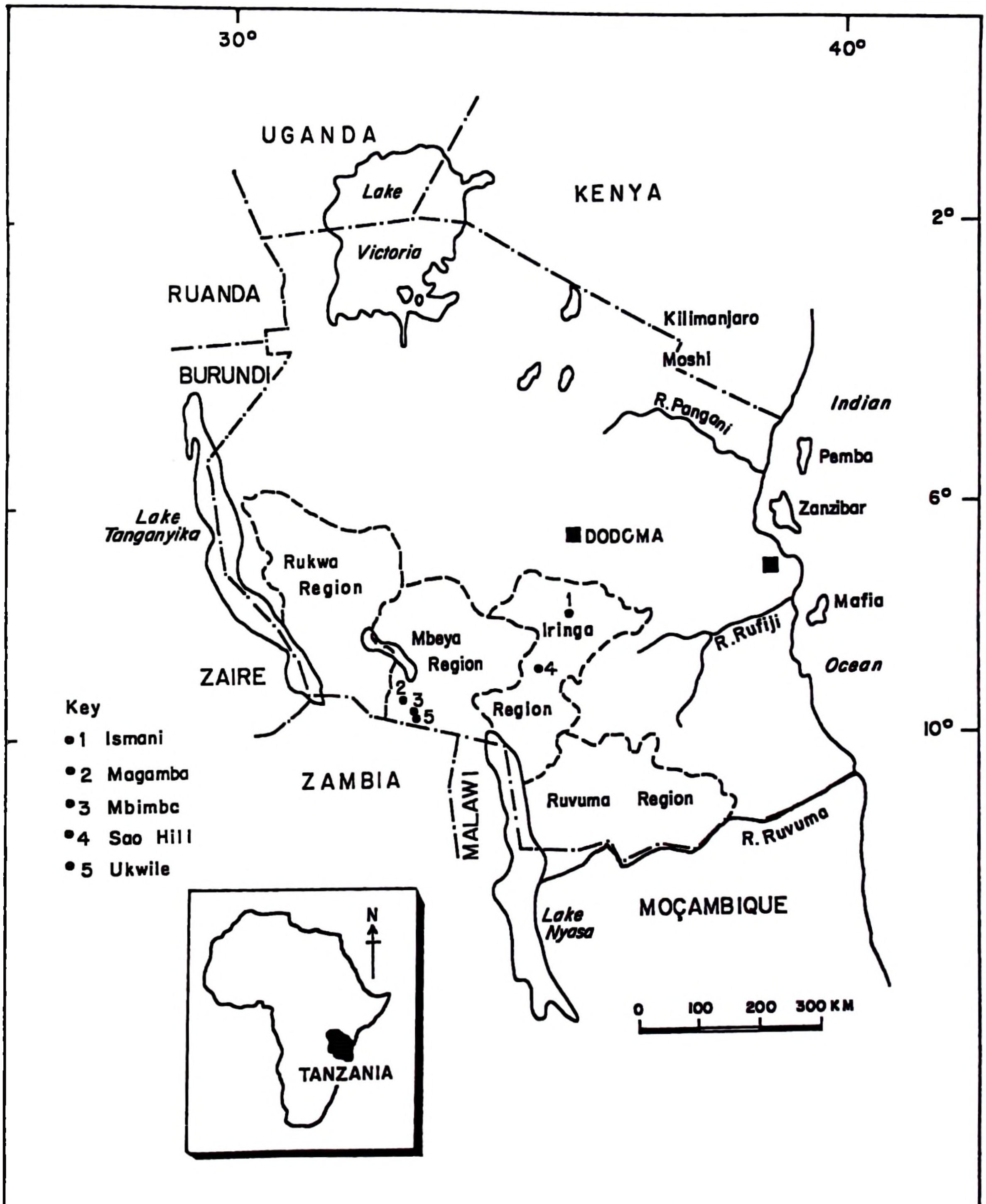


Figure 2·1 Map of Tanzania indicating regions under the research mandate of the Uyole Agricultural Centre and the sites sampled (•).

Table 2.1 Site details

Site and Location	Classification[1]	Estimated altitude (m)	Rainfall (mm a^{-1})	Soil textural class name	Soil microstructure
Ismani 6°51'S, 35°29'E	Paleustalf (Eutric Nitosol)	1370	550	Sandy clay loam	Hardsetting
Magamba 9°25'S, 32°39'E	Paleudoll (Luvic Phaeozem)	1530	1000	Clay loam	Intermediate
Mbimba 9°31'S, 32°55'E	Paleudalf (Eutric Nitosol)	1650	1100	Clay	Intermediate
Sao Hill 8°47'S, 34°58'E	Orthox (Xanthic Ferralsol)	1860	1000	Sandy clay	Strongly microaggregated
Ukwile 9°43'S, 32°53'E	Paleustult (Acrisol)	1460	1000	Clay	Well microaggregated

1 Classification is according to US taxonomy (FAO in brackets)

referred to as 'cultivated' and 'fallow' treatments, respectively. Information given on the timing and ease of cultivation for each site was obtained from discussions with the local station managers, farmers and other local staff and from a small experiment conducted before the main study. Soil microstructural descriptions are those given by Dr. Webster, according to the system of Trapnell and Webster (1986).

2.1.1 Ismani

Ismani is a substation of the U.A.C. The site lies 30 km north of Iringa town at an altitude of about 1370 metres above sea level and receives an annual rainfall of about 550 mm (Table 2.1). This rain falls within a period of 3 to 4 months from December to March/April. The site is near the bottom of a long gentle slope with fresh rock (basic gneiss) on an erosion surface well below the plateau at Iringa (1560 m). The soil is dark red clay down to 1.2 m over partly weathered rock. Plate 2.1 shows a soil profile pit dug on the site. Although the soil has a microstructure tending towards microgranular, it has physical properties that are closer to hardsetting than the friable behaviour expected of a microaggregated soil. The Ismani soil cannot be dry-cultivated even by tractor although dry-planting would be an advantage if it could be done. A brief description of the soil structure in the soil profile dug on the Ismani site is provided in Table 2.2. The cultivated treatment was located on plots which had been under continuous cultivation for more than 10 years. In the 1988/89 and 1989/90 seasons, these plots were under maize followed by beans. The fallow treatment was

Plate 2.1 Profile pit of hardsetting soil at Ismani. Note the impressions left on the pit face by the pick axe.

conducted on plots which had been left uncultivated (under natural grass) for at least 10 years. The fallow and cultivated treatments were adjacent to each other.

Table 2.2 Profile description of the Ismani soil (after R. Webster and M.A. Oliver, 1991; unpublished)

Location:		In fallow area, adjacent to fallow treatments.
0-22 cm:		Plough layer.
	Colour:	2.5YR 3/4 - dry.
	Structure:	Microaggregates less than 1 mm and bleached sand grains about the same size linked by clay bridges; porous. Network of sparse cracks 1 mm wide with 2-10 cm separation. Cracks are often discontinuous.
	Clay skins:	Weakly developed along root channels.
	Texture:	Sandy clay.
	Roots:	Frequent.
	Consistence:	Hard when dry, friable when moist.
22-120 cm:		Gradual change from above.
	Colour:	2.5YR 3/6
	Structure:	Compound structure of blocky peds 0.5 to 1 cm and microaggregates 0.5 mm and less. Quartz grains visible. Ped faces weakly developed.
	Clay skins:	Moderately developed on pedfaces, moderately developed in pores.
	Texture:	Clay.
	Roots:	Few.
	Consistence:	Hard when dry, friable when moist.

120–142 cm:		Fairly sharp change.
	Colour:	2.5YR 3/6.
	Structure:	Compound structure of blocky peds and few microaggregates. Rock fragmented to 2–3 cm fragments. Rock fragments platy and tubular and more-or-less *in situ*.
	Clay skins:	Frequent, moderately developed.
	Texture:	Clay loam.
	Roots:	None.
	Consistence:	Hard when dry, firm when moist.
142 cm + :		Augered into soft weathered rock. Some soil intermixed with the rocks. Rock disintegrated to its individual crystals when crushed between fingers. Ferromagnesian minerals and feldspars. Below 181 cm weathered rock becomes paler, quartz-rich. At 188 cm hit more resistant quartz-rich material.

2.1.2 Magamba

This site is within the Mbozi Maize Farms Ltd., some 30 km north-west of Mlowo on the main road (Mlowo is about 40 km south-west of Mbeya town). The site has an average altitude of 1530 m, with an annual rainfall of about 1000 mm per annum (Table 2.1). The rain falls from October to April/May. The landscape is a very gently undulating plateau with a relief of no more than about 30 m. The soil is typically clayey plateau soil which seems to be underlain by laterite for much of its extent. The experimental site itself lies on the plateau only some 50 m from the foot of a small quartzite inselberg. The soil has a dark brown sandy clay top horizon over a reddish brown clay. Its structure is dominated by microaggregates (tending towards fragmental), but some larger weak blocky peds exist in the subsoil. The soil is difficult to dry-cultivate even with a tractor when under continuous maize. The fallow plots had been under natural grass for more than 10 years whereas the cultivated plots had been under continuous cultivation for more than 10 years. In the 1989/90 growing season, the plots allocated to the cultivated treatment were under sunflowers. The fallow and cultivated plots were established adjacent to each other. The profile description for the Magamba soil is given in Table 2.3. As with the Ismani profile pit, the profile pit and Magamba was dug in the fallow area.

Table 2.3 Profile description of the Magamba soil (after R. Webster and M.A. Oliver, 1991; unpublished).

Location:		In fallow area, adjacent to fallow treatments.
0-18 cm		Organic rich layer.
	Colour:	7.5YR 3/2.
	Structure:	Weak granular, dominantly microaggregated.
	Texture:	Sandy clay.
	Roots:	Many.
	Consistence:	Friable.
18-69 cm		Boundary between topsoil and subsoil is fairly sharp and is wavy because of variation in thickness.
	Colour:	5YR 3/4 - dominant with few redder patches.
	Structure:	Compound, weak blocky with microaggregation.

Clay skins: Weakly developed on pedfaces - colour darker - 5YR 3/2.

Texture: Clay.

Roots: Frequent.

Consistence: Firm.

69-97 cm: Gradual change from above.

Colour: 5yr 3/4.

Structure: Entirely microaggregated.

Clay skins: Fewer than in the horizon above and weak.

Texture: Clay.

Roots: Frequent.

Consistence: Friable.

97-156 cm: Sharp change.

Colour: 5YR 3/3. Colour not uniform.

Structure: Massive with cylindrical or round pores.

Clay skins: On surface of rock, well developed; evidence of water movement along these.

Texture: Sandy clay loam.

Roots: Sparse.

Consistence: Brittle, dense.

- Large stones in this horizon, schistose gneiss-quartzite. Found reddish weathered gneiss in this layer.

2.1.3 Mbimba

Mbimba is the Uyole Agricultural Centre's substation near Mbozi, some 50 km south-west of Mbeya town. It was chosen as a possible 'spare' site and was, subsequently, planted as an insurance measure against mishaps on the Magamba or Ukwile sites. It is by the main road occupying almost level ground on the Mbozi plateau at 1650 m. The flora in the uncultivated land is characterized by *Pteridium*. The topsoil is dark grey brown, rich in organic matter to 30 cm, over dark reddish-brown clay loam. The soil has a pH of 5.4, the most acid in the district. The surface soil is very porous, easily crumbled but with microaggregates that are stable on wetting. The surface structure remains intact during rain. Mbimba receives about 1100 mm of rainfall annually, falling between November and May, with some lighter rains in August and September. The plots allocated the fallow treatment were adjacent to a planted forest of cypress trees and had been under natural grass for about 10 years. The cultivated plots were in a part of the site which had been under continuous cultivation for the last 15 years. The distance separating the fallow plots from the cultivated ones was not more than 50 m. Information on the general characteristics of Mbimba site appears in Table 2.1. No profile description was obtained for this site.

2.1.4 Sao Hill

This site belongs to the Sao Hill National Forest Project. It lies on the main Southern Highland plateau at 1860 m, some 90 km south-west of Iringa town. The site is on a plateau with convex interfluves. Granite is exposed on the lower slopes towards valley bottoms. The remnants of natural vegetation (*e.g. Brachystegia spiciformis*) suggest that formerly it carried miombo woodland. The soil is yellow clay to at least 2 m. Its structure consists entirely of stable microaggregates, referred to as microgranules (Trapnell and Webster, 1986) and larger pellets which lack internal structure. The soil was very porous and strongly sub-plastic in the Australian (Butler, 1955) terminology. This deep plateau soil [Ferrallitic in D'Hoore's (1964) classification] is typical of much of the land at this level. The average annual rainfall at Sao Hill is about 1000 mm, most of which falls between December and March. Both the fallow and cultivated land can be dry-cultivated by hand, oxen or tractor-drawn implements. The fallow plot was last ploughed (but not planted with any crop) in 1984 (7 years previously) while the cultivated plot had been under continuous maize for more than 10 years. In the 1989/90 season it was under a maize/beans intercrop.

Tables 2.1, 2.4 and Plate 2.2 show, respectively, the general characteristics of the site, profile description of Sao Hill soil and the profile pit dug on the fallow area at Sao Hill.

Table 2.4 Profile description of the Sao Hill soil (after R. Webster and M.A. Oliver, 1991; unpublished).

Location:	Fallow area, adjacent to fallow treatments.
0-26 cm:	Plough layer. Organic staining with extensions to 55 cm along old root channels.
Colour:	10YR 4/3.
Structure:	No macrostructure. Microgranular structure with pellets 0.5 to 1 cm in diameter. Pellets are much denser than the surrounding soil. Microaggregation dominates.
Clay skins:	None.

Texture: Sandy clay loam.

Roots: Frequent.

Consistence: Very friable, subplastic.

26-61 cm: Changes gradually from plough layer.

Colour: 7.5YR 5/6.

Structure: As for plough layer.

Clay skins: None.

Texture: Sandy clay.

Roots: Few.

Consistence: Friable, subplastic.

61-181 cm: Changes gradually from above level.

Colour: 7.5YR 5/8.

Structure: As for plough layer.

Clay skins: None.

Texture: Sandy clay.

Roots: Few.

Consistence: Friable, subplastic.

181 cm + : Changes gradually from above.

(Augered)

Structure: Microaggregation still present but soil more compact.

Clay skins: None.

Texture: Clay.

Roots: Could not record from auger sample.

Consistence: Friable.

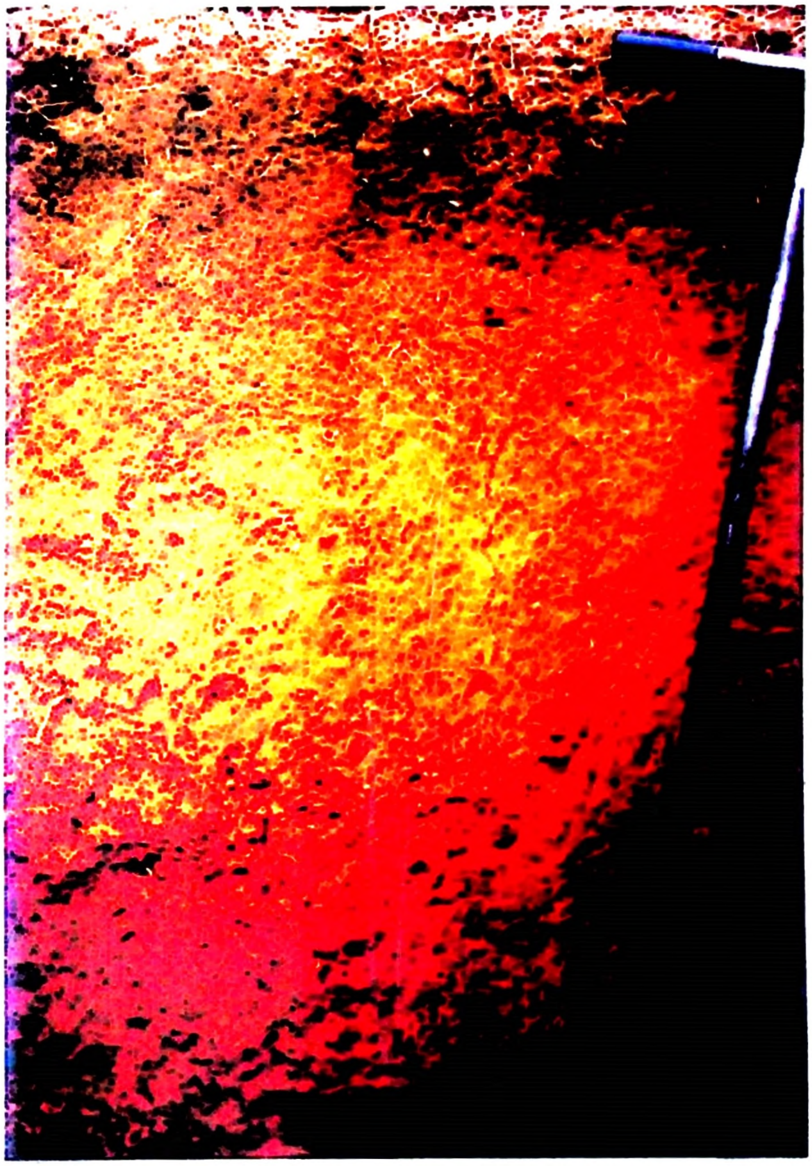


Plate 2.2 Profile pit of microaggregated soil at Sao Hill.
Note the friable appearance.

2.1.5 Ukwile

The site is within the Mbozi Agricultural Development Project (A.D.P.) Farm, some 20 km south-west of Mbozi (about 70 km south-west of Mbeya town). It lies on very gently sloping ground at about 1460 m on the edge of the main Mbozi Plateau. The average annual rainfall is about 1000 mm and falls between November and May, with some light rains falling from August to/or September. The vegetation is now grassland with widely spaced well-grown *Parinari curatellifolia*, regenerating miombo trees and saplings. The soil is red clay with a compound structure of microaggregates and larger blocky peds; it has a sticky consistence when wet. The microstructure is characteristically fragmental. The subsoil has small weakly developed clay skins. The fallow land can only be cultivated with a tractor when dry. On the other hand, land that has been under continuous cultivation can be dry cultivated even by hand. The fallow plots adopted for the study had been uncultivated for 10 years until 1988 when the land was disc-ploughed but not planted to any crop. The land on which the cultivated treatment was located was first cleared and cultivated in 1979, sown to beans for 2 seasons then, alternately, sown to maize and beans. In the 1989/90 growing season, the cultivated plots had beans. The general characteristics of the Ukwile site are shown in Table 2.1. Table 2.5 shows the soil profile description at Ukwile. The profile pit was located near to the fallow plots, 5 metres from the nearest fallow replicate.

Table 2.5 Profile description of the Ukwile soil (after R. Webster and M.A. Oliver, 1991; unpublished)

Location:		Near to the fallow plots in the fallow area.
0-20 cm :		Organic staining.
	Colour:	2.5YR 3/3.
	Structure:	Moderate blocky and microaggregation well developed.
	Texture:	Clay.
	Roots:	Frequent.
	Consistence:	Friable.
20-74 cm:		Gradual change from above.
	Colour:	2.5YR 3/5.
	Structure:	Weak blocky - 0.5 - 1 cm in size with blocky microaggregates. Network of fine cracks about 5 cm apart giving rise to a large scale weak blocky structure.
	Clay skins:	Moderately developed. Their colour is darker than the main body of the soil.
	Texture:	Clay.
	Roots:	Few.
	Consistence:	Firm.
74-157 cm:		Gradual change from above, but cracking stopped at 74 cm because moist at this level.
	Colour:	2.5YR 3/5.
	Structure:	Dominantly microaggregated with few weakly developed larger blocky peds.

Clay skins: Present on cleavage faces (microaggregate surfaces).

Texture: Clay.

Roots: Sparse.

Consistence: Friable.

157-267 cm: Gradual change; augered to 267 cm.

Colour: 2.5YR 5/6.

Structure: Microblocky.

Clay skins: Small, on microaggregate surfaces.

Texture: Clay.

Roots: Could not count roots on augered sample.

Consistence: Friable.

2.2 Methods

2.2.1 Location of plots

The locations of duplicate fallow and cultivated plots were chosen to be as similar in topsoil and subsoil texture as possible. Uniformity of soil texture between and within the fallow and cultivated plots at each site was established by visual inspection as well as by hand texturing.

Two relatively uniform subplots measuring 8.1 m by 12.0 m were demacarted to form two replicates for each treatment at each site.

2.2.2 Rainfall stations

At each site, with the exception of Mbimba, a tipping-bucket raingauge (Environmental Measurements Ltd., type ARG 100) capable of measuring 0.02 mm rainfall, and a data logger (Grant Instruments

Ltd., type: Squirrel SQ32 IVI 1A) were installed before the start of the growing season. The dataloggers were installed in underground concrete boxes with lockable lids to avoid vandalism. In all stations the distance from the rainfall station to either treatment was not more than about 500 m. At the Mbimba site rainfall data was obtained from a non-recording raingauge belonging to the substation. Plate 2.3 shows the rainfall station at Ukwile.

2.2.3 Land preparation, sowing and yield

Dates of all field operations are given in Table 2.6 (section 2.2.5).

At the Ukwile site both the fallow and cultivated plots were ploughed by an oxen drawn mouldboard plough, a common local practice in Mbozi District. Plots at Ismani, Mbimba and Sao Hill were disc-ploughed with a tractor. Due to problems of the availability of both oxen and tractors, the fallow plots at Magamba were cultivated using a hand hoe while the cultivated plots were disc ploughed by tractor. At all sites harrowing was not done. This is normal practice. Maize was used as the test crop. At Ismani variety Ukiriguru Composite A (UCA) was used because it does well even under low rainfall regimes. In the remaining four sites maize hybrid (H614) seed was sown by dibbling at a spacing of 30 × 90 cm. Two seeds were put into each hole. At two weeks after emergence, the seedlings were thinned to one plant per hole, giving a population of about 37 000 plants ha^{-1}. Phosphate fertilizer in the form of triple superphosphate was applied at a rate of 40 kg P ha^{-1} before planting. Urea was applied at a rate of 120 kg N ha^{-1} in a split

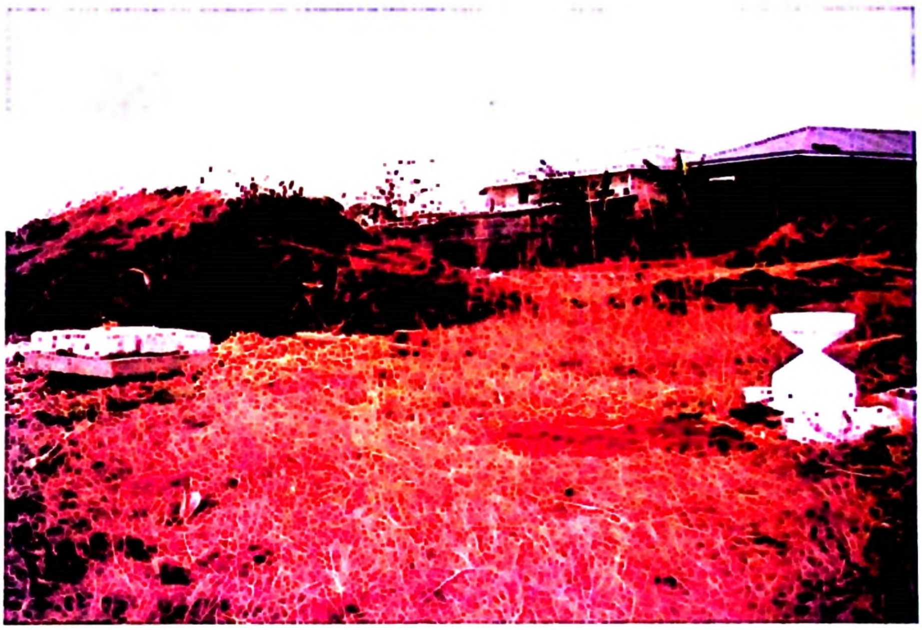
(b)  (a)

Plate 2.3 Rainfall station at Ukwile:
(a) raingauge
(b) concrete lid on top of concrete box housing the data logger.

application: 1/3 at planting, 2/3 at four weeks after emergence. Birds and mice were major pests especially in the fallow plots. Scarecrows were used but to little effect. Maize was harvested and maize yield was expressed at 14% moisture content.

2.2.4 Collection and storage of soil samples

Dates of sample collection are given in section 2.2.5.

2.2.4.1 Minicores

Undisturbed soil minicores were sampled using equipment designed to ensure easy and rapid transfer of soil cores from the corer to a split-mould in the field (Young *et al.*, 1990). Figure 2.2 shows the minicorer. The corer is made of brass and has one end tapered to a 10° angle to minimize compaction within the core during coring.

The sleeve facilitated the transfer of the soil sample from the corer to the split-mould and was made of brass. One end of the sleeve was recessed to allow the split-mould to sit within the sleeve during core transfer. During coring in the field the sleeves were held together by one layer of sellotape.

The inner wall of the brass corer was smeared with a very thin layer of cooking oil to minimize friction with the soil and, thus, compaction. Compaction was further minimized by starting coring at approximately 20 mm depth (top 20 mm of soil cleared) and finishing about 20 mm below the required finishing depth. Coring in this fashion enabled sampling from the middle portion thus minimizing the

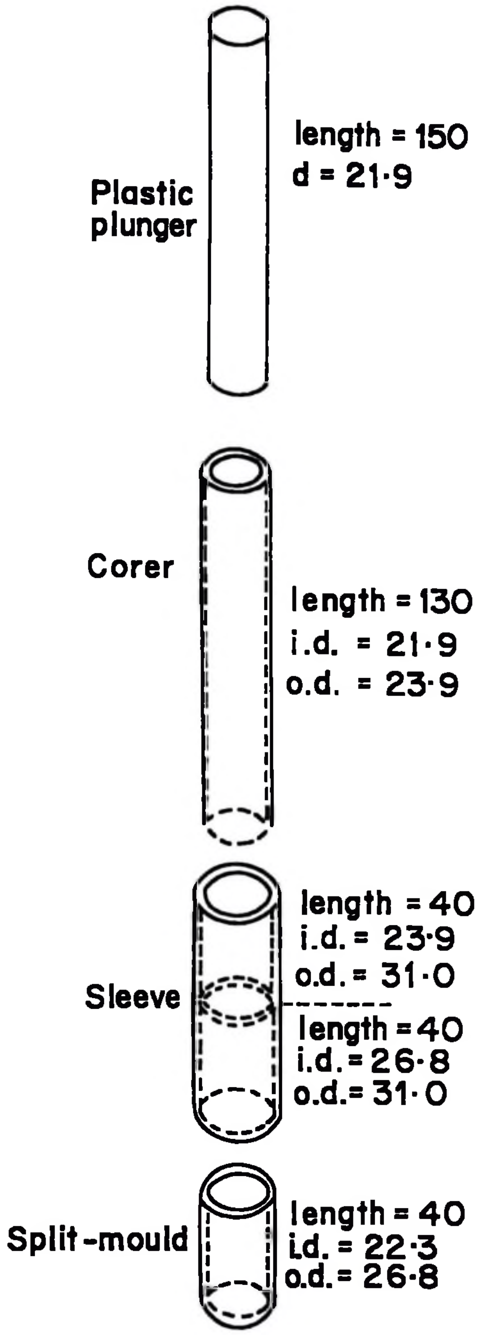


Figure 2·2 Devices used for sampling minicores, all dimensions in mm (after Young et al.,1990).

compaction experienced at either end of the sample during coring and transfer of the core to the mould.

Starting at 20 mm below the surface, the corer was carefully pushed into the soil, tapered end first, at a slow but uniform rate with a flat-ended piece of wood. Care was taken to ensure the corer was perpendicular to the soil surface and that the resultant core surface within the corer was level with the soil surface outside the corer. Where excessive (> 2 mm) compaction had occurred during coring, the core was discarded. Thus no cores were compacted by more than 5% of their length. When it was not possible to avoid compaction altogether, compaction was recorded and corrected for when calculating dry bulk density. Minicores were taken at the depths of 20 - 60 mm (top soil), 80 - 120 mm (mid-cultivation depth) and 300 - 340 mm (about 100 mm below cultivation depth). After inserting the corer to the desired depth, the corer was twisted sharply to sever the base of the core and then it was gently pulled out. Next, the corer was placed into the brass sleeve and the split mould was placed into the opposite recessed end. The minicore was carefully slid into the split mould using the plastic plunger until 20 mm of soil protruded beyond the end of the sleeve. The protruding part was cut off and the minicore levelled using a scalpel. The corer was finally used to push the split mould out of the brass sleeve. The remainder of the minicore was pushed out of the brass corer and cut off level with the other end of the mould. Both ends of the mould containing the minicore were sealed with tight-fitting plastic caps. The minicores were carefully packed into polystyrene-lined boxes and transported carefully to the laboratory where they were placed into plastic bags and stored in a cold room at 5°C until needed.

Minicore samples taken before cultivation were from patches which had been prewetted because the soil was, otherwise, too dry for the corer to penetrate. In each replicate plot, an area about 60 cm × 60 cm was cleared and an embankment about 20 cm high was built around it, forming a 'pond'. Grass was then put into the 'pond' to avoid water splashing and compacting the soil. Water was then gently poured into the pond until the soil was wet to a depth of more than 360 mm. This took about 200 l water and a period of about 6 to 8 hours. The soil was then left for 12 - 14 h for the excess water to drain off before minicore sampling.

As an absolute minimum 10 minicores were collected from each subplot for each depth: before planting, shortly after planting and towards the end of the physiological maturity of the test crop. Minicores from a depth of 300-340 mm were collected only once assuming that physical conditions at this depth did not vary significantly from season to season.

2.2.4.2 Needle penetrometer cores

Cores for needle penetration resistance measurement were sampled twice from a depth of 55 - 95 mm: during the early stages of maize establishment, and towards the end of the growing season; and once from a depth of 220 - 260 mm.

Six undisturbed cores per subplot were taken from the appropriate depth by carefully driving into the soil sharpened steel cores with internal diameter and length of 56 and 40 mm, respectively. The top 50 mm of soil was cleared and then the corer was pushed into the soil, sharpened end first, with the aid of another corer (blunt end sitting on blunt end of the lower corer) and a piece of wood until about 5 mm of soil protruded above the lower core. The core was then carefully dug up using a field knife and panga. Both the lower and upper edges of the core were trimmed flush using a scalpel. These cores were sealed at both ends using tight fitting caps. They were transported to the laboratory in sponge-lined boxes and stored in sealed plastic bags at 5°C until needed. The sampling positions are shown in Figure 2.3.

2.2.5 Dates of field operations, sampling and measurements

Table 2.6 shows the dates during which different samples were collected from the field. It also shows the timing of various field operations/measurements.

2.2.6 Field measurements

2.2.6.1 Field penetrometer resistance, matric potential and water content determinations

Penetrometer resistance (PR) was measured in the field with a hand-held penetrometer (Leonard Farnell & Co. Ltd.). The penetrometer was fitted with a cone with a 15° semi-angle, 129 mm^2 end area and had a relieved shaft. Its operating limit was 5.6 MPa. Penetrometer readings were taken at 75 mm - depth intervals to 375 mm, 10 cm from the plant base. Twelve penetrations were made in each subplot both at the early stage of maize growth and at the middle stage and/or towards the end of the growing season. Individual penetrometer measurements within a row were located 1.2 m

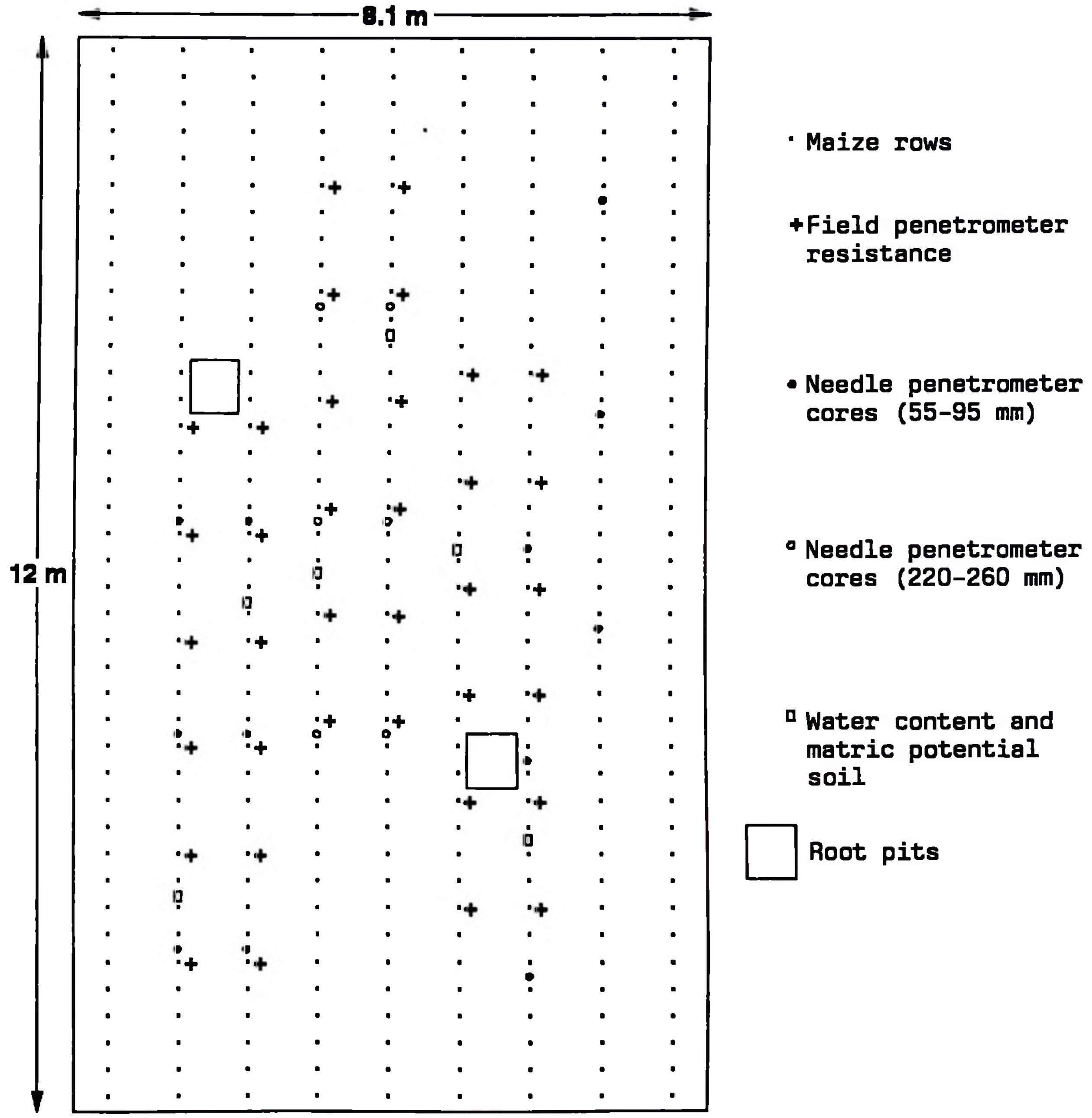


Figure 2.3 Locations for needle and field penetrometer resistance, matric potential and roots measurements.

Table 2.6 Sampling dates and timetable for field operations. Key: F1, application of TSP and first dose of urea; F2, second dose of urea; Pf, field penetrometer resistance, matric potential and water content; Pn, needle penetrometer resistance; R, roots count; So, maize sowing; Sti, indirect tensile and unconfined compressive strength.

(a) Ismani site

Date	Fallow Plots	Cultivated Plots
23-25.05.90	Cleared the plots	
11.07.90	Sti	
23.10.90	Rainfall station established	
17.11.90	Difficulty of cultivation in dry season test	
23.11.90		Sti
21.12.90	Ploughed	
28.12.90		Ploughed
03.01.91	So,F1	So,F1
22.01.91	Pf,Pn (55-95 mm)	
23.01.91		Pf,Pn (55-95 mm)
11.02.91	F2,Pf,Pn (220-260 mm),Sti	F2,Pf,Pn (220-260 mm),Sti
11.03.91	Pf	Pf
12.03.91	R	R
27.03.91	Pf	Pf
11.05.91	Pn (55-95 mm),Sti	Pn(55-95 mm),Sti
02.07.91	Harvested	

(b) Magamba site

Date	Fallow Plots	Cultivated Plots
01-03.07.90	Cleared	
05.07.90	Sti	
09.10.90		Cleared
25.10.90	Rainfall station established	
07.11.90	Difficulty of cultivation in dry season test	
08.11.90		Sti
20.11.90		Ploughed
15.12.90	Ploughed	
20.12.90	So,F1	So,F1
19.01.91	Resowed (part)	
04.02.91	F2,Pf	F2,Pf
23.02.91	F2 (for resowed part)	
23.03.91	Pf,Pn (55-95 & 220-260 mm), R,Sti	Pf,Pn (55-95 & 220-260 mm), R,Sti
10.04.91	Sti	Sti
26.05.91	Pf,Pn (55-95 mm), Sti	Pf,Pn (55-95 mm), Sti
21.07.91	Harvested	

(c) Mbimba Site

Date	Fallow Plots	Cultivated Plots
23-24.06.90	Cleared	Cleared
25.06.90	Sti	Sti
05.11.90		Ploughed
10.11.90	Difficulty of cultivation in dry season	
17.12.90	Ploughed	
19.12.90	So,F1	So,F1
23.01.91	F2	F2
20.03.91	Pf,Sti	Pf,Sti
21.03.91	Pn (55-95 mm), R	Pn (55-95 mm), R
10.04.91	Pn (220-260 mm)	Pn (220-260 mm)
18.05.91	Sti	Sti
19.05.91	Pn (55-95 mm)	Pn (55-95 mm)
21.05.91	Pf	Pf
28.07.91	Harvested	Harvested

(d) Sao Hill site

Date	Fallow Plots	Cultivated Plots
12-13.10.90	Cleared	Cleared
29.10.90	Rainfall station established	
19.11.90	Difficulty of cultivation in dry season	
20.11.90	Sti	Sti
21.11.90		Ploughed
27.12.90	Ploughed	
01.01.91	So,F1	So,F1
23.01.91		Pn (55-95 mm)
24.01.91	Pf,Pn (55-95 mm), Sti	Pf,Sti
12.02.91	F2,Sti	F2,Sti
13.03.91	Pf,Pn (220-260 mm), Sti	Pf,Pn (220-260 mm), Sti
27.03.91	Pf	Pf
10.05.91	Pn (55-95 mm), Sti	Pn (55-95 mm), Sti
11.05.91	Pf, R	Pf, R
02.08.91	Harvested	Harvested

(e) Ukwile site

Date	Fallow Plots	Cultivated Plots
18.06.90	Cleared	
20-21.06.90	Sti	
06.09.90		Cleared
08.09.90		Sti
13.09.90	Rainfall station established	Rainfall station established
15.11.90		Ploughed
18.12.90	Ploughed, So,F1	So,F1
21.01.91	F2	F2
25.01.91	Pf,Pn (55-95 mm)	Pf,Pn (55-95 mm)
22-23.03.91	Pf,R,Sti	Pf,R,Sti
19.05.91	Sti	Sti
20.05.91	Pf,Pn (55-95 mm)	Pf,Pn (55-95 mm)
16.07.91	Harvested	Harvested

apart. Locations of field penetrometer resistance measurements have already been shown in Figure 2.3. At the same time, duplicate soil samples were collected from 75 mm and 225 mm depths from each subplot, within the rows from which penetrometer measurements were taken (see Figure 2.3). The soil samples were placed in pre-labelled pre-weighed heat resistant (autoclavable plastic) bottles (64 mm diameter, 50 mm deep) with labelled 55 mm diameter Whatman No. 42 filter papers for the determination of water content and matric potential. During sampling, the sampling locations were shielded from direct sunlight. Sampling was done immediately after exposing the soil. Each sample was taken by half-filling the plastic bottle with loose soil, placing the filter paper on top of the soil, then adding just sufficient soil to fill the container when the lid was screwed down. Each container was taped with masking tape to minimize loss of moisture. The sealed containers were immediately placed in a thermally insulated (picnic) box that was kept shaded both in the field and during transport to the laboratory. The lagged box was kept in a constant temperature room and left to equilibrate for 3 to 7 days depending, respectively, on whether the soil was moist or dry. The insulated box was inadequate when placed on a concrete floor but was found to work satisfactorily when placed on a 2 cm layer of expanded polystyrene. After equilibrium was reached, each filter paper was removed with tweezers. Any loose soil adhering to it was brushed off with an artist's paint brush. The filter paper was transferred into a pre-labelled pre-weighed bottle whose cap was quickly screwed down. This transfer was carried out in a cardboard box whose base and sides were lined with paper towels to provide high humidity to avoid loss of vapour from the filter papers. The whole procedure took about 20 seconds. The bottles with filter papers were weighed, then dried overnight at 105°C (after removing the caps). After drying the bottles plus caps were reweighed with and without the papers and the gravimetric water content of each filter paper was determined. This was converted to matric potential using a calibration curve previously determined as described by Fawcett and Collis-George (1967, see below). The gravimetric water content of the soil in the plastic bottles was also determined by drying at 105°C.

Calibration of the filter papers: The calibration was performed using the same 10 boxes of Whatman No. 42 filter papers with a single batch number that were used for the experiment. Sets of 10 filter papers, one from each box, were calibrated at each of three matric potentials: -1, -10 and -64 kPa using a tension table. Because of hysteresis and since the papers were intended to be used on a wetting curve, the filter papers were also calibrated on a wetting curve. A set of ten filter papers was placed on the flat, porous ceramic plate of a tension table which had been equilibrated for at least 8 h at the required potential. The papers were covered with a polythene sheet, a thick sheet of glass, and a set of weights evenly distributed to apply a pressure of approximately 1.5 kPa (see Greacen et *al.*, 1987). The whole assembly was covered to prevent evaporation and allowed to equilibrate for 7 days. Papers were then removed with tweezers one by one, transferred to sealed, preweighed weighing bottles, and weighed to the nearest mg. Because the filter papers can suffer significant water loss, papers remaining on the tension table were kept covered by the plastic sheet. The transfer to, and closing of the weighing bottles was performed within 20 s. After drying overnight at 105°C, the bottles were weighed with and without the papers and their water contents (*m*) were determined.

In common with other workers (*e.g.* Fawcett and Collis-George, 1967; Greacen *et al.*, 1987; Greacen et *al.*, 1989) I plotted the logarithm of matric suction *versus* water content and fitted two straight lines: one for the small matric suction obtained from the calibrated papers, and one for the large matric suctions using Fawcett and Collis-George's (1967) values. Greacen *et al* (1987) suggested that the function given by Fawcett and Collis-George (1967) for large matric suctions may be used as a universal calibration function. They supported this by plotting some of the results obtained by McQueen and Miller (1968). I, therefore, used the calibration function given by Fawcett and Collis-George for large matric suctions.

Since matric potential (ψ_m) is held at an accurately known value during calibration while *m* is variable, I regressed *m* on $\ln(|\psi|_m)$ and inverted the resulting equation to derive my calibration functions (Webster, 1989).

2.2.6.2 Root measurements

Root distribution was determined by the trench profile method of Bohm (1979). Two pits were dug in each subplot, each in between two rows of maize. The pits were 60 cm deep and 60 cm long to accommodate a frame 0.5 × 0.5 m (inner dimensions) which supported 10 × 10 cm wire grids. The walls of the pits were dug parallel to the rows of maize and cut back to within 10 cm of the stems. A field knife was used to remove a few millimetres of soil from the face of the pit to reveal all protruding roots which were then counted. Unusual features such as cracks on the pit wall, holes (whether made by termites or by rotting tubers), the diameter of abnormally thick roots *etc.* were recorded. Plate 2.4 shows the equipment used for counting roots.

2.2.7 Difficulty in cultivation during the dry season

Duplicate strips (1 × 10 m) were cultivated with a hand hoe during the dry season. The depth of cultivation achieved and the time taken were recorded as well as the water content and matric potential of the soil at 0 - 10 and 10 - 20 cm depth.

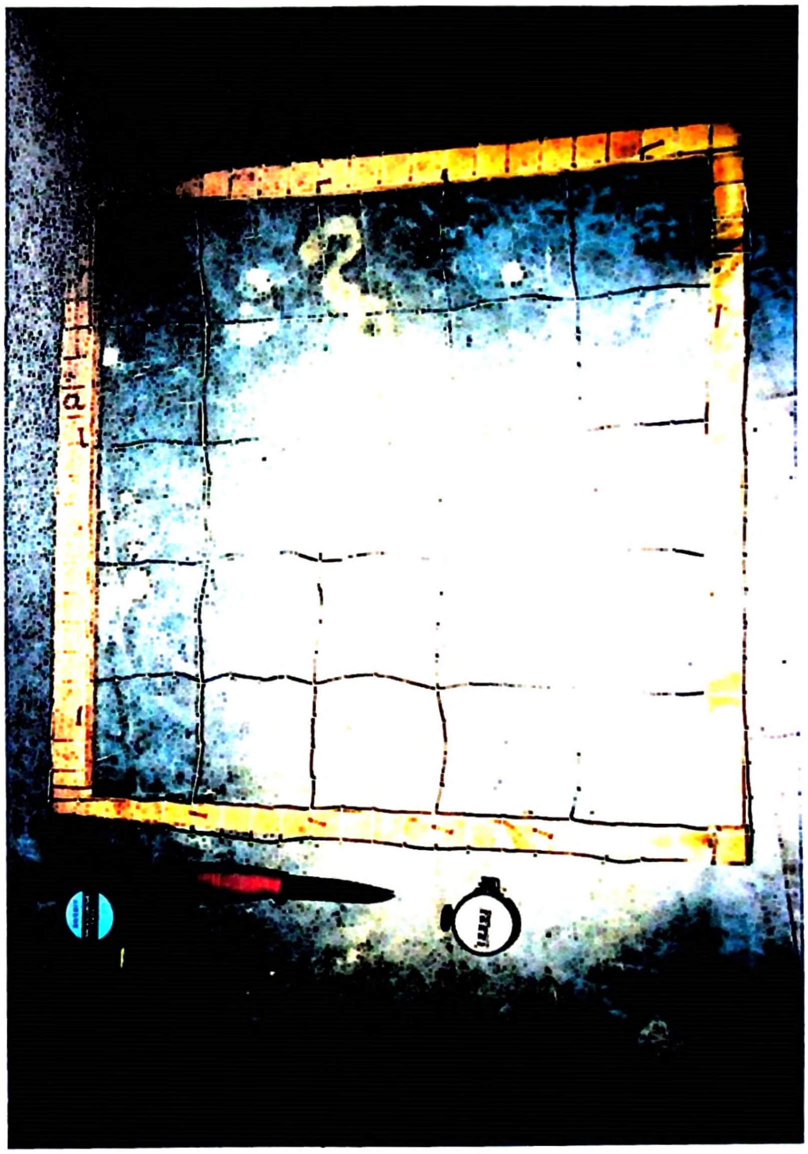
2.3 Laboratory measurements

2.3.1 Preparation of samples for tensile and compressive strength testing

Ten minicores from each subplot were brought to a matric potential (ψ_m) of -10 kPa using tension tables after slowly wetting them at zero tension. The tension tables were improvised from ceramic plates supplied for the pressure plate apparatus. The minicores were placed on tension tables and the base of each sample was slightly wetted from a wash bottle with a small jet, the aim was to cause some softening and/or structural breakdown at the base of each sample in order to establish hydraulic contact with the table. The tension tables were then covered to minimize evaporation. The

(a)

(b)



(c) (d)

Plate 2.4 Equipment used for root measurements:
(a) frame
(b) tape measure
(c) field knife
(d) counter

minicores were equilibrated within their split-moulds to avoid settling. Equilibration on the tension table was achieved in about 2 days. Minicores equilibrated at a ψ_m of -10 kPa were either tested directly, further equilibrated in a pressure plate apparatus at -100 or -300 kPa or, owing to our inability to use the pressure plate apparatus at higher pressure (because of unreliable electricity supply), allowed to dry with their plastic sleeves removed for a predetermined number of hours to reach arbitrary matric potentials before strength testing. These potentials were subsequently determined by the filter paper method (Deka *et al.*, 1992). Equilibration was reached in about 7 days in the pressure plate apparatus. The following scheme was normally followed:

Approximate ψ_m	-10 kPa	-100 kPa	-300 kPa	-1 MPa	-10 MPa	-100 MPa
Tensile	2	1	2	1	1	1
Compressive	—	1	—			1
Method	From tension table	From pressure plate	By air drying for fixed periods			By air drying for ≥ 7 days

Because the water release characteristic of each set of samples (site, treatment and depth) was not known, the appropriate drying time was initially guessed from a release curve for hardsetting Australian soils (Mullins *et al.*, 1990). Two samples from the tension table (ψ_m = -10 kPa) were strength-tested and a set of samples was left to dry for 19 h. If the soil was hardsetting, and had a similar water release characteristic to the Australian soils, then its strength after 19 h of drying would be about 10 times that of the -10 kPa samples. The following drying times were tried:

Strength (in terms of hardsetting soil)*	1x	7x	10x	12x	? etc.
Drying time, h:	0	14	19	24	34
Estimated ψ_m:	-10 kPa	-100 kPa	-300 kPa	-1 MPa	-10 MPa

* microaggregated or organically stabilized/structured soils will have smaller values from 14 hours of air drying onwards.

The drying times were recorded for future reference. If the 19 h strength was about 10 times the strength at -10 kPa, other drying times of 21, 24, 34 h and air-dry (*i.e.* ≥ 7 days) were used. Where the 19 h air-drying strength was more than 10 times the strength at -10 kPa, the drying times were reduced by some factor (*i.e.*10/actual multiplier). For example, if the 19 h strength was 20 × strength of minicores at ψ_m = -10 kPa, the new drying time would be: 10/20 multiply 19 h = 9.5 h. A 19 h strength which was less than 10 × the strength at -10 kPa indicated that the sample originated from a soil which was not hardsetting. The drying times adopted for non-hardsetting soils were 14, 24, 34 h and air-dry (≥ 7 d).

2.3.2 Strength testing

Air-dry minicores and those at -10 kPa were individually removed directly from the drying board or tension table, respectively, and strength-tested (after removing the split mould, in the case of -10 kPa minicores). Minicores equilibrated in the pressure plate assembly or dried for periods less than 7 days were 'stopped' by being kept in sealed 35 mm diameter containers to minimize any moisture loss before strength testing. Indirect tensile and unconfined compressive strengths were measured using a modified lever arm torsion balance as described by Mullins and Panayiotopoulos (1984). Individual samples were loaded between the top of the balance and a perspex platen fixed to a rigid metal frame. A steady load was applied by constantly adding water into a bucket at the other end of the balance until the sample failed. Failure of a sample was detected by a fracture of the sample and/or a sudden drop of the bucket. A constant head of water and a clip were used to control the rate of water flow into the bucket so that it always took > 3 minutes to fail a sample.

Indirect tensile strength (hereafter referred to as tensile strength) measurement was accomplished by loading and failing a sample across its diameter (Carneiro and Barcellos, 1953). Tensile strength, *Y*, was calculated from:

$$Y = \frac{2F}{\pi dL} \tag{2.1}$$

where F is the load at failure (*i.e.* weight of water in the bucket x 4.38, the mechanical advantage of the balance), d is the diameter of the minicore and L its length. The diameter of the sample was an average of 4 readings while the length was an average of 2 readings measured with vernier calipers.

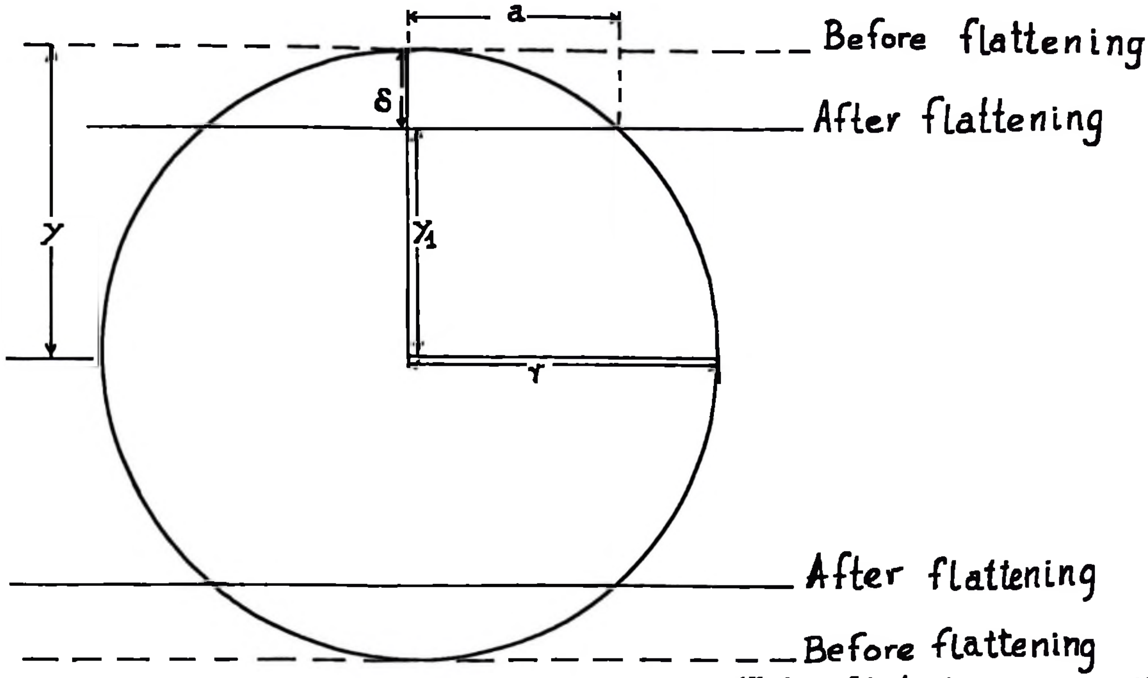
The Brazilian or indirect tension test developed by Carneiro and Barcellos (1953) involves the compression of a cylindrical specimen placed lengthwise between two opposed generators, leading to failure in tension along the diameter contained in the plane formed by these two generators.

This method of load application is not always applicable in the testing of soils because soil and soil stabilized specimen are weak materials and may deform appreciably at the loading points even with a packing strip distributing the load. Additionally, it is often convenient to use small cylindrical specimens (such as the 2 cm dia. × 4 cm length minicores used in this study) for testing soil strength [Ingles and Frydman, 1963 (quoted by Frydman, 1964)], in which case packing strips of a size too small to handle conveniently would be required. As a result, soil and stabilized soil specimens are often tested without the use of packing strips and generally undergo some flattening at the loading points before failure.

The actual tensile strength (Y_a) at the centre of the deformed specimen is given by

$$Y_a = \frac{2F}{\pi dL} g(Y_a) \qquad (2.2)$$

where, F, d and L are as defined in equation (2.1) and $g(Y_a)$ is the Frydman factor (Frydman, 1964), which approaches 1 as the sample deformation approaches zero. The variable $g(Y_a)$ is given as a function of (a/y_1) (see the illustration, below) in Frydman (1964).



$$g(Y_a) = f(a/y_1) \tag{2.3}$$

Sketch illustrating a disc before and after it has undergone flattening at the loading point.

During sample testing deformation was regularly monitored and recorded as the number of divisions that the balance pointer had moved just before the sample failed. Each division was 2.50 mm wide, equivalent to 0.572 mm of sample deformation (*i.e.* 2.50 mm/4.371, the mechanical advantage of the torsion balance). Assuming a core diameter of 21.5 mm, and assuming that δ^2 is negligible,

$$a = (2 \times 21.5\ \text{mm} \times \delta\ \text{mm})^{\frac{1}{2}}, \tag{2.4}$$

$$a/y_1 = \frac{(2 \times 21.5\ \text{mm} \times \delta\ \text{mm})^{\frac{1}{2}}}{(21.5 - \delta)\ \text{mm}} \tag{2.5}$$

and
$$\delta = \frac{\text{No. of divisions}}{2} \times \frac{0.572 \text{ mm}}{\text{Division}} \tag{2.6}$$

Then a/y_1 values corresponding to 0.5, 1, 1.5, ---, 8, 8.5, 9 divisions were calculated. The a/y_1 values were used for reading off the corresponding $g(Y_a)$ values in the curve for this function given by Frydman (1964). The Frydman factor [$g(Y_a)$] was tabulated for 0.5 to 9 divisions and was used to correct the tensile strength for the sample deformation just before failure. The tensile strength reported in this study was calculated from Equation (2.2).

Compressive strength was calculated as the load at failure divided by the cross-sectional area of the sample before strength testing. The type of failure and, for samples with a single clearly identified plane of failure, the angle of failure were also recorded.

After strength testing, each sample was quickly but lightly crushed between the thumb and fingers. Half the sample was put into a pre-labelled, pre-weighed equilibration bottle, a quarter of a Whatman No. 42 filter paper was put on top of the sample and the rest of the sample was added, sandwiching the filter paper. The matric potential and gravimetric water content of the sample were then determined as described in section 2.2.6.1.

2.3.3 Needle penetrometer resistance (PR)

PR measurements were performed on air-dry samples, samples equilibrated at matric potentials of -10, -100 and -300 kPa, and samples dried to lower potentials. "Air-dry" cores were taken from the cold room, air dried for $\geq$ 7 days and then tested for needle penetration resistance. Other cores were first wetted on a tension table to −10 kPa. One set of cores was tested straight from the tension table while other sets were tested individually after equilibration on a pressure plate apparatus to −100 kPa or −300 kPa or after drying in air (in their rings) for 48 h or 72 h. These were 'stopped' by covering both ends of the ring with tight-fitting plastic caps, sealing with masking tape and placing them in an "Esky" (a thermally insulated picnic box) until required.

The needle used for testing had a diameter of 2 mm and a 15° semiangle cone with a relieved shaft. It was held by a piston weighing 1412g, counterbalanced by a mass of 736g. The needle was released by a clock motor at the rate of 10.6 × 0.4 mm min^{-1}. The clock motor was run by a lead-acid battery. The needle diameter was measured in two directions before each set of measurements. Figure 2.4 and plate 2.5 show the apparatus used for measuring needle penetration resistance.

The needle was held in a hole in the piston by a lightly tightened set screw. The counterweight was allowed to hang freely. This acted as a plumb line to give verticality. The stand was adjusted (using wedges at the base, and/or a counterbalance and/or some adjustment of the top clamp screw) to make the needle hang parallel to the side of the counterweight. For PR testing, a core was weighed to the nearest mg in its ring on a tared plastic lid. The core was then transferred to an Oertling balance (with an operating limit of 4.5 MPa) and a plastic sheet template with 3 holes (see Figure 2.5) put on top of the core and held by a rubber band. The core and needle were then lined up and the balance was tared.

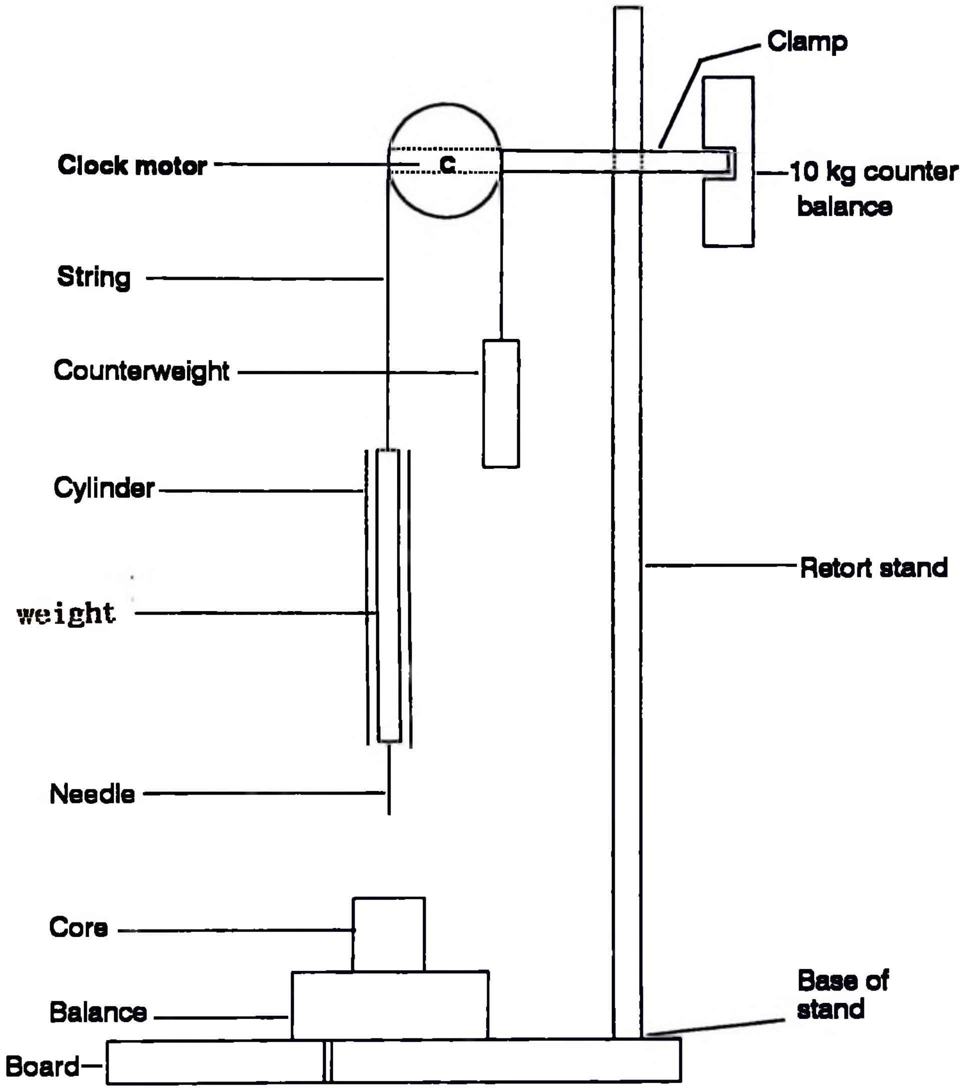


Figure 2.4 Schematic diagram of the needle penetrometer assembly

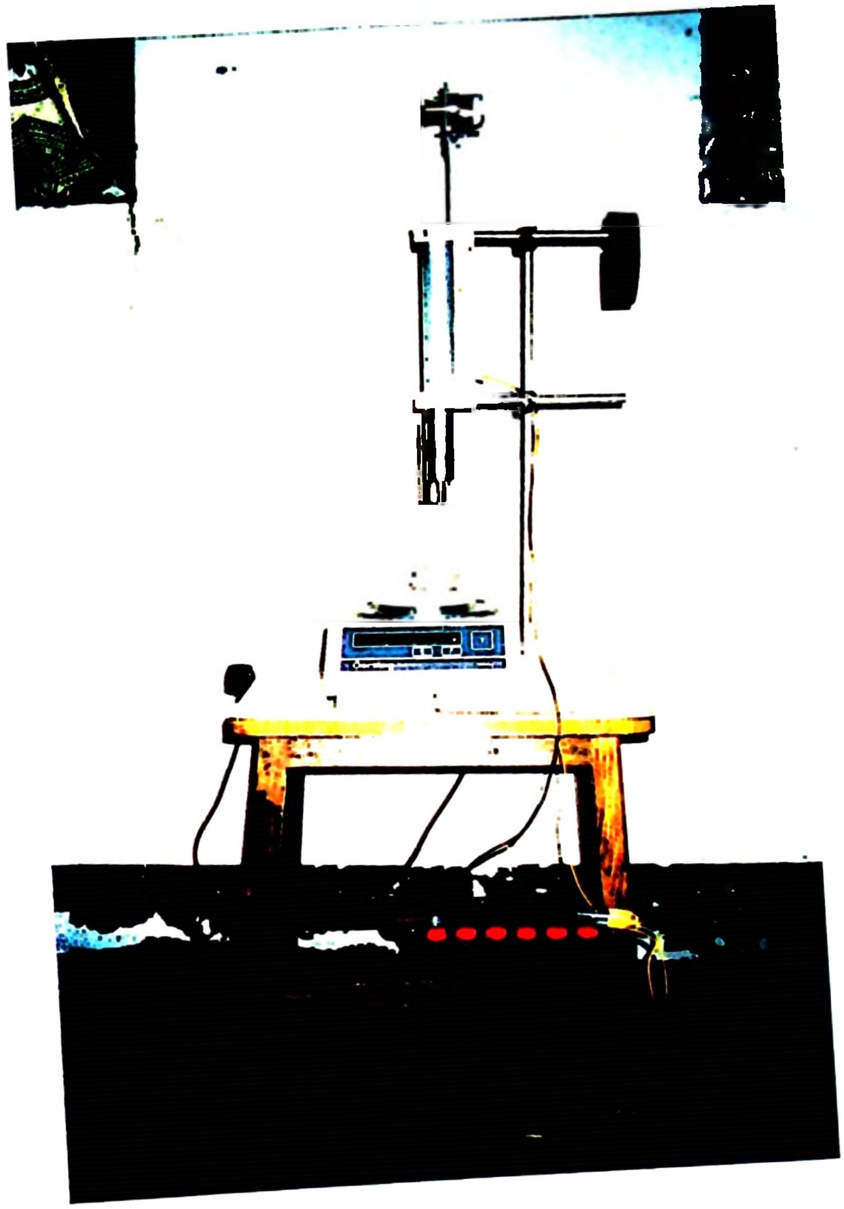


Plate 2.5 Set up for the needle penetrometer resistance measurements.

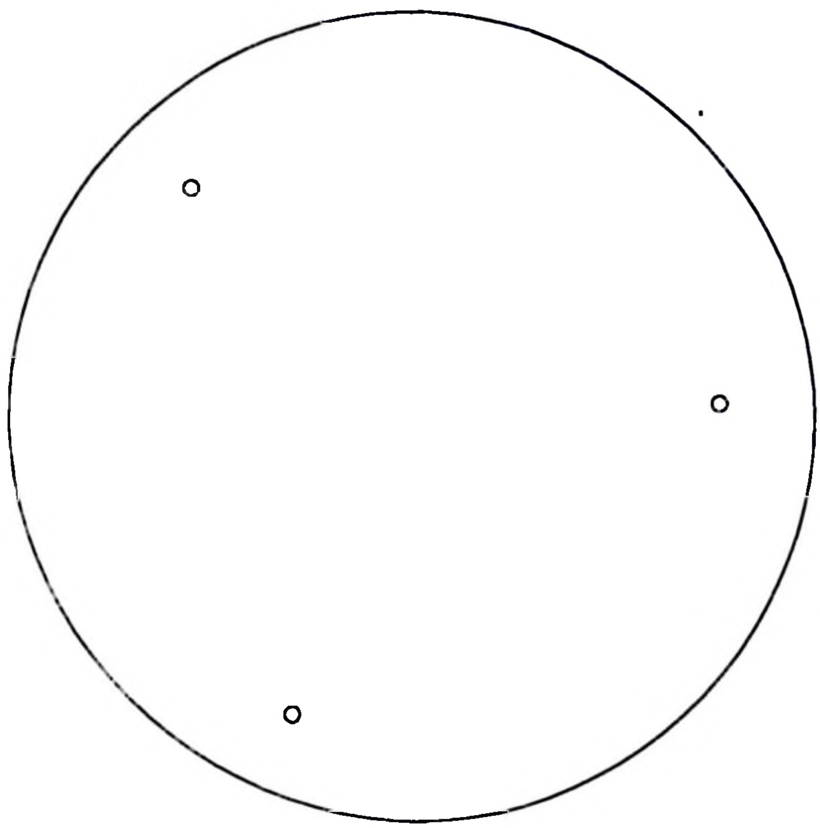


Figure 2.5 Plastic sheet template with 3 holes (○) through which a needle was introduced into the sample to measure needle PR.

The needle was adjusted to be within 1 mm of the core surface, the motor was started and readings were recorded after 34 s, 1 min 8 s, 2 min 16 s, 2 min 50 s and 3 min 24 s. These corresponded to 6 mm depth intervals. The motor was then stopped and the core was held with one hand while the needle weight was lifted with the other, allowing the string to slip over the pulley. This procedure was repeated for the second and third holes.

Most of the soil was then transferred into a weighing bottle for equilibration with a whole filter paper for the determination of gravimetric water content and matric potential as described in section 2.2.6.1. The weights of the empty core and ring were recorded. Needle PR was calculated from

$$PR = \frac{4F}{\pi d^2} \qquad (2.7)$$

where F is the force required to penetrate the core and d is the diameter of the needle cone.

2.3.4 Particle size analysis

Particle size analysis was done on topsoil (2-6 cm) and subsoil (30-34 cm) samples by the pipette method (Day, 1965). This involved destruction of organic matter with H_2O_2, treatment with acid and filtration followed by wet sieving for the sand fractions. Silt and clay were dispersed for sedimentation and pipette sampling.

2.3.5 Microaggregation tests

2.3.5.1 Ahn's test

The method (Ahn, 1979), consists of carrying out two parallel particle size analyses, with and without a dispersing agent. The soil was initially treated with H_2O_2 to destroy organic matter and shaken without a dispersant (a mixture of sodium bicarbonate and sodium polyphosphate). The sand fractions were removed by wet sieving. Silt and clay were determined by the pipette method (Day, 1965). Presence or absence of microaggregation was assessed by comparing the particle size distribution of the dispersed soil (see section 2.3.4) with that of the soil shaken without a dispersing agent.

2.3.5.2 Comparative (Trapnell and Webster's) test by microscopic observation of dry and wet soil samples

A blind test was carried out in the laboratory to determine whether it is easy for researchers to independently recognize microaggregated soils according to the criteria of Trapnell and Webster (1986). Four panellists with some varying experience with microaggregated soils, including Dr. Webster [co-author of the Trapnell and Webster (1986) paper] attempted the test.

Soil samples identified only as soil samples A to X were tested when dry and after wetting. Needles, hand lenses and a binocular microscope were used for identification according to the following criteria:

<u>Criteria</u>

1. Appearance when dry (use a broken surface).

   a) Microgranular

   Spheroidal microaggregates that are clearly separate from their neighbours.

   b) Microaggregates that are easily displaced with the point of a needle (without deforming the microaggregates or the remaining soil).

   c) Rough or smooth but continuous mass without surface flaws (*i.e.* cracks); flaws can be round if small, or irregular.

   d) Rough angular surface with (i), or (ii), without flaws.

   e) Microblocky angular-like but discrete aggregates like (a) (+ or -b).

   f) e - a intergrade

   g) Rough surface with bulges with or without flaws.

2. Immersion (fast) wetting.

   Size: < 10 mm; slaking within 5 minutes

   a) Slakes. b) Does not slake

   c) Partially slakes into (not including sand grains):

   (i) spheroidal bits (ii) angular bits

   (iii) subangular bits (iv) subrounded/gibbous bits.

3. Tension wetting

   a to c as in (2) but with:

   d) aggregates do not swell

   e) aggregates swell.

The scores for each sample were entered in a score sheet and tabulated for comparison.

2.3.6 Emerson's test

Air dry soil aggregates with sizes ranging from 3 to 5 mm were immersed in distilled water and observed for dispersion and, if necessary, further treated according to the scheme of Emerson (1967, see Figure 2.6).

2.3.7 Soil chemical analysis and the identification of the clay mineralogy

2.3.7.1 Soil chemical analysis

Air-dry soil was used in all analyses. However, the results reported are recalculated on an oven-dry basis.

Soil pH was analysed both in water and in 0.01M $CaCl_2$ solution by the glass electrode method (McLean, 1982) using a soil:solution ratio of 1:1 and 1:2, respectively. 10g air-dry soil was used.

The cation exchange capacity (C.E.C.) was measured as described by Chapman (1965) using 25g air-dry soil. The exchangeable cations were displaced with 500 ml of 1M ammonium acetate solution at pH 7.0. The soil sample was then washed with 500 ml 80% ethanol. The ammonium soil was finally leached with 250 ml acidified 1M sodium chloride solution. The leachate was collected and used for C.E.C. determination. 25 ml of the leachate were mixed with 5 ml of a buffered borax solution and 10 ml of a boric acid indicator mixture. The whole mixture was titrated with 0.05M hydrochloric acid from a 10 ml semi-micro burette until the colour changed from blue to purple-red.

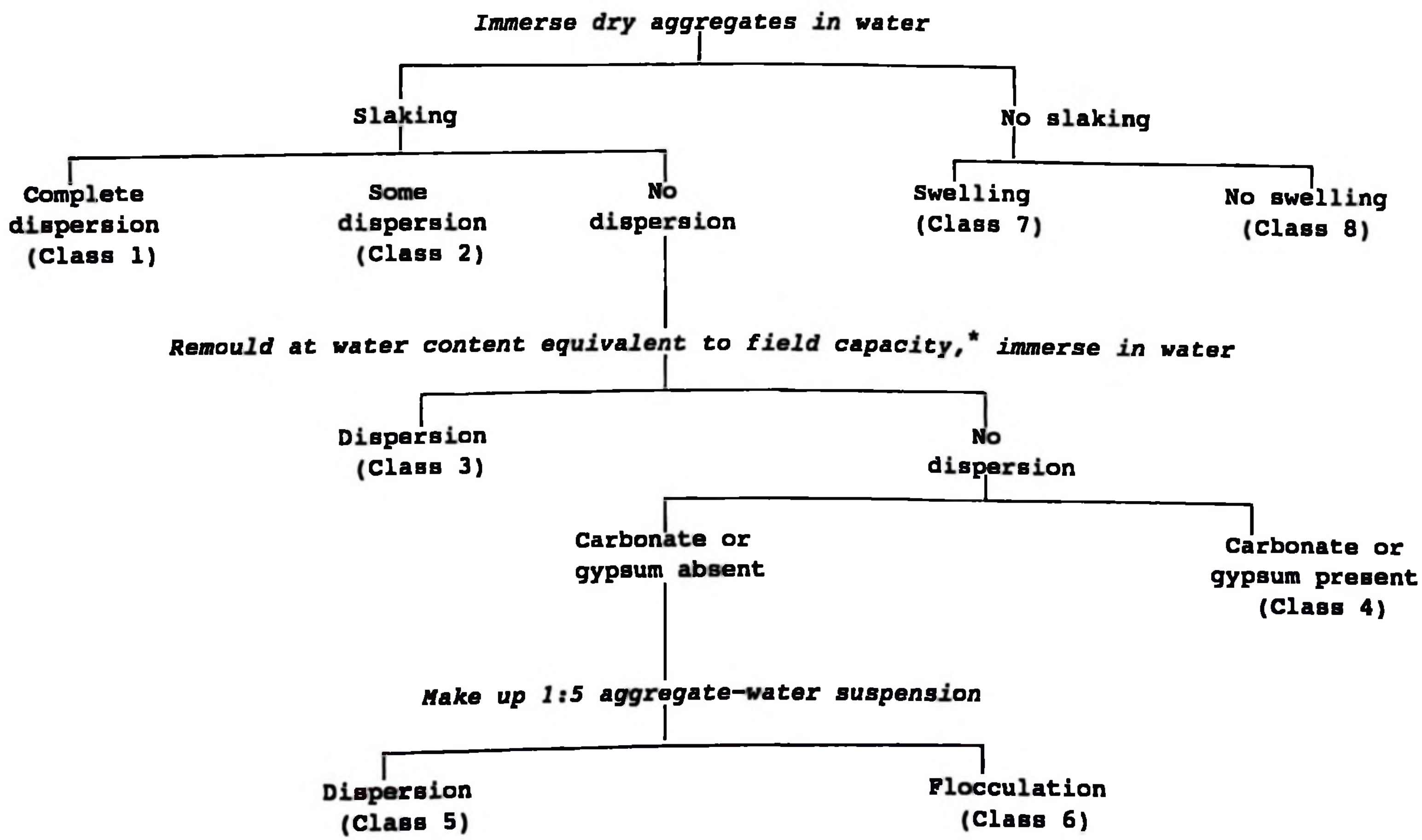


Figure 2.6 Scheme for determining class numbers of aggregates. After Emerson (1967).
* Field capacity taken as 6 kPa suction in this study.

Organic carbon (O.C.) was determined by the wet digestion (potassium dichromate) method (Nelson and Sommers, 1982). 10.0 ml of 0.1667M potassium dichromate ($K_2Cr_2O_7$) solution were added to 1g of soil ground to pass through a 0.5 mm sieve in an Erlenmeyer flask. The flask was gently swirled to disperse the soil in the solution. Using a measuring cylinder, 20 ml concentrated H_2SO_4 was added and the mixture was swirled for 1 minute. The Erlenmeyer flask was left on a wooden pad for 30 minutes. Next, 200 ml of deionized water was added, followed by 10 ml of phosphoric acid. 1 ml of diphenylamine indicator was added to the mixture. The sample was then titrated with ammonium ferrous sulphate. Near the end-point the colour changed to deep violet-blue; the titration was slowed down by adding the ammonium ferrous sulphate dropwise. At the end-point the colour changed sharply to brilliant green. After the titration of the blank, the burette reading was taken. Again 10 ml of 0.1667M $K_2Cr_2O_7$ was added to the titrated blank and titrated again with ammonium ferrous sulphate. This second titration was used to standardize the ammonium ferrous sulphate solution. Organic carbon content was calculated as

$$\% \text{ O.C.} = \frac{(B-T)}{W} \times f \times 0.39$$

where B is the volume (ml) of ammonium ferrous sulphate used for the first blank titration, T = ml ammonium ferrous sulphate used for the sample, W = weight (oven-dry basis) of the soil sample, f = the strength (M) of the ammonium ferrous sulphate and 0.39 is a constant factor which accounts for the amount of C in 1 ml of 0.1667 $K_2Cr_2O_7$, and the incomplete digestion of organic compounds [only about 75% of organic compounds in the soil are oxidized into C (Peech *et al.*, 1947; Greweling and Peech, 1960)].

Organic matter was determined as O.C. × 1.72.

Extractable Fe and Al were determined by the citrate-bicarbonate-dithionite method as described by Jackson et *al.* (1986). 5g of air-dry soil was used. The extractants used were 40 ml of 0.3M sodium citrate ($Na_3C_6H_5O_7.2H_2O$), 5 ml of 1M sodium bicarbonate ($NaHCO_3$) and 1g of pure grade sodium dithionite ($Na_2S_2O_4$). The standards for Fe and Al were prepared from hydrated ammonium ferrous sulphate [$(NH_4)_2SO_4.FeSO_4.6H_2O$] and hydrated aluminium chloride ($AlCl_3.6H_2O$), respectively. Extractable Fe was measured by atomic absorption spectrometry (AAS) while Al was measured by flame emission spectrometry (FES) using a N_2O-C_2H_2 gas flame. Before measuring Al by FES, 2000 ppm K as KCl was added to the standards and samples in order to bring about preferential ionization of K and avoid self-ionization of Al brought about by the high temperature emanating from the N_2O-C_2H_2 gas flame (Kirkbright and Sargent, 1974).

Extractable Mn was determined according to the procedure of Ure and Berrow (1970) using 10g of air-dry soil and 50 ml 0.05M EDTA as the extracting solution. Standards for determining EDTA-extractable Mn were prepared from hydrated manganese chloride ($MnCl_2.4H_2O$), and measurement was made by AAS.

Acid oxalate-extractable Si was determined by a shaking method (Blakemore et *al.*, 1987) on 1.0g air-dry soil. One part of 0.2M ammonium oxalate [$(NH_4)_2C_2O_4.H_2O$] buffered at pH 3 was mixed with 0.75 parts of oxalic acid ($H_2C_2O_4.2H_2O$), giving a total oxalate strength of 0.2M. 100 ml of this acid-oxalate solution was used as the extractant. The standards used were prepared from sodium fluorosilicate ($NaSiF_6$). Si was measured by FES using a $N_2O-C_2H_2$ gas flame.

2.3.7.2 Mineralogy of the clay-sized fraction

The mineralogy of the clay-sized fraction was determined by the X-ray diffraction (XRD) procedure (Jackson, 1975; Whittig and Allardice, 1986). The clay fraction (< 2 µm diameter) used in XRD was separated by sodium carbonate solution at pH 9 by sedimentation and centrifugation. The instrument used for XRD analysis was a Phillips PW 710 X-ray generator and goniometer, with Fe-filtered Cu Kα radiation. It had a 0.25° divergence slit and a 0.1 mm receiving slit behind which was placed a 0.25° scatter slit. Clay samples were individually scanned at a speed of 0.033° s^{-1} between 4° 2θ and 42° 2θ. The printing recorder PM 8210 produced the diffractograms.

Interpretation of XRD charts: The recording pen travels from right to left across the chart paper so that the low-angle spacing is on the right; conversely, low d-spacings are on the left. The runs were carried out using a programme which starts at 4° 2θ and the commencing line corresponds with one of the vertical lines on the chart. Since the recording pen always starts from the base line and the background tends to be high in the starting region, an almost vertical line was seen at the beginning of most traces. This vertical line was extrapolated to the base line to give the exact commencing point where the two lines intersected, *i.e.* 4°.

Peak positions and peak heights in counts per second were printed on the charts. Data presented were converted to nanometers and values adjusted to 3 significant figures. On occasions there was a 'ghosting' effect after a large peak, resulting in a spurious peak print-out where no peak existed. Such 'peaks' were ignored during interpretation. Whether a peak is recorded automatically or not depends on the particular peak heights and widths (Jackson, 1975). Not all peaks were, therefore, recorded. Peaks that had not been automatically recorded were therefore manually recorded.

A small approximation is involved in the scanning speed of the goniometer since the rate is 0.033° s^{-1} and not 2° min^{-1}. For most purposes (and for the purpose of the present study), this will make no difference, but it should be taken into consideration with very precise measurements.

Qualitative interpretation of diffraction patterns involves identification of crystalline species from the array of diffraction maxima obtained from a sample (Whittig and Allardice, 1986). I accomplished this by measuring diffraction spacings and comparing these spacings with known spacings of standard minerals. Once peak positions had been determined, the calculation of d-spacings was made using conversion tables. The d-spacings thus obtained were used to identify the types of minerals present using tables relating d-spacing (in nm), diffraction order and the mineral.

Normally, qualitative diffraction analysis has to be contrasted to (semi)quantitative analysis whose aim is to determine the mineral percentages (Jackson, 1975). Quantitative criteria include selective dissolution analysis, measurement of C.E.C., thermal analysis, surface analysis, elemental analysis and other species-specific chemical methods (Jackson, 1975; Allardice and Whittig, 1986). It was decided that at the present stage of the investigation, quantitative analysis, which requires not only the specialized chemical methods but also a lot of experience in interpretation of the results (N. Livesey, pers. comm.), should not be done.

CHAPTER 3

RESULTS AND DISCUSSION

Results obtained from the five sites are presented and discussed in this chapter. Presentation is by subject rather than site by site. Laboratory results are presented first followed by field results, with the exception of field penetrometer resistance and matric potential results which are presented together with needle penetrometer resistance results.

The following abbreviations are used when referring to treatments: F, "fallow" (previously uncultivated); C, "cultivated" (previously cultivated). The sites are referred to as: Is, Ismani; Ma, Magamba; Mb, Mbimba; Sh, Sao Hill; and Uk, Ukwile. Discussion of statistical significance refers to a probability of P = 0.05 unless it is stated otherwise.

3.1 General soil physical properties

3.1.1 Particle size distribution and bulk density

Table 3.1a shows the particle size distribution of the soils at the 5 sites. Particle size analysis was conducted on soil samples collected from the study sites at 2-6 and 30-34 cm depths. The dry bulk density was determined on minicores collected from depths of 2-6, 8-12 and 30-34 cm. Bulk density results are presented in Table 3.1*b*.

The particle size distribution of top soils (2-6 cm) from the contrasting treatments were similar except for the clay content of the cultivated treatment at Ismani which was considerably lower than

Table 3.1a Particle size distribution (Psd) for soils from Ismani (Is), Magamba (Ma), Mbimba (Mb), Sao Hill (Sh) and Ukwile (Uk). Psd results are expressed as a percentage by mass of total mineral matter.

Depth (cm)	Site and Treatment	Sand 2000-600	Sand 600-200	Sand 200-60	Silt 60-20	Silt 20-6	Silt 6-2	Clay <2	Textural Class (USDA)
2-6	Is F	4.8(0.3)	20.5(0.3)	30.5(0.8)	9.3(0.4)	3.2(0.1)	0.0(0.0)	31.7(0.9)	Sandy clay loam
	Is C	6.0(0.1)	18.6(0.1)	32.2(1.0)	7.7(0.2)	5.1(0.3)	6.2(0.2)	24.2(0.7)	Sandy clay loam
	Ma F	3.2(0.2)	15.2(0.2)	20.1(0.6)	10.2(0.8)	9.1(0.3)	13.9(0.5)	28.3(0.7)	Clay loam
	Ma C	2.7(0.3)	12.2(0.4)	22.1(0.3)	10.6(0.4)	12.7(0.2)	9.5(0.1)	30.2(0.8)	Clay loam
	Mb F	1.7(0.2)	10.8(0.2)	11.4(0.4)	7.4(0.4)	13.0(0.2)	12.5(0.1)	43.2(0.8)	Clay
	Mb C	0.7(0.1)	7.1(0.3)	13.3(0.2)	8.4(0.3)	12.3(0.4)	11.2(0.1)	47.0(1.0)	Clay
	Sh F	4.8(0.1)	28.7(0.9)	23.2(0.7)	3.2(0.1)	1.6(0.0)	0.5(0.0)	38.0(0.8)	Sandy clay
	Sh C	4.9(0.2)	30.8(0.8)	21.8(0.0)	1.1(0.1)	2.6(0.1)	1.1(0.1)	37.7(0.9)	Sandy clay
	Uk F	2.7(0.2)	7.7(0.2)	16.2(0.2)	7.0(0.2)	9.7(0.3)	8.1(0.2)	48.6(0.6)	Clay
	Uk C	3.3(0.1)	10.1(0.1)	12.5(0.2)	9.1(0.3)	10.2(0.4)	9.1(0.3)	45.7(0.8)	Clay
30-34	Is F	5.8(0.3)	15.0(0.4)	22.9(0.5)	5.9(0.1)	4.0(0.0	0.8(0.1)	45.6(0.9)	Clay
	Is C	5.3(0.1)	15.4(0.2)	22.4(0.5)	6.7(0.2)	2.7(0.1)	4.0(0.2)	43.5(0.4)	Clay
	Ma F	1.8(0.1)	7.7(0.4)	13.8(0.8)	8.0(0.4)	11.1(0.3)	13.9(0.6)	43.9(0.8)	Clay
	Ma C	1.8(0.1)	5.5(0.2)	12.5(0.1)	5.5(0.0)	12.6(0.1)	11.8(0.3)	50.3(0.9)	Clay
	Mb F	0.4(0.0)	3.4(0.3)	7.2(0.6)	6.0(0.2)	11.8(0.1)	11.2(0.7)	60.0(0.4)	Clay
	Mb C	0.4(0.0)	2.9(0.1)	6.5(0.5)	9.3(0.3)	6.2(0.4)	12.3(0.1)	62.4(0.4)	Clay
	Sh F	2.6(0.1)	21.1(0.7)	22.6(0.8)	2.6(0.3)	0.5(0.0)	3.4(0.1)	47.2(0.2)	Clay
	Sh C	2.7(0.0)	20.3(0.1)	24.5(0.1)	2.9(0.4)	1.0(0.1)	0.8(0.1)	47.8(0.5)	Clay
	Uk F	1.1(0.0)	2.5(0.2)	5.7(0.0)	5.1(0.1)	4.8(0.2)	3.5(0.3)	77.3(1.0)	Clay
	Uk C	1.2(0.1)	5.0(0.1)	8.6(0.6)	5.5(0.5)	6.9(0.3)	8.0(0.2)	64.8(0.1)	Clay

Percentage in the particle size range (µm) of sand, silt and clay.

The figures in brackets indicate the range/2 (±)

Table 3.1*b* Variation of dry bulk density (Mg m^{-3}) of soils at Ismani, Magamba, Mbimba, Sao Hill and Ukwile. Standard errors are shown in parentheses.

Site and Treatment	Depth (cm)					
	n	2–6	n	8–12	n	30–34
Is F	47	1.51(0.02)***	30	1.53(0.02)*	14	1.47(0.02)***
Is C	47	1.60(0.01)	30	1.61(0.02)	14	1.61(0.02)
Ma F	63	1.25(0.02)ns	28	1.35(0.02)ns	12	1.29(0.02)*
Ma C	63	1.25(0.01)	28	1.37(0.02)	12	1.40(0.02)
Mb F	34	0.98(0.02)***	25	0.97(0.02)***	10	1.03(0.03)**
Mb C	34	1.14(0.01)	25	1.19(0.01)	10	1.20(0.02)
Sh F	80	1.25(0.01)***	40	1.30(0.01)**	20	1.35(0.01)**
Sh C	80	1.21(0.01)	40	1.25(0.01)	20	1.43(0.01)
Uk F	48	1.27(0.01)***	30	1.34(0.01)***	14	1.34(0.02)**
Uk C	48	1.12(0.01)	30	1.08(0.02)	14	1.22(0.02)

ns, the fallow and cultivated treatments do not differ significantly (P = 0.05);

*, **, ***, the fallow treatment differs significantly from its contrasting cultivated treatment (P = 0.05, 0.01, 0.001), following a t-test for paired samples.

that of the fallow treatment. However, the contrasting treatments at each site had the same textural class name, implying that all paired plots selected were broadly similar in soil texture. The subsoils (30-34 cm) at all sites had more than 40 percent clay. The clay content in the subsoils followed the same pattern as that of topsoils and was in the order

Ismani < Sao Hill < Magamba < Mbimba < Ukwile.

However Ukwile and Magamba fallow subsoils had respectively, more and less clay than their cultivated counterparts.

Sao Hill soils had the least silt content at both depths, with 5 to 7 percent silt. The Magamba soils had the highest content of silt (above 30 percent) in both the topsoil and the subsoil. The sand fraction was dominant in the Ismani and Sao Hill soils, accounting for >50 percent of the topsoils and above 40 percent of the subsoils. In the absence of phenomena like hardsetting and compaction, the Ismani and Sao Hill soils would be expected to offer least resistance to cultivation even when dry.

There was no clear distinction for the dry bulk density to vary between dates and replicates. Further, although in most replicates the bulk densities of air dry samples was at least 0.01 Mg m^{-3} higher than those of samples equilibrated at matric potentials of -10 kPa, this increase in bulk density due to shrinkage was not significant. The soil bulk density values of minicores taken on different dates and equilibrated at different matric potentials were therefore pooled.

Over all, the soils at Mbimba had the lowest bulk density values for both treatments. The bulk density of Mb F ranged from

0.97 Mg m^{-3} (at 8-12 cm) to 1.03 Mg m^{-3} in the subsoil, while the bulk density of the topsoil was 0.98 Mg m^{-3} (Table 3.1*b*). At the other extreme, the Ismani cultivated treatment had the highest bulk density of 1.60 Mg m^{-3} (topsoil) to 1.61 Mg m^{-3} at both 8-12 and 30-34 cm depths. In the remaining 3 sites, the bulk density was between 1.08 Mg m^{-3} (Uk C 8-12 cm) and 1.43 Mg m^{-3} (Sh C 30-34 cm). At Ismani and Mbimba (all depths) and Magamba and Sao Hill (30-34 cm) the bulk density was significantly greater in the cultivated than in the fallow plots. This trend was reversed at Sao Hill (2-6 and 8-12 cm) and Ukwile (for all depths, Table 3.1*b*) where the bulk density was significantly greater in the cultivated plots. The bulk density values at Magamba (2-6 and 8-12 cm) did not differ significantly between the two main treatments.

Increases in bulk density are correlated with increases in penetration resistance (PR) (Bauder *et al.*, 1981; Meek *et al.*, 1992) and/or poor aeration (Bowen, 1981). Soil bulk density values which exceed 'rule of thumb' magnitudes of 1.55, 1.65, 1.80 and 1.85 Mg m^{-3} have been suggested by Bowen (1981) to severely impede root growth in clay loams, silt loams, fine sandy loams and loamy fine sands, respectively. As a crude criterion, if a bulk density exceeding 1.55 Mg m^{-3} is taken as a critical value for our soils (ranging from sandy clay loam to clay, see Table 3.1a), then the Ismani cultivated plots would be expected to show serious physical problems at all depths (Table 3.1*b*).

3.1.2 Microaggregation tests

3.1.2.1 Ahn's (1979) test

Table 3.2 shows results from particle size analyses *(w) with and (wo)* without a dispersing agent. Both the sand and silt fractions are divided into coarse, medium and fine fractions according to British Standard 1377. The results indicate that in all sites and for both treatments the clay content significantly increased (by at least 5 percent, with the exception of Is C, Table 3.2) when a dispersing agent was used. The Mbimba topsoils showed the greatest increase in clay content (an average increase of about 60% of the value without a dispersant) when analysed with a dispersing agent, followed by Ukwile (47%), Sao Hill (42%) and Magamba (31%) while Ismani exhibited the lowest average increase of about 19 percent in the clay fraction. At the same time, except for Is C and Ma F, there was a significant decrease in the medium plus coarse silt (20-6 and 60-20 µm) fractions of about the same magnitude as the increase in the clay fraction, when soil was analysed with compared to without a dispersing agent (Table 3.2).

If incomplete dispersion in the absence of a dispersant is used as a criterion for microaggregation, these results suggest that:

(1) the soils at all 5 sites were microaggregated to a certain degree,

(2) the microaggregates were of medium to coarse silt size, and

(3) Ismani soil showed the least microaggregation.

The distinction in the degree of microaggregation also varied between treatments. In particular, the Ismani fallow treatment topsoil indicated microaggregation whereas the cultivated treatment topsoil

Table 3.2 Particle size distributions with and without a dispersing agent for topsoils, expressed as a percentage by mass of total mineral matter.

Site and Treatment	Sand (µm)			Silt (µm)			Clay (µm)
	2000–600	600–200	200–60	60–20	20–6	6–2	<2
Is F_w	4.8(0.3)*	20.5(0.3)ns	30.5(0.8)ns	9.3(0.4)*	3.2(0.1)**	0.0(0.0)***	31.7(0.9)*
Is F_{wo}	6.1(0.2)	21.1(0.6)	29.2(0.4)	7.3(0.5)	7.3(0.3)	5.1(0.2)	23.9(0.8)
Is C_w	6.0(0.1)ns	18.6(0.1)*	32.2(1.0)ns	7.7(0.2)ns	5.1(0.3)ns	6.2(0.2)ns	24.2(0.7)ns
Is C_{wo}	6.2(0.4)	19.2(0.1)	31.7(0.4)	8.7(0.4)	5.7(0.4)	5.6(0.3)	23.0(0.6)
Ma F_w	3.2(0.2)*	15.2(0.2)ns	20.1(0.6)ns	10.2(0.8)ns	9.1(0.3)**	13.9(0.5)ns	28.3(0.7)**
Ma F_{wo}	4.4(0.2)	15.6(0.1)	18.6(0.2)	11.6(0.1)	14.3(0.3)	13.3(0.0)	22.2(0.3)
Ma C_w	2.7(0.3)ns	12.2(0.4)ns	22.1(0.3)ns	10.6(0.4)**	12.7(0.2)*	9.5(0.1)**	30.2(0.8)**
Ma C_{wo}	2.9(0.1)	12.7(0.4)	21.6(0.0)	13.4(0.1)	13.9(0.2)	12.8(0.2)	22.7(0.5)
Mb F_w	1.7(0.2)ns	10.8(0.2)ns	11.4(0.4)ns	7.4(0.4)*	13.0(0.2)**	12.5(0.1)**	43.2(0.8)**
Mb F_{wo}	2.6(0.3)	11.4(0.3)	10.9(0.3)	10.5(0.5)	17.7(0.2)	17.1(0.4)	29.8(0.7)
Mb C_w	0.7(0.1)*	7.1(0.3)*	13.3(0.2)*	8.4(0.3)**	12.3(0.4)**	11.2(0.1)**	47.0(1.0)**
Mb C_{wo}	1.1(0.0)	8.7(0.3)	14.1(0.1)	14.7(0.1)	17.9(0.4)	16.8(0.5)	26.7(0.3)
Sh F_w	4.8(0.1)*	28.7(0.9)ns	23.2(0.7)ns	3.2(0.1)**	1.6(0.0)***	0.5(0.0)**	38.0(0.8)**
Sh F_{wo}	4.0(0.1)	30.1(0.7)	22.8(0.2)	4.8(0.2)	4.8(0.2)	6.3(0.6)	27.2(0.2)
Sh C_w	4.9(0.2)*	30.8(0.8)ns	21.8(0.0)ns	1.1(0.1)**	2.6(0.1)**	1.1(0.1)**	37.7(0.9)**
Sh C_{wo}	4.1(0.1)	30.7(0.5)	22.0(0.3)	4.8(0.3)	5.9(0.3)	6.4(0.4)	26.1(0.5)
Uk F_w	2.7(0.2)ns	7.7(0.2)*	16.2(0.2)**	7.0(0.2)**	9.7(0.3)**	8.1(0.2)**	48.6(0.6)**
Uk F_{wo}	3.4(0.2)	9.0(0.3)	17.2(0.0)	12.2(0.5)	13.3(0.3)	12.1(0.3)	32.8(0.6)
Uk C_w	3.3(0.1)ns	10.1(0.1)ns	12.5(0.2)*	9.1(0.3)**	10.2(0.4)**	9.1(0.3)**	45.7(0.8)**
Uk C_{wo}	3.1(0.2)	10.4(0.1)	13.6(0.1)	14.2(0.3)	14.1(0.2)	13.1(0.3)	31.5(0.4)

The range/2 (+ or −) is indicated in parentheses.
w, wo; with dispersing agent; without dispersing agent; ns, the two treatments (with and without dispersing agent) do not differ significantly (P = 0.05); *, **, ***, the two treatments differ significantly at P = 0.05, 0.01 and 0.001, respectively (using t-test for unpaired samples).

indicated very little microaggregation according to this test. This could have been a genuine result, but there was some evidence that flocculation was occurring in the absence of a dispersant in which case the observed effects would not be wholly attributable to microaggregation. Therefore, a further test was done in which both the dispersant and acid treatment were omitted on the grounds that *(a)* if microaggregates are cemented by oxides or oxyhydroxides of Fe and Al then the acid would have dissolved these and *(b)*, the acid pretreatment (even after washing) may leave the final suspension sufficiently acid to cause flocculation.

Only soils from the sites which had shown the greatest contrast in physical behaviour were tested. Table 3.3 shows results of the parallel particle size analyses for the Ismani and Sao Hill topsoils and subsoils. When the Ismani topsoil was analysed with and without an acid pretreatment and a dispersing agent the clay fractions did not differ significantly. However, the clay content of the Ismani subsoil was significantly increased from 23.8 to 44.6 percent (averaged over both treatments) as a result of the full treatment. The greatest corresponding significant decreases were in the coarse silt, from an average of 17.1 percent (without dispersant and acid pretreatment) to only 6.3% (with the full treatment); medium silt (from 8.7% to 3.4%), and fine silt (8.7 to 2.4%). This suggests that the Ismani subsoil had some microaggregation.

The Sao Hill topsoil clay fraction increased almost four-fold from an average of 7.7% (without dispersant and acid pretreatment) to 37.9% (with the full treatment). This increase was highly significant ($P = 0.001$). There was a corresponding significant ($P =$

Table 3.3 Particle size distributions of the Ismani and Sao Hill topsoils (2-6 cm) and subsoils (30-34 cm) with (w) and without acid treatment and dispersing agent (wo).

Depth (cm)	Site and Treatment	Percentage Sand 2000-600	Sand 600-200	Sand 200-60	Silt 60-20	Silt 20-6	Silt 6-2	Clay <2
2-6	Is F_w	4.8(0.3)*	20.5(0.3)**	30.5(0.8)^{ns}	9.3(0.4)^{ns}	3.2(0.1)**	0.0(0.0)***	31.7(0.9)^{ns}
	Is F_{wo}	7.8(0.5)	15.8(0.1)	28.3(0.8)	8.3(0.3)	2.0(0.1)	4.9(0.1)	32.9(1.1)
	Is C_w	6.0(0.1)^{ns}	18.6(0.1)^{ns}	32.2(1.0)^{ns}	7.7(0.2)^{ns}	5.1(0.3)^{ns}	6.2(0.2)*	24.2(0.7)^{ns}
	Is C_{wo}	5.8(0.2)	19.9(0.6)	29.6(0.4)	6.8(0.3)	5.8(0.5)	4.4(0.2)	27.7(1.0)
	Sh F_w	4.8(0.1)^{ns}	28.7(0.9)*	23.2(0.7)^{ns}	3.2(0.1)***	1.6(0.0)***	0.5(0.0)**	38.0(0.8)***
	Sh F_{wo}	5.1(0.2)	23.7(0.2)	21.9(0.4)	40.2(0.9)	0.0(0.0)	2.0(0.2)	7.1(0.2)
	Sh C_w	4.9(0.2)^{ns}	30.8(0.8)*	21.8(0.0)**	1.1(0.1)***	2.6(0.1)***	1.1(0.1)***	37.7(0.9)***
	Sh C_{wo}	5.1(0.0)	25.9(0.4)	19.4(0.3)	40.9(0.7)	0.5(0.0)	0.0(0.0)	8.2(0.3)
30-34	Is F_w	5.8(0.3)*	15.0(0.4)^{ns}	22.9(0.5)*	5.9(0.1)***	4.0(0.0)**	0.8(0.1)***	45.6(0.9)*
	Is F_{wo}	4.9(0.1)	14.4(0.7)	20.0(0.6)	18.1(0.3)	9.3(0.4)	9.3(0.1)	24.0(0.9)
	Is C_w	5.3(0.1)^{ns}	15.4(0.2)**	22.4(0.5)*	6.7(0.2)***	2.7(0.1)**	4.0(0.2)**	43.5(0.4)**
	Is C_{wo}	6.0(0.4)	18.5(0.2)	19.8(0.4)	16.1(0.2)	8.0(0.3)	8.0(0.2)	23.6(0.5)
	Sh F_w	2.6(0.1)*	21.1(0.7)^{ns}	22.6(0.8)*	2.6(0.3)***	0.5(0.0)***	3.4(0.1)***	47.2(0.2)***
	Sh F_{wo}	4.1(0.4)	19.2(0.5)	18.2(0.5)	50.9(0.8)	0.0(0.0)	0.5(0.0)	7.1(0.0)
	Sh C_w	2.7(0.0)***	20.3(0.1)*	24.5(0.5)*	2.9(0.4)***	1.0(0.1)*	0.8(0.1)**	47.8(0.5)***
	Sh C_{wo}	4.0(0.0)	19.0(0.2)	20.3(0.6)	47.1(1.0)	1.5(0.1)	1.5(0.0)	6.6(0.2)

The range/2 (+ or −) is indicated in parentheses.
ns, results from the full particle size analysis treatment (with acid treatment and dispersing agent) do not differ significantly from those of the without acid treatment and dispersing agent (P = 0.05); *, **, ***, the full particle size analysis treatment differs significantly from the without acid treatment and dispersing agent treatment, P = 0.05, 0.01 and 0.001, respectively, following t-tests for unpaired samples.

0.001) decrease in coarse silt from an average of 40.6% to 2.2%. Similar results were found in the subsoil, where the clay fraction increased from an average of 6.9% (without dispersant and acid pretreatment) to 47.5% clay (with the full treatment), an almost six-fold increase. The dominant corresponding decrease was in the coarse silt fraction, from an average of 49 percent to 2.8 percent. This suggests that both Sao Hill topsoil and subsoil were strongly microaggregated mainly in the 60-20 µm-sized microaggregates. This is within the size range identified by Trapnell and Webster (1986) who, writing of soils in tropical Africa, state that the clay component there consists of microaggregates which range in size from 30 to 1000 µm. Ahn (1979) also reported microaggregates ranging in size from coarse silt (60-20 µm) to fine sand (200-60 µm) for an Ultisol from Kenya and an Oxisol from Ghana. However, he did not indicate whether he used an acid pretreatment in either of his analyses. The results given here have shown that, at least for the soils studied, the difference between a microaggregated soil and one which is not microaggregated only becomes clear when acid treatment is omitted in the 'without-dispersing agent' analysis.

3.1.2.2 Trapnell and Webster's test by microscopic observation of dry and wet soil samples

The aim of this blind test was to see whether a scientist could independently identify a microaggregated soil in the field according to the criteria of Trapnell and Webster (1986). The panellists to the blind test were Drs. Chris Mullins (C), Richard Webster (R), Margaret Oliver (M) and myself (P).

The scores made by each panellist for those samples attempted by at least 3 members are presented in Table 3.4. Appendix I presents results for all samples that were attempted by at least one member. The criteria used are as given in section 2.3.5.2.

Following the joint blind test we were in agreement that the Sao Hill fallow subsoil fulfilled the criteria set for microaggregation. We were also in agreement that the Ismani fallow subsoil (Is F_{ii}) had slaked completely and that the slaked fragments had rough subrounded surfaces (see Appendix I). The Ismani cultivated topsoil did not slake readily and was quite strong. Whereas Dr. Webster considered that when Is F_{ii} was tension-wet it had a compound structure with a mainly rough surface with flaws with some irregular microaggregates, both Drs. Mullins and Oliver maintained that the rough angular fragments with rounded bits were not microaggregates. This raises the question whether it is possible to distinguish after slaking between fragments and microaggregates.

Because this blind test was conducted in the laboratory on a single occasion one would have expected the four of us to agree on which soils tested were microaggregated. This was not the case. The soils looked very similar when dry and the identification of some of them as microaggregated was subjective. It was also apparent that modest proportions of what appeared to be microaggregates can still be present in a hardsetting soil.

Table 3.4 Results of the blind Trapnell and Webster's test for 4 sites.
See section 2.3.5.2 for the description of the criteria.

Site and Treatment	Panellist	Criterion 1	Criterion 2	Criterion 3
1. Is C_i	C	d (i) subangular (e)	a (fast)	porous within microblocks
	M	e		microblocky
	P	e	a (fast)	porous within microblocks
	R	compound smaller round microaggregates all stick together (into?) larger blocks	a (fast)	
2. Ma C_i	C	f but only with difficulty	b but only held by fibres (i)-(iii)	
	M	a, b	b (i)	b, e
	P	a, b	b	b, d
	R	g	a, b moist subrounded/ gibbous	b
2 Sh F_{ii}	M	a, b	b (i)	b, e
	P	a	b	b
	R	g, (i)	b, microgranular	
4 Uk F_{ii}	C	d (i) but not b		
	M	c, d (i)	a (ii)	c (microblocky when wet)
	P	c	a (ii)	b, e?
	R	d (i)	a	

3.1.3 Emerson's test

Both the topsoils and subsoils from the 5 sites were tested for slaking using the scheme developed by Emerson (1967).

The results indicate that the topsoils from all sites were more stable (scored higher) than the corresponding subsoils (Table 3.5), probably due to a greater organic matter content suppressing slaking. Except at Sao Hill, previously cultivated topsoils scored one or 2 points lower. This suggests that the previous cultivations have resulted in some reduction in stability, possibly through increased microbial decomposition of organic matter derived from plant polysaccharides.

The Ismani cultivated topsoil aggregates slaked (Table 3.5, Plate 3.1). This indicates a sensitivity of this topsoil to hardsetting because slaking is one of the necessary preconditions for hardsetting (Young and Mullins, 1991). This result also demonstrates that changes in soil management can produce large changes in the physical behaviour of this soil.

All subsoils except Sao Hill fallow slaked. The greater stability of Sh F subsoil cannot be explained sufficiently by differences in particle size distribution because it does not differ much from Sh C subsoil (Table 3.1a). Although Sh F subsoil is more microaggregated than the Ismani subsoils (Table 3.3), for example, it is microaggregated to the same degree as Sh C, implying that the difference in stability between Sh F and Sh C subsoils cannot be explained by the degree of microaggregation either. It is probable that the Sao Hill fallow subsoil had a smaller organic matter content than the previously cultivated subsoil. Otherwise subsoils from the

Table 3.5 Soil aggregate stability classification using Emerson's test.

Depth (cm)	Site and Treatment	Stability Class
2-6	Ismani fallow	7
	Ismani cultivated	5
	Magamba fallow	8
	Magamba cultivated	7
	Mbimba fallow	8
	Mbimba cultivated	7
	Sao Hill fallow	8
	Sao Hill cultivated	8
	Ukwile fallow	8
	Ukwile cultivated	7
20-34	Ismani fallow	2
	Ismani cultivated	2
	Magamba fallow	6
	Magamba cultivated	6
	Mbimba fallow	6
	Mbimba cultivated	6
	Sao Hill fallow	7
	Sao Hill cultivated	6
	Ukwile fallow	6
	Ukwile cultivated	6

Plate 3.1 Soil aggregates undergoing a stability test on a tension table. Note on top picture, top left, the slaking Ismani cultivated topsoil.

different treatments did not differ significantly. Ismani subsoil was the least stable of them. Again it is difficult to explain this difference because its particle size distribution was not different from that of Magamba (or Sao Hill, for that matter) although it had significantly less clay than Mbimba (Table 3.1). Overall, Ismani and Sao Hill represent the extremes while Magamba, Mbimba and Ukwile all behaved in the same way.

3.2 Soil chemical properties

Table 3.6 shows some chemical properties of the soils studied.

Mbimba and Sao Hill soils had the lowest soil pH, followed by Ukwile, Magamba and Ismani. Farmers around the Sao Hill and Mbimba sites sometimes lime their soil in order to improve maize yields. At Ismani, Mbimba and Sao Hill the pH (in water) of the topsoils was significantly higher in the fallow than in the cultivated treatments. The fallow and cultivated topsoils at Magamba and Ukwile showed no significant difference in pH. In the subsoil, Magamba and Sao Hill fallow soils had significantly higher pH values, while the Ukwile cultivated subsoil exhibited higher soil pH than its contrasting fallow treatment. These higher topsoil pH values in the fallow treatments may be attributed to the significantly higher organic matter concentrations in the fallow treatment topsoils from all sites (except for Ukwile topsoil). The soil pH values measured at the 5 sites are within the range reported for many tropical soils (Sanchez, 1976).

There was no significant difference in organic matter concentration between the treatments at Ukwile. At the other sites, the fallow plots had significantly higher organic matter

Table 3.6 Some chemical properties of the soils.
(a) Soil pH, organic matter and cation exchange capacity (C.E.C.).

Depth (cm)	Site and Treatment	pH (H_2O)	Range/2 (±)	pH (0.01M $CaCl_2$)	Range/2 (±)	Organic matter (g kg^{-1})	S. error (±)	C.E.C. (meq kg^{-1})	Range/2 (±)
2-6	IsF	6.3	(0.04)**	5.5	(0.06)^{ns}	23.5	(1.5)*	116.4	(13.0)^{ns}
	IsC	6.1	(0.00)	5.3	(0.04)	19.5	(0.7)	114.3	(10.0)
	MaF	5.6	(0.07)^{ns}	5.1	(0.08)^{ns}	38.7	(0.3)**	131.8	(2.4)*
	MaC	5.7	(0.05)	5.0	(0.05)	28.6	(1.0)	112.5	(1.7)
	MbF	5.2	(0.02)**	4.9	(0.07)**	61.7	(1.2)***	174.8	(8.2)*
	MbC	4.8	(0.05)	4.3	(0.05)	40.3	(1.1)	146.5	(1.4)
	ShF	6.0	(0.05)**	5.0	(0.07)**	34.5	(0.8)*	72.0	(1.1)*
	ShC	5.2	(0.05)	4.2	(0.04)	29.8	(0.6)	55.6	(3.0)
	UkF	5.6	(0.07)^{ns}	4.7	(0.06)^{ns}	31.8	(0.4)^{ns}	114.3	(1.3)^{ns}
	UkC	5.7	(0.09)	4.7	(0.09)	30.9	(0.6)	111.3	(1.9)
30-34	IsF	6.8	(0.04)^{ns}	5.9	(0.09)*				
	IsC	6.9	(0.04)	6.1	(0.00)				
	MaF	6.4	(0.03)*	5.5	(0.06)^{ns}				
	MaC	6.2	(0.03)	5.3	(0.04)				
	MbF	5.4	(0.08)^{ns}	4.6	(0.09)^{ns}				
	MbC	5.5	(0.01)	4.6	(0.01)				
	ShF	5.6	(0.01)**	4.6	(0.03)*				
	ShC	5.0	(0.03)	4.2	(0.03)				
	UkF	5.5	(0.06)*	4.7	(0.05)*				
	UkC	5.9	(0.05)	4.9	(0.05)				

ns, the treatments do not differ significantly ($P = 0.05$); *, **, ***, the two treatments differ significantly ($P = 0.05$, 0.01 or 0.001, respectively) following t-tests for paired samples (for organic matter, based on 5 observations) or t-tests for unpaired samples (pH and C.E.C.).

Table 3.6 (Continued)
(b) Dithionite-extractable Al and Fe, EDTA-extractable Mn and Acid-oxalate extractable Si for topsoils (2-6 cm) at Ismani, Sao Hill and Ukwile.

Site and Treatment	Extractable Mn (mg kg^{-1})	Mn Site Means	Extractable Al (mg kg^{-1})	Al Site Means	Extractable Fe (mg kg^{-1})	Fe Site Means	Extractable Si (mg kg^{-1})	Si Site Means
Is F	322.3(12.4)	315.5(6.8)	448.7(17.9)	452.2(3.5)	17784.0(0.0)	17613.5(170.5)	3.4(0.3)	3.1(0.3)
Is C	308.7(0.0)		455.7(26.6)		17443.0(303.0)		2.8(0.5)	
Sh F	36.6(0.0)	28.8(7.9)	2298.0(98.0)	2364.0(66.0)	8666.0(455.0)	9120.5(454.5)	1.2(0.1)	1.2(0.1)
Sh C	20.9(0.4)		2430.0(62.0)		9575.0(152.0)		1.1(0.0)	
Uk F	863.1(0.0)	902.1(39.0)	1918.0(27.0)	1767.5(150.5)	26435.0(155.0)	26086.5(348.5)	7.3(0.1)	7.4(0.1)
Uk C	941.1(0.0)		1617.0(27.0)		25738.0(0.0)		7.5(0.0)	
Treatment	S.E.(±)		S.E.(±)		S.E.(±)		S.E.(±)	
Means: F	407.3(242.3)		1554.9(563.9)		17628.3(5130.1)		4.0(1.8)	
C	423.6(271.8)		1500.9(572.9)		17585.3(4666.4)		3.8(1.9)	
LSD Treatments (0.05)	4.1		ns		ns		ns	
Sites		13.0		130.3		573.6		0.5

Figures in brackets indicate the range/2 (+ or −) unless it is stated otherwise; ns, the fallow and cultivated treatment means do not differ significantly (L.S.D. 0.05).

concentrations than their cultivated counterparts. Continuous cultivation, especially where crop residues are not returned into the soil, decreases the soil organic matter concentration. For example, Gupta and Germida (1988) measured the organic carbon concentrations of Mollisol samples from a grassland and a field cultivated for 69 years located 200 m away. They reported that the grassland soil had an organic carbon concentration of 28.6 mg g^{-1} compared to only 20.40 mg g^{-1} measured in the continuously cultivated soil. They attributed the decrease in organic carbon concentration to cultivation. While the organic matter concentrations at Ismani, Magamba, Sao Hill and Ukwile fall within the range reported for many tropical soils (e.g. Ley *et al.*, 1989), the value at Mbimba was rather high. The high organic matter concentrations measured in the Mbimba fallow plots may be attributed to additions and the subsequent breakdown of leaves, roots and other plant parts because the treatment was located adjacent to a forest. The cultivated plots at Mbimba were established in 1975 after forest clearing. Since then they have been used for various experiments, including the establishment and incorporation of sunnhemp (*Crotalaria ochroleuca* and *Crotalaria pallida*). These may have helped to maintain the high organic matter concentration in the cultivated treatment.

At all sites the soils had a low cation exchange capacity (C.E.C.). As with organic matter concentration, the C.E.C. at all sites was higher (although not significantly so at Ismani and Ukwile) in the fallow than in the cultivated treatment. This may be attributed to the higher organic matter concentrations in the fallow plots (see Table 3.6*a*). Overall, the Sao Hill Oxisol had the lowest C.E.C. of about 56 and 72 meq kg^{-1} for the cultivated and fallow treatments, while the Mbimba Alfisol had the highest C.E.C. (about 147 and 175 meq kg^{-1} in the cultivated and fallow topsoils, respectively).

Aluminium, iron, manganese and silicon were measured because they can act as cementing agents, bonding soil particles together. The topsoils at Ismani, Sao Hill and Ukwile were chosen for analysis of extractable Mn, Al, Fe and Si because of their contrasting physical behaviour. The results are presented in Table 3.6*b* . Generally, topsoils at all 3 sites differed significantly in extractable Mn, Al, Fe and Si. Ukwile topsoil had the highest concentration of extractable Mn (about 2.8 and 31 times that of Ismani and Sao Hill respectively). It also had significantly more extractable Fe and Si than both the Ismani and Sao Hill topsoils. On the other hand, Sao Hill topsoil had about 5 times more extractable Al than the Ismani topsoil. It also had about 1.3 times as much extractable Al as the Ukwile topsoil. The low pH observed at both Sao Hill and Ukwile (Table 3.6*a*) may account for the high Al content in soils at these two sites. The concentration of Fe at Ismani is comparable to that reported by Mullins et *al*. (1992*a*) for a hardsetting Australian Alfisol (17600 *versus* 15300 mg kg^{-1}). Extractable Si, however was much lower than the 177 mg kg^{-1} reported by Mullins et *al*. (1992*a*). It was also lower than that reported by Trapnell and Webster (1986), who measured water soluble SiO_2 concentrations of 55 mg kg^{-1} in a microaggregated soil in Malawi. However, it is unclear whether the low concentrations of Si at my three sites is a reflection of the true status of extractable Si in these soils since clogging of the nebuliser of the atomic absorption spectrometer may have led to an underestimation of Si.

Edwards and Bremner (1967) proposed the linking of organic matter and clay with polyvalent cations in the formation and stabilization of microaggregates. Later, Giovannini and Sequi (1976*a; b*) selectively extracted Fe and Al and postulated that they were involved in the linking role proposed by Edwards and Bremner (1967). Recently, Chaney and Swift (1986) have suggested that humic materials associated with amorphous Fe, Al and Si are the persistent binding agents of microaggregates (Tisdall and Oades, 1982). Because both Sao Hill and Ukwile have good physical properties, it is possible that Al and Fe may be involved in improving the physical conditions by acting as a cementing material in these soils. However, the Ismani soil was hardsetting despite its high concentration of extractable Fe. Thus, the concentrations of potential cementing agents does not give any clear indication of the observed physical behaviour and, as suggested by Aylmore and Sills (1978), it is likely that successful structure formation depends on the particular form and combinations of the constituents required to effect bonding.

Table 3.7 shows some of the clay-sized minerals for the 5 sites. Kaolinite was the dominant clay-sized mineral at all 5 sites since it was identified most often.

Table 3.7 Some of the clay-sized fractions identified in the soils at the 5 sites.

Site and Treatment	Mineral
Is F	Kaolinite, Hydrous mica, Haematite, Feldspar, Quartz, Pyroxene, Vermiculite.
Is C	Kaolinite, Hydrous mica, Haematite, Feldspar, Quartz, Pyroxene, Vermiculite.
Ma F	Kaolinite, Halloysite, Feldspar,Muscovite, Magnetite, Chlorite.
Ma C	Kaolinite, Halloysite, Feldspar, Muscovite, Chlorite. Pyroxene.
Mb F	Kaolinite, Feldspar, Halloysite, Muscovite, Pyroxene, Attapulgite.
Mb C	Kaolinite, Feldspar, Halloysite, Muscovite, Pyroxene, Attapulgite.
Sh F	Kaolinite, Muscovite, Biotite, Halloysite, Gibbsite, Haematite, Quartz.
Sh C	Kaolinite, Halloysite, Gibbsite, Haematite, Chlorite, Pyroxene.
Uk F	Kaolinite, Halloysite, Pyroxene, Feldspar, Haematite, Muscovite.
Uk C	Kaolinite, Halloysite, Haematite, Muscovite, Pyroxene, Feldspar.

3.3 Measurements on the minicores

3.3.1 Water release characteristics

The SuperCalc 5 spreadsheet programme was used to examine for wild values which were then checked in the raw data and any coding errors were corrected. After careful visual inspection of data plots it was established that:

i) results obtained on different sampling dates and from duplicate plots did not differ and were therefore pooled;

ii) despite a certain scatter due to the field variability between minicores, the points lay on a smooth monotonically decreasing curve.

Similar curves were obtained for all plots at all depths. The smooth nature of these curves was taken as confirmation that the filter paper technique was giving reliable values. The filter paper values were therefore used in preference to those obtained from the pressure plate apparatus since there was some doubt as to whether the equilibration period for such tall samples was sufficient. In addition, erratic electricity supply problems with the pressure plate apparatus made it difficult to ensure complete equilibration.

Figure 3.1 shows, as an example, the water release characteristics of the Ismani and Sao Hill top soils (see Appendix II for the rest). Because the filter papers used were small, the water content was expected to be a more accurate measurement and was used as the independent variable with matric potential (matric suction) as the dependent variable for regression.

The function

$$\log \psi = a + b \log (\theta/\theta_s), \qquad (3.1)$$

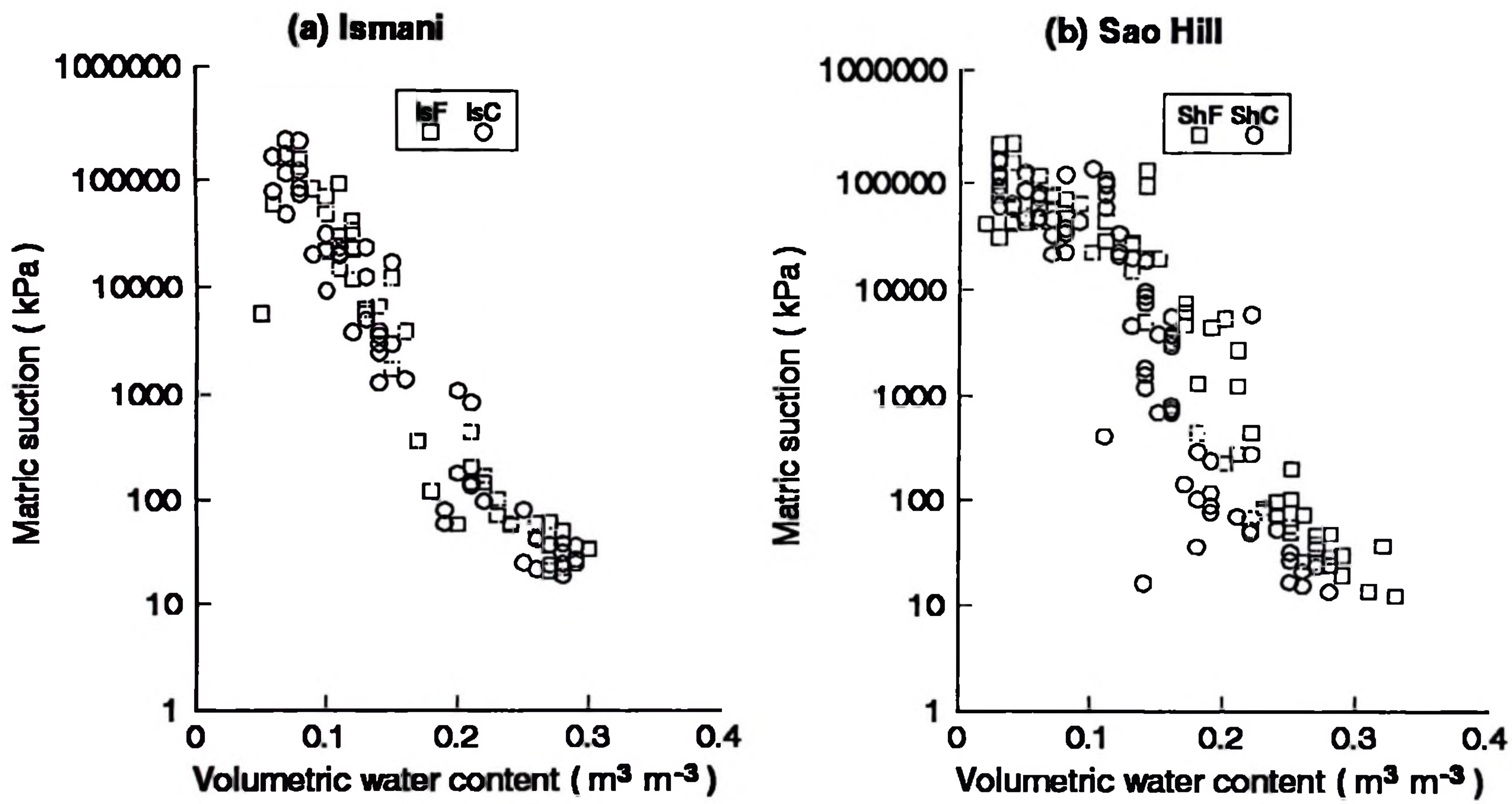


Figure 3.1 Water release characteristics for Ismani and Sao Hill topsoils (2-6 cm).

where ψ is matric suction (in kPa), θ is volumetric water content, θ_s is the volumetric water content at saturation, and *a* and *b* are constants, is commonly used to describe the water release characteristic (Buchan & Grewal, 1990). This function was fitted to the results for each site, treatment and depth. To do this, θ_s was calculated from the bulk density and density of solids (assumed to be 2.65 Mg m^{-3}) of each sample, and a regression of log ψ on log (θ/θ_s) was performed. Values of *a*, *b* and θ_s are shown in Table 3.8 as well as the correlation coefficient *r*. In nearly all cases, *r* was highly significant (P = 0.001) indicating a good fit of the data to the function.

Significant differences between treatments are indicated in the column marked VR. The treatments at Mbimba and Ukwile differed significantly at all three depths, and at Ismani and Magamba they differed significantly in the subsoil. Since the soils at all of the paired treatments except Ismani topsoil and Ukwile subsoil had closely similar particle size distributions (Table 3.1a), these small but significant differences in release characteristics cannot be attributed to particle size differences and must be related to differences in pore size distribution resulting from differences in packing. This can be verified by considering the between-treatment differences in θ_s (θ_s is equal to the total porosity). All paired treatments that had significantly different release characteristics had values of θ_s that differed by 0.04 or more whereas θ_s differed by less than 0.032 between treatments whose release characteristics were not significantly different. Except for Ukwile, these differences corresponded to a greater porosity in the fallow treatments.

Table 3.8 Coefficients in the equation $\log \psi = a + b \log (\theta/\theta_s)$ (Buchan and Grewal, 1990) for describing the water release characteristic, for 5 Tanzanian soils. ψ is matric suction in kPa, θ is volumetric water content, $\theta_s = \theta$ at saturation, and a and b are fitting constants. Standard errors are given in brackets. VR indicates where there are significant differences ($P = 0.05$, *; 0.01, **; and 0.001, ***) in the release characteristic between treatments.

Depth (cm)	Site and Treatment	*a*	*b*	*r*	VR	θ_s
2-6	IsF	0.8(0.7)	-5.4(0.5)	0.87	ns	0.431(0.006)
	IsC	0.6(0.4)	-6.2(0.3)	0.95		0.400(0.003)
	MaF	0.6(0.6)	-4.9(0.3)	0.92	ns	0.528(0.006)
	MaC	0.9(0.6)	-4.6(0.3)	0.91		0.530(0.005)
	MbF	0.8(0.7)	-5.4(0.4)	0.90	*	0.629(0.008)
	MbC	1.3(0.7)	-5.1(0.5)	0.87		0.569(0.004)
	ShF	1.1(0.7)	-3.7(0.2)	0.87	ns	0.525(0.003)
	ShC	1.0(0.8)	-3.8(0.3)	0.82		0.543(0.003)
	UkF	1.2(0.8)	-4.7(0.4)	0.86	**	0.520(0.006)
	UkC	0.5(0.7)	-5.0(0.4)	0.89		0.578(0.005)
8-12	IsF	1.7(0.9)	-4.5(0.7)	0.76	ns	0.423(0.009)
	IsC	1.1(0.7)	-5.5(0.6)	0.87		0.393(0.007)
	MaF	0.9(0.5)	-5.0(0.3)	0.95	ns	0.490(0.005)
	MaC	1.2(0.6)	-4.5(0.4)	0.93		0.482(0.006)
	MbF	0.7(0.8)	-5.1(0.7)	0.84	***	0.632(0.007)
	MbC	1.4(0.8)	-5.4(0.4)	0.91		0.551(0.004)
	ShF	1.1(0.7)	-4.1(0.4)	0.84	ns	0.509(0.005)
	ShC	1.0(0.7)	-3.8(0.4)	0.86		0.528(0.004)
	UkF	1.4(0.8)	-4.7(0.5)	0.85	***	0.495(0.005)
	UkC	0.1(0.6)	-5.4(0.5)	0.91		0.593(0.007)
30-34	IsF	-0.1(0.5)	-8.2(1.0)	0.91	*	0.444(0.007)
	IsC	0.6(0.5)	-8.1(1.0)	0.90		0.394(0.004)
	MaF	0.7(0.5)	-5.2(0.6)	0.94	**	0.514(0.008)
	MaC	1.4(0.8)	-6.1(1.4)	0.73		0.471(0.009)
	MbF	0.5(0.4)	-5.1(0.4)	0.97	**	0.611(0.010)
	MbC	2.0(0.9)	-5.6(1.2)	0.74		0.547(0.009)
	ShF	1.7(1.1)	-3.4(0.9)	0.65**	ns	0.487(0.022)
	ShC	1.4(1.0)	-4.7(0.9)	0.74		0.460(0.021)
	UkF	0.9(0.8)	-9.3(2.8)	0.66**	*	0.494(0.008)
	UkC	0.9(0.8)	-5.1(1.8)	0.60*		0.540(0.008)

All coefficients of correlation, *r*, were significant at $P = 0.001$ except where indicated.

3.3.2 Strength characteristics

3.3.2.1 Soil strength and the concept of effective stress

The strength of the soil in bulk is affected by the strength of the bridging material (soil or water) that joins aggregates together. The strength of these bridges, in turn, is influenced by matric potential. The matric potential influences soil strength by affecting the effective stress. According to the Coulomb-Mohr theory of strength, shear failure occurs in a material when some critical shear stress τ is exceeded. The shear stress (τ) may be expressed as

$$\tau = c + \sigma \tan \phi, \tag{3.2}$$

where σ is the normal stress on the plane of failure and c and ϕ, the cohesion and angle of friction, are two constants which characterize the material. When a saturated porous material is subjected to external stress, the pore water, because it has no shear strength, is ineffective in mobilizing shearing resistance. Therefore, ignoring any possible effects due to trapped air, the effective stress σ^1 is given by

$$\sigma^1 = \sigma - u \tag{3.3}$$

where σ is the externally applied normal stress on the plane of failure and u is the pore water pressure. Likewise, when the pore water is under a tension ψ, the tension supplements any externally applied stress so that in a saturated soil the effective stress is given by

$$\sigma^1 = \sigma + \psi. \tag{3.4}$$

It has been demonstrated that in saturated kaolinite, for example, pore water tensions of up to 400 kN m^{-2} are equivalent to an isotropic externally applied mechanical pressure (Towner, 1961). Thus it is appropriate to substitute σ^1 for σ in Equation (3.2) since σ^1 is the total normal stress on the plane of failure.

Assuming that the air in soil pores is at atmospheric pressure, the effective stress in an unsaturated soil is given by

$$\sigma^1 = \sigma + \chi|\psi|, \tag{3.5}$$

where χ is the proportion of the matric potential that contributes to the effective stress. The factor χ is dependent upon the degree of saturation and the organisation of the fine material in the soil and is approximately equal to the degree of saturation in a wet soil. In a saturated soil, χ takes the value 1 and decreases to zero in a dry soil. Thus soil strength would be expected to increase in a drying soil as the matric suction increases up to the point where the reduction in χ limits any further increase in strength and may cause a decrease. Mullins and Panayiotopoulos (1984) were able to show that effective stress can make a major contribution to the strength of sand-kaolin mixtures. Mullins *et al.* (1987) suggested that a sharp drop in matric potential over a narrow range of moisture contents and a corresponding increase in strength clearly indicate the contribution of effective stress to soil strength in hardsetting soil. Thus in the study reported here, the effect of the degree of saturation, matric potential and, therefore, effective stress on soil strength were investigated.

3.3.2.2 Tensile strength

Mullins and Panayiotopoulos (1984) proposed physically based models for tensile and compressive strength characteristics that should be appropriate for both hardsetting and microaggregated soils. For tensile strength, Y, they proposed the equation

$$Y = c - \chi\psi \qquad (3.6)$$

where c is cohesion, ψ is matric potential and χ is a factor related to the degree of saturation, S. This model was improved by Mullins *et al.* (1992*b*). For tensile strength (Y), Mullins et *al.* (1992*b*) proposed the equation

$$Y = c - \chi\psi/(f(S) \qquad (3.7)$$

where $f(S)$ is a function that depends on the shape of flaws (pores or cracks) within the soil and c, χ and ψ are as already defined. The variable $f(S)$ is equal to 2 for spherical flaws and becomes progressively larger for more elongated flaws. Because matric potential is always negative or zero, the second term on the right-hand side is positive or zero. The factor χ may be approximated by S in wet soils but it is not clear how dry the soil may become before this approximation may become unacceptable (Mullins and Panayiotopoulos, 1984). When there are no externally applied stresses, the term $-\chi\psi$ represents the effective stress that is experienced by the soil.

To understand how tensile strength is likely to vary with ψ, it is necessary to consider how c may vary with matric potential. In a moist soil, particles of clay and other particles with a net negative surface charge, will be held apart by the long-range double-layer force of repulsion. However, it has been shown by Mullins et *al.*

(1992*b*), for example, that structurally stable soils have a small wet strength even when at zero potential. This demonstrates that a small amount of chemical bonding can exist in a saturated soil. As the soil dries out, the increase in effective stress pulls the particles together. However, there will be no net increase in cohesion until the particles are close enough for short-range chemical bonds to form. Mullins *et al.* (1992*b*), therefore, proposed that c remains constant over a range of matric potentials to a point where chemical bonding and, hence, c start to increase.

To compare the field behaviour of the soils studied and show how tensile strength (Y) varies with matric suction (ψ) I have plotted Y *versus* ψ for topsoils of the two contrasting soils using logarithmic axes for convenience, to represent the wide range of potentials and strength. I have also regressed the log of Y on the log of matric suction (ψ) for all soils and at all depths. Graphs and a discussion of how Y varies with effective stress and the significance of the shape of this relationship are given in section 4.2.

Figure 3.2 shows the tensile strength characteristics for Ismani and Sao Hill topsoils (2-6 cm) obtained from the minicore results. Results obtained on different sampling dates and from duplicate plots were not different and have therefore been pooled. Results in Figure 3.2 include the strongest (Ismani) and the weakest (Sao Hill, cultivated) of the topsoils at the five sites at any given matric suction. The tensile strength of air dry (100 MPa suction) IsC topsoil was about 90 kN m^{-2} while that of ShC topsoil was about 10 kN m^{-2} (Figure 3.2). On the other hand, tensile strength values

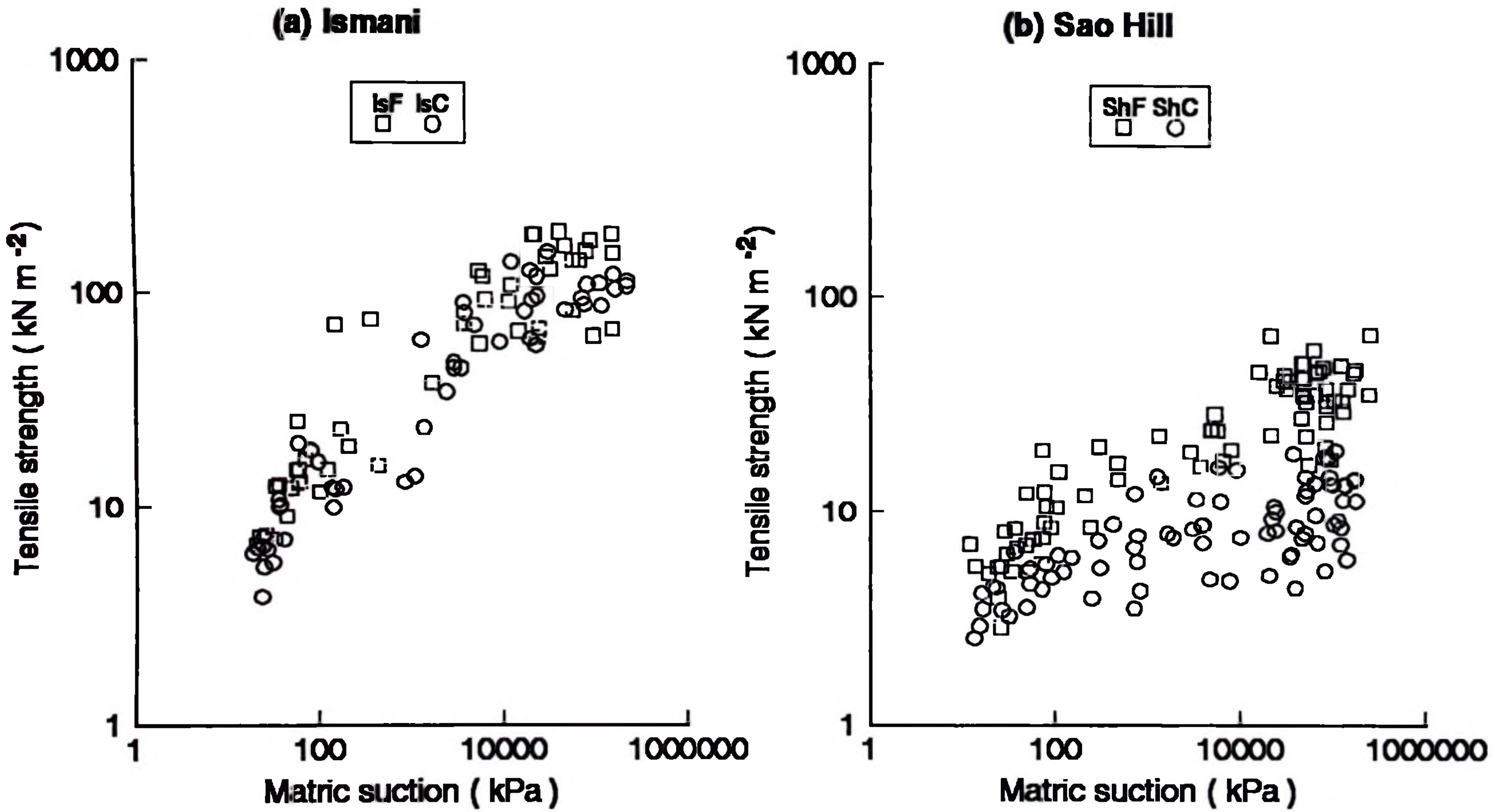


Figure 3.2 Tensile strength characteristics for Ismani and Sao Hill topsoils (2-6 cm).

of about 180 kN m^{-2} and 60 kN m^{-2} were recorded for IsF and ShF topsoils, respectively (Figure 3.2). Similar plots were obtained for other sites and at other depths (8-12 and 30-34 cm) (see Appendix II).

The empirical function

$$\log Y = a + b \log \psi \qquad (3.8)$$

where Y is the tensile strength in kN m^{-2} and ψ is matric suction in kPa was fitted to the first portion of these plots up to a maximum suction of ψ_{max} (see Table 3.9a). At greater matric suctions the tensile strength was often found to vary little with matric suction and mean values of Y are then given for $\psi > \psi_{max}$. The only exception to this procedure was Sao Hill fallow topsoil (2-6 cm) where two separate regression lines have been fitted at small and large matric suctions.

A comparison between results from the two treatments at each site (Table 3.9a) shows that, where significant and sizeable differences exist, the fallow topsoil had a greater tensile strength than the cultivated topsoil at any given matric suction. Thus for Magamba (2-6 cm), Sao Hill (2-6 cm) and Ukwile (8-12 cm), the coefficient a was considerably greater for the fallow treatment, and for Sao Hill (2-6 and 8-12 cm) and Ukwile (2-6 cm) the coefficient b was considerably greater. At these three sites there is therefore clear evidence that a period of continuous cultivation has been beneficial in terms of reducing tensile strength and hence reducing the energy required for further cultivations. At Ismani there is also some evidence (Table 3.9a and Figure 3.2) that continuous cultivation has resulted in small reductions in the tensile strength

Table 3.9a Tensile strength characteristics of 5 Tanzanian soils specified by coefficients in the equation $\log Y = a + b \log \psi$, where Y is tensile strength in kN m^{-2} and ψ is matric suction in kPa. Linear regression of $\log Y$ on $\log \psi$ was performed up to ψ_{max} above which a mean tensile strength is given (and coefficient of variation is given as a percentage in brackets). VR indicates where the strength characteristics differ between treatments at P = 0.05, *; 0.01, ** or 0.001, ***.

Depth (cm)	Site and Treatment	a	b	r	VR	log (ψ_{max})	log mean tensile strength in kN m^{-2}
2-6	IsF	0.40(0.16)	0.40(0.03)	0.93	*	4.18	2.11(8.1)
	IsC	0.26(0.17)	0.41(0.03)	0.91		4.18	2.00(5.1)
	MaF	0.74(0.27)	0.27(0.05)	0.66	***	4.60	1.92(8.6)
	MaC	0.44(0.22)	0.30(0.03)	0.81		4.60	1.76(8.0)
	MbF	0.57(0.18)	0.31(0.03)	0.90	ns	4.48	1.92(5.9)
	MbC	0.48(0.18)	0.31(0.03)	0.90		4.48	1.86(9.1)
	ShF	0.31(0.15)	0.45(0.11)	0.61	***	2.08	
	+ShF	0.71(0.14)	0.18(0.02)	0.72		>2.08	
	ShC	0.44(0.16)	0.12(0.01)	0.72			
	UkF	0.40(0.23)	0.41(0.07)	0.79	***	3.00	1.94(7.6)
	UkC	0.35(0.20)	0.28(0.02)	0.91			
8-12	IsF	0.38(0.13)	0.43(0.04)	0.95	**	4.00	2.12(5.0)
	IsC	0.45(0.15)	0.35(0.02)	0.95		4.78	2.07(4.0)
	MaF	0.45(0.17)	0.44(0.10)	0.75**	ns	3.30	2.04(9.4)
	MaC	0.51(0.14)	0.38(0.04)	0.91		3.70	1.98(10.4)
	MbF	0.83(0.23)	0.22(0.04)	0.83	*		
	MbC	0.46(0.14)	0.35(0.03)	0.94		4.70	1.98(7.6)
	ShF	0.43(0.11)	0.30(0.02)	0.93	***	4.00	1.66(10.0)
	ShC	0.38(0.22)	0.21(0.04)	0.71		4.00	1.13(13.1)
	UkF	0.26(0.22)	0.53(0.08)	0.85	***	3.48	2.00(5.2)
	UkC	0.13(0.23)	0.42(0.09)	0.82		4.04	1.73(6.6)

Table 3.9a (Contd.)

Depth (cm)	Site and Treatment	*a*	*b*	*r*	VR	log (Ψ_{max})	log mean tensile strength in kN m^{-2}
30-34	IsF	0.18(0.22)	0.50(0.08)	0.90	ns	4.00	2.16(0.5)
	IsC	0.22(0.14)	0.43(0.03)	0.97			
	MaF	0.47(0.16)	0.36(0.06)	0.91	ns	3.85	1.96(5.2)
	MaC	0.35(0.21)	0.43(0.04)	0.92			
	MbF	0.57(0.15)	0.26(0.03)	0.93	***		
	MbC	0.49(0.12)	0.35(0.02)	0.97			
	ShF	0.63(0.16)	0.25(0.06)	0.80**	ns	4.00	1.68(6.3)
	ShC	0.65(0.16)	0.24(0.03)	0.91			
	UkF	0.12(0.23)	0.69(0.13)	0.89**	ns	3.00	2.01(7.8)
	UkC	0.15(0.38)	0.64(0.19)	0.75*		3.00	1.67(20.5)

+ linear regression coefficients for $\psi > \Psi_{max}$
The correlation coefficient, *r*, is significant at P = 0.001 except where indicated.

of the air-dry ($\psi \sim 10^5$ kPa) topsoil. At Mbimba differences in clay content (Table 3.1*a*) mean that no interpretation can be reliably put on differences or similarities between treatments.

3.3.2.3 Compressive strength

Table 3.9*b* shows compressive strength results at matric suctions of 100 kPa and 100 MPa. A contrast similar to that shown by tensile strength results exists in terms of compressive strengths of the Ismani and Sao Hill topsoils (Table 3.9*b*). These results however, can only be considered as rough estimates because limited replication has resulted in large standard errors.

3.4 Measurements on 40 mm cores

3.4.1 Penetration resistance characteristics

High soil strength, and the related high mechanical impedance or resistance to root growth, can severely affect the plant's ability to emerge from crusted soils, to extend its root system into unexplored soil volumes, to transport photosynthates from shoots to roots, to transport water from roots to shoots or to allow below-ground expansion of root crops (Rendig and Taylor, 1989). High mechanical impedance may lead to the stunting of the root system and reduce crop yield. However, if sufficient water and nutrients are available to a stunted root system, shoot growth (and, hence, crop yield) may not be reduced (Goss, 1977).

It is difficult to study the effect of mechanical resistance on root growth through soil due to the complicating factors of soil heterogeneity and the effects of restricted aeration or restricted

Table 3.9*b* Compressive strength results at two matric suctions.

Depth (cm)	Site and Treatment	Compressive strength ($kN\ m^{-2}$) 100 kPa	100 MPa
2-6	IsF	94.3 (8.1)	651.1
	IsC	85.3(11.2)	586.5 (55.2)
	MaF	113.7(19.4)	692.6(126.9)
	MaC	65.3 (6.3)	292.2 (59.9)
	MbF	101.2(12.7)	463.7(115.1)
	MbC	134.0	630.7 (58.8)
	ShF	60.1 (6.9)	153.3 (28.1)
	ShC	32.1 (5.5)	63.3 (7.6)
	UkF	129.9 (4.9)	622.2 (96.1)
	UkC	50.8 (7.0)	283.4 (30.8)
8-12	IsF	112.9(11.9)	814.5
	IsC	135.4(22.1)	643.4
	MaF	128.5 (7.5)	633.1(223.8)
	MaC	184.7(41.5)	337.4 (30.4)
	MbF	63.8(19.7)	474.6(164.8)
	MbC	85.3	797.4 (90.5)
	ShF	91.2	245.7 (43.2)
	ShC	37.4	80.3 (15.9)
	UkF	88.3	949.6
	UkC	76.1(15.3)	441.5
30-34	IsF	122.2	
	IsC	94.9 (3.1)	
	MaF	104.2	724.5
	MaC	89.9	
	MbF	63.1	348.0
	MbC		1138.5(222.2)
	ShF	44.1	160.4
	ShC	123.4	412.8

Standard errors are indicated in parentheses.

supply of nutrients or water (Eavis, 1972; Voorhees et *al.*, 1972). Hence, root growth has often been studied in artificial systems which permit careful control of the root environment (Gill and Miller, 1956; Barley, 1962).

Soil resistance to root growth has been indirectly estimated using many devices, the most common being measuring soil resistance to a metal probe or penetrometer (Davidson, 1965). The resistance encountered by roots and penetrometers is a complex function of soil compressibility and other variables related to strength (Greacen et *al.*, 1968., Greacen, 1986).

As a root or penetrometer probe enters the soil, it deforms it. Soil resistance to deformation is made up of frictional forces at the interparticle contact areas that resist the sliding of particles and cohesion forces that hold the particles together (Terzaghi and Peck, 1948; Capper and Cassie, 1963; Yong and Warkentin, 1966). These factors can vary between and within different soils (Greacen et *al.*, 1968; Camp and Gill, 1969). According to Haines (1927) and Aitchison (1961), the magnitude of the frictional forces is determined by the frictional properties of the soil material and the extent and condition of interparticle areas of contact, whereas soil cohesion is determined by cementing materials present and the strength of moisture "bonds" holding the particles together (*i.e.* effective stress in the absence of external forces). The contribution of this effective stress has already been described in section 3.3.2.1. It is a function of matric suction, pore-size distribution and the degree to which the various-sized pores are drained (Capper and Cassie, 1963; Williams and Shaykewich, 1970).

As a soil dries from field capacity (5 kPa suction) to wilting point (1.5 MPa suction), this factor is more likely to vary within any one soil than frictional properties and content and strength of the cementing materials. As discussed in section 3.3.2.1, with increasing matric suction, effective stress initially increases. As matric suction is increased further, sufficient pore space may be drained to result in a net decline in soil strength even though the "bonds" associated with any remaining undrained pores might be very strong (Mirreh and Ketcheson, 1972).

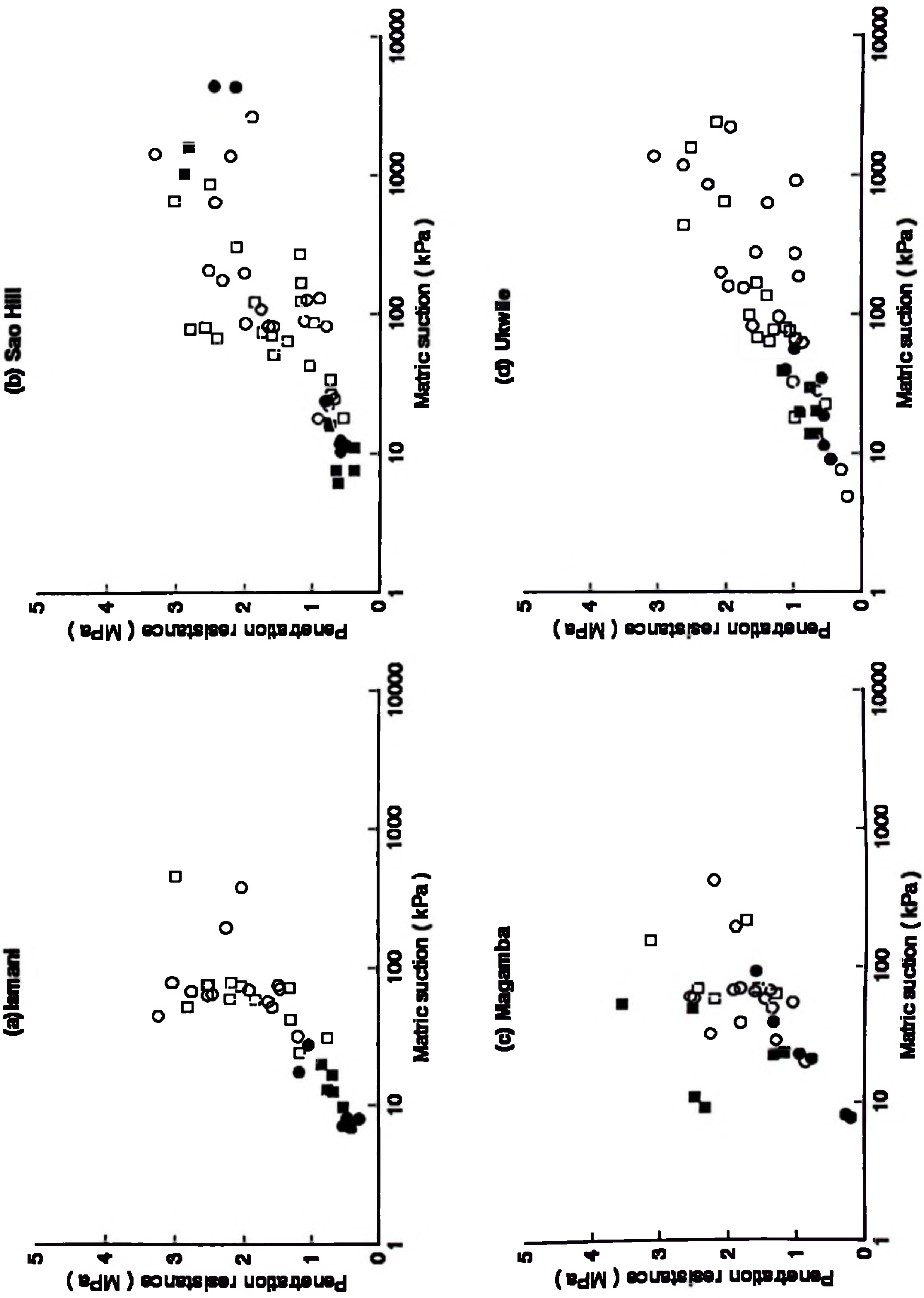
As a consequence of the complexity of the factors affecting penetration resistance (*PR*), it is difficult to derive a theoretically based model based on the relation between *PR* and soil water content or matric potential. However, empirical relations that show a linear relation between *PR* and soil water content and matric suction at low suctions (between 0 and 10 kPa) are available for a number of soils (Mirreh and Ketcheson, 1972; Paul and De Vries, 1979; Mandiringana, 1984). Steinhardt (1974) found that within a limited tension range close to saturation the rate of change of resistance to penetration of a 60° cone could be expressed as

$$\frac{d(PR)}{dh} \approx K_c N_c \chi \tan \phi \qquad (3.9)$$

where *PR* = cone penetration resistance (kg cm^{-2}); *h* = soil water tension (cm of water or kg cm^{-2}); K_c = a dimensionless cohesion modifying factor dependent on the mode of shear failure; N_c = a dimensionless modifying factor dependent only on the angle of shearing resistance, ϕ; χ = a dimensionless factor related to the degree of saturation (Bishop, 1960; Mullins and Panayiotopoulos, 1984; Snyder and Miller, 1985; Mullins *et al.*, 1992*b*); and ϕ = the internal, consolidated, drained angle of shearing resistance, in degrees. Unfortunately, the variables involved in these empirical relations are very time-consuming to obtain and do not cover a sufficiently wide range of potential. Despite the many differences between metal probes and plant roots (see section 4.2.2), the penetrometer test is still the most common and best means of detecting root-impeding zones (Bengough, 1991).

This section presents results for both needle penetration resistance (PR) determined on 40 mm cores and field PR. PR characteristics for all topsoils are shown in Figure 3.3. See Appendix III for both topsoils and subsoils (22-26 cm). Curves obtained on different sampling occasions and from either replicate were not found to differ therefore these results have been pooled. With core sampling and laboratory equilibration there is always a concern that some experimental bias may have been introduced. However, the agreement between field and laboratory results implies that the laboratory results are a reliable indication of field soil behaviour. Because the penetrometer arrangement could not record PR values greater than 4.5 MPa, points where more than 3 of the 15 PR measurements used to obtain each average were offscale have not been plotted. As a consequence many of the PR points at larger matric suctions for Ismani, Mbimba and Magamba have been omitted because they contained too many offscale values.

Since none of the soils studied had major macrostructural features that would allow roots to bypass the bulk of the soil, these PR characteristics should provide some indication of the comparative


(a) Isamani
(b) Sao Hill
(c) Magamba
(d) Ukwile
Penetration resistance (MPa)
Matric suction (kPa)
0
1
2
3
4
5
1
10
100
1000
10000

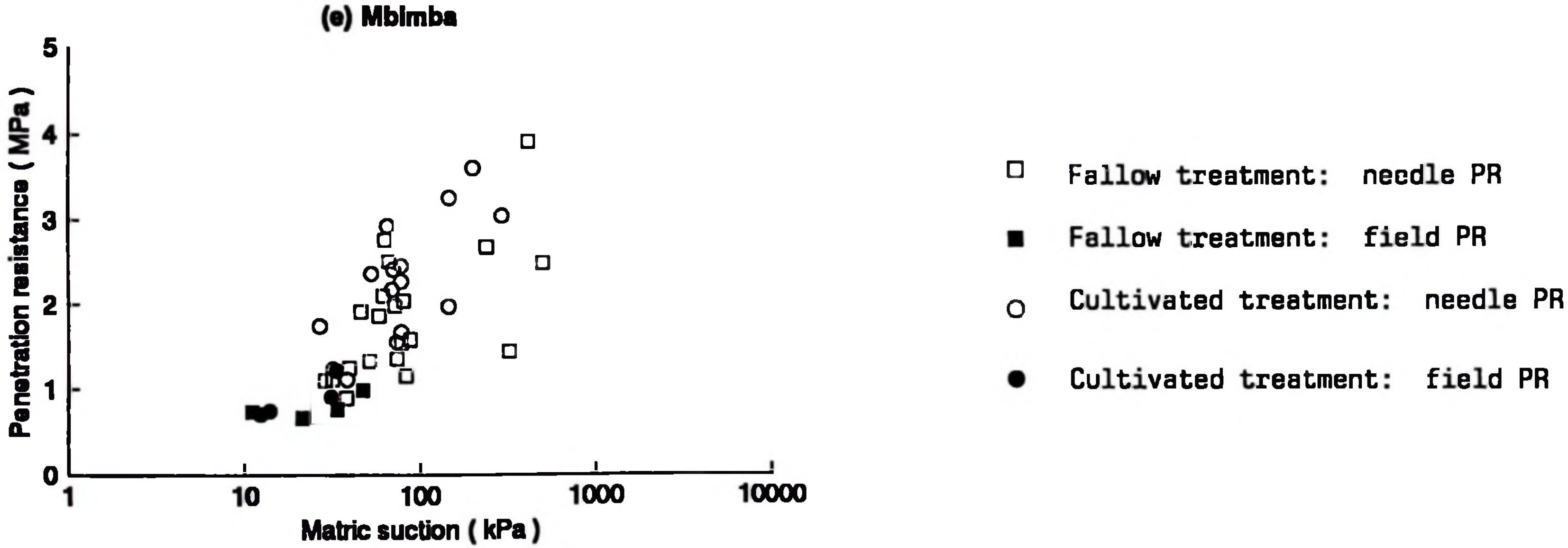


Figure 3.3 Penetrometer resistance (PR) characteristics for all 5 sites for topsoils (5.5 - 9.5 cm).

effects of the topsoils on root growth. Considering that a PR of 1 MPa is sufficient to cause a substantial reduction in root growth rate, and that values greater than 3 MPa can halt or impede root growth greatly (Veihmeyer & Hendrickson, 1948; Bengough and Millins, 1990; Glinski & Lipiec, 1990), it is possible to rank the topsoils in terms of their effect on roots at any given matric suction. To do this it is necessary to consider the missing offscale points for Ismani, Mbimba and Magamba. When this is done, Sao Hill and Ukwile are clearly the best or most easily rootable topsoils at any given matric potential, Ismani the worst, and the other two are not quite as bad as Ismani. The effect of these rooting restrictions on the water available to crops is discussed further in section 4.2.2. Use of a penetrometer with a greater upper limit would have allowed this distinction to be made more clearly.

3.5 Field measurements

3.5.1 Rainfall data

Figure 3.4 and Table 3.10 show, respectively, the daily and monthly rainfall data at Ismani, Sao Hill and Mbimba. No rainfall information is provided for the Magamba and Ukwile sites because the raingauges failed for part of the season. There were no manual raingauges at these latter two stations.

The 1990/1991 season was a generally dry growing season in Tanzania. The rains started late at all sites except at Mbimba. Sao Hill received only about 56 percent of its long term average annual rainfall (Table 3.10). The total rainfall received at both Ismani and Mbimba during the 1990/1991 growing season was about 91%

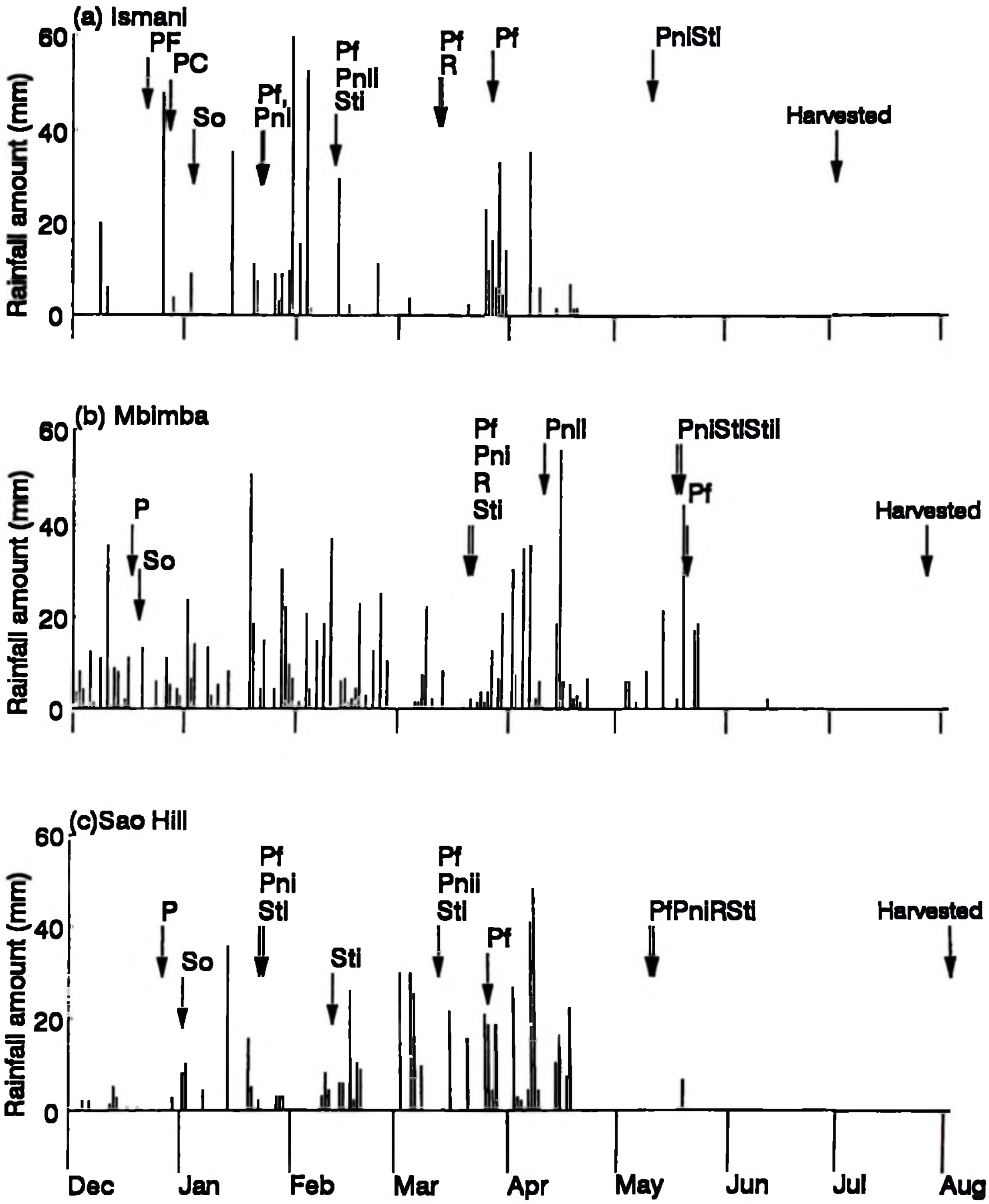


Figure 3.4 Daily rainfall and timing of some field operations. C, cultivated treatment; F, fallow treatment; P, ploughing; Pf, field PR, matric potential and water content determination; Pni, Pnii, Needle PR (5.5-9.5 cm, 22-26 cm depth); R, root count; So, sowing; Sti, Stii, minicoring (2-6 cm, 8-12 cm depth).

Table 3.10 Monthly rainfall data for Ismani, Sao Hill and Mbimba from 01.12.1990 to 20.06.1991.

Site	Total rainfall (mm)							Total for the season (mm)	Percentage of long-term average
	December	January	February	March	April	May	June		
Ismani	76.8	151.4	110.9	110.8	51.3	0	0	501.2	91.1
Sao Hill	17.8	89.0	73.7	188.8	181.5	6.6	0	557.4	55.7
Mbimba	152.4	230.5	187.5	93.6	213.0	122.7	2.0	1001.7	91.1

of the long term average at both sites. However, whereas the rainfall events were well distributed at Mbimba, 6 storms (two in January, and one each in December, February, March and April, Figure 3.4) accounted for about 52% of the total rainfall received at Ismani, with the remaining 27 rainfall events accounting for only 48% of the total rainfall in the growing season. It is important therefore to consider both total rainfall and rainfall distribution pattern when comparing the Ismani and Mbimba rainfall data.

3.5.2 Crop establishment and pests

Dates on which the different sites were ploughed, sown to maize and harvested have already been given in Table 2.6 (see section 2.2.5).

Ploughing and planting were delayed at all sites due either to the rains starting late or to the unavailability of tractors or oxen or due to both reasons (*e.g.* at Magamba). Sown seeds as well as emerging seedlings were seriously attacked by birds and mice. Although scarecrows were used, they did not deter these pests. Maize sown in the fallow treatment plots suffered the most. At Magamba, for example, maize in the fallow treatment had to be resown after about 50 percent of it was destroyed by pests. At all other sites gap filling was done especially in the fallow treatment by using seed or seedlings (*e.g.* at Mbimba where local farmers fill gaps by transplanting). As a result of this, comparisons of yield between fallow and cultivated treatments may not be very relevant.

3.5.3 Root measurements

Root measurements were carried out when maize had attained > 50% tasselling at each site. Plate 3.2 and Figure 3.5 show, respectively, an example of root distribution for the Mbimba and Ukwile sites and root measurement results for all sites except Magamba. Root measurement data for the Magamba site are not presented because the two treatments were sampled when the maize crops were of different age (following resowing the fallow treatment).

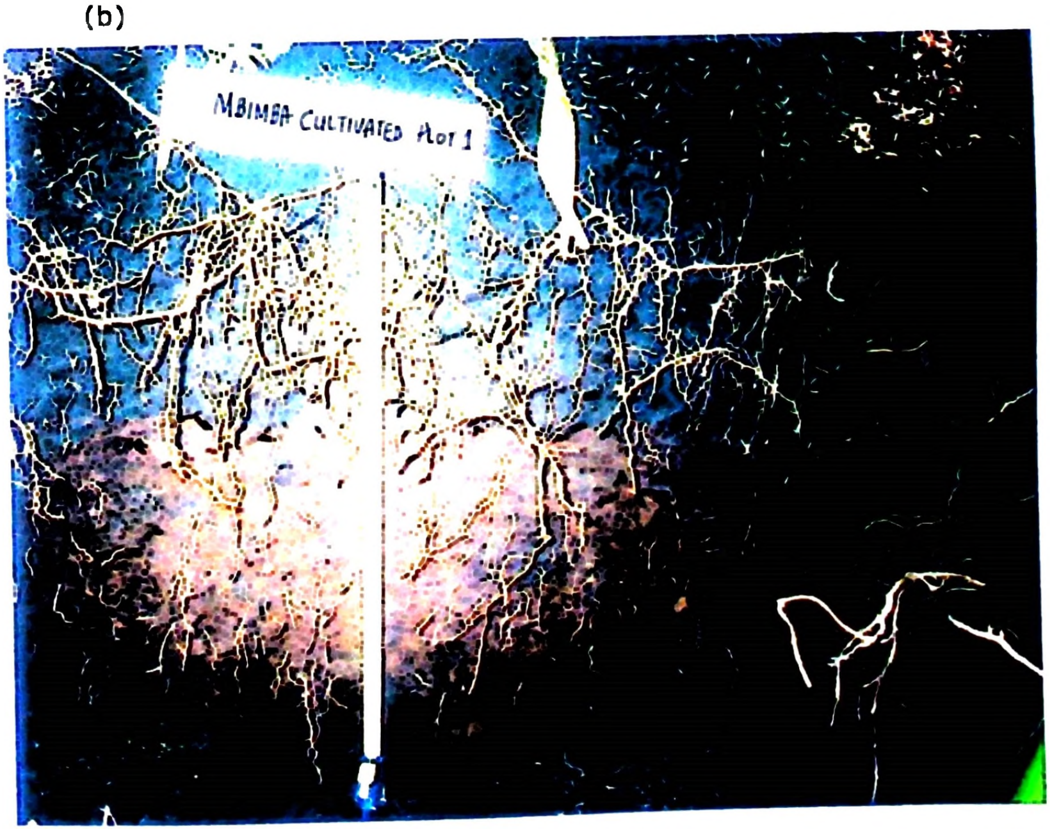
At all sites the previously cultivated treatments had a greater rooting density in the top 0-10 cm than the previously fallow treatments. However, this difference was only significant at Ukwile and Sao Hill (Figure 3.5, Table 3.11). At Ismani there was no significant difference in rooting density between treatments at any depth. This site had the lowest total number of roots although we cannot tell whether this was an inherent varietal characteristic (maize sown at this site was a composite as opposed to hybrid maize seed used in the other sites).

At Sao Hill, the cultivated treatment had significantly more roots in the top 0-10 cm. This trend was reversed from 10-20 cm downward where the fallow treatment had significantly more roots (at 20-30, 30-40 and 40-50 cm depths) than the cultivated treatment. This may be explained partly by the higher bulk density in the cultivated treatment (higher by 0.08 Mg m^{-3}, see Table 3.1*b*).

At Mbimba the treatments differed significantly from 20-30 cm down to 40-50 cm depths although the cultivated treatment maintained a higher rooting density at all depths. There was a big increase in

(a)

(b)



(c)

(d)

Plate 3.2 Pits for root counting at Mbimba fallow (a) and cultivated (b) and at Ukwile fallow (c) and cultivated (d) treatments.

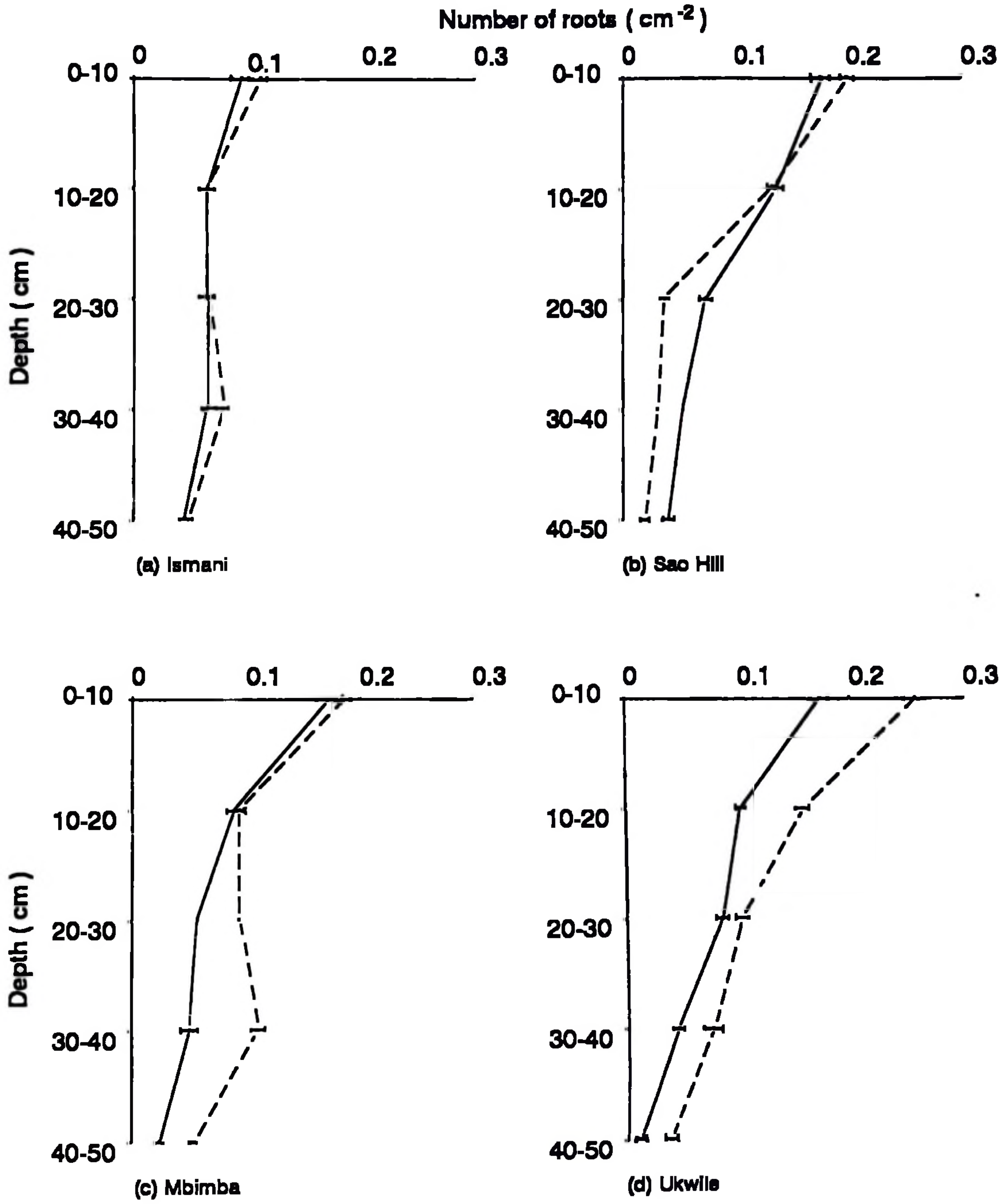


Figure 3.5 Rooting density versus depth for fallow (—) and cultivated (--) treatments. Each point is an average of 40 observations.

Table 3.11 Rooting density[1] (per 100 cm^2) of maize at ≥ 50% tasselling in fallow and cultivated treatments.
Standard errors are given in brackets.

Site and Treatment	Depth (cm) 0-10	1.0-20	20-30	30-40	40-50
Is F	9.4(0.71)^{ns}	6.3(0.42)^{ns}	6.2(0.42)^{ns}	6.3(0.46)^{ns}	4.2(0.41)^{ns}
Is C	10.8(0.67)	6.2(0.43)	6.3(0.51)	7.4(0.48)	4.5(0.40)
Mb F	17.4(0.84)^{ns}	9.0(0.65)^{ns}	5.5(0.61)***	4.8(0.88)***	2.2(0.37)***
Mb C	18.4(0.70)	9.1(0.44)	9.1(0.65)	11.2(0.63)	5.3(0.33)
Sh F	17.9(0.64)*	13.8(0.70)^{ns}	7.5(0.55)**	5.6(0.46)***	4.3(0.47)**
Sh C	19.8(0.62)	13.5(0.73)	4.0(0.41)	3.1(0.48)	2.3(0.37)
Uk F	17.5(0.86)***	10.3(0.60)***	8.5(0.71)*	4.8(0.55)***	1.3(0.29)**
Uk C	25.4(0.89)	15.9(0.71)	10.2(0.51)	7.9(0.68)	3.8(0.46)

1 Average of 40 readings.

ns, fallow and cultivated treatments do not differ significantly (P = 0.05); *, **, ***, fallow and cultivated treatments differ significantly at P = 0.05, 0.01 and 0.001, respectively, following t- tests for paired samples.

rooting density at 30-40 cm depth due to loose patches of soil caused by dead tubers in two of the four pit faces. Although the fallow treatment had lower bulk density in both the topsoil and subsoil, this was not expressed in rooting density. This can be explained by the competition exerted by tree roots (thick roots in Plate 3.2) because this treatment was established adjacent to a planted forest.

It was only the Ukwile cultivated treatment which had significantly more roots cm^{-2} from 0-10 cm depth down to 40-50 cm depth. This is almost certainly due to its bulk density being lower than that of the fallow treatment by at least 0.12 Mg m^{-3} in both the topsoil and subsoil (see Table 3.1*b*).

3.5.4 Maize grain yield

Table 3.12 shows maize grain yield at the 5 sites. Some of the maize at Ismani was stolen by local people whose maize crop had failed. Staff at the Ismani substation harvested the remaining maize and kept the yield data for us. Unfortunately they did not determine the number of plants harvested, those which had cobs with grain (hereafter called productive plants) and those which either did not have cobs or their cobs had no seed (called unproductive plants). It was therefore not possible to determine grain yield/productive plant. I lost some maize to thieves at Ukwile as well. At both sites the thieves selected large ears only.

Because of the limited replication, yield results should be considered as rough estimates only.

It is difficult to know how much of the loss in yield at Ismani can be attributed to theft. The Ismani cultivated treatment gave a

Table 3.12 Maize grain yield at Ismani, Magamba, Mbimba, Sao Hill and Ukwile for the 1990/91 growing season.

Site and Treatment	Average no. of plants harvested per subplot per treatment						
		Unprovudctive maize plants		Productive maize plants			
	Total	Total	% of expected stand	Total	% of expected stand	g $plant^{-1}$	Mg ha^{-1}
Ismani F	nd	nd	nd	nd	nd	nd	1.2(0.2)**
Ismani C	nd	nd	nd	nd	nd	nd	3.4(0.2)
Magamba F	157.0(5.0)*	18.0(3.0)*	6.7(1.1)*	139.0(2.0)**	52.3(0.8)**	135.9(7.3)**	2.6(0.1)**
Magamba C	181.0(2.0)	7.5(0.5)	2.8(0.2)	173.5(1.5)	65.2(0.6)	208.9(3.3)	5.1(0.1)
Mbimba F	235.5(18.5)ns	11.5(10.5)**	4.3(0.2)**	224.0(18.0)ns	84.2(6.8)ns	185.3(5.3)**	5.8(0.6)*
Mbimba C	232.5(2.5)	1.0(0.5)	0.4(0.4)	231.5(6.5)	87.0(2.4)	271.1(4.4)	8.7(0.1)
Sao Hill F	155.5(23.5)ns	24.0(6.0)ns	9.0(3.8)ns	131.5(13.5)*	49.4(5.1)*	122.8(3.9)*	2.3(0.2)*
Sao Hill C	204.0(7.0)	18.0(10.0)	6.8(0.4)	186.0(6.0)	69.9(2.3)	135.8(0.3)	3.5(0.1)
Ukwile F	121.0(16.0)ns	19.0(2.0)ns	7.1(0.8)ns	107.0(9.0)ns	40.2(3.4)ns	213.8(28.5)ns	3.2(0.2)*
Ukwile C	125.5(7.5)	14.0(10.0)	5.3(3.8)	111.5(2.5)	41.9(0.9)	262.5(8.1)	4.1(0.1)

The range/2 (+ or −) is indicated in parentheses.

nd, not determined; ns, the results from the fallow treatment do not differ significantly (P = 0.05) from those from the cultivated treatment; *, **, the results from the fallow treatment differ significantly (P = 0.05 and 0.01, respectively) from those of the contrasting cultivated treatment (following a t-test for unpaired samples).

grain yield which was 75% of the average yield expected in a normal year and under good management (about 4 Mg ha^{-1}, according to the station manager). The discussion which follows does not consider yield results from the Ismani site.

At Magamba, Mbimba, Sao Hill and Ukwile the previously fallow treatments had more unproductive plants, fewer productive plants and generally yielded significantly less maize grain (both per productive plant and per hectare) when compared to the cultivated treatments. This may be attributed to the greater pest damage in the fallow treatments which necessitated gap filling. Seedlings arising from gap filling did not have the advantage of the headstart enjoyed by the rest of the seedlings. It is evident at Mbimba, for example, that although the previously fallow treatment had more maize plants (per unit area) than the contrasting previously cultivated treatment, many of the plants were either unproductive or yielded less per productive plant (185 g $plant^{-1}$ against 271 g $plant^{-1}$, see Table 3.12). Many maize plants in the fallow treatment at Mbimba had been transplanted and grew less vigorously than maize which had not been transplanted. Local farmers at both Mbimba and Ukwile usually fill gaps by transplanting because they argue that if gaps are filled using seed the pests eat the seed or seedlings again.

Low plant populations (Hughes *et al.*, 1992) and a small topsoil rooting density (Adeoye and Mohamed-Saleem, 1990; Taylor and Brar, 1991; Young *et al.*, 1991) may have caused the low grain yield in the fallow plots.

It is not possible to determine the influence of drought on grain yield (*e.g.* at Sao Hill which received only about 56% of its annual rainfall) because of the complexing factor of pest attack which led to low plant populations. However, the maize crop at Mbimba seems to have benefited most from the near-normal rains (91% of the annual total, see Table 3.10).

3.6 Difficulty of cultivation in the dry season

A comparison of the difficulty of cultivation on experimental plots during the dry season is presented in Table 3.13. The results indicate that, with the exception of Sao Hill, all sites were cultivated at suctions drier than the wilting point (1.5 MPa) but not quite air-dry (100 MPa). Two particular features are worth comment. Firstly, observation of local practice suggests that farmers can dry-cultivate on all sites except Ismani and at Ukwile on previously uncultivated land. Results of this study are consistent with this. Secondly, at Ismani, dry cultivation of previously uncultivated land was possible but the previously cultivated land could not be dry cultivated to an adequate depth.

Table 3.13 A comparison of the difficulty in dry cultivation on experimental plots.

Site and Treatment	Average cultivation time (min)	Average depth of cultivation (cm)	Matric suction in MPa depth (cm) 0-10	Matric suction in MPa depth (cm) 10-20	Gravimetric water content (kg/100 kg) depth (cm) 0-10	Gravimetric water content (kg/100 kg) depth (cm) 10-20
Ismani F	24.8(0.42)*	12.0(0.00)**	9.0(2.00)*	3.0(0.50)**	4.7(0.01)***	6.8(0.10)***
Ismani C	26.3(0.18)	6.0(1.00)	19.0(1.50)	10.0(0.50)	2.9(0.01)	2.9(0.09)
Magamba F	28.5(0.50)^{ns}	7.5(0.50)**	24.0(3.00)^{ns}	10.0(1.00)*	8.0(0.02)*	11.5(0.02)***
Magamba C	27.5(0.50)	10.0(0.00)	30.0(1.00)	22.0(1.50)	5.8(0.05)	11.0(0.02)
Mbimba F	19.3(0.08)	10.5(0.50)	26.0(4.00)	5.0(0.50)	17.5(0.50)	23.0(0.40)
Mbimba C	nd	nd	nd	nd	nd	nd
Sao Hill F	27.0(1.00)**	11.0(0.00)*	0.1(0.04)^{ns}	0.1(0.01)^{ns}	16.6(0.10)^{ns}	17.2(0.30)*
Sao Hill C	25.0(0.00)	9.0(0.50)	0.1(0.06)	0.1(0.01)	16.4(0.20)	18.9(0.27)
Ukwile F	20.9(0.38)^{ns}	5.0(0.00)**	53.0(2.50)*	22.0(2.00)^{ns}	9.4(0.09)**	16.0(0.80)*
Ukwile C	19.1(0.97)	12.0(0.50)	43.0(2.00)	13.5(2.00)	8.9(0.01)	13.9(0.04)

The range/2 (+ or −) is indicated in parentheses.

nd, not determined; ns, the results from the contrasting fallow and cultivated treatments do not differ significantly (P = 0.05); *, **, ***, the results from the contrasting fallow and cultivated treatments differ significantly at P = 0.05, 0.01 or 0.001, respectively, following t-tests for unpaired samples.

CHAPTER 4

FURTHER DISCUSSION

This chapter discusses the definitions of microaggregation and their limitations. The results from Ahn's test, Trapnell and Webster's test and Emerson's test are further discussed and conclusions are drawn. A scheme for arriving at a standard definition of microaggregation is proposed in this chapter. Furthermore, the effects of microaggregation on strength characteristics (and hence on physical edaphology) are discussed. Strength characteristics from the present study are compared with those from other studies conducted on similar soil types. Maize establishment and grain yields in this study are discussed in the light of microaggregation and climatic data for the 1990/1991 growing season. Finally I have highlighted the uses to which the results from this study can be put and what the future research needs in this field are.

4.1 Microaggregation

4.1.1 Introduction

Microaggregation is important in tropical soils because microaggregates are the largest aggregates to be observed in many such soils. In contrast, in soils in temperate regions there is often considerable macroaggregation and microaggregation, where present, is of less importance because the macroaggregates themselves influence the soil physical properties.

There are two main kinds of microaggregates:

1) those stabilized by inorganic cementing materials and

2) microaggregates in which organic matter is an important component of bonding.

Of the 5 sites, only Mbimba had soils with high organic matter concentrations. These high organic matter concentrations may have contributed to microaggregation. At the remaining 4 sites the topsoil organic matter concentrations were low; therefore where microaggregation existed, it is likely to have mainly been due to inorganic cements such as Fe, Al, Mn and Si oxides and oxyhydroxides.

4.1.2 Definition

In the literature, microaggregates are defined either by size (*e.g.* Beaudou, 1972; Chauvel *et al.*, 1978; Trapnell and Webster, 1986) or according to some process by which they may be detected, such as wet sieving (Edwards and Bremner, 1967; Tisdall and Oades, 1982; Oades, 1984).

Where microaggregation is defined by wet sieving or a similar test based on the stability of fragments, it is inevitable that the microaggregates collected will be more stable than the material from which they were produced. This does not necessarily mean that the starting material had microaggregates no bigger than those <250 μm [suggested by Edwards and Bremner (1967)] since only microaggregates less than 250 μm diameter are looked for. It is also important to note that the disruption of aggregates during wet sieving is more severe than the action of raindrops in the natural soil in the field. In addition, it is not clear and remains to be proven whether the material obtained by wet sieving consists of microaggregates *sensu stricto* or simply fragments of larger aggregates that have been produced by slaking but did not exist as discrete entities within those larger aggregates. In practice the distinction is difficult to make. Experiments by Chan and Mullins (1993), for example, provided tests that could disprove the existence of microaggregates in some soils but could not provide sufficient evidence to establish their existence in others.

Water-stable slaked fragments that were not originally discrete microaggregates in the untreated soil may not make any contribution to soil friability, weakness or porosity in contrast to microaggregates *sensu stricto*. Thus the distinction is an important one.

To be able to determine microaggregation *sensu stricto*, the following scheme of testing with several pathways (Figure 4.1) is proposed:

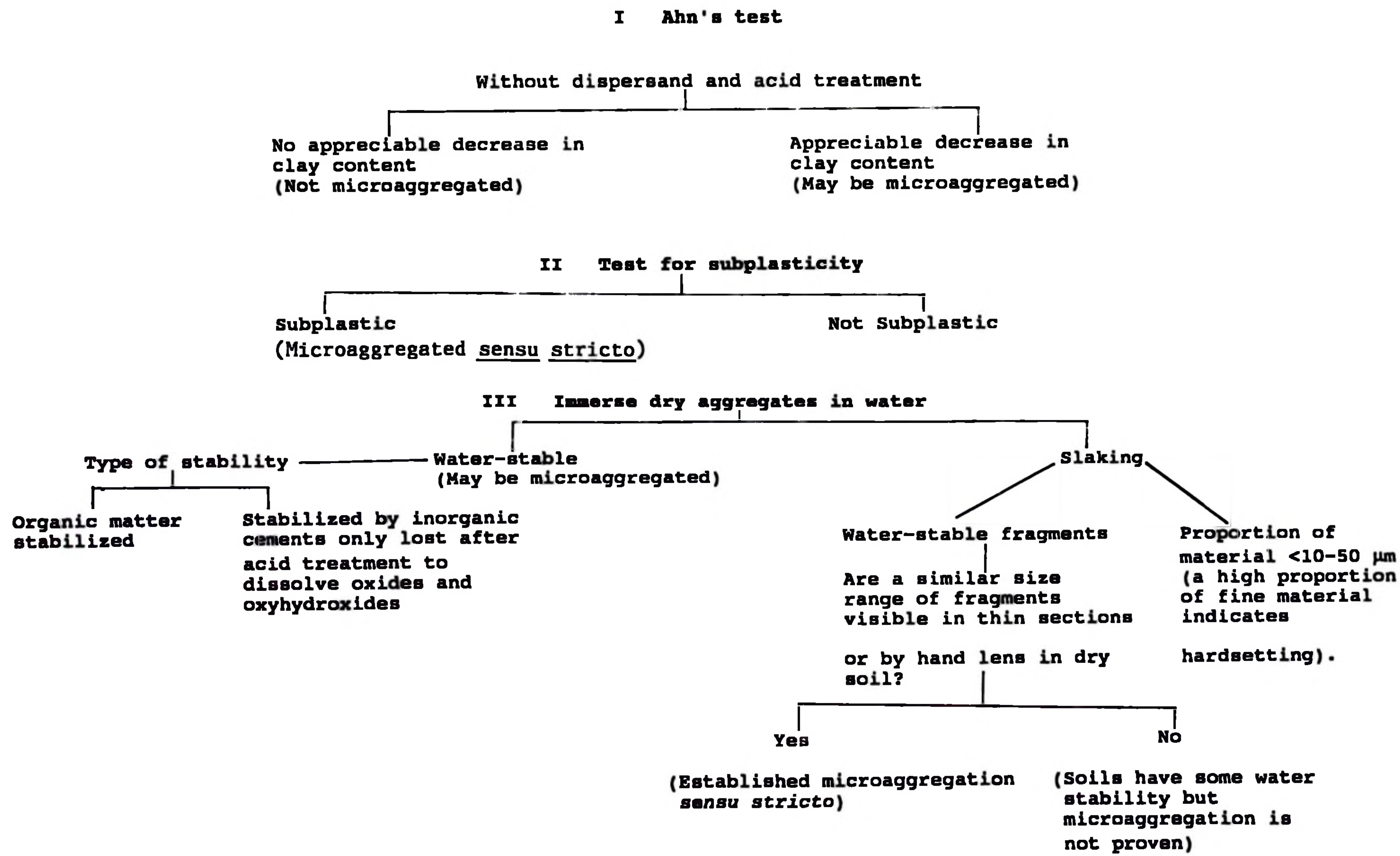


Figure 4.1 **Scheme for determining microaggregation.**

Notes for Figure 4.1

1) The Ahn's test in itself is not sufficient to establish that a soil has microaggregates *sensu stricto* even if there is an appreciable decrease in clay content in the 'without dispersant and acid treatment' analysis, since many soils will not release as much clay if a dispersing agent is not used. To establish that a soil has true microaggregation: *(i)* flocculation of the suspension should be avoided when carrying out the test and *(ii)* Ahn's test results must be supported by visual or other tests. However, the test is useful in disproving the existence of microaggregation.

2) Subplasticity is probably sufficient in itself to establish microaggregation. However, it is useful to combine this with visual observation of the wetted soil to confirm that the fragments released on wetting correspond with mioroaggregates visible in the dry soil with a hand lens or low power microscope.

3) If the soil is not subplastic, it may still contain microaggregates but they may not be strong enough to show up as subplastic behaviour. If the soil aggregates are water stable, it will not be possible to deduce whether or not they contain microaggregates except by some kind of visual and/or micromorphological observation.

If the aggregates slake and the slaked fragments are closely comparable to the fragments identified in the dry soil with a hand lens or thin section, then it seems highly probable that the material consists of microaggregates *sensu stricto*.

The scheme proposed above (Figure 4.1) is useful since it avoids the assumption that water-stable slaked soil fragments are necessarily microagggregates.

4.1.3 Results of Ahn's, Trapnell and Webster's and Emerson's tests

Ahn's test attempts to determine microaggregation *sensu stricto* by revealing the microaggregates contained as fine sand-to silt-size material. However, the flocculation which was observed when the 'without dispersant' test was carried out with an acid pre-treatment casts doubt on whether the results obtained using this test were genuine. When both the dispersant and acid pretreatment were omitted flocculation did not occur and hence any changes in percentage clay between the whole treatment and the 'without dispersant and acid' treatment could be wholly attributed to microaggregation (see section 3.1.2.1).

When the soils were analysed with and without dispersant and acid treatment, Ahn's test failed to demonstrate microaggregation in the IsF and IsC topsoils. This was indicated by the absence of any significant change in percentage clay between the full particle size analysis and the 'without acid and dispersant' treatment. The clay contents for the full analysis and 'without dispersant and acid' treatments were 31.7 and 32.9 percent, respectively, for IsF topsoil and 24.2 and 27.7 percent respectively for IsC topsoil (Table 3.3).

The IsF and IsC subsoils had some degree of microaggregation.

The Sao Hill fallow topsoil had 40.2% coarse silt (Table 3.3), and subtracting from this the actual coarse silt (with dispersant and acid pre-treatment) of 3.2%, shows that 37% of this soil consisted of microaggregates with a size of 60-20 μm. Likewise, the percentages of soil consisting of microaggregates 60-20 μm diameter for ShC (topsoil), ShF and ShC (subsoils) were: 39.8, 48.3 and 44.2 percent, respectively.

The Trapnell and Webster test that I performed was aimed at identifying microaggregates *sensu stricto* by observing both the dry and wet soil according to procedures set by Trapnell and Webster (1986). The results showed that soils at Sao Hill were microaggregated as they fulfilled all criteria for microaggregation (Trapnell and Webster, 1986). This test, however, did not give conclusive results for soils which were either not microaggregated or had a small degree of microaggregation. As in wet-sieving, the Trapnell and Webster test produced slaked fragments which were not necessarily true microaggregates. This test on its own was insufficient in relating microaggregation to soil strength. For example, microaggregation was identified by some observers in IsC soil which behaved in a hardsetting fashion.

The Emerson test (Emerson, 1967) is a stability test that divides slaking soils into 6 classes and those which do not slake are divided into 2 classes: class 7 and class 8. This test did not distinguish as clearly between microaggregated and nonmicroaggregated soils as I would have liked. All top soils (except IsC which was class 5) were grouped in either class 7 or class 8 including IsF which behaved as a hardsetting soil. It is important to note, however, that this test was consistent with Ahn's and Trapnell and Webster's tests in that it showed conclusively that the Sao Hill topsoils and ShF subsoil were stable. The test further indicated that ShC subsoil as well as soils at Magamba, Mbimba and Ukwile were not stable (*i.e.* they slaked, class 6), with IsF and IsC being the least stable.

A summary of results of some of the tests conducted on the Ismani and Sao Hill soils is given in Table 4.1.

The following conclusions can be drawn from the results of the three tests:

1) Sao Hill topsoil and subsoil had microaggregation *sensu stricto* because: microaggregates could be seen in the dry soil, the soil felt subplastic, Ahn's and Trapnell and Webster's tests indicated without any reasonable doubt that there was microaggregation. Emerson's test also indicated that the Sao Hill soil was as stable as or more stable than soils at the remaining 4 sites.

2) Ismani subsoils probably had a small proportion of discrete microaggregates (as suggested by Ahn's test) embedded in a non-microaggregated hardsetting matrix. The Ismani cultivated top soil and IsF as well as IsC subsoils slaked indicating low stability which is one of the prerequisites for hardsetting (Mullins *et al.*, 1987; Young and Mullins, 1991). This suggests that it is quite possible to have a small proportion of microaggregates within a material with

Table 4.1 Summary of results of some microaggregation tests conducted on the Ismani and Sao Hill soils.

Site and Treatment	Subplastic ? (Yes/No)	Ahn's test (% 60-20 μm)	Trapnell & Webster test (microaggregated ?)	Emerson test (Class)	Comments
IsF_i	No	(-1.0)	No	7	W-s but not microaggregated
IsC_i	No	(-0.9)	Not sure	5	Not microaggregated
IsF_{ii}	No	(12.2)	No	2	Small degree of microaggregation
IsC_{ii}	No	(9.4)	Not sure	2	Small degree of microaggregation
ShF_i	Yes	37.0	Yes	8	W-s, microaggregated
ShC_i	Yes	39.8	Yes	8	W-s, microaggregated
ShF_{ii}	Yes	48.3	Yes	7	W-s, microaggregated
ShC_{ii}	Yes	44.2	Yes	6	Slaking, microaggregated

i, ii, W-s = topsoil; subsoil; water stable

% 60-20 μm = was calculated by subtracting % 60-20 μm in Table 3.3*a* from % 60-20 μm in Table 3.3*b* for the respective sites, treatments and depths.

hardsetting behaviour because the microaggregates are insufficient to cause soil weakening.

3) One test is not sufficient to identify microaggregation in soils that are not subplastic. Where soils have various degrees of microaggregation a combination of at least two tests is recommended (see Figure 4.1).

4) More tests are needed to classify the soils at Magamba, Mbimba and Ukwile with certainty.

4.2 Soil strength characteristics

4.2.1 Tensile strength

Tensile strength results indicate that there was a reduction in tensile strength at any given matric suction with continued cultivation (see Figure 3.2 and Table 3.9a, section 3.3.2). These findings are both surprising and interesting. It is often found that the reduction in soil organic matter concentration that usually accompanies sustained cultivation results in a reduction in aggregate stability (Tisdall and Oades, 1982) and is assumed to result in worse physical properties. In the present case however, despite a reduction in organic matter concentration, the soil strength characteristic has improved.

A possible explanation for this observed reduction in tensile strength is that the previously cultivated soils sustained a much greater plant biomass than the newly cultivated treatments which had only sustained scrub vegetation. Consequently there will have been more frequent, substantial and intimate additions of decaying root biomass to the cultivated treatments and this may have resulted in more effective soil weakening than in the fallow treatments. This question is important for soil management in the tropics. It merits further research because it suggests that, under certain conditions, cultivation and good soil management can improve some soil physical properties.

The most useful comparison between sites can be made for soil that is near to an air-dry state (a matric suction of about 10^5 kPa) since this reflects how easy it would be to cultivate soil during the dry season. At the two extremes are Ismani and Sao Hill. At Ismani, the station manager reported that it was not possible to cultivate during the dry season and my own attempts with a hand hoe also confirmed this point (see section 3.7). At Sao Hill it was relatively easy to cultivate during the dry season. For air-dry topsoils, the Ismani and Sao Hill cultivated treatments had tensile strengths that differed by a factor of about 9 times (both at 2-6 and 8-12 cm depths) with Ismani having the greater strength. The tensile strength values for IsC and ShC topsoils were, respectively, 90 kN m^{-2} and 10 kN m^{-2} (Figure 3.2, section 3.3.2.2). However for the fallow treatment, the Ismani topsoil was only about 3 times stronger than the Sao Hill one (180 kN m^{-2} for IsF *versus* 60 kN m^{-2} for ShF, see Figure 3.2). These latter results are consistent with earlier findings that the Ismani soils are predominantly hardsetting while soils at Sao Hill are truly microaggregated, and consequently have a better soil strength characteristic because the microaggregation permits tensile failure.

Figure 4.2 shows the variation of tensile strength (Y) with effective stress (σ', calculated as $\psi \times S$, where ψ is the matric

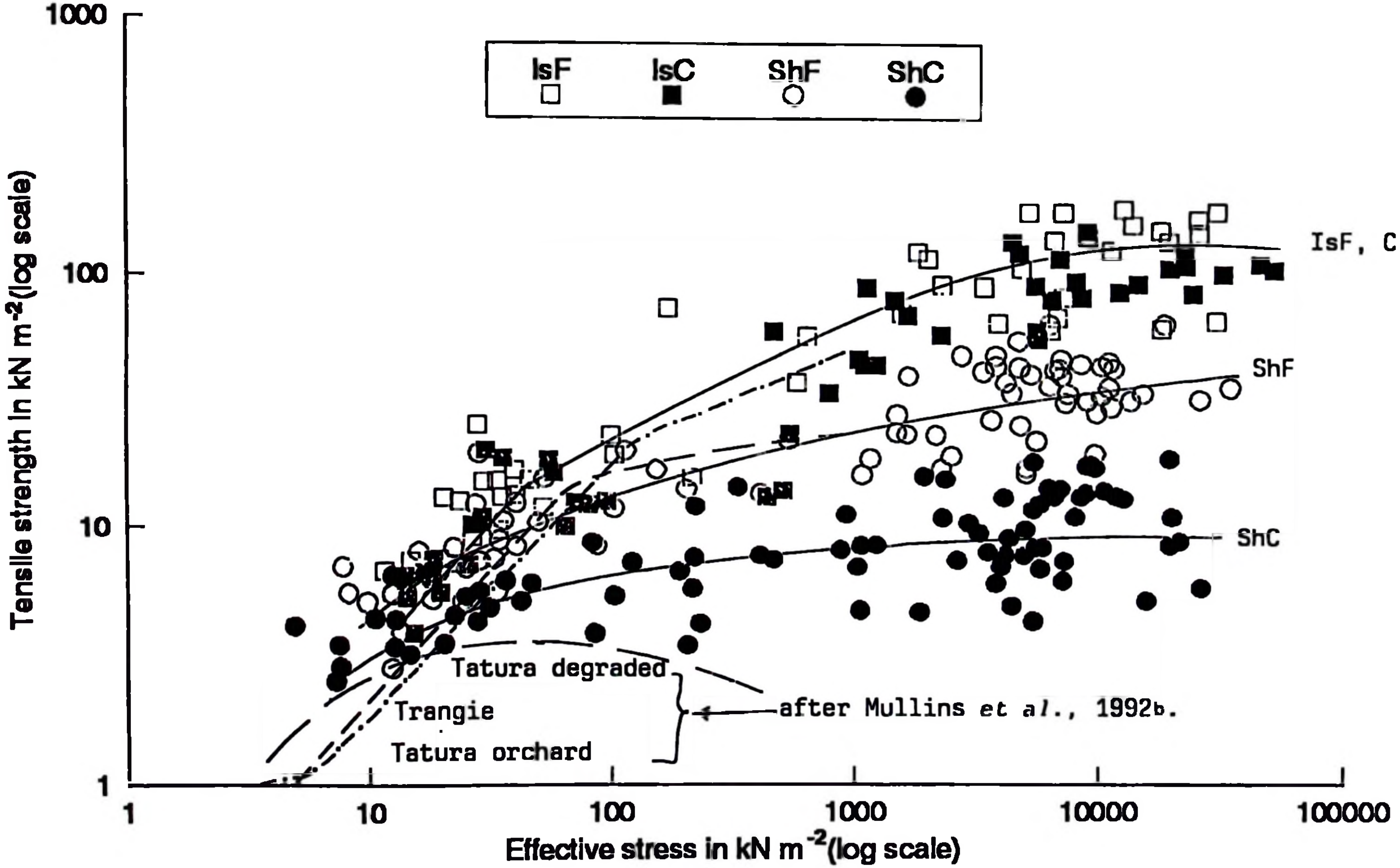


Figure 4.2 Log-log plot of tensile strength versus effective stress for topsoils from Ismani and Sao Hill and plots produced by Mullins *et al.* (1992b) for Australian soils.

suction and S is the degree of saturation) for topsoils at Ismani and Sao Hill. Lines obtained by Mullins *et al.* (1992*b*) are included for comparison. Since the previously fallow and previously cultivated treatments did not differ significantly for the Ismani topsoils only one line was drawn. For the Sao Hill topsoils two lines were drawn to represent the two treatments. All lines were hand-fitted.

As shown in Figure 4.2 and predicted by Equation (3.7), the relationship between Y and σ' for values of σ' less than 100 kN m^{-2} for the three soils was consistent with the linear relationship observed by Mullins *et al.* (1992*b*).

The Sao Hill cultivated topsoil had the best (weakest) tensile strength at any σ' value. In contrast the Ismani topsoils had the worst strength characteristics of any of the 5 soils (Figure 4.2). At an effective stress of > 1000 kN m^{-2} (which was near air-dry), the Sao Hill cultivated topsoil was 10 times weaker than the Ismani topsoils (at σ' = 1000 kN m^{-2}, Y for ShC and Is, respectively = 9 and 90 kN m^{-2}; see Fig. 4.2), and the Sao Hill fallow topsoil was 2 to 3 times weaker than the Ismani topsoils. The strength results for the Sao Hill fallow soil imply that it would be difficult to cultivate at σ' greater than 1000 kN m^{-2}. However, the field cultivation trials during the dry season showed that this was not the case. The high degree of variability of tensile strength of ShF may account for the ease with which it could be dry cultivated in contrast to the Ismani soils since the soil disturbed by a hand hoe has a greater freedom to fail along preferred lines of weakness than that contained within the small test sample.

The Ismani topsoils have a tensile strength characteristic similar to the hardsetting Tatura degraded soil reported by Mullins *et al.* (1992*b*) although they were much stronger at $\sigma' < 100$ kN m^{-2} (Figure 4.2). The Sao Hill cultivated topsoil whilst it has a better strength characteristic compared to either the hardsetting Tatura degraded or Trangie soils of Australia, is stronger than the weakest (Tatura orchard) soil reported by Mullins et *al.* (1992*b*; Figure 4.2). The topsoil of the Sao Hill previously fallow treatment has a similar strength characteristic to the hardsetting Trangie soil of Australia. As already suggested, these results may not be a true reflection of the field behaviour of the Sao Hill soil because of the high variability of its strength.

Both Table 3.9*a* and Figure 4.2 show that for nearly all soils and at all depths strength reached a plateau at high suctions. This indicates that the relationship between tensile strength and effective stress deviates from linearity at high suctions. As the soil approaches air-dryness (at very high suctions), the term $\chi\psi$ in Equation (3.7) tends to zero because the area of interparticle or interaggregate contact joined by water films becomes minimal such that above a critical matric suction it is only the factor c [in Equation (3.7)] which contributes to soil strength. This can result into a net decline in soil strength in non-cohesive soils such as sandy soils. However, in more clayey soils, the interparticle and interaggregate bonding produced by effective stress pulling surfaces closer together results in a high strength of air-dry soil and hence a high c. Thus although c is low in most wet soils, it can become very high as clayey soils approach air-dryness. In between the potential at which the strength deviates from a linear relationship with potential, and air-dryness, it is difficult to predict how strength might vary with potential.

To explain what happens when strength begins to deviate from a linear increase with increasing effective stress, Mullins *et al.* (1992*b*) have suggested that there is probably a decrease in pore spherecity and/or the opening up of crack-shaped pores that weaken the soil. Once this process begins it is not clear how strength might vary with decreasing potential as the soil sample approaches air-dryness. Therefore these results, showing a gradual decrease in the rate of increase of strength with effective stress until it reaches a plateau, are of considerable interest, especially as few people have studied the variation of strength with potential in this range of potentials. It is interesting to note that the soils studied have attained most of this final air-dry strength by the time the soil was a little drier than the wilting point (-1.5 MPa).

4.2.2 Penetrometer resistance (PR)

Penetrometers of various sizes and shapes have been widely used to investigate soil physical properties and their effect on plant root growth (Barley and Greacen, 1967). The three main groups of penetrometers are *(a)* those which measure the pressure required to push a tip of specific distance into the soil (usually called *static penetrometers*), *(b)* those that measure the pressure (or force) required to move the tip through the soil at a more or less constant rate (referred to as *moving-tip penetrometers*) and *(c)* those which record the number of blows required to drive the penetrometer tip through a specific depth of soil (known as *impact penetrometers*). However, the most commonly used is the *moving tip* penetrometer.

There are many differences between penetrometers and plant roots (Barley and Greacen, 1967; Whiteley et *al*., 1981). The main differences between penetrometers and plant roots have been summarized by Bengough (1991) and appear in Table 4.2, and are briefly discussed below.

Whereas root tips have diameters of between 0.1 and 2 mm, penetrometer tip diameters range from <0.2 mm for small needle penetrometers (Groenevelt *et al*., 1984) to >10 mm for large field penetrometers (Ehlers *et al*., 1983). Penetration resistance depends on the diameter of the probe since soil particles of a finite size must be displaced. This is usually only observed in very small probes (with a tip diameter of <2 mm) which may have to displace particles of a comparable size.

There are contradictory reports about the influence of probe diameter on penetration resistance. For example, Whiteley *et al*. (1981) found no significant effect of probe diameter on mean penetration resistance (PR) in undisturbed clods or remoulded soil. They used penetrometers with diameters ranging from 1 to 2 mm. Likewise, Bradford (1980) found no significant difference in average resistance experienced by probes of 3.8 and 5.1 mm diameter penetrating field cores. Using probes of 1, 2 and 3 mm diameter and 30° semiangle to penetrate a remoulded sandy loam soil, Barley *et al*. (1965) also found no significant effect of probe diameter on penetration resistance. In contrast, other researchers (*e.g*.

Table 4.2 Main differences between plant roots and penetrometers (After Bengough, 1991).

Characteristic	Roots	Penetrometers
Diameter	Generally 0.1-2 mm	Generally 0.1-20 mm
Shape	Approximately paraboloid, but may expand radially if mechanically impeded	Usually conical
Friction	Unknown; probably small due to mucilage secretion and cells sloughing off root cap	Considerable friction on probe tip and on shaft (if non-relieved)
Penetration rate	$< \sim 1$ mm h^{-1}	Often > 1 mm min^{-1}
Flexibility	Can follow cracks or planes of weakness through the soil	Rigidly mounted; follow a linear path through the soil
Water uptake	Extract water from the soil as they grow	Do not extract water

Whiteley and Dexter, 1981) have reported that probes with very small diameters (<2 mm) gave significantly greater PR readings.

Penetrometer diameter can influence also probe resistance indirectly through friction on the shaft of the penetrometer. This is relatively more important for smaller probes (Bengough, 1988). The soil-metal shaft friction is normally reduced by using penetrometers with a shaft with a smaller diameter than the probe tip (*i.e.* a relieved shaft).

Although penetrometer shapes may vary from cylinders (Groenevelt *et al.*, 1984) to shapes resembling root tips (Eavis, 1967), the most commonly used design has a conical tip. The shape of the probe or root tip determines both the mode of soil deformation as well as the amount of frictional resistance experienced by the tip. Plant roots and narrowly tapered probes are believed to cause cylindrical soil deformation (Greacen *et al.*, 1968), which theoretically requires less pressure than the spherical probes and cylindrical probes with a large angle (Farrell and Greacen, 1966; Greacen et *al.*, 1968). Additionally, in contrast to penetrometers, the radial expansion that occurs behind the tip of severely impeded roots (Abdalla *et al.*, 1969) may aid root penetration by bringing soil in front of the root tip closer to failure (Hettiaratchi and Ferguson, 1973).

Greacen et *al.* (1968) have predicted that in the absence of shaft friction, the frictional resistance on the penetrometer tip can account for more than half the total penetration resistance. The secretion of mucilage and sloughing off of root cap cells (Oades,

1978) is expected to have a lubricating action that reduces root penetration resistance (Cockroft *et al.*, 1969).

Roots grow at a very slow rate, typically ≤ 1 mm h^{-1} (Stolzy and Barley, 1968), compared to the rates at which penetrometers are pushed into the soil (Whiteley *et al.*, 1981).

Voorhees *et al.* (1975) noted a small decrease in the penetrometer resistance of sandy loam and clay at rates below 1.2 mm h^{-1}. In contrast, Eavis (1967) found no effect of penetration rate on the penetrometer resistance of a silty clay loam at rates between 6 and 300 mm h^{-1}. However, at lower rates of penetration there was a small decrease in resistance (resistance decreased by about 13% at a penetration rate of 0.3 mm h^{-1}). Thus penetrometer resistance is only weakly dependent on the penetration rate in soil in the range of water contents commonly encountered. According to Bengough (1991), the effect of the slower rate of root growth when compared with the rate of probe penetration is likely to be of greatest importance in relatively wet impermeable soil and of much less importance in dry sandy soil.

Direct comparisons of penetrometer resistance with root resistance indicate that penetrometers experience a resistance of about 2 to 8 times greater than roots (*e.g.* Eavis, 1967; Eavis and Payne, 1969; Whiteley *et al.*, 1981; Misra *et al.*, 1986).

In spite of all these differences between penetrometers and roots, the penetration test which is quick and easy, is still the most common and best means of detecting root-restricting zones.

The variability of penetrometer results often creates problems in interpreting their implications for root behaviour since roots may selectively exploit weaker zones in the soil (Davis *et al.*, 1968; Nash and Baligar, 1974; Voorhees et *al.*, 1975; Russell, 1977). For example, Ehlers *et al.* (1983) found that while root growth was severely limited at a penetrometer pressure of 3.6 MPa in conventionally tilled soil, the corresponding limit in untilled soil was higher (about 5 MPa). They concluded that the untilled soil contained more cracks and biopores (*e.g.* channels left by earthworms and decayed roots), which were available for root growth but were not detected by the 11 mm diameter field penetrometer. Nevertheless the results for Ismani show that in both treatments, with the exception of the three outlying points, the topsoil has become virtually unrootable at a matric suction of less than 100 kPa (Figure 3.3a). In common with many hardsetting soils (Mullins et *al.*, 1990), there was a sharp increase in PR over a comparatively small range of suctions (and hence water contents). This behaviour has very serious implications for crop establishment, especially since the first set of results was obtained only 19 days after sowing, showing that any transient benefits of cultivation had been lost by this stage. During this period two heavy rainfall events (47 mm on December 26th and 35 mm on January 14th, see Figure 3.4 section 3.5.1) must have caused slumping of the cultivated layer and been responsible for loss of the cultivated tilth. Weaich et *al.* (1992) sowed maize in hardsetting (Trangie) soil with a PR characteristic similar to Ismani topsoil (given in Mullins et *al.* 1992*b* and Figure 4.2) and found that, under unfavourable climatic conditions, although the seeds germinated none of the shoots were able to penetrate the soil surface before it had set too hard to permit emergence. Shoot as well as root growth is slowed by increasing soil mechanical impedance and Weaich *et al.* (1992) observed no emergence on plots where the PR had reached 2 MPa.

In contrast to Ismani, PR results for Sao Hill and Ukwile topsoils indicate that, even at matric suctions greater than wilting point (1.5 MPa), these soils were not strong enough to halt root growth. The broad scatter of points (Figure 3.3*b*, *d*) is an indication of the spatial variability of PR and no attempt has been made to draw a 'representative' line through these points. It would be difficult to determine how much different plant roots can exploit this spatial variability although there is a clear suspicion that it should be of considerable advantage in allowing parts of the root system to proliferate in the weaker zones. At none of the sites is there a clear indication that the previously cultivated soil differed in its PR characteristic from the previously uncultivated (fallow) treatment.

The ease of root penetration is also affected by how much the soil profile dries out since matric suction is dependent on the latter. This depends both on the climate at each site (rainfall and evapotranspiration) and also on the water release characteristic of each soil. Table 3.8 shows that generally the water release characteristics curves for Ismani have the steepest slopes (except at 8-12 cm depth) as indicated by the large $|b|$ fitting constant. In contrast, the microaggregated Sao Hill soils have the least steep slopes. This implies that the soils at Ismani dry out faster than those at Sao Hill. Thus, if the same rainfall was received at the two contrasting sites and then the soil profiles were allowed to dry, plant roots at Ismani would experience impedance before those at Sao Hill. In practice, Ismani was also the driest of the five sites and hence this effect will be even more pronounced.

The function $\log \psi = a + b \log (\theta/\theta_s)$ in Equation (3.1) was used to calculate the permanent wilting point of each soil. Field capacity (at 10 kPa matric suction) was estimated directly from measured values obtained from the tension table. The results were tabulated and are presented in Table 4.3.

The data in Table 4.3 show that the microaggregated Sao Hill Orthox had a greater available water capacity (at any depth) than most other soils while Ismani had the least. For two of the sites (Ismani and Mbimba) root growth in the topsoil may be expected to have virtually ceased before these soils reached the permanent wilting point because they exceeded a PR of 3 MPa at matric suctions less than 1.5 MPa (see Figure 3.3). At these sites, profile drying, and hence root water extraction, would have been limited even before the soil reached 1.5 MPa suction if the crop was relying for water on an advancing rooting front. Consequently, Ismani which had the driest climate and the lowest available water capacity would be even further disadvantaged in seasons where depth of the rooting front is restricted by high soil PR.

As pointed out in section 3.4.1, the degree of saturation is one of the factors affecting penetrometer resistance [the χ factor in Equation (3.8)]. In attempting to compare penetrometer results on a common basis, Weaich *et al.* (1992) plotted PR *versus* the degree of saturation. In order to compare the behaviour of the soils from my sites with the hardsetting Trangie soil plotted by Weaich et *al.*

Table 4.3 The available water capacity of soils at Ismani, Magamba, Mbimba, Sao Hill and Ukwile.

Depth (cm)	Site and Treatment	Volumetric water content at 10 kPa	Volumetric water content at 1500 kPa	Available water capacity
2-6	Ismani F	0.276(0.014)	0.156(0.036)	0.120(0.050)
	Ismani C	0.276(0.010)	0.154(0.017)	0.129(0.027)
	Magamba F	0.302(0.020)	0.157(0.054)	0.145(0.034)
	Magamba C	0.307(0.018)	0.170(0.041)	0.137(0.061)
	Mbimba F	0.422(0.022)	0.228(0.056)	0.194(0.078)
	Mbimba C	0.378(0.006)	0.244(0.061)	0.134(0.064)
	Sao Hill F	0.310(0.008)	0.144(0.057)	0.166(0.061)
	Sao Hill C	0.284(0.010)	0.145(0.060)	0.139(0.070)
	Ukwile F	0.341(0.018)	0.197(0.067)	0.144(0.085)
	Ukwile C	0.324(0.041)	0.169(0.041)	0.155(0.082)
8-12	Ismani F	0.283(0.009)	0.199(0.080)	0.084(0.089)
	Ismani C	0.275(0.005)	0.165(0.020)	0.110(0.025)
	Magamba F	0.315(0.015)	0.172(0.031)	0.143(0.046)
	Magamba C	0.309(0.003)	0.175(0.042)	0.134(0.045)
	Mbimba F	0.354(0.006)	0.207(0.056)	0.147(0.062)
	Mbimba C	0.359(0.008)	0.258(0.079)	0.101(0.087)
	Sao Hill F	0.285(0.016)	0.159(0.048)	0.126(0.064)
	Sao Hill C	0.271(0.006)	0.141(0.044)	0.130(0.050)
	Ukwile F	0.345(0.013)	0.207(0.068)	0.138(0.081)
	Ukwile C	0.310(0.040)	0.160(0.024)	0.150(0.064)
30-34	Ismani F	0.267(0.001)	0.177(0.008)	0.090(0.009)
	Ismani C	0.281(0.006)	0.189(0.012)	0.092(0.019)
	Magamba F	0.284(0.029)	0.172(0.020)	0.112(0.049)
	Magamba C	0.265(0.019)	0.241(0.045)	0.024(0.064)
	Mbimba F	0.360(0.009)	0.183(0.019)	0.177(0.028)
	Mbimba C	0.395(0.004)	0.337(0.108)	0.058(0.162)
	Sao Hill F	0.289(0.003)	0.179(0.102)	0.110(0.105)
	Sao Hill C	0.286(0.021)	0.193(0.081)	0.093(0.102)
	Ukwile F	0.391(0.086)	0.281(0.014)	0.110(0.048)
	Ukwile C	0.373(0.048)	0.193(0.003)	0.180(0.051)

The range/2 (+ or −) is indicated in parentheses

(1992) I have plotted penetration resistance *versus* the degree of saturation in Figure 4.3.

Figure 4.3 shows the penetration resistance (PR) *versus* degree of saturation relationships for the Ismani and Sao Hill topsoils. A line representing the hardsetting Trangie soil from Australia (Mullins *et al.*, 1992*b*; and Weaich *et al.*, 1992) is included for comparison.

The PR values for the Ismani previously fallow and previously cultivated treatments were not significantly different hence they are represented by one line. Due to the great variability in PR and the limited maximum PR that could be measured in the present study (PR of 4.5 MPa against PR of > 10 MPa reported by Weaich *et al.*, 1992) the graph does not show a clear distinction between the PR characteristics of the Ismani and Sao Hill soils. At a degree of saturation below 0.7, however, the PR were Is > Trangie > ShF > ShC (Figure 4.3). This result indicates that the hardsetting Trangie soil from Australia (Mullins *et al.*, 1992*b*; Weaich *et al.*, 1992) was not as impeding to root growth as the hardsetting Ismani soil from Tanzania at a degree of saturation below 0.7. This difference could be attributed to differences in bulk density [1.45 Mg m^{-3} for the Trangie soil (Mullins *et al.*, 1992*b*) compared to an average bulk density of 1.56 Mg m^{-3} for the Ismani topsoil (see Table 3.1*b*)]. Mirreh and Ketcheson (1972) also indicated that soil resistance is affected by bulk density. Generally, Figure 4.3 shows the difficulty of relating PR to root growth where PR is variable.

There is substantial evidence in the raw data (Appendix III) and from field observations that, in the air-dry state, Is topsoil

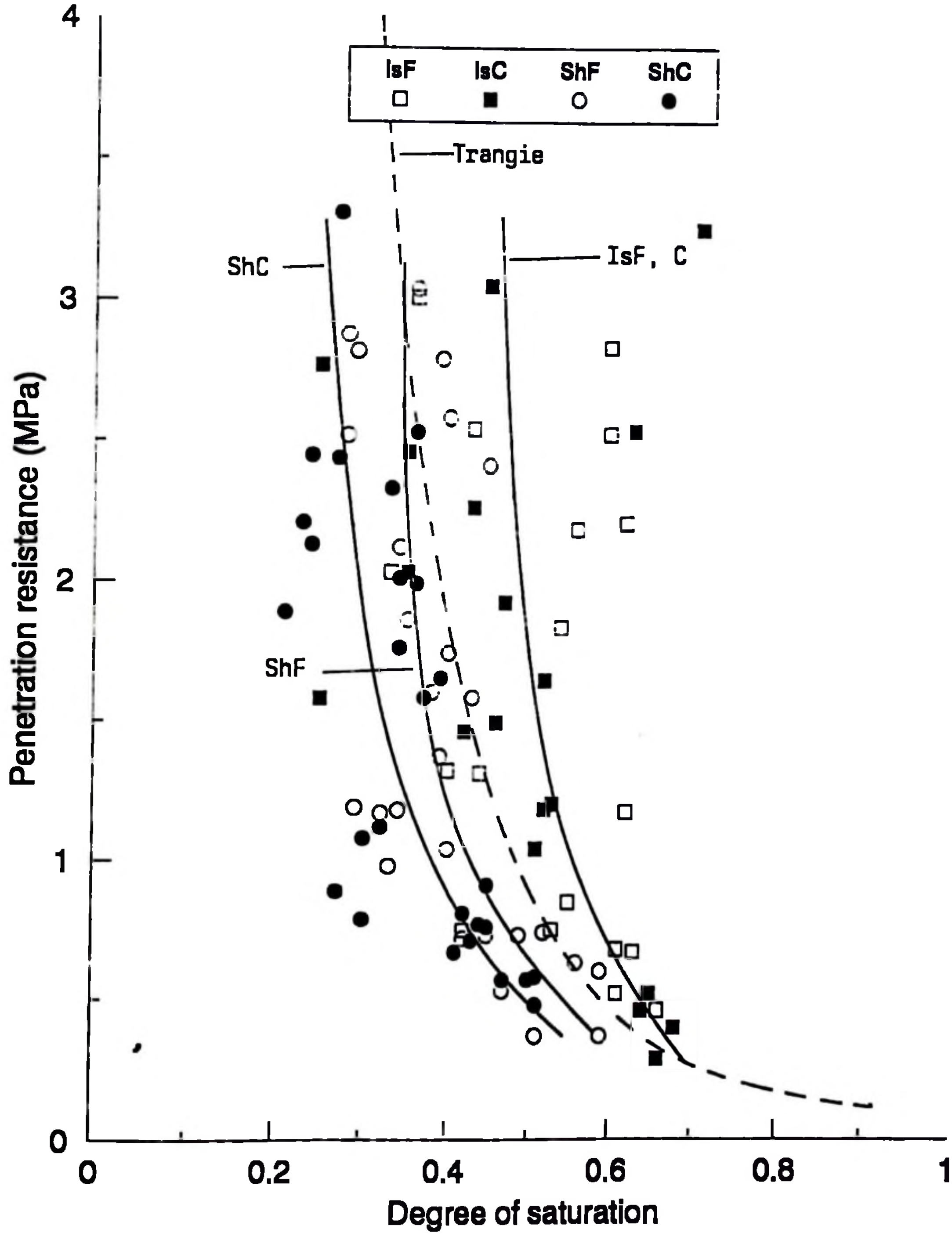


Figure 4.3 Penetration resistance versus degree of saturation for topsoils from Ismani and Sao Hill.
The dotted line represents a plot for the Trangie soil (Mullins *et al.*, 1992b; Weaich *et al.*, 1992).

was harder than ShF or ShC but this could not be shown graphically because the penetrometer used could record up to PR values of 4.5 MPa only. In future PR measurements need to be carried out over a greater range of matric potentials and closer to air-dryness. This would give the greater number of readings needed to draw out clear distinctions between the PR characteristics of hardsetting and of microaggregated soils. Such distinctions are needed to indicate the extent to which hardsetting soils limit root growth in drying soils and to what extent this is worse than the well structured microaggregated soils. In addition, variability needs to be looked at in more detail.

Although the differences in penetration resistance observed in the different soils studied could be genuine, errors could have arisen from several sources:

(i) When 'undisturbed' soil cores were taken from the field for PR measurements, soil compaction was not accounted for. Some of the difference in the observed PR, therefore, could be due to compaction which occurred during coring. However, most compacted cores were rejected.

(ii) Cores that were air-dried for a specific number of hours before being strength-tested may not have been given enough time for the moisture to equilibrate throughout the sample. Moreover, not all samples were 'held' (*i.e.* covered with plastic lids on both ends of the ring) for an equal number of hours after the end of the drying cycle before testing. The moisture gradient that built up between the top of the core and the rest of the sample could bring about

differences in PR values within and between samples. However, PR values were not found to vary systematically with depth. In future work it would nevertheless be advisable to 'hold' the samples for at least 2 days after the nominal time of drying.

(iii) During needle penetration measurements, three penetrations were made for each soil core (see section 2.3.3 and Figure 2.5). Greacen *et al.* (1969) have cautioned that where more than one penetration is done per sample, PR may decrease if tensile failure cracks form between penetration holes. Thus, it is possible that some cracks may have formed during testing, consequently affecting the PR results. However, careful examination of my results showed no evidence of the first penetration affecting others.

4.3 Crop establishment and yield

Maize establishment, growth and, probably, grain yield were adversely affected by both pests (especially in the previously fallow treatments at all sites) and the erratic rainfall especially at Ismani, Magamba, Sao Hill and Ukwile. At Ismani, for example, the growth and yield of maize were adversely affected by the drought that occurred between 23 February and 24 March, 1991 (only 5.7 mm of rainfall was received), during which period the maize was tasselling. According to Mr. Bilali (station manager at the Ismani substation, pers. comm.), in the past there have been maize yield reductions of > 90% at Ismani when drought has persisted from maize tasselling to silking.

It is interesting to note that although the maize crop at Ismani had, on average, fewer roots per unit area (Table 3.11), it had a reasonable root distribution throughout the profile depth compared to that at Sao Hill, Mbimba and Ukwile. This suggests that if the emergence problem can be overcome, farmers may be able to get better yields at Ismani. In contrast Ley (1988) reported serious root growth limitations in some strongly hardsetting soils in Nigeria with some plots having no roots at depths as shallow as 10-20 cm. This suggests that the Ismani soil may not have been as strongly hardsetting as that studied by Ley. However, the difference could have been due to the timing of rainfall. These results demonstrate that, in order to predict and model root growth it is necessary to consider the timing of rainfall events and the matric suction and hence strength of the profile as a function of time, in relation to root growth.

The importance of early planting and, hence, the ability to cultivate in the dry season in the tropics was emphasized at Ismani. Most of the large maize cobs at Ismani were stolen by local people whose maize crop had failed completely due to late planting. Plate 4.1 shows two fields of maize: one is from the Ismani site (reported in the present study) while the other is a farmer's field (about 10 km south of the Ismani site) taken on the same day. The farmer's field was planted only about a week after the Ismani treatments were sown to maize but it was completely destroyed by the ensuing drought!

Crop establishment, growth and yield in the present study were affected by many factors, including drought, theft, pest attack and varietal differences. This makes it impossible for meaningful

(a)

(b)

Plate 4.1 Effect of timing of planting on maize growth (a) early planting at the Ismani site and (b) late planted maize in a neighbour's (10 km away) farm.

comparisons to be made regarding the crop production potentials of the well structured microaggregated (Sao Hill) and the hardsetting (Ismani) soils.

4.4 Use of the results and future research needs

4.4.1 Use of the results

Soil analytical and field strength data for the Ismani and Sao Hill soils have already been passed to scientists in Nottingham University for incorporation into a new subroutine of their PARCH (Bradley and Crout, 1992) crop growth model. They will also be incorporated in a model for predicting crop establishment in the semi-arid tropics, a project whose application to the Overseas Development Administration (ODA) is under consideration.

The results from this study will also be availed to farm managers and extension workers in the Southern Highlands (Tanzania) where, it is hoped, they will be useful to these soil management planners.

4.4.2 Future research needs

The concept of microaggregation has proved difficult to pin down. This is reflected in the many and often contradictory ways in which microaggregation is used in the literature (see Section 1.1). Results in this thesis indicate that, whereas it is relatively easy to recognize in the field, soils at the extremes of microaggregation and hardsetting behaviour, there exists a wide range of intermediate types of soil strength behaviour that cannot be deduced from simple field examination. Since it is actually the strength-characteristic that is relevant to ease of cultivation (tensile and/or compressive strength) and root growth (penetrometer resistance) there is now a considerable need to establish a database of such characteristics to allow modelling of cultivation timeliness and crop root growth.

In the study reported in this thesis, there were too many sites and too little site control. In future work, it would be important to concentrate on the two sites with the most contrasting physical behaviour, the hardsetting Ismani soil and the microaggregated soil at Sao Hill. This would permit more intensive studies to be carried out.

Below are some particular experiments that could be carried out.

I. Physical Properties

1. Tensile and shear strength measurements

In the current study there were contradictions between laboratory and field results. For example, whereas the test on 'difficulty of cultivation in the dry season' (and local farmers' practices) showed that the Sao Hill fallow topsoil could be dry-cultivated, laboratory results suggested that when air-dry (100 MPa suction), ShF topsoil could not be cultivated (Figure 4.2). There is need, therefore, to determine (at both sites) tensile and shear strength in the laboratory and, concurrently, to measure in the field the force needed to cultivate the soil. The latter can be done by attaching a dynamometer between a tractor (or a pair of oxen) and a plough. The dynamometer indicates the force (pull) which can then be converted to draught by multiplying it by the cosine of the angle of pull.

Both laboratory and field tests should be done on soil which is approximately at the same matric potential. This can be achieved by taking soil samples from the same field that will be ploughed, and strength-testing them at the field water content (at which the ploughing is done).

2. Other physical factors that affect edaphology, such as hydraulic conductivity, and susceptibility to erosion could be quantified for the two contrasting soils.

3. **Penetration resistance (PR)**

In this study I could not make meaningful comparisons of the PR results because too many readings were offscale (see section 3.4.1). Assuming that a penetration resistance of 6 MPa is sufficient to halt root growth (Bengough and Mullins, 1990), it would be necessary to use a balance capable of reading a maximum penetration resistance of at least 9 MPa so as to accommodate some variability in the soil (since 6 MPa is an average PR). Alternatively, a smaller needle, say with a cone diameter of 1.5 mm could be used in combination with the balance that was used here.

Again, it would be important to compare laboratory with field results. In addition to measuring field penetrometer resistance a crop should be established and root growth and development in a drying profile should be monitored. The following may be done:

(i) The same maize variety should be used at both sites.

plants *Crotalaria ochroleuca* and *C. pallida* are widely used as natural sources of nitrogen fertilizer. The effect of these plants (and their symbiotic bacteria) on soil microaggregation and stability could be investigated.

CHAPTER 5

SUMMARY AND CONCLUSIONS

The effect of both soil type and a previous history of cultivation on soil strength were investigated. Soil strength was characterized by measuring tensile strength and penetration resistance (PR) as a function of matric potential, to give the strength characteristics. Five Tanzanian soil types were compared. The soils ranged from a hardsetting Paleustalf at Ismani at one extreme of strength behaviour, through a Paleudoll (at Magamba), Paleudalf (Mbimba) and a Paleustult (Ukwile), to a strongly microaggregated Orthox at Sao Hill at the weak end of the scale. At each site soils that had a history of 7 or more years of continuous cultivation and cropping were compared with newly cultivated soils, to form the 2 contrasting treatments. Additionally, a study of techniques for quantifying microaggregates was made.

The major findings and conclusions from this study are summarized below.

5.1 <u>Soil strength characteristics</u>

5.1.1 Tensile strength - characteristics

The microaggregated Orthox at Sao Hill had the most favourable tensile strength-characteristic, while the hardsetting Paleustalf at Ismani had the worst characteristic. For example, at air-dryness (100 MPa suction), the Paleustalf previously cultivated topsoil had a tensile strength of 90 kN m^{-2} compared to a value of only 10 kN m^{-2} recorded for the contrasting microaggregated Orthox. The previously uncultivated Paleustalf topsoil was 3 times stronger than the previously uncultivated Orthox topsoil (tensile strengths of 180 kN m^{-2} and 60 kN m^{-2}, respectively, for the hardsetting Paleustalf and microaggregated Orthox previously uncultivated topsoils). Moreover, whereas the mciroaggregated Orthox could be dry-cultivated by a hand hoe (or oxen plough), the hardsetting Paleustalf either could not be dry-cultivated at all or could not be dry-cultivated to a depth that was adequate for crop establishment.

5.1.2 Penetrometer resistance (PR) - characteristics

Penetrometer resistance results also showed clear differences between sites but not between treatments. The hardsetting Paleustalf (Ismani) topsoil would probably have been unrootable at matric suctions in excess of 100 kPa. The microaggregated Orthox and Paleustult ranked as the most easily rootable topsoils. The Orthox (Sao Hill) topsoil had a PR of less than 3 MPa up to wilting point (1.5 MPa), suggesting that even at wilting point the PR would not impede root growth.

5.2 Effect of a history of cultivation

Soil pH, organic matter concentration and cation exchange capacity were generally higher in the plots which had been uncultivated for a period of 7 or more years. Nevertheless, for three of the soils (Orthox, Paleudoll and Paleustult), a previous history of cultivation was found to have significantly and substantially reduced the tensile strength of the topsoil at any given matric suction compared to the newly cultivated soil.

5.3 Techniques for quantifying microaggregation

The current techniques for quantifying microaggregation were found to be insufficient when used singly for soils which are neither strongly microaggregated nor strongly hardsetting. A scheme which combines several currently used techniques for determining microaggregation is proposed. The scheme avoids the assumption that all water-stable slaked fragments are necessarily microaggregates.

5.4 Conclusions

1. Soil microaggregation appears to confer good (weak) soil strength characteristics that permit dry cultivation as well as ease of rooting in some tropical soils.

2. The observed improvement in strength characteristics of topsoils with continuous cultivation in some soils suggests that, under certain conditions, cultivation and good soil management can improve some soil physical properties.

3. The current techniques for describing/quantifying microaggregation are insufficient and may even be misleading when used for soils which have a small degree of microaggregation. For such soils, it is suggested to use the scheme proposed in this thesis. Additionally, even for strongly microaggregated soils (such as the Orthox at Sao Hill) where field examination may be sufficient to establish microaggregation, in general there is no substitute for measuring the soil physical properties affecting edaphology.

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APPENDIX I

Results of the blind Trapnell and Webster's test
for all sites.
See section 2.3.5.2 for the description of the criteria.

Site and Treatment	Panellist	Criterion 1	2	3
IsCi	C	d(i) subangular (e)	a (fast)	porous within microblocks
	M	e		microblocky
	P	e	a (fast)	porous within microblocks
	R	compound smaller round microaggregates all stick together into larger blocks	a (fast)	
IsCii	M	f	a (i) ?	a
	R	d - g (i)	b	
IsCii	R	g (i) very porous	b	
IsFi	M	f	c	b, e
	R	d - g (i) porous		
IsFii	P	d (i)		
	R	d - g (i) porous	a, separates into microsubangular bits	
IsFii	R	d - g (i)	c (ii) mainly slaked	
MaCi	C	f but only with difficulty	b but only held by fibres (i) - (iii)	
	M	a, b	b (i)	b, e
	P	a, b	b	b, d
	R	g	a, b subrounded/ gibbous moist	b
MaFii	C	d (i) = b		
	M	rough with spheres	a (iii)	a

Site and Treatment	Panellist	Criterion 1	Criterion 2	Criterion 3
MbCi	M	d (ii), f	b (i)	b, e
	P	e + b	b	b, e
MbCii	M	d (ii), f	c (iii)	b
	P	c	a (slowly) (iii)	b
MbFi	M	f	b	b
ShCii	C	d (i) - e, b+		
	R	g (i)		
ShFii	M	a, b	b (i)	b, e
	R	g (i)	b, microgranular	
	P	a	b	b
ShFii	C	d but not b (only with difficulty)		
	R	d (i)	b	
UkCi	C	a but not b easily	c (iii)	
UkFi	C	c + d but not b		
UkFii	C	d (i) but not b		
	M	c, d (i)	a (ii)	c microblocky when wet
	P	c	a (ii)	b, e ?
	R	d (i)	a	

APPENDIX II

Soil tensile strength characteristics

THE DATA FOR SOIL TENSILE STRENGTH CHARACTERISTICS ARE CONTAINED IN THE FLOPPY DISK LABELLED APPENDIX II WHICH CAN BE RUN ON THE SUPERCAL 5 (OR HIGHER VERSION) PROGRAM.

Appendix II has 15 files each of which contains the following columns:

1.	Subplot and depth	2.	Core volume
3.	Grav. water content	4.	Bulk density
5.	Vol. water content	6.	Degree of saturation
7.	Estimated potential	8.	Filter paper potential
9.	Tensile strength	10.	Effective stress

The files are:

Site	File name
Ismani	STIPL1 STIPL2 STIPL3
Magamba	STMAPL1 STAMPL2 STAMPL3
Mbimba	STMBPL1 STMBPL2 STMBPL3
Sao Hill	STSPL1 STSPL2 STSPL3
Ukwile	STUPL1 STUPL2 STUPL3

1,2,3 = 2-6 cm; 8-12 cm and 30-34 cm sampling depth.

APPENDIX III

Soil penetrometer resistance characteristics

THE DATA FOR SOIL PENETROMETER RESISTANCE CHARACTERISTICS ARE CONTAINED IN THE FLOPPY DISK LABELLED APPENDIX III WHICH CAN BE RUN ON THE SUPERCAL 5 (OR HIGHER VERSION) PROGRAM.

Appendix III has 9 files each of which contains the following columns:

1.	Subplot and depth	2.	Core volume
3.	Grav. water content	4.	Bulk density
5.	Vol. water content	6.	Degree of saturation
7.	Estimated potential	8.	Filter paper potential
9.	Mean PR	10.	Std. error of the PR

<u>The files</u> are:

<u>Site</u>	<u>File name</u>
Ismani	NPIPL1 NPILP2
Magamba	NPMAPL1 NPMAPL2
Mbimba	NPMBPL1 NPMBPL2
Sao Hill	NPSPL1 NPSPL2
Ukwile	NPUPL1

1,2 = 5.5-9.5 cm; 22-26 cm sampling depth (needle PR)
= 7.5 cm; 22.5 cm sampling depth (field PR).

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