

SOIL PHYSICAL CONSTRAINTS TO PLANT GROWTH AND CROP PRODUCTION



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Foreword

This publication considers root requirements of the soil environment, the role of soil structure including its maintenance and improvement, tillage and the effects of water storage and irrigation on crop production. The significance of soil biota and organic matter in maintaining and improving soil structure is also emphasized. The case for use of conservation tillage systems to reduce crusting and erosion is addressed, and details of simple water harvesting and irrigation methods, which make effective use of the soil physical environment, are also presented.

Following the brief introduction, soil texture and structure are given in Chapter 2. Emphasis is placed in the following chapters on the development and stabilization of soil structure to comprehend other soil physical properties, i.e. soil water, aeration, soil pores, temperature, mechanical properties and susceptibility to crust development and erosion.

Soil structure is important for all aspect of soil use and management. The process which contribute to structure development, and the conditions which encourage them, are broadly understood. But the details are so complex that as yet it is not possible to predict precisely the impact that a particular management option will have on structure. Crop cultivation too frequently results in degradation of soil structure to some degree. Common causes include poor tillage, decomposition of organic matter, compaction by machinery and exposure to raindrop energy. Repeated cultivation, without any efforts to redress the decline of structure, will lead to a decrease in soil productivity in the longer term, if not immediately. The natural process of soil structure development, in particular the activity of soil organisms, is hindered in poorly structured soils, which exacerbates the problem further.

In Chapter 3 the role of soil water in plant growth is discussed. This Chapter includes discussion of methods such as water conservation, water harvesting, and small-scale irrigation methods in semi-arid areas. Chapter 4 discusses the effect of structural breakdown in surface crust development. Erosion, soil aeration, temperature and mechanical impedance are discussed in Chapter 5. Chapter 6 provides information on tillage operations to ameliorate soil physical conditions with discussion on conservation tillage to minimize soil erosion and improve other physical attributes, i.e. structure and aeration. Conventional tillage improves soil porosity and structure by increasing the number of large pores present. However, more than tillage is required to increase the number of aggregates and pores of small sizes. Usually favourable soil physical conditions plus inputs of organic matter, and active roots and soil organisms, are necessary. Lasting structural improvement is only obtained slowly. It can take many years. As yet there are no quick remedies. Research continues into the use of soil conditioners to regenerate soil structure, but this would be a costly operation.

Chapter 7 highlights the area of soil physical behaviour that needs more information and points out the area for future research.

Policy-makers and advisers need to recognize what impact, beyond the field, proposed changes to long established practices may have on soil physical conditions, and the repercussions for crop yields. Traditional farming practices have often served very well without causing degradation problems until more recent pressure on land to improve productivity. The most sophisticated prediction of yield benefits will be worthless if the grower in the field is unable to implement the necessary changes through misunderstanding or economic constraints. This publication sheds some light on these issues.

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Consideration as to how best to implement new techniques, or adopt old ones, is necessary for everyone involved in the crop production system. The time devoted through their wide experience by Catriona M.K. Gardner from the University of Ulster, Northern Ireland and K.B. Laryea and Paul Unger, USDA ARS, Bushland, Texas, USA, to this document is greatly acknowledged. Utilization of the most recent literature in the area has added a special value to this publication.

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Chapter 1

Introduction

Plants require soil to obtain water and nutrients for growth, and for anchorage and stability. Seeds will germinate, seedlings emerge and grow to produce a crop under a great variety of conditions. Plant growth in the context of crop production demands conditions adequate to yield a crop which is economically worthwhile. For efficient crop production, it is important to understand the soil environment in which plants grow, to recognize the limitations of that environment and to ameliorate where possible without damaging the soil quality. Soil is one of the most important natural resources for crop production. It is estimated that the rate of soil formation is about 2.5 cm every 150 years (Friend, 1992); i.e. soil is non-renewable within the human-life-span. It is in the interests of the farmer, and the population as a whole, to ensure that good soil management is practised so that this resource is preserved for continued use by the current and future generations.

For satisfactory plant growth, it is essential that the soil provides a favourable physical environment for root development that can exploit the soil sufficiently to provide the plant's needs for water, nutrients and anchorage.

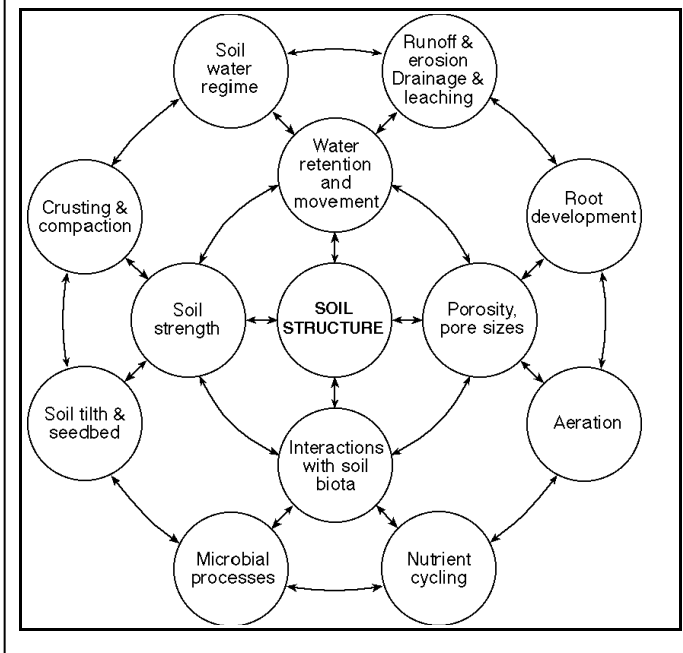
Soil in its natural state rarely provides the most favourable physical conditions for crop growth. The benefits of soil cultivation and of adding/removing water, to improve the soil physical condition, combined with appropriate crop selection for the enhancement of yields, has been long appreciated. Farmers for millenia have recognized many of the soil physical constraints to plant growth and crop cultivation. Although unable to describe and quantify them scientifically, they have set about and achieved the amelioration of conditions in many instances. The greater degree of intervention through the engine driven mechanization has often been beneficial, improving the extent and manner of soil cultivation and enabling much greater areas to be farmed through use of irrigation and/or drainage schemes. However, such exploitation though initially improving soil physical conditions, can in time lead to a deterioration in soil quality through, for example, degradation of soil structure, or increase in erosion susceptibility. Management of soil physical conditions to ameliorate the constraints for plant growth will not only preserve the soil quality for the future but also contribute to the mitigation of soil degradation.

A soil consists of mainly clay, silt, sand and gravel sized particles which are products of weathering, organic materials arising from the growth of flora and fauna in and on the soil, and the soil atmosphere and soil water which fill the voids between the solid particles. Usually much

of the solid material, mineral and organic, is very finely divided and its behaviour is dominated by the nature of its surfaces. The soil water exists in such thin films that its properties are very different to that of a bulk volume of the same water. The organic fraction forms complex interactions with the mineral, solute, water and organisms of the soil, compounding the complexity of the system. Furthermore, soil is a dynamic open system, continually subject to inputs and losses of energy as well as water, organic and inorganic materials.

Soil texture indicates much about the possible limitations to crop production in a given soil. However the limitations arise predominantly from the manner and degree to which the particles are bound together with organic materials to form aggregates, between and within which a network of interconnecting voids of a wide range of sizes is present. These aggregates are known as soil structure. The structure of a soil influences the physical extent to which a plant root system can develop, its ability to provide an adequately aerated medium for root development, its potential for supplying a crop with water, with dissolved nutrients and the soil temperature conditions (Figure 1). Soil structural properties also influence the susceptibility of a soil to wind and water erosion. The aim of tillage operations is consequently to improve soil structure for plant growth. However, under some circumstances tillage can in the longer term damage structure.

FIGURE 1
The central importance of soil structure (after Lal, 1994)



SOIL PHYSICAL PROPERTIES AND ROOT SYSTEM DEVELOPMENT

A root system is a living entity and comprises a branching arrangement of individual living roots. Under field conditions, the root system of a plant continues to develop and extend through the growing season. Individual roots cease to function and die whilst new ones grow and maintain the supply of water and nutrients to the plant shoot; the lateral roots of some species may only live for a few days. Roots do not have an intrinsic ability to find water and nutrients in soil. Growth often persists beyond the point at which the needs of the developing shoot are adequately met, e.g. growth often continues in moist soil at times when the water requirement of the crop is small. Root hairs increase root contact with the soil and presumably increase the absorbing surface for water nutrients, although the importance of this appears to vary with different species and various ions (Kramer, 1995). Under favourable conditions the roots of cereal crops in temperate climates will increase the depth of rooted soil at rates of up to 2 cm d⁻¹. Rates of 2 to 4 cm d⁻¹ have been observed for various annual tropical crops. Much slower

growth is probable in soils where water shortage, mechanical impedance or poor nutrient supply occur.

For growth, roots require carbohydrate which is supplied initially from reserves in the seed or tuber, and subsequently from the leaves and stems where it is photosynthesized. Oxygen is required to make use of the carbohydrate energy source and this is mainly taken from the soil atmosphere. Poor aeration will result in reduced growth in most species although some are adapted for growth in poorly aerated soil. Poor aeration can cause development of toxic substances which may interfere with root growth.

Different species express different tolerances to soil temperature conditions. Root growth rates are reduced at low and high temperatures and growth ceases under extreme conditions. Mechanical impedance to root development occurs where spaces of appropriate size are not available for roots to grow into, and/or the soil is too compacted so that it can not be pushed aside as root growth proceeds. Access to water is also essential for roots. They use water directly themselves. In addition, if the supply of water with its solute load to the shoot is restricted so that shoot development is inhibited, there will be a feedback effect on root growth. Soil water is important indirectly to root growth and it influences soil mechanical strength but also affects the degree of aeration and soil temperature.

In the course of a growing season, variation in soil physical conditions due to temperature and particularly water fluctuation, is usual. Thus the environment in which roots grow is not static. Table 1 details the root system characteristics which can be affected by soil physical conditions.

TABLE 1

Root system characteristics that can be affected by soil physical conditions (from Atkinson and Mackie-Dawson, 1991)

Category	Characteristics Affected
Anatomy	Cell size, cortex width, balance of xylem cell types, epidermal wall form, root diameter, root shape
Features of individual roots	Diameter, growth rate, angle, length, mass, root longevity, root hair length and density, mycorrhization, pressure
Branching pattern	Amount, density, number of orders, position, distance between branches
Feature of whole root system	Horizontal and/or vertical distribution, length, mass, absolute and relative distribution
Function	Absorption of nutrients and water, production of biologically active molecules e.g. enzymes

The functioning of the cells which comprise roots can be directly influenced by the physical properties of the growing environment. This may directly lead to change in the functioning of the root, and/or to alterations to the anatomical structure of an individual root and consequent modification in the root's growth and processes. The physical environment may therefore modify the functioning of a root in terms of its ability to take up and supply water and nutrients, expressed as uptake per unit root length. The combined result of these effects is that the length, diameter and extension rate of individual roots can be modified.

Factors which influence the morphology of a root system and its rate of extension, effect the total soil volume exploited by roots and the root density within this volume. This has

implications for the uptake of water and nutrients as well as the anchorage function of the roots. In many species, the roots produce hormones, such as abscisic acid, cytokinins and gibberellins, which maybe essential to shoot as well as root development and functioning. Factors which effect root development adversely may have a detrimental impact through interference with the hormone production. Most plant root systems exist in a symbiotic relationship with mycorrhizal fungi. Factors which influence the behaviour of the mycorrhiza may indirectly influence root growth or processes.

Research has shown that root systems are generally very elastic in their response to adverse physical conditions (Atkinson and Mackie-Dawson, 1991). For example, inhibition of root elongation due to mechanical impedance may be compensated for by an increase in root diameter and/or branching of the root system.

Root growth commences from a seed or seed organ, such as a tuber, when the surrounding physical conditions are favourable. Seeds need to imbibe water to germinate. Seed-soil contact and soil water content are therefore, with temperature, the principal factors influencing germination. Once germination has succeeded, seedling emergence may be impeded by the soil surface structure whilst development of the root system is influenced principally by the factors described above. Tillage operations are particularly directed towards providing a favourable physical environment for germination and seedling establishment. Ideally a seedbed should provide sufficient heat and water plus a layer of soil between the seed and soil surface which is readily penetrated by the shoot.

The aim of this publication is to review how soil physical properties influence plant growth and how adverse conditions can be ameliorated by management techniques. The emphasis is on the limits to plant growth *per se* rather than limitations for procedures involved in crop production, e.g. trafficability and use of machinery. The theory and research behind present understanding of each aspect of soil physics (structure, soil water etc.) is briefly considered with the implications for plant growth, to enable appreciation of the principles underlying management methods, and their success or failure. Soil texture is considered briefly in the following chapter, particularly with respect to its influence on soil structure which is then discussed in detail. An understanding of the development and stabilization of soil structure is necessary to comprehend most other soil physical properties, i.e. soil water, aeration, temperature, mechanical properties and susceptibility to crust development and erosion, which are considered in later chapters.

Chapter 3 is devoted to the role of soil water in plant growth and includes discussion of methods for enhancing soil water conditions through use of water conservation, water harvesting and small scale irrigation methods in semi-arid areas. Chapter 4 summarizes the effect of structural breakdown in surface crust development. Crusting has significant consequences for seedling emergence but may also be a precursor to erosion. Erosion as well as soil aeration, temperature and mechanical impedance are considered more briefly in Chapter 5. Tillage operations to ameliorate soil physical conditions are described in Chapter 6, with discussion of no-tillage and reduced-tillage methods to minimize erosion and/or improve other soil physical attributes e.g. structure and aeration. Finally, Chapter 7 highlights omissions in our knowledge of soil physical behaviour for plant growth and suggests priorities for future research.

The complex inter-relationships between the many physical properties of soils can be expressed mathematically. However, the many mathematical equations are often

incomprehensible to the non-specialist. The aim of this text is to provide explanations of soil physical phenomena and the concepts underlying soil physics theory, which are accessible to all. The number of equations used here is minimal, but the level of explanation is no simpler than necessary. References which give more detail about the topics are supplied throughout the text. For more information about soil physics theory and application the reader should examine soil physics texts such as those published by Hillel (1980a, 1980b), Marshall and Holmes (1988) and Jury *et al.* (1991). A very useful overview of soil conditions for plant growth has been edited by Wild (1988).

Much research has been conducted into the effects of soil water temperature, soil structure and mechanical impedance on seed germination and subsequent seedling development. For example, statistical relationships have been developed to predict the success of germination and early development from these soil factors (Lindstrom *et al.*, 1976; Schneider and Gupta, 1985). Bouaziz and Bruckler (1989) have simulated wheat germination and seedling growth satisfactorily using a physically based model which incorporated the same factors. However, models which are applicable to the wide variety of situations observed in the field have yet to be developed (Townend *et al.*, 1996).

Chapter 2

Soil texture and structure

The physical arrangement of the soil solids dictates, to a large extent, the distribution possibilities of the liquid and gaseous components within a soil, for both occur in the voids between the soil solids. The voids are referred to as the soil pores or pore space, irrespective of their shape or size. The size and disposition of the pores may simply be determined by the size and arrangement of the primary soil particles as in the case of a loose sand. However, in most soils several processes associated with the presence of plant roots, the soil fauna, micro-organisms and organic matter, as well as physical forces due to the presence of water, result in the non-random arrangement of the primary soil particles and development of aggregation and so soil structure. In its broadest sense, the term soil structure defines the size, shape, and arrangement of the primary soil particles and the aggregates they form. Soil structure determines the size, shape and arrangement of the pore space between and within aggregates. The relative proportions of sand, silt and clay sized materials present in a soil determine its textural characteristics. Much can be inferred about the general behaviour of a soil from its texture, including its propensity for aggregation.

For a particular soil, maintenance of and improvements to the existing structure, will come through optimizing the organic matter content and the activity and species diversity of the soil biota (Lal, 1994). In most cases, optimizing means increasing the organic matter content which will lead to increased faunal and microbial activity. Without organic matter additions, possibilities for soil structural improvement are restricted by the mineralogy and chemistry of the inorganic fraction. Physical cultivation e.g. ploughing or harrowing, enhances soil structure but often only temporarily. If organic material is present this may encourage more permanent structural improvement. Generally, the conditions which favour successful plant growth also favour biological activity in the soil and so structural improvement.

This chapter considers soil particle size and texture initially, then focuses on the processes by which soil structure develops naturally and can be encouraged by tillage. The processes resulting in the development and improvement of soil structure are the focus here; Chapter 6 deals with the management techniques which may be employed to effect structural improvement. The importance of structure to plant growth arises directly in providing pores and mechanical weaknesses in the soil for the plant root system to grow into, and indirectly through the control it exerts on the soil water and soil atmosphere. These are discussed in Chapters 3 and 5. Breakdown of good soil structure has deleterious consequences for plant growth. Causes are discussed briefly here, but two phenomena, soil crusting and soil erosion, which are associated with structural deterioration, are considered in Chapters 4 and 5.

SOIL TEXTURE

The useful concept of soil texture encompasses how a soil feels in the hand and behaves under tillage. A sandy soil is probably easily worked, freely draining, warm in spring, but susceptible to lack of water in dry periods. A clay soil is more likely to be difficult to work, sticky and plastic when wet and prone to drainage problems, but hard when dry. Between these extremes are loamy and silty soils. Loams comprise sand, silt and clay sized particles and generally make good agricultural soils. Silts are similarly good soils for cultivation but prone to structural problems. The presence of organic matter in a soil usually makes it feel and behave more like a loam.

Determination of the proportion of mineral particles of different size categories in a soil (particle size analysis) is conventionally used to quantify the textural properties of a soil. Textural diagrams such as illustrated in Figure 2 facilitate textural classification of soil after particle size determination. However, the correlation between texture determined by analysis, and texture as observed in the field by hand, is not necessarily good. This is because the field assessment is relatively subjective, whilst the particle size analysis only includes the finer inorganic fraction of the soil; the effect of stones, organic matter and cementing agents such as carbonates is ignored. The size limits used to distinguish the sand, silt and clay particles of the inorganic soil constituents are usually:

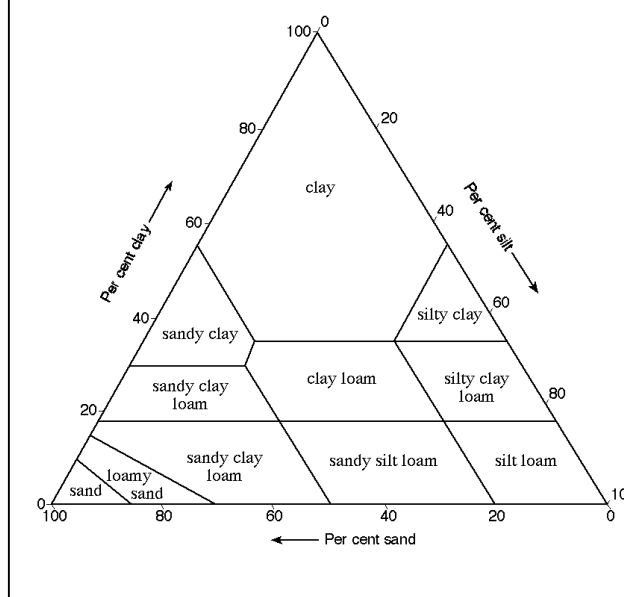
coarse sand	2 to 0.2 mm
fine sand	0.2 to 0.05 mm
silt	50 μ m to 2 μ m
clay	less than 2 μ m

Variations in the definition of the sand/silt boundary do occur. For some purposes it may be necessary to subdivide the groups further. Figure 3 shows how the size of sand, silt and clay particles relates to the size of other soil components. In most soils the solid phase is predominantly inorganic. However, highly organic soil layers may develop at the surface under wet conditions e.g. peats.

Sand and silt

Sand and silt sized particles are largely made up of resistant residues of rock minerals. Quartz, which is very durable, is often the principal component. This is particularly so in soils formed upon sedimentary rocks or more recent sedimentary deposits. In soils developed upon igneous rocks, the mineralogical composition of the sand and silt fractions will reflect the mineralogy of the parent rock. Silt and/or sand sized particles may also occur due to the cementing of finer particles into small aggregates by carbonates, iron or aluminium hydroxides or silica.

FIGURE 2
A soil texture triangle



Particles of this size range are almost inert, in sharp contrast to clay sized materials. Adjacent particles have no affinity for one another and additional materials are required to cement them together to form aggregates. A sand offers a good degree of pore space suitable for drainage/aeration of soils and root penetration. The much smaller pores which occur between silt particles are limiting in this respect and aggregation to create larger pores is essential for improvement of conditions for plant growth.

Clay

The clay size fraction is dominated by crystalline clay minerals i.e. hydrous aluminosilicates with a layer-lattice structure. These may be micas and chlorites derived directly from the soil parent material. But clay minerals also develop during the soil forming process, particularly kaolinites, illites and smectites. Calcite (CaCO_3) may comprise an important component of the clay size fraction in alkaline arid soils and those developed on limestone. Crystalline and poorly crystalline forms of silica, and iron and aluminium oxides often form a significant part of the clay size fraction in tropical soils, influencing both their physical and chemical characteristics.

FIGURE 3
Sizes of the principal soil components: particles, aggregations, organisms and pore spaces, and the water retention properties of pores of different sizes (after Kay, 1990)

Particles	Aggregations	Water retention	Organisms	Scale
Atoms	Amorphous minerals	Absorbed and intercrystalline water	Organic molecules	0.0001 μm
Molecules				0.001 μm
Macromolecules				0.01 μm
Colloids	CLAY MICRO-STRUCTURE	Matric potential < -1.5 MPa	Polysaccharides Humic substances Viruses	0.1 μm
Clay particles			Bacteria	1 μm
Silt	Domains	Plant available water	Fungal hyphae	10 μm
			Root hairs	100 μm
Sand	Micro-aggregates	Matric potential > 10 kPa	Roots Insects	1 mm
	Aggregates	MACROPORES AND CRACKS		10 mm
Gravel	Clods	Aeration	Worms	100 mm
Rocks		Fast drainage	Moles	1 m

The importance of the clay particle size fraction for soil structure arises from firstly the layer-lattice crystalline form of the clay minerals present and their consequent surface chemistry, and secondly the fact that much of the material is colloidal in size. Soils containing even small quantities of smectite clays tend to be less stable than when smectites are absent (Stern *et al.*, 1991). Much better aggregate stability is characteristic of soils where either kaolinite or illite clays are prevalent. Hard-setting may be a problem in kaolinitic soils. This is attributed to the combination of the poor shrink-swell properties of kaolinites and their potential for strong bonding (Mullins *et al.*, 1987). Illite and smectite clays have shrink-swell properties which contribute to the processes of aggregate formation where soils undergo wetting and drying. A comprehensive review of clay behaviour in soils is provided by Sposito (1984), and texts such as Dixon and Weed (1988) provide general detail on soil mineralogy.

SOIL STRUCTURE

Good soil structure means the presence of aggregation which has positive benefits for plant growth. These benefits arise from the wider range of pore sizes which result from aggregation. The nature of the pore spaces of a soil control to a large extent the behaviour of the soil water and the soil atmosphere, and influence soil temperature. These all affect root growth, as does the presence of soil pores of appropriate size to permit root elongation. Favourable soil structure is therefore crucial for successful crop development. The destruction of soil structure may result in a reduction in soil porosity and/or change to the pore size distribution. In some circumstances a structureless soil mass can result, or physical re-arrangement of particles into crusts and pans can occur.

Soil structure is described in terms of its form and its stability. Structural form can be considered from two perspectives: the arrangement of the primary particles in aggregates, or the consequences of this arrangement for the size, shape and continuity of the pore space between and within the aggregates. Structural stability is the soil's ability to maintain its structural form despite the application of stresses due to tillage, machinery or rain drop impact. Soil structural form is discussed before an account of the processes responsible for the creation of soil structure and its stability. Recent reviews by Dexter (1988), Kay (1990), Oades (1993) and Horn (1994) provided the basis for the account that follows.

Aggregates

The presence of structure in a soil is readily recognizable. On handling, the soil mass will part along natural failure zones into aggregates. Aggregates are semi-permanent features, persisting through wetting and drying cycles. Aggregates, which may also be called peds, are distinct from the clods which arise on mechanical disturbance such as digging and ploughing when the soil mass may break along natural failure zones but also cleaves in other directions. Failure zones arise where only a relatively small proportion of the primary particles are strongly bonded together due to either weak interparticle bonding, or the presence of cracks or many pores.

Soil structural form is described and classified in terms of the shape, orientation, size and degree of development of the aggregates present (Figure 4). Aggregates generally possess a well developed internal structure. Even small spheroidal soil aggregates will part into smaller structures on gentle handling. In fact structural organization occurs at all scales. The aggregates visible to the eye in the field represent the upper end of a hierarchy of structural form.

The smallest aggregates, micro-aggregates are approximately 100 μm in diameter (Figure 3). They are built-up of smaller structures comprising parcels of clay and other colloidal material in assemblages which are formed of packets of clay type crystals. At each level of arrangement the particles within the structure are held together more firmly than the bonds between structures, thus micro-aggregates are stronger than aggregates. This means that disaggregation should occur stepwise, larger structures collapsing before the smaller ones. However, this is not always the case. Oades (1993) has suggested that long periods of development under permanent vegetation, preferably grassland, are required for strong development of the hierarchical structure. Therefore, internal organization of aggregates will be less marked in new soils or those subject to continuous tillage.

FIGURE 4
Features of the principal soil structural types (after White, 1979)

Name	Appearance	Descriptions of aggregates	Example occurrence
Spheroidal		Approximately round in shape hence appreciable porosity between them. Further classified: If aggregates porous, crumb structure. If aggregates relatively non-porous, granular structure. Size - From < 2mm to 20mm dimension but generally < 10mm.	Most common in top soils, particularly under grass. Soil organisms, organic matter and roots necessary for development.
Blocky		Aggregates have flat or rounded surfaces which fit into the faces of the adjacent aggregates when wet. Shrinkage on drying opens up vertical and horizontal cracks. Faces may be coated with deposits of organic matter, clay or mineral oxides. These cracks used for root penetration. Further classified into angular and subangular blocky according to sharpness of faces. Size - From < 2mm to 500mm maximum dimension but generally < 300mm.	Usual in subsoil (B) horizons where smoothness and often coloration of faces aid identification.
Prismatic		Vertical cracking is better developed than horizontal so structures prism shaped. As with blocky structure, aggregate faces fit into one another and may be coated, and on wetting, swelling results in closing up of cracks. If top of prism structures rounded, termed columnar structure. Size - Long axis from < 100mm to 1m or greater.	Characteristic of subsoil (B and C) horizons of heavy clay soils, especially if prone to waterlogging.
Laminar (platy)		Natural cracking is predominantly horizontal so that plate-like aggregates occur. Size - Vertical axis from < 5mm to 500mm.	Characteristic of kaolinitic soils, and top soil (A) above an impermeable subsoil (B) horizon.

Pores

The pore space or porosity of a soil is defined as the ratio of the volume of the pores to the total soil volume. Total porosity is an important soil attribute but the character of the pore space is important for water and air movement as well as root growth and the activity of micro-organisms. Pores can be assigned to different size classes according to their significance for different processes. Thus drainage due to gravity will only occur from pores larger than about 30 μm in diameter whilst water in pores of less than 0.2 μm is unavailable to plants. Root hairs and larger soil micro-organisms can grow or move into pores larger than 10 μm in diameter. Smaller micro-organisms can exploit pores as small as 1 μm in diameter (Figure 3). Pores larger than about 60 μm diameter can be seen with the naked eye. They, and larger diameter pores are significant for rapid soil drainage and consequently soil aeration.

Defining soil pore sizes as above implies that pores form an interconnecting system of cylindrical tubes of different diameters through soil. That is not the case. Pores may be planar in shape, completely irregular, or cylindrical. A pore may widen and narrow along its length. The narrowest point determines its functionality in terms of water and air movement, or root or micro-organism exploitation. Pores may end without connecting to another pore, or be totally unconnected to other pores. Thus parts of the pore system, and the air or water within it, may be unconnected or only poorly connected to the main system. One result of the hierarchical nature of soil structure is that micro-aggregates are denser and include smaller pores than aggregates. Thus structural breakdown can produce a distinct change in pore size distribution as well as loss of total porosity.

PROCESSES RESPONSIBLE FOR THE CREATION OF SOIL STRUCTURE

The processes causing the arrangement of soil primary particles into microstructures and aggregates, and the stabilization of the aggregates, cannot be readily separated. In large part it is interaction between the clay, other inorganic and organic colloidal particles which control the arrangement and stabilization of the aggregates. The flocculation of the soil colloidal material is very important in the binding of primary particles at the micro-scale and in aggregate stabilization. Stable aggregate formation in silt or sands in the absence of clay requires the presence of organic material.

The expression of aggregation in a flocculated soil, at the micro- as well as at the field scale, at a given time, results from the net effect of drying and wetting, freezing and thawing, compression and shear due to animals or agricultural equipment, and biopore formation as a result of the growth of plant root systems, and activity of soil fauna and micro-organisms. These processes introduce physical forces to the soil medium which result in re-arrangement of the soil particles at both the micro- and macro-scale. The result is that particles in some zones of the soil are brought closer together, enhancing the possibilities for bonding between them. In adjacent zones greater porosity is created and so a potential failure zone.

Flocculation and dispersion in soils

A soil is said to be dispersed if there is no adhesion between the colloidal sized particles, i.e. those $<1\ \mu\text{m}$ in diameter. Flocculation occurs when conditions are created such that the colloidal particles do adhere together. Flocculation and dispersion are principally controlled by the attractive and repulsive forces of the electric double layer which surrounds colloidal particles. Sumner (1992) has recently provided an account of the processes and factors influencing flocculation and dispersion in soils and the subject will be dealt with only briefly here.

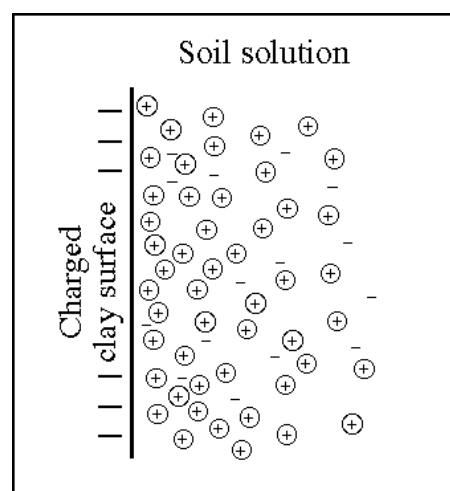
Electric double layer

The electrical double layer arises because the colloidal particles are charged. In aqueous solution, the charge at the colloid surface attracts a layer of counterions to neutralize the surface charge. Figure 5 illustrates the ion distribution at a negatively charged clay mineral surface; cations congregate at the colloid surface attracted by the negative charge; a deficit of anions develops at a distance from the surface. The character of the electrical double layer therefore depends upon the nature of the colloid particles and the solution in which they are suspended.

Charge on colloid particles

The planar surfaces of clay minerals are permanently negatively charged and so attract cations. The charge at the edge of the clay plates depends on pH, becoming net positive

FIGURE 5
Distribution of ions in the electrical double layer at a negatively charged clay surface



as pH falls from about 9 to 5. The variable edge charge is dominant in kaolinites but unimportant in 2:1 lattice clay minerals such as smectites and illites which have much greater planar surface areas. Variable surface charge is characteristic of the oxides and hydrated oxides of iron and aluminium, and the amorphous minerals such as allophane found in soils.

The surface charge of humic materials is also pH dependent. It is predominantly negative increasing with pH above pH 3, so that in top soils it augments the permanent negative charge of clay minerals. There are many possibilities for interaction between organic substances and clay colloids; for example, organic materials may be adsorbed onto clay surfaces and vice versa, altering colloidal behaviour.

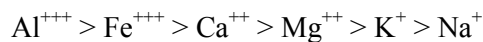
Attraction between colloid particles

Van der Waals forces operate between individual atoms in colloid particles and attract particles together. These forces are due to electric and magnetic polarizations which cause a fluctuating electromagnetic field. Although the Van der Waals forces between a pair of atoms are small, and decline rapidly with distance between the atoms, the attraction between many pairs of atoms in adjacent particles is additive so that strong attraction can occur. Van der Waals forces are particularly effective in holding clay plates together, face to face.

Attraction also occurs between oppositely charged surfaces. The importance of this form of attraction depends upon the mineralogical makeup of the soil as well as soil pH. It tends to lead to edge to edge, and, edge to face attraction between clays and sesquioxides particles. Kaolinites can form stable micro-aggregates as a result of this type of attraction reinforcing the plate to plate attractions. Interaction between positively and negatively charged surfaces is most probable in acid subsoils which may be more resistant to dispersion than the overlying top soil.

Repulsion between colloid particles

When two particles come together, their electrical double layers interact setting up repulsive forces. As the double layers overlap, so the repulsion between them increases. This repulsion increases with particle size but is inversely related to the concentration and valence of the counterions, increasing as either are reduced. The impact of cation type on improving flocculation in most soils is in the following order:



Soils in which sodium is a dominant cation are most susceptible to dispersion. The importance of sodium can be quantified by measuring the exchangeable sodium percentage, ESP:

$$\text{ESP} = \frac{\text{exchangeable Na} \times 100}{\text{cation exchange capacity}}$$

As the ESP rises, a much more concentrated soil solution is required to maintain flocculation. Dilution of the soil solution by rainwater, or by adding irrigation water which has a low dissolved salt content, will result in clay dispersion.

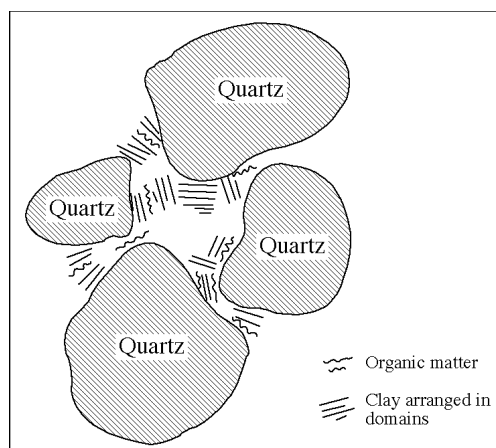
Repulsion also occurs between the hydrated surfaces of colloid particles. As particles approach one another, the surface ions must lose some of their water which requires energy; in effect this counteracts some of the attractive Van der Waals forces. If the concentration of the soil solution is diluted, hydration increases easing dispersion. The adsorption of organic materials on to colloid surfaces can modify their behaviour. Thus, hydrophobic surfaces may be rendered hydrophilic and so more likely to repulse one another, and, the variable charge of inorganic constituents may be altered or reversed reducing possibilities for attraction of oppositely charged surfaces. Inorganic anions may be specifically adsorbed and also cause charge reversal at positively charged sites and so repulsion between particles.

Adhesion and stabilization of particles within aggregates and the role of organic matter

Whether colloidal particles adhere together depends on the net attractive force. Whilst the attractive forces are predominantly a function of the nature of the colloid particles, the electrical double layer repulsion forces are influenced by the composition and concentration of the soil solution. The degree of flocculation of a soil, and hence its structure, can therefore be altered by chemical means. Use of soil amendments such as gypsum is effective for improving flocculation of clays and thus stabilization of soil structure (e.g. Bridge, 1968; Barzegar *et al.*, 1996; Borselli *et al.*, 1996a). The improved aggregate stability is associated with displacement of sodium and magnesium on the clay colloidal complex by calcium. The colloidal complex of most saline and alkaline soils is dominated by monovalent cations, particularly sodium. Applying gypsum replaces the monovalent ions with divalent calcium cations that impart desirable structure by flocculating the clay in the soil.

Exactly how the flocculated clay and organic colloids are organized with silt and sand sized particles to form micro-aggregates and aggregates is as yet uncertain. The model of Emerson (1959) illustrated in Figure 6 is generally accepted. It is possible that different mechanisms operate for different sizes of aggregate; smaller, more stable structures may be bound together to form larger ones by different agents. In certain soils, particle adhesion and structural stability occurs due to the presence of inorganic colloidal materials, such as iron and aluminium oxides, and in clays a degree of stability can be achieved without organic matter. However, in most soils the presence of organic matter, growing plants and an active soil flora and fauna promotes stabilization.

FIGURE 6
Schematic diagram of the binding together of silt and sand sized particles by clay and organic material as proposed by Emerson (1959)



Organic polymers are probably very important in bonding the sand and silt particles with the clay microstructures. Dorioz *et al.* (1993) observed that polysaccharides are widely present at the interface of organisms and soil. Colonies of micro-organisms and the polysaccharide mucilages which they as well as roots and fungal hyphae exude about them, bind particles together. Roots and fungal hyphae may also have a more physical influence in binding of

collections of micro-aggregates into aggregates of 2 mm or greater size. In addition, the decomposition products of plants and organisms may directly cause bonding through creation of colloidal materials.

In any soil where clay is present, interaction between the polysaccharide exudates, organic colloids and other products of decomposition, with clay particles, can enhance the effects of clay flocculation promoting stability. Chenu (1993) demonstrated that polysaccharides changed the clay micro-structure into an organo-mineral network with extensive inter-particle bridging. The physical properties of such clay-polysaccharide associations differs from that of the original clays. Water retention properties generally increase and the shrink-swell behaviour is also modified. The production of microbial extracellular polysaccharides, and so aggregate stabilization can be improved through nutritional management of agricultural soils; the presence of adequate nitrogen is most important (Roberson *et al.*, 1995).

In laboratory studies Dorioz *et al.* (1993) found that the role of roots, fungi and bacteria in clay particle organization supported the hierarchical nature of soil structure. Polysaccharides exuded from bacteria influenced a small area around the organism. Those from fungi penetrated further into the surrounding soil influencing a larger environment 5 to 20 μm across whilst those from root hairs and roots affected a greater volume, 20 to 200 μm . Bacteria with clay particles adhering to their outer cell walls have been observed in soils and this almost certainly contributes to the aggregation process.

Aggregation

The process of aggregation requires some means of moving soil particles apart so that pores are created in the soil mass, and a mechanism for maintaining that arrangement. The processes responsible for creating porosity and hence aggregates include drying and wetting, freezing and thawing, tillage and the activity of roots and the soil biota.

Drying and wetting

Evaporation of water at the soil surface, drainage or water uptake by plant roots and other organisms, are responsible for drying at the surface and in the soil mass. Shrinkage occurs on soil drying due to removal of water from within and between clay microstructures. Removal of intracrystalline water causes closer packing of the clay plates. As water is lost between clay structures, surface tension forces increase, pulling them closer together. Water is also removed from organic colloidal material, further reducing the soil volume. This shrinkage initiates cracking when the tensile stresses introduced exceed the tensile strength of the soil. Cracking may occur at the microscale and/or macroscale, depending on the extent and spatial variation of water extraction. Soil tensile strength decreases with water content and so cracking tends to occur in wetter parts of the soil. The overall effect is increased porosity in the zones where cracking occurs but a pore reduction in the zones between the cracks. However, drying has little effect on the structure of sandy soils because the mineral particles are in good contact.

On wetting, water moves into the lattice structure of 2:1 clays, and adsorbs onto the outer surfaces of the micro-structures so causing clay swelling. Organic materials also swell due to hydration. Rewetting a cracked soil results in swelling and consequent closing up of the cracks. However, the impact of the earlier drying may not be completely reversed so that greater porosity persists at the position of the crack. Thus a potential failure zone is created. Wetting,

particularly when rapid, can also induce soil cracking due to differential swelling of wetted soil and/or compression of air trapped in pores, to the point that the tensile strength of the surrounding soil is exceeded. Gentle wetting may therefore improve aggregation but rapid wetting causes slaking (Grant and Dexter, 1989).

Soil exposed to a series of wetting and drying cycles, in the absence of other aggregation processes, undergoes a progressive decline in aggregate strength and decrease in aggregate size; arid and semi-arid soils are especially prone to this (Piccolo *et al.*, 1997). However, it may be possible to use these processes to repair the structure of a damaged soil. Sarmah *et al.* (1996) found that five cycles of wetting and drying of a Vertisol compacted due to machinery tracks were effective in introducing cracking and a consequent increase in porosity and associated reduction in bulk density.

Freezing and thawing

Soil water may freeze *in situ* or migrate towards ice forming in larger pores. Freezing *in situ* of pore water sets up stresses which may fracture the surrounding soil. Water movement results in drying and hence shrinkage of some parts of the soil, and development of large ice structures elsewhere, leading to cracking at both the micro- and macroscale (Kay, 1990). On thawing the increase in porosity where the ice formed, or shrinkage occurred, persists to some extent. A brief freeze is beneficial in breaking up clods arising from cultivating wet clay soils. However, repeated freeze-thaw cycles could cause increasing aggregate breakdown with a deleterious effect on the porosity of the same soil.

Tillage

During tillage operations the soil is subject to shearing, compressive and tensile stresses. A pure shear stress causes a change in shape without change in soil volume. Pure compression results in volume change without change in shape. In practice shear and compression usually occur together in soils. Tensile stresses cause tensile failures which open up fissures and cracks; this decreases the bulk density of the soil but causes little alteration to the soil between the failure zones. The stresses that tillage imposes result in deformation of the soil and failure. Brittle failure, compressive failure or tensile failure may occur. Brittle failure results when compression causes deformation along a few well defined planes, but the intervening soil is little altered. Compressive failure results due to compression causing failure along many planes and hence compaction of the soil mass. The type of failure which occurs depends in part upon the resistance exerted by the surrounding soil on the deforming soil, i.e. the confining stress. When the confining stress is low, tensile and brittle failure are more likely to occur. If the confining stress is great, compressive failure will result. Where the soil water content is high, or its density low, compressive failure will occur at lower confining stresses.

The effect of tillage can therefore create new failure zones and weaken existing ones. Alternatively, where compaction has occurred, failure zones can be strengthened. The soil water content at the time of the tillage operation has a significant impact on the effectiveness of the work. Tillage also has other effects. In particular the impact of wetting and drying cycles in the surface soil is increased, due to increased porosity, and so possibilities for structural change due to shrink-swell processes are enhanced. However, tillage increases the rate of loss of organic matter and so can lead to a decline in soil structure if management practice does not compensate for this.

Although tillage may result in apparently favourable increases in porosity, it may not benefit crop production as intended because the newly formed pores are too large. For example, a comparison of the porosity of conventionally tilled and no-tillage plots found that tillage increased porosity from 19.7 to 28.0% due to the introduction of many elongated pores more than 500 μm in diameter (Pagliai and De Nobili, 1993). These large pores were mainly planar, surrounding or separating the aggregates and clods formed during tillage operations. However, the number of elongated pores in the size range was important for water transmission and plant uptake remained smaller (5 to 50 μm) in the tilled plots than in those which had not been tilled.

This account of the role of tillage in soil structural change is necessarily brief. Greater detail is provided in reviews by Koolen and Kuipers (1983), Hettiaratchi (1988) and Kay (1990).

Roots and the soil flora and fauna

Plant roots and the organisms which live in soil are influential both in the creation of pores and aggregates, and the maintenance of structural form. Oades (1993) has provided a comprehensive account of the role of soil biology in the formation and stabilization of soil structure, and also its significance in structural degradation. Lee and Foster (1992) have reviewed the part played by soil fauna in creating and stabilizing soil structure. The volume edited by Brussard and Kooistra (1993) provides many reports of research into the inter-relationships between soil structure and soil biota.

Biotic process in soils can influence structural form by either encouraging the development of aggregates or encouraging the creation of pores through aggregates. The processes may be direct. This is the case in soil ingestion and excretion as faecal pellets and casts by the larger fauna, particularly earthworms. Pores through the soil may be created by the movement of soil fauna, especially earthworms but also termites, ant, beetles and various larvae. Earthworms create new pores and enlarge existing ones by ingestion and/or exerting a radial pressure against the sides of the pore, compacting the soil around it. The pressure which they can exert is not great, less than about 0.2 MPa. Thus they are most effective in damp structured soils which they can readily ingest but also deform, so creating larger pores. Under favourable conditions such as temperate grassland, it has been estimated that earthworms can cast between 40 and 50 $\text{t ha}^{-1} \text{yr}^{-1}$, equivalent to 3 to 4 mm depth of soil (Lee, 1985).

The combined use of earthworm inoculation with organic inputs may be an efficient means of improving soils in the humid tropics where slash and burn agriculture is traditional. Inoculation at a rate of 36 g fresh weight of earthworms per square metre, in the presence of crop residues resulted in an increase in the proportion of macro-aggregates > 1cm by 25%, and a decline the proportion of micro-aggregates (< 2 mm), and hence a net increase in bulk density and decrease in total porosity (Alegre *et al.*, 1996). However, longer term experimentation is recommended to establish that the activity of the earthworms is not eventually detrimental.

Soil compaction is often cited as a limiting factor in pasture production in tropical rangelands. Macro-invertebrates including earthworms, subterranean termites and beetles in the decomposition of cattle dung play a part in ameliorating such soil conditions (Herrick and Lal, 1995). Their numbers increase in the vicinity of dung patches and their activity leads to improvements in soil structure in the upper 5 cm, and a resulting improvement in soil infiltration rates.

Root growth into a soil mass with an impedance greater than 3 MPa is generally limited by 80%. Most of the pressure due to rooting is exerted radially as the growing root expands in diameter behind the root. This probably weakens the soil in front of the root tip permitting further elongation at the tip. The fibrous root systems of grasses and cereal crops are limited to a greater extent by strong soil than tap root systems or the woody roots of perennial bushes and trees. However, Cresswell and Kirkegaard (1995) doubt the so-called biological drilling effect of growing plant roots on poor subsoil conditions. Review of several experiments, and their own work, indicated that the direct impact of rooting was a minor process in the amelioration of compacted subsoils. Indirectly the effect of root growth, plus growth of hyphae and bacterial colonies, is to cause soil drying and consequent shrinkage. Growth occurs preferentially through existing pores and cracks but the associated use of water enhances aggregation through the tensile stresses created on shrinkage.

Biotic processes are most effective in creating and stabilizing soil structure where the organic content of the soil is maintained through inputs of plant residues, leaf litter, or manures, and good soil conditions for the growth of roots, earthworms and the other soil fauna and flora persist. Roberson *et al.* (1995) noted that the production of microbial extracellular polysaccharides, and so aggregate stabilization, can be improved through nutritional management of agricultural soils, the presence of adequate nitrogen being most important. The impact of biotic processes is much reduced in soils where conditions are unfavourable due, for example to extreme temperatures, lack of water or poor aeration as a result of frequent water logging. Amelioration of such conditions will encourage soil structural improvement as well as directly benefitting crop production.

The soil biota respond to different tillage and residue retention practices. Retention of crop residues provides a source of energy for the growth and activity of the soil biota and often such practice leads to significant increases in the biomass and activity of micro-organisms as well as of the meso- and macro-fauna (Roper and Gupta, 1995). The manner in which residues are managed may alter the relative importance of bacterial and fungal populations. Generally under no-tillage, micro-organisms are concentrated closer to the soil surface because the soil structure there is not disrupted and mixed periodically. The effect of such increases in biological activity is most often significant structural improvement. For example, Pagliai *et al.* (1995) compared the structure of silt loam and clay alluvial soils after ten years of conventional and minimum tillage. In both soils, the minimum tillage system led to an increase in the numbers of pores in the size range 0.5 to 50 μm diameter, i.e. the size range significant for water storage, and an increase in the length of pores of 50 to 500 μm diameter, i.e. those which are important for water transmission. Under the minimum tillage a more homogeneous soil with better aggregate stability and so less prone to crusting, had developed. The impact of reduced and no-tillage systems is discussed further in Chapter 6.

Often no-tillage and other residue retention systems lead to increased herbicide usage to control weeds. Continued herbicide usage has been shown to significantly depress numbers of certain groups of micro-organisms and their activity in Australia (Roper and Gupta, 1995). Little information about this effect is available presently; there is a need to study longer-term impacts of biodiversity.

Little is known about the role of micro-organisms in the soils of arid areas. However, wetting has been observed to rapidly trigger microbial activity with a consequent improvement in structural stability (Sarig and Steinberger, 1993). Experiments with organic amendments to semi-arid soils, which ranged from horse manure to fresh uncomposted urban refuse and

sewage sludge, have demonstrated that such treatments may have little beneficial effect unless appropriate fungal and microbial populations are present, or introduced with the organic material (Roldan *et al.*, 1996). Horse manure was found to be ineffective at improving soil aggregate stability whilst the uncomposted refuse was most effective. A significant correlation between the size of the fungal population and aggregate stability was evident.

STRUCTURAL DEGRADATION

The preceding account of the processes of soil structure generation and stabilization has emphasized the continually changing nature of the soil structure. Processes which in some circumstances improve structural form or stability, may at other times lead to structural degradation. The impact depends on the start condition. Thus repeated wetting and drying, or freeze-thaw, may be beneficial in reducing clods produced by tillage of rather wet clay soils to a tilth. However, continuation of the processes indefinitely, without any biological activity, could result in a structure of small, dense aggregates. Reduction of structure to smaller aggregates will cause the loss of the coarse pores important for soil drainage and aeration.

Structural degradation may be induced by tillage if the soil is cultivated at an inappropriate water content, and as a consequence of the loss of organic matter due to oxidation. Continued cultivation without organic additions can result in loss of micro-aggregation leaving a soil very vulnerable to compaction and erosion. Repeated tillage to the same depth, particularly in clay soils, can create a smeared and compacted layer just below the tilled soil which can restrict root penetration and soil drainage.

Movement of agricultural machinery and animals over soil may result in compaction as a result of both shear and compressive stresses. Deep tracks, ruts and hoof marks will result where the soil is unable to support the applied load and shearing predominates. The impact of field traffic depends on the kind and weight of the machinery and how often and the speed at which it is used as well as the water content of the soil, its texture and existing structural characteristics. The effect is most often deleterious to some extent and the advantages of use of equipment have to be weighed against the benefits of the field operation.

Much research into the effect of field machinery on soil structure has been carried out. More details can be gained from the summaries by Koolen and Kuipers (1983) and Hakansson *et al.* (1988). O'Sullivan and Simota (1995) have reviewed developments in the modelling of soil compaction and noted that the main problems arise when attempts are made to couple compaction effects with crop production. They concluded that mechanistic crop production models were more useful than empirical examples for predicting the effects of compaction. However, for wide scale application, models incorporating simpler soil water balance approaches, rather than detailed soil water models are necessary.

The grazing of livestock at times of higher water content when the soil is most susceptible compression and shear deformation can also seriously reduce soil structure. But compaction and structural breakdown may also result from overgrazing of drier pastures as in semi-arid areas (Herrick and Lal, 1995). Warren (1987) has reviewed the effects of livestock on soil hydraulic properties.

The clay micro-structure is difficult to destroy by management practices unless changes to the electrolyte type and concentration of the soil solution are caused, in which case

dispersion may result. This can be caused by irrigation of soils having a high exchangeable sodium percentage, with water that contains little dissolved salts and so dilutes the soil solution. Dilution of the soil solution by rainfall also may cause dispersion at the soil surface. Structural collapse due to raindrop impact and the associated rapid soil wetting entrapping and compressing air in pores to cause aggregate failure, combined with clay dispersion, result in slaking of aggregates under heavy rainfall. Heavy overhead irrigations can have the same effect. Surface slaking leaves a soil vulnerable to erosion by removal of particles in water flowing over the surface. It may lead to crust formation and erosion (see Chapters 4 and 5).

CONCLUSIONS

Soil structure is important for all aspects of soil use and management (Figure 1). Each of the soil physical properties described in the following chapters is influenced by soil structure. Because of its affect on root growth and how well a root system develops, soil structure is also important for plant nutrient uptake. Therefore, maintenance of a favourable soil structure is essential for crop production.

The processes which contribute to structural development, and the conditions which encourage them, are broadly understood. But the detail is so complex that as yet it is not possible to predict precisely the impact that a particular management option will have on soil structure. However, Daniells *et al.* (1996) have demonstrated that research results and farmer experience can be combined to produce useful decision support systems for managing soil structure in specific conditions, with SOILPAK, a soil management package for cotton production on cracking clay soils. SOILPAK has successfully aided cotton growers with management decisions and moving towards minimum tillage systems with permanent beds and controlled traffic.

Crop cultivation too frequently results in degradation of soil structure to some degree. Common causes include poor tillage, oxidation of organic matter, compaction by machinery and exposure to raindrop energy. Repeated cultivation, without any effort to redress the decline of structure, will lead to a decrease in soil productivity in the longer term, if not immediately. The natural processes of soil structure development, in particular the activity of soil organisms, is hindered in poorly structured soils which exacerbates the problem further.

Conventional tillage improves soil porosity and so structure by increasing the number of large pores present. However, more than tillage is required to increase the number of aggregates and pores of smaller sizes. Usually favourable soil physical conditions plus inputs of organic matter, and active roots and soil organisms are necessary. Lasting structural improvement is only obtained slowly. It can take many years. As yet there are no quick remedies. Research continues into the use of soil conditioners to regenerate soil structure (e.g. Levy *et al.*, 1992) but this will always be a costly option. Prevention is the best remedy. Careful management, as described in Chapter 6, can enhance the soil condition for crop growth yet prevent structural degradation.

Chapter 3

Soil water

The water content of a field soil can vary from a few percent by volume to more than 50 percent. Water content change is measured to establish how much soil water a crop has abstracted and so determine water use efficiencies. However, the water retention and transmission properties of a soil control how much incoming water - rainfall or irrigation - infiltrates, and is then retained in soil and available at a given time for crop usage. Water retention properties are measured in terms of soil water potential. Soil water potential determines whether water is accessible to plants and differences in potential cause water movement from one part of the soil profile to another. The magnitude of water transmission under the prevailing soil water potential conditions is controlled by the hydraulic conductivity of the soil.

The state of water in a field soil changes continually in response to modifications caused by inputs of water and/or evapotranspiration losses. Where plants are present, the soil and plants can be regarded as parts of a system through which there is a continual flow of water. Understanding plant water-use (i.e. transpiration), its response to the atmospheric conditions and to soil water conditions, is therefore essential to comprehension of the soil water regime. Where water is limiting, transpiration rates are reduced which may cause physiological stress and thus have major consequences for crop development and yield. In drier environments, making the best use of all available water to maximize water-use efficiency is usually essential.

This chapter describes the mechanisms by which water infiltrates into, is held in and moves through soil, and how it is taken up by plants from soil. The availability of soil water to plants is discussed. The effects of water shortage on the roots and above ground parts of plants are described. Farming systems to manage soil water, including water harvesting and micro-irrigation methods are considered.

Much more detailed accounts of soil hydraulic properties and hydrological behaviour are given by Nielsen and Kutilek (1993) and soil physics texts such as Marshall and Holmes (1988) and Jury *et al.* (1991). The volume edited by Taylor, Jordan and Sinclair (1983) provides a very comprehensive overview of the limitations to efficient water use by crops.

SOIL WATER RETENTION

Water is present in soils in pore spaces. The saturated water content is determined by the total volume of pore space present. The size of a pore influences how strongly water is held and how readily water may be transmitted through the soil. The several forces responsible for holding water in soils, including the effect of pore size, are quantified using the concept of potential energy. Water moves in soils and in plants, along potential energy gradients, from zones of high

potential to zones of low potential. Water will move into plant roots if the root water potential is less than that of the surrounding soil.

Soil water potential

In an unsaturated soil, the water present completely fills some pores but only forms thin films over the surface of others. Water is held there by capillary and surface absorption forces. The narrower the water filled pores and the thinner the water films, the greater these forces. Their strength depends, therefore, on the size and the configuration of the pores of the soil matrix and the soil water content. The energy required to remove water from a soil, against the forces attracting the water to the soil matrix, increases as the water content decreases. This is because the size of the pores which remain water filled, and the thickness of the water films present, decreases as water is removed.

Additional energy is required to overcome gravity if the water movement necessitates a change in elevation from a given depth to a shallower depth, or to the soil surface. If the soil water contains an appreciable quantity of dissolved salts, extra energy is required to separate the water from the solutes.

The energy with which water is held in soil is quantified through the measurement of soil water potential. The potentials corresponding to the soil matrix, gravity and osmotic forces (and in, some soils, pneumatic (soil air pressure) and overburden forces), all contribute to the total soil water potential. In practice it is not usually necessary to identify and measure all the components of soil water potential. Because solutes move through soil pores in the soil solution, osmotic potentials are not relevant to consideration of liquid water movement. However, osmotic potentials are significant for water abstraction by plants and can be very important for plant-water relations in saline soils.

For many purposes, soil water potential can be described in terms of matric and gravity potentials alone; their sum is known as the hydraulic potential. At saturation, the soil water is in equilibrium with free water and the matric potential is zero. The hydraulic potential therefore equals the gravity potential at the water table, and below the water table level positive potentials occur.

For soil and plant water studies potential energies are conventionally expressed in terms of either pressure equivalents (e.g. kPa), or water head equivalents, metre water. That is, the energy required to move soil water is expressed per unit volume, or per unit weight of water transported, respectively. Under unsaturated conditions, soil water potentials are negative, and become more negative as the soil dries and the matrix forces of the soil increase. For example, a potential of -1200 kPa is low relative to a measurement of -30 kPa; a potential of -0.8 m water head is low relative to -0.03 m water head.

It is more difficult for plants to uptake soil water held at low matric and/or osmotic potentials, than water held at higher potentials. Gravity is also a factor in plant water use. The plant takes water from the soil through its roots and stems against the force of gravity, but this is not generally a very large contribution relative to the other potentials involved.

The soil water retention characteristic

The water retention properties of a soil can be defined by measurement of the soil water retention characteristic, i.e. the relationship between soil water matric potential and volumetric water content, as the soil dries from saturation (0 kPa) to near oven dryness (about -1×10^6 kPa). The soil water retention characteristic is also referred to as the soil moisture characteristic, the soil water release curve and the pF curve (pF being the logarithm to the base 10 of the matric potential measured in units of cm head).

If the same measurements are made as a soil is wetted up, the resulting wetting curve is displaced relative to the drying curve (Figure 7). This is because at a given potential the soil holds more water when drying than when wetting. This phenomenon, known as hysteresis, means that at a given potential the water content of a field soil will vary depending on the recent drying/wetting history of the soil. In practice, hysteresis is more evident in soils such as sands having a large proportion of larger pores.

Figure 8 shows water retention characteristics for a sand and a clay. As the potential falls, the water content of the sand declines much more rapidly than that of the clay due to the absence in the sand of fine pores which are needed to hold water at lower potentials. Indeed the water retention characteristic can be regarded as a pore size distribution curve.

WATER TRANSMISSION

The rate and direction of water movement through soils is determined by hydraulic potential and hydraulic conductivity. Water moves from zones of high potential to low potential, the rate of flow depending on the gradient of hydraulic potential and the hydraulic conductivity. Movement will continue, if the hydraulic conductivity permits, until potential equilibrium is reached.

FIGURE 7
Hysteresis in the relationship between matric potential and water content

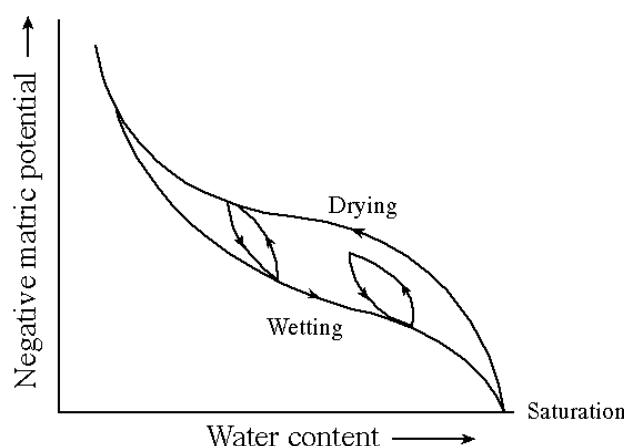
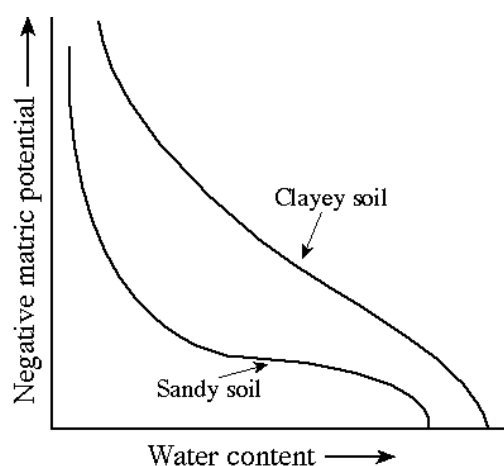


FIGURE 8
Soil water retention curves for soils of contrasting texture



Hydraulic conductivity is a measure of how conductive soil is to water. It has the dimensions of a velocity and is usually expressed as either m s^{-1} , or m d^{-1} . The hydraulic conductivity of a soil is greatest when saturated for the number of water conducting pathways and their continuity is maximized. At saturation the conductivity is constant and is called the saturated hydraulic conductivity or saturated permeability. The unsaturated hydraulic conductivity of soil depends on the amount of water present. As soil dries, the remaining water is held in smaller pores and thinner films; in addition the continuity of the water phase is reduced and so the number of possible flow pathways is reduced whilst their tortuosity is increased (Figure 9).

Water movement is most rapid in large diameter pores and thick films as frictional drag due to the surrounding walls is reduced. Flow through a cylindrical pore is proportional to the fourth power of the pore radius, thus the presence of a few large water filled pores is very significant. Unsaturated hydraulic conductivity consequently declines rapidly with falling soil water content as the large pores and fissures, which are only filled at or close to saturation, empty (Figure 10).

Values of hydraulic conductivity range between about 10^{-3} m s^{-1} and $5 \times 10^{-5} \text{ m s}^{-1}$ at saturation in sandy soils, the higher rates occurring in coarser sands. These values are approximately equivalent to 100 and 5 m d^{-1} respectively. Saturated hydraulic conductivity values for clays range from 10^{-6} to 10^{-9} m s^{-1} , i.e. between about 1 m d^{-1} in a well structured, cracked clay, and 0.5 mm d^{-1} .

If the unsaturated hydraulic conductivity of a soil falls below 10^{-4} to $10^{-5} \text{ mm d}^{-1}$, the restriction of the flow of water to plant roots and so plant uptake, will be so great as to limit plant development. Dexter (1988) reports unsaturated conductivities greater than this at potentials lower than -1.5 MPa, i.e. wilting point, in some soils. In such cases, hydraulic conductivity may only be a limiting factor in plant development under conditions where transpiration rates are very high.

Potential gradients can operate in any direction. Water may move downward though a soil profile, or upward if appropriate hydraulic gradients persist. Horizontal movement also occurs but is normally most significant in the root zone. The uptake of water by plant roots results in low potentials immediately around them and so development of potential gradients encouraging water movement to the roots. In practice, soil water is continually in a state of

FIGURE 9

Distribution of water in an unsaturated soil. The thin water films, their poor continuity and the tortuosity of the possible flow pathways means that the hydraulic conductivity is much less than when the same soil is saturated.

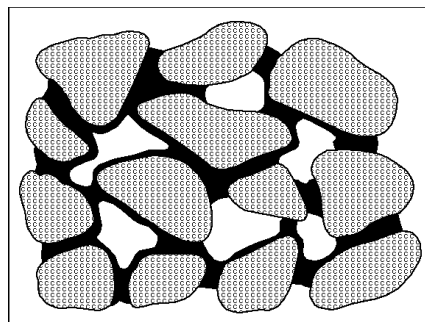
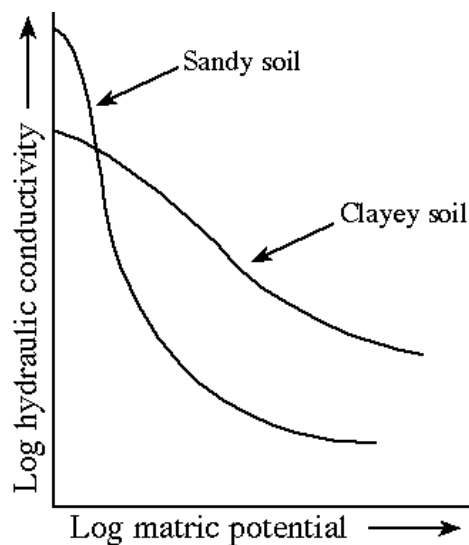


FIGURE 10

Soil hydraulic conductivity as a function of matric potential for soils of contrasting texture



dynamic equilibrium, movement taking place along gradients of hydraulic potential such that potential energy differences between different soil zones are minimized. The system is disturbed by rainfall/irrigation inputs of water, and/or plant water use. Where either the crop cover is not spatially uniform, or the water application is non-uniform as in the case of drip or furrow irrigation, significant lateral water movement may occur. Figure 11 illustrates in 2-dimensions the hydraulic potential conditions developed under drip-irrigated sugar cane (Hodnett *et al.* 1991). The drip irrigation line is placed below the row of sugar cane plants. There is a strong contrast between the soil beneath the row and that under the inter-row space, the latter being much drier. The contrasting conditions induce lateral water fluxes but these are countered by water uptake by the cane plants.

Macropore flow

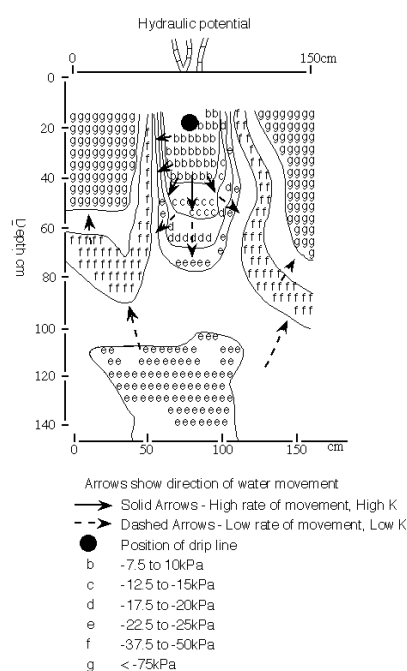
The presence of a few macropores, large pores (>2 mm diameter), or cracks as in a drying clay, can considerably influence the flow of surface applied water into and through soil. When water-filled they can carry large amounts of water at velocities much greater than flow through the soil matrix. Indeed, a single continuous pore of 0.3 mm diameter can conduct more water than the rest of a 100 mm diameter sample (Smettem and Collis-George, 1985).

The flow by-passes the surrounding soil which may not be saturated when the macropores fill and flow takes place. However, macropores need to at least partially fill to be important. They may be hydrologically ineffectual in field soils if saturation does not occur or rainfall/irrigation water is dispersed throughout the matrix due to the pore size characteristics of the soil at the surface (Gardner *et al.*, 1990). The presence of macropores can substantially increase rates of movement of soluble pollutants from soils and much of the research on this topic has been in the context of solute transport (White, 1986; Edwards *et al.*, 1993). As yet there is no complete theory to describe soil macropore flow (Jury *et al.*, 1991).

Vapour movement

Water vapour pressure differences due to temperature cause movement from warm to cooler parts of the soil but only contribute significantly to water transmission to roots in conditions where strong temperature gradients are set up. Under semi-arid conditions with large diurnal temperature fluctuations and low water contents, upward vapour fluxes at night can be very important for plant growth. Rates depend on the temperature gradient, soil porosity and the relative proportions of air and water present in that porosity. Vapour fluxes can take place in the opposite direction to liquid water flow caused by gradients of hydraulic potential.

FIGURE 11
Hydraulic potential conditions developed in a soil where the water input and extraction are not spatially uniform. Water is supplied via a drip irrigation line placed below the row of sugar cane (after Hodnett *et al.*, 1991)



WATER ENTRY INTO SOIL - INFILTRATION

As in bulk soil, water flow into a soil at a surface is determined by hydraulic gradients in the surface soil, and its conductivity. Under ideal conditions, if water is continuously ponded onto a soil surface, infiltration is initially primarily controlled by the matric potential component of the hydraulic potential gradient, and the form of the surface pores. As time proceeds, the soil wets to saturation, and the hydraulic gradient is due only to gravity. The rate of flow thus approaches the saturated hydraulic conductivity. Infiltration rate is therefore a function of initial soil water content, and decreases with time.

In practice air entrapment in coarser pores at the commencement of wetting will slow infiltration though the air may dissolve in time. If the soil itself contains clay or organic matter, a degree of swelling on wetting is probable with a consequent reduction in pore sizes and so conductivity. Infiltration into heavy clays varies considerably between wet and dry season conditions. At the end of the dry season cracking may increase infiltration rates greatly, whereas once the soil has swelled in a wet season, the same soil may be almost impermeable. Collapse of aggregates due to slaking on wetting can also lead to change in pore size distribution and possibly blocking of pores as fine particles are washed into the underlying soil. Crusting can markedly alter infiltration rates (Chapter 4). Infiltration into crusted soils presents a slightly different situation for the poorly permeable crust, which may be only a very few mm thick, overlies more conductive soil.

As in the case of flow through bulk soil, the presence of a few large pores or fissures can influence infiltration rates considerably. Infiltration rates as high as 10 m day^{-1} occur in very permeable soils but as low as 10 mm day^{-1} in others (Payne, 1988). This can cause wide variation in infiltration in field soils and so soil wetting by flood or furrow irrigation may be very non-uniform. In the case of furrow irrigation, spatial variation in the length of time that water is present in the furrows will also lead to non-uniformity in irrigation because of the effect of duration of wetting on infiltration. Rainfall (or overhead irrigation) will lead to ponding of water at the soil surface, and/or runoff, only if the rainfall intensity exceeds the maximum possible infiltration rate of the surface soil, or raindrop impact and slaking on wetting result in a decline in hydraulic conductivity and subsequent ponding.

EVAPORATION FROM BARE SOIL SURFACES

Evaporative loss of water to the atmosphere occurs where bare soil is partially or completely exposed. Bare wet soil evaporates water at a rate similar to evaporation from an open water surface. As the water content decreases from saturation, the evaporation rate declines in the absence of a shallow water table. This is due to the reduction in the hydraulic conductivity of the surface layer. A stage is reached when the water content and hence hydraulic conductivity of the surface soil are so low that liquid water movement to the soil surface is not possible. Only very slow water loss will continue thereafter due to vapour movement to the surface. Coarse textured soils are often self-mulching; i.e. the hydraulic conductivity of the surface declines rapidly on drying effectively preventing further loss of soil water. Where a shallow water table is present, more rapid evaporation may continue indefinitely if the unsaturated conductivity of the soil at the surface is sufficient to sustain unsaturated flow from the water table (Gardner, 1958).

Large amounts of water may be lost to the atmosphere from the soil surface in the course of the growing season of an annual crop (Harrold *et al.*, 1959). This is particularly so early in the season prior to the establishment of the leaf canopy. Seed germination may be thwarted due to rapid drying. Part of any rainfall or irrigation additions of water will be lost by direct

evaporation. In general, the more frequent the wetting of the soil surface, the greater the total water loss. For example, water balance measurements in flood irrigated maize in Zimbabwe demonstrated that between sowing and seedling emergence, 79% of rainfall and irrigation additions were evaporated from the soil surface, and over the growing season plant transpiration accounted for only 46% of the total water use (Batchelor *et al.*, 1996).

FIELD CAPACITY

The field capacity of a soil is defined loosely as the maximum amount of water that it can retain against drainage due to gravity. It corresponds to the water content when pores $>30\ \mu\text{m}$ have emptied after the soil has been saturated, and matric potentials have declined to between -5 and -33 kPa (different users adopt different definitions). In the field, field capacity is taken as the quantity of water remaining in the soil profile about two days after thorough wetting by rainfall or irrigation. The soil water content that is actually achieved under such conditions depends upon the soil's hydraulic properties. Where there is no shallow water table, drainage after thorough wetting is initially rapid but the rate slows quickly as the unsaturated hydraulic conductivity of the soil decreases. In freely draining coarse textured soils, drainage generally ceases within two days because very low values of unsaturated hydraulic conductivity are quickly reached. Slow drainage may continue from finer textured soils for several days and even weeks (Wellings and Bell, 1982). Where a shallow water table is present, the field capacity water content is determined by the position of the water table. The soil drains until the hydraulic potentials in the profile above the water table come into equilibrium with it.

The concept of a field capacity water content is useful, if not physically accurate. It assumes that if water is added to a soil at field capacity, the added water will drain more or less immediately and not be of benefit to plants. Once the water content has fallen below the field capacity threshold, it suggests that all subsequent water loss is due to plant uptake. The difference between the soil water storage of a drying soil and its field capacity water content is referred to as the soil water deficit (or soil moisture deficit). It is assumed that additions of water to a dry soil will result in reduction of the soil water deficit. Drainage will only occur if the water addition increases the soil water content to exceed field capacity. Where irrigation is used, optimal conditions will occur if the soil water content can be maintained at about field capacity: the supply of water to plants is maximized without wastage due to drainage, yet the soil is also well aerated.

In irrigation scheduling and research on annual crops, field capacity frequently is taken to be the water content of the soil profile at the commence of the growing season. This is satisfactory in terms of comparing relative water use by crops in that season but may be misleading if comparisons from year to year are required (Gardner and Field, 1983).

AVAILABLE WATER

The available water capacity of a soil refers to the maximum quantity of water that can be extracted from the soil profile by plants. It is generally defined as the difference in the amounts of water held by a soil when at field capacity and when at its permanent wilting point (-1.5 MPa matric potential). In fact, the soil water content at which non-recoverable wilting occurs is crop dependent. Because of the shape of the water retention curve at low water potentials (see Fig.3.2), precise definition of permanent wilting point is less critical than that of field capacity. If a matric potential of -10 kPa is taken as field capacity, then all soil pores of greater than 30 μm diameter (equivalent cylindrical diameter), are air filled. At wilting point, -1.5 MPa, all

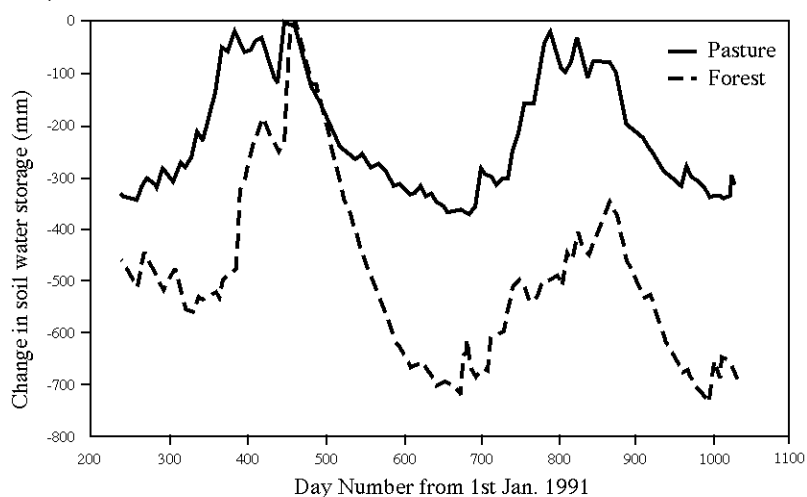
pores up to 0.2 μm diameter will be water filled. The available water capacity of a soil will therefore be maximized when its structure is such that the volume of pores of diameter 0.2 μm to 30 μm is maximized.

The quantity of available water is expressed usually as either a percent by volume or as mm per given depth of soil. Values range between 6% and 10% (60 mm to 100 mm per 1 m depth of soil) in coarse sands, to about 25% for fine sandy loams (250 mm per 1 m depth of soil). Greater values occur in some highly organic soils and in peats. The available water capacity of clays depends to a great extent on structural development but is usually in the range of 16% to 20%.

Presenting a single figure to indicate the availability of water to plants in a given soil can be misleading. Two soils may have the same available water capacity but the range of matric potential over which the greater part of that water is available may be very different depending on the shape of the water retention characteristic (see Figure 8). In general, a much greater proportion of the available water in sandy soils is held at high matric potentials than in loam or clay soils. Water availability is also influenced by the hydraulic conductivity function of the soil. Water may be present, but if it cannot move to plant roots, or the roots cannot extend to it, it will not be usable.

The available water capacity of soil at a given depth can be defined if the field capacity and wilting point thresholds are known. But, in the field it is necessary to consider also the depth of soil that can be exploited by the crop. Shallow rooting crops will not have access to as much water as deeper rooting ones. For example, Figure 12 shows change in soil water storage below forest in Amazonia, Brazil, and adjacent pasture developed on the same soil after forest clearing.

FIGURE 12
Change in soil water storage under forest and pasture growing in the same soil in Brazil (after ABRACOS, 1994)



The pasture grasses can extract water only from the top 1 to 2 metres. The trees of the forest can root much more deeply and water extraction at 4 m has been monitored (ABRACOS, 1994).

Soil structure is important in determining the amount of water present at field capacity because of its control over pore size distribution and therefore retention of water against gravity at high potentials. Management techniques which result in an increase in the total volume of pores of diameter less than about 30 μm , without destroying finer pores, will result in an increase in field capacity water content and so in available water capacity. Tillage will generally improve the overall porosity of a soil but not necessarily the amount of available water. For example, Pagliai and De Nobili (1993) measured a porosity of 19.7% in no-tilled plots compared with 28.0% in tilled plots. However, the increase was due mainly to the formation of large sized pores which drained rapidly. The tillage was therefore ineffective at increasing the available water capacity of the soil. However, the presence of such pores could be beneficial indirectly by increasing opportunities for rooting and so extending the depth of soil exploited for water. In situations where waterlogging is a problem, such an increase in the volume of large pores would increase soil drainage and improve aeration.

THE SOIL-PLANT-WATER RELATIONSHIP

The principal constituent of a plant is water. When growing under optimal conditions, plants may require access to several times their own mass of water every day. This is because there is a continual flow of water through the plant from the soil to the atmosphere. In order to photosynthesize, plants need to open the stomata on their leaves to permit inward diffusion of carbon dioxide for conversion into sugars. The necessary opening of the stomatal apertures allows outward diffusion of water as vapour from the cell tissues of the plant leaf, i.e. evaporation of water from the leaf tissues which is known as transpiration. Transpiration only takes place during the hours of daylight for photosynthesis requires solar radiation; it ceases at night. The transpiration loss rate depends on how wide the stomata open, and the ambient atmospheric conditions - the atmospheric evaporative demand.

The concept of potential energy used to describe and quantify water retention in soils may be extended to the water held in the cells of the plant structures. Water moves through plants along potential gradients. Thus, for water movement into the root to occur, root water potentials must be lower than in the surrounding soil. Similarly leaf water potentials must be more negative than those of the root system if flow of water to the leaves is to take place. The main components of leaf water potential are the osmotic potential and the turgor potential. As water is lost from leaf cells by transpiration, their water content will decline unless the water flux from the root zone to the leaves equals the transpiration flux. Net removal of water from the leaf cells causes reduction in both the osmotic potential and the cell volume. The volume change decreases the positive pressure exerted by the cell walls, i.e. the turgor pressure or turgor potential.

Any decline in turgor pressure has a fundamental impact on plant growth processes which involve elastic extension of tissues. Influx of water into new cells is induced by their osmotic potential and causes cell expansion. This influx is countered by the turgor pressure against the cell walls and membranes creating a tendency for outflow of water. Cell growth only continues if the turgor pressure is enough to maintain a continuous strain on the cell walls. Root, stem and leaf elongation are all reduced if turgor pressure declines.

In addition to requiring water to satisfy the atmospheric demand, plants use water for various metabolic processes including photosynthesis, for the transport of nutrients and metabolites within the plant, and for the maintenance of the plant's physical form by turgor. Water is also crucial to the germination process. Plants therefore have an ongoing need for water from the time that a seed imbibes water at the initiation of germination.

Over time, the crop's requirement for water as well as the external conditions alter. For the majority of crops, optimal conditions are achieved when the soil water supply is maintained such that stomatal closure due to water stress, and consequent restriction of photosynthetic rates are minimized. However, at certain times, soil water stress may have a less deleterious impact on crop production than at others. Indeed some crops are managed so that water stress occurs at certain times, often shortly before harvest, to encourage sugar to starch conversion in seed.

Transpiration

The rate of water loss, the transpiration rate, is controlled by the microclimate of the air immediately surrounding the plant leaves, and the resistance to vapour diffusion imposed by the number and size of stomatal apertures in the leaf surface, the stomatal resistance. The plant controls the degree to which the stomata open. If the evaporative demand exceeds the rate at which the plant can move water from the soil to the leaves for transpiration, a large net loss of water from the plant structure is prevented by reduction of the stomatal apertures which increases the stomatal resistance thereby reducing the transpiration rate. By day, rapid fluctuations in solar radiation due to variations in cloudiness, are often reflected in changes in stomatal opening and leaf water potential. Where the crop cover is incomplete, the transpiration rate may be influenced by sensible heat from dry soil surrounding transpiring plants. This "clothesline" effect, arising when hot dry air from the interrows passes through the plant rows, can result in transpiration rates double those which would occur from a full crop canopy under the same meteorological conditions (Tanner, 1957).

The majority of the stomata of most plants are located in the surfaces of the leaves but stomata may also be found in the surface of stems. Water may also be lost directly through the cuticle layer which forms the outer surface of the leaves and stems. Estimates for cuticular loss of water range from a fraction of a percent to more than 20 percent of total water use for different species in varying climates. For most crops cuticular loss probably represents about 10 percent of total water use but is not distinguished from transpiration.

The atmospheric factors, which control the transpiration rate, also control evaporation of water from the soil surface. Often it is difficult to distinguish between soil evaporation and transpiration as causes of water loss from the soil profile, and for many purposes distinction is not necessary. The term *evapotranspiration* is used here to refer to the loss of soil water to the atmosphere via both pathways. Rain or irrigation water intercepted by the leaf canopy of a crop may quickly fall to the soil surface and infiltrate. However, water that remains on the leaves for any length of time will be subject to evaporation back into the atmosphere. The presence of water on the canopy reduces the transpiration rate temporarily. Many studies do not separate this form of water loss from transpiration and soil evaporation, because of the difficulty of measuring canopy interception and evaporation thereof. Thus *evapotranspiration* measurements may include a water component that neither infiltrated into the soil nor passed through the plant.

Atmospheric evaporative demand

There are two components to the atmospheric evaporative demand:

- the energy available at the evaporating surface governs the amount of water that can be evaporated;
- the speed of the air moving over the leaves, and its water content, determine the rate at which the water vapour can be dispersed away from the leaf surfaces.

Penman (1948) combined the energy budget and aerial relative humidity components into a theory of evaporation and provided an expression permitting calculation of open water

evaporation rates from meteorological measurements. The same principles were applied to the process of water transpiration from a well watered green crop, resulting in the Penman formula for estimating potential transpiration rates. Daily potential transpiration rates may range from less than 0.5 mm on winter days in cool temperate climates to more than 8 mm per day in hot arid environments.

Many combination formulae to calculate potential evaporation and transpiration from readily available meteorological data have been produced since that of Penman (Marshall and Holmes, 1988). Further refinements were incorporated in the Penman equation by Monteith who provided procedures to account for the process at leaf surface (canopy and air resistance) (Monteith, 1965). The methodology has been further adapted by FAO to allow routine calculations for estimating reference crop evapotranspiration from available climatic data (FAO, 1998).

Estimating transpiration rate under conditions of limited water availability

Several empirical models have been proposed to represent the change of transpiration rate under conditions where soil water is limiting. For example, Penman introduced the concept of crop specific root constants. Transpiration was assumed to continue at the optimal rate when the soil water content was at field capacity. When the water content declined from field capacity, transpiration would continue at the optimal rate until a threshold soil water deficit, the root constant, was reached. Thereafter, the transpiration rate would be reduced to a fixed fraction of the potential rate until the soil water reservoir was replenished. Other models assume that the transpiration rate declines gradually with water content (e.g. Thompson *et al.*, 1981). A procedure to estimate crop evapotranspiration under soil water stress and the effect on yield has been presented by FAO in 1979 (FAO, 1979).

However, as has been emphasized, the soil-plant-water system is dynamic. Such models, though useful for water budgeting for irrigation purposes, ignore the dynamic aspects of the soil-plant-atmosphere interactions. A variety of physically based models for simulating plant water use and crop yields, in response to soil conditions and water inputs, are now available. Many of these are very sophisticated, simulating in detail water flow along changing potential gradients at rates determined by changing soil unsaturated conductivity conditions, root water potentials, flow through the growing plant to the leaves and leaf water potentials, interception and evaporation of rain/irrigation water, evaporation from the soil surface, growth and closure of the crop canopy.

An example of such a soil water flow model is SWATRE which simulates one dimensional transient unsaturated flow in a heterogeneous soil (Belmans *et al.*, 1983). The soil is divided into compartments. The upper boundary condition is the maximum evapotranspiration flux. The boundary condition at the base is the water table, a specified soil water potential or a drainage flux. Uptake of water by roots is a function of simulated transpiration and the matric potential in the root zone. A crop production simulation model, CROPR, calculates both potential and water limited daily crop growth (Feddes *et al.* 1978). It can be coupled with SWATRE to simulate water movement and crop productivity for many purposes (e.g. Bouma and Broeke, 1993).

Models such as these can assist considerably in the understanding of the soil-plant-water system and its responses where the necessary input data are available. However, they often require soil data that are not readily available, i.e. water retention curves and conductivity functions. So the user is forced to make assumptions about the similarity of her/his soil and others for which the necessary information has been published in the literature. Alternatively, further models may be used to estimate these hydraulic properties from more readily measured

properties, usually particle size. Given the recognized sensitivity of soil water models to the hydraulic conductivity function in particular, the use of rather arbitrary data for input is dubious. The frequent mis-match between the sophistication of many physically based models and the quality of available soil data means that their applicability is limited. Use of simpler modelling procedures is often much more appropriate. Use of simpler modelling procedures is often more appropriate and extensively used for irrigation scheduling and water balance calculation such as applied in the FAO CROPWAT model (FAO, 1992).

EFFECT OF SOIL WATER SHORTAGE ON PLANTS

An overview of the influence of soil physical properties on root systems is provided in Chapter 1. Here, the specific impact of water stress on roots is briefly reviewed. Water shortage also affects the above ground parts of plants and can seriously reduce yield quality and/or quantity in most crops.

Root systems

A root grows because new cells are formed at its tip which then expand in volume. For cell expansion to occur, the turgor pressure of the root cells must be sufficient to overcome the constraints imposed by the surrounding soil. Change of water content in the soil immediately surrounding a root causes change in the root cell osmotic and turgor pressures. A decline in soil water content, and associated decrease in soil matric potential, results in a reduction in water uptake, a decrease in root cell osmotic potential, a reduction in cell wall extension and decrease in the root's ability to overcome the mechanical constraints of the soil (Taylor, 1983). The osmotic adjustment will allow growth to continue as if sufficient water were available, but the other changes tend to reduce growth rates. Low soil water content also appears to increase root death, thus the rooting density may decline.

The above explanation emphasizes the hydraulic response of the root to water shortage. However, chemical change occurs too. Increasing evidence suggests that abscisic acid has a particularly important role in regulating many of these responses (Hartung and Davies, 1991). Root growth at low water potentials appears to be dependent upon abscisic acid accumulation (Saab *et al.*, 1990; Rigby *et al.*, 1994).

It is difficult to isolate the direct impact of soil water on root growth for it indirectly influences several other soil factors, including soil strength, aeration, and temperature, the composition of the soil solution, as well as plant growth. Taylor (1983) reviewing the evidence suggests that if soil matric potential is maintained above -1 MPa, there is no direct effect on root growth. Some growth has been observed in maize and tomato roots at soil matric potentials as low as -4 MPa (Portas and Taylor, 1976). Although very little water is abstracted from soils at low potentials, roots that penetrate through dry zones may reach wetter soil where greater water uptake is possible.

Plant yield

It is well established that soil drying can reduce water uptake by roots such that consequent dehydration of leaves results in stomatal closure, and due to the limited supply of carbon dioxide for photosynthesis, reduced growth. Whether the physiological response of the plant shoot to soil drying results from hydraulic and/or chemical signals is as yet unclear (Trejo and Davies, 1994).

Stomatal resistance to carbon dioxide diffusion is greater by a factor of 1.6 than resistance to water vapour. Despite this, evidence suggests that plants become more efficient in terms of photosynthetic production per unit of water transpired during short drought periods, although the rate of photosynthesis is nevertheless reduced (Haverkoort and Goudriaan, 1994).

If water stress continues, assimilation is reduced further because of reduction of the photosynthetic capacity of the plant.

Different species adapt in different ways to water stress. For example, in addition to stomatal closure and lowering of osmotic potential, both diurnally and over longer periods, leaf rolling and leaf shedding has been observed in sugar cane (Batchelor and Soopramanien, 1993). The growth rate of different parts of the plant may be affected differently by water stress. In sugar cane, daily stem extension rates decline more rapidly than daily leaf extension rates, and recover more slowly when the stress is removed. This differential response has implications for the management of limited irrigation water supplies. Individual small irrigations of stressed cane stimulate more leaf than stem growth (Batchelor and Soopramanien, 1993).

Haverkoort and Goudriaan (1994) distinguish three types of drought which have different implications for crop growth, development and quality of the final product:

- a dry spell early in the growing season causing retardation of emergence and early growth;
- a short transient drought at some stage during the growing season only slightly reducing growth but with a potentially important effect on crop development and quality of the harvest;
- a drought which intensifies in the course of the growing season, leading to premature senescence of the crop.

An early drought is less harmful to crops such as potato, than to cereal and other small seed crops. This is firstly because the tuber does not require water for sprouting and initial growth. Secondly, the seed organ (the potato tuber) is large and so has much greater capacity to support root and shoot growth despite reduced photosynthesis. As a consequence, an early drought of short duration may have little impact on yield from potato and similar crops.

A short transient drought may be compensated for by greater activity after rewetting than in plants which have not been stressed. However the interference to crop development may result in poorer quality yields.

Another aspect of water shortage is that susceptibility to disease may be increased when a plant is water stressed. Alternatively, weed species which withstand drought may be encouraged, competing for the already limited water supply. Nutrient supply to the above ground parts of a plant is hindered by water shortage, particularly in soils of low fertility. Crop tolerance to drought in poor soils can be often markedly improved by fertilizer applications. Nitrogen application in particular, even at low levels, can have significant yield benefits, but this does not occur to such great effect in soils which are already well fertilized (Power, 1983).

WATER USE EFFICIENCY

The term water use efficiency can be defined as biomass yield per unit of water used. Water use efficiency can be based on:

- the quantity of water directly transpired from the crop, i.e. the transpiration efficiency. Generally if allowance is made for differences in atmospheric evaporative demand between sites, transpiration efficiency is a reasonably stable quantity for most green crops having a closed canopy. This is to be expected because of the close link between carbon dioxide usage for photosynthesis and plant water use;
- the quantity of water lost through soil evaporation and weed transpiration as well as crop transpiration, usually referred to as the water use efficiency; or

- productivity per unit of irrigation water applied, i.e. irrigation efficiency. This measure includes water lost due to leakage or other wastage in the irrigation system, as well as soil, weed and crop evapotranspiration.

Biomass yield can be assessed either as total dry matter or marketable yield and the distinction between these two as well as the measure of water use used should be made clear as very different answers result depending on which measures are chosen.

The economic importance of efficient crop water use is most apparent in areas where crop production requires irrigation with scarce water supplies. To obtain maximum yield benefits to justify the application of costly water to a crop, attention needs to be given to irrigation technique, reduction of soil evaporation, weed growth and improving the soil physical conditions and nutrient status. Selection of crops to grow in such regions is of prime importance but will be necessarily influenced by factors such as market demand, fertilizer requirements, as well as water use efficiency.

A publication of the Association of Applied Biologists (1994) brings together results of recent work on crop water use efficiency in several countries. Taylor *et al.* (1983) have provided a very comprehensive review of work on all aspects of efficient water use in crop production up to 1983.

Measuring water use efficiency

In the field, the water use element of water use efficiency is generally measured by monitoring soil water storage in the soil profile at the time of planting and through the growing season to harvest e.g. Harris (1994), Groves and Bailey (1994). Water storage is usually measured by the neutron probe method or more recently using dielectric methods. Water use during the intervals between measurements is calculated assuming a simple water balance which separates the water inputs and outputs of the soil water reservoir:

$$P + I - Q = ET + D + \Delta W$$

where P is the amount of precipitation, I is the amount of any irrigation applied, Q is runoff, ET is evapotranspiration, D drainage to soil below the depth of profile specified and ΔW the change in the water content of the soil profile above that depth. The equation represents the average conditions over the chosen time period. ΔW may be either positive or negative over the period. In situations where a shallow water table is present, D may be negative due to a net upward flux of water into the measured profile. If run-on occurs, Q will be positive.

The equation can be re-arranged so that ET can be determined, or if ET is known, or a good estimate is available, D can be calculated. Measurement of drainage is more relevant to determining wastage of irrigation water, or if solute concentrations in the drainage water are known, measuring fertilizer or other leaching losses. The drainage term in the water balance may be difficult to quantify. Where soil water potential data are not available so that the direction of water fluxes cannot be ascertained and the drainage loss element determined directly, drainage loss may be ignored or a slow drainage function applied (e.g. Parkes *et al.*, 1994).

Where crop cover is incomplete, the calculated evapotranspiration includes water lost by soil evaporation and any weed water uptake plus transpiration by the crop in question. It also includes change in the water component of the plant structure. However, as an actively growing crop may transpire several times its own mass of water in a single day, assuming that the

change in the amount retained in the structure of the plant is negligible has a trivial impact on the evapotranspiration calculation.

SOIL WATER MANAGEMENT

There are many aspects to soil water management but the focus here is on practices to increase soil profile water storage by increasing infiltration and reducing run-off and reducing evaporation from the soil surface, and enhancement of soil water conditions through the use of water harvesting and micro-irrigation techniques. The removal of excess water by the control of internal soil water drainage is considered briefly. A well structured soil which does not crust under rainfall inputs, will provide optimal soil water conditions if the water inputs are sufficient. Water harvesting and irrigation techniques involve increasing the water supply to the soil to be cropped by directing or concentrating rainfall waters, or by using water from streams, boreholes surface reservoirs or other sources.

Surface water retention systems

A number of *in situ* soil management systems prevent excessive runoff. They concentrate and redistribute runoff in order to increase water use efficiency of crops (Laryea, 1992). These systems involve the manipulation of the soil surface roughness or topographic modification of the land (land configuration) to trap and allow more time for infiltration of surface water to occur. Common among these runoff-retaining systems are the conventional graded furrows, conventional contour furrows, wide furrows, large contour furrows (constructed with Orthman tri-level equipment) (Jones, 1981), broadbed and furrow (BBF), terraces, pitting (scoops or small depressions on the soil surface), and tied ridges.

The conventional graded furrows are usually formed on 1-m centers having about 0.25 percent grade in the rows. Furrows are normally ridged across the upper end to prevent off-site run-on. The conventional contour furrows are similar to the graded furrows, except that the rows are put on the contour (zero row grade). The wide furrows have 1-m wide beds and 1-m wide furrows (2-m bed-furrow spacing). The maximum potential surface water storage capacity of the wide furrows is about 120 mm, which is double the capacity of conventional contour furrows.

The Orthman system consists of large contour furrows with 0.75-m wide beds and 0.75-m wide furrows (1.5-m bed-furrow spacing). The center of the furrows have small folds or grooves designed to hold runoff from small storms. These grooves prevent ponding of the seeded rows, thus minimizing soil crusting, which tends to hinder seedling emergence. The maximum potential surface-water storage of the furrows in this system is about 120 mm. The BBF system consists of 100-cm raised beds separated by 50-cm wide furrows (furrow grade of 0.4 to 0.8 percent) that drain into grassed waterways in a watershed.

Terraces are earth embankments, channels or combinations of embankments and channels constructed across the slope at suitable spacings and with acceptable grades (ASAE, 1983). Terraces are used for one or more of the following purposes: (i) to reduce soil erosion, (ii) to provide for maximum retention of water for crop use, (iii) to remove surface runoff water at a non-erosive velocity, (iv) to reform land surface, (v) to improve farmability, (vi) to reduce sediment content in runoff water, and (vii) to reduce peak runoff rates to installations downstream.

Terraces may be classified according to either alignment (e.g., parallel and nonparallel) or cross section (e.g., broadbase terrace, flat-channel, or Zingg conservation bench (Zingg and Hauser, 1959), steep-backslope). They may also be classified according to the grade (e.g., level

or graded). Alternatively, terraces may be classified according to their outlet (e.g., blocked outlet, grassed waterway, or underground outlets). With the blocked outlets, all water infiltrates into the terrace channel. With the grassed waterway, however, water is removed by vegetated waterways to minimize erosion. Underground outlets remove water from terrace channels through underground conduits and thus stop erosion and remove less land from production. On steep lands, however, drop structures or stone pavements have to be installed in the waterway to regulate the flow of water (Unger, 1984a).

In high rainfall regions, the surface water capacity of closed or contour furrows or border dykes may be exceeded during high intensity rainstorms leading to overtopping and breaching of the conventional contour furrows. The Orthman contour furrows, wide furrows, and terraces (mini-bench or Zingg conservation bench terrace) have been reported to retain most of precipitation (Jones, 1981) and may, therefore, be suitable for medium to low rainfall regions.

Pitting (scoops) creates small cavities made on the soil surface to increase the surface roughness and to trap runoff water for the enhancement of soil water and related crop production (Pathak and Laryea, 1991). In addition to pitting, there are a number of microcatchments (e.g., semicircular and triangular microcatchments) that are used to trap runoff. These techniques consist of small catchments shaped either as semicircles or as triangles, and with their tips on the contour. Water is impounded behind the bunds to the level of the contour, overflowing eventually with water spreading to the next lower tier of bunds (Finkel and Finkel, 1986). This system may induce more erosion if the small catchments are not well-designed and well-constructed.

All the above land configuration systems have been reported to increase profile soil water, particularly in erratic and seasonally-dry semi-arid regions. They also have increased crop yields and water-use efficiency (Tables 2 and 3) (Pathak and Laryea, 1991; Jones and Stewart, 1990; Jones, 1981). The benefits of water enhancement schemes have to be reviewed over several seasons when rainfalls are so variable. For example, in Zimbabwe yields of different crops varied considerably over several seasons and the advantages of using a tied furrow season system were most marked in dry years (Table 4). However, results may not be so good on sandier soils with lower water retention properties, and lower fertility. The increased infiltration of water may in such circumstances result in leaching of nutrients beyond the root zone, causing a further decline in nutrient availability. Increased fertilizer application may redress the situation and maximize water usage (Nyamudeza *et al.*, 1991).

A number of soil profile conditions do not easily lend themselves to either tillage or land surface manipulation to promote soil water storage. These conditions include natural horizons that are dense and very slowly permeable, compacted horizons due to traffic, fragipans, sandy surface soils underlain by dense clay, and soil profiles with rocky and indurated layers near the surface. Soil management methods that have been used to correct such cases include deep ploughing (> 30 cm), subsoiling, chiseling, paraploughing, trenching, ripping, and/or profile modification (mixing to either 0.5-m, 1.0-m, or 1.5-m depth) (Burnett and Tackett, 1968; Eck and Taylor, 1969; Willardson and Kaddah, 1969; Heilman and Gonzalez, 1973; Musick and Dusek, 1975; Kaddah, 1976). In some cases, ripping of fragipans at depths of 2.0 m have been done (Bradfield and Blanchar, 1977). Because they are carried out at considerable depth, these operations are energy-intensive and expensive. They require careful appraisal of cost and expected returns before they are performed. Furthermore, they should be performed under appropriate soil conditions to ensure that future benefits that will accrue from them will be realized.

TABLE 2
Grain sorghum yields (kg ha⁻¹) with selected land forming treatments^a

Treatment	1975	1976	1977	1978	Mean	Increase over graded furrow %
Conventional graded furrow	3080 c	210 d	970 c	550 d	1200 c	0
Conventional contour furrow	3700 ab	420 c	1440 bc	1750 bc	1830 b	52
Wide furrow	3880 ab	610 ab	1500 bc	1280 cd	1820 b	51
Orthman	3770 ab	610 ab	2150 a	1100 d	1910 b	59
Conservation mini-bench terrace	3750 ab	390 c	2020 ab	2040 a	2050 b	70
Mini-bench terrace	4090 a	470 bc	2560 a	2410 a	2380 a	98

^a From Jones (1981)

* Yields followed by the same letter within a column were not significantly different at the 0.05 level according to the Duncan multiple range test.

TABLE 3
Water-use efficiency (WUE) in kg ha⁻¹ mm⁻¹ for grain sorghum production on selected land forming treatments. WUE was computed for the growing season (planting to harvest) and for the total 4-year period. Percent increase in WUE over graded furrow also shown (From Jones, 1981).

Treatment	Growing season WUE					4-year WUE [#]	WUE increase %
	1975	1976	1977	1978	Mean		
Conventional graded furrow	10.8 b	1.2 d	4.2 d	2.7 d	4.7	3.5 d	0
Conventional contour furrow	12.7 a	2.2 c	4.9 cd	7.0 b	6.7	4.7 c	34
Wide furrow	12.8 a	3.3 ab	4.8 cd	6.0 bc	6.7	4.7 c	34
Orthman	11.8 ab	3.5 a	7.2 ab	4.4 cd	6.7	4.9 bc	40
Conservation mini-bench terrace	11.6 ab	2.1 cd	5.8 bc	8.2 ab	6.9	5.3 b	51
Mini-bench terrace	11.5 ab	2.6 bc	7.6 a	9.6 a	7.8	6.0 a	71

Column values followed by the same letter do not differ significantly at the 0.05 level according to the Duncan Multiple Range test.

Includes 6-month fallow period between crops.

TABLE 4
Rainfall (mm) and yields (t/ha) of cotton, sorghum and maize grown in tied-furrows, and on the flat, in seven seasons at Chiredzi, Zimbabwe (Data from Jones and Nyamudeza, 1991).

Season	Rainfall	Cotton-furrow	Cotton-flat	Sorghum furrow	Sorghum flat	Maize-furrow	Maize-flat
1983 to 84	370	0.49	0.3	0.57	0.4	0	0
1984 to 85	590	2.85	2.43	2.89	2.77	3.63	3.47
1985 to 86	590	1.36	9.4	2.63	2.02	2.88	2.31
1986 to 87	250	0.94	0.56	0.74	0.47	0.13	0
1987 to 88	520	0.9	0.67	0.69	0.05	0	0
1988 to 89	360	0.61	0.56	0.21	0.19	0	0
1989 to 90	410	1.57	0.7	2.77	1.87	2.74	1.75

Water harvesting

Water harvesting schemes require direction of surface run-off waters to the area to be cultivated. Many different methods have been applied and at different scales (Critchley and Siegert, 1991). Essentially run-off from areas which remain uncultivated is used to enhance the water content of soil in the cultivated area. If the uncultivated area is similar or larger in size to that cultivated, then, assuming little or no infiltration in the uncultivated area (the presence of crusting can be beneficial in this respect), the rainfall input to that cultivated is increased by 100% or more. In the Negev (Israel) and some regions in the Middle East water harvesting is enhanced through inducement of runoff water from a catchment area by either compacting the soil or treating it with chemicals (Evelt and Dutt, 1985a, 1985b; Boers *et al.*, 1986; Laryea,

1992). Evaporation losses, which together with seepage constitute the major losses of water in surface water storage systems such as dams, reservoirs, and farm ponds, are minimized with water harvesting systems.

In Sudan, a relatively large scale scheme involves diversion of the floodwaters of an ephemeral stream to an area of about 75 ha (Van Dijk, 1997) by means of a system of 0.35 m high, 3 m wide earth embankments constructed at 40 to 70 m intervals across a very gentle (0.9%) slope, and some channels. These force the floodwaters to spread laterally away from the watercourse.

At a much smaller scale, in Niger, run-off across slopes ranging from 1 to 3% is trapped in micro-catchments by construction of V-shaped earthen dykes; the open side of the V faces upslope. About 1.4 ha was developed with a catchment density of 166 per hectare (Tabor, 1995). The cultivated area within each micro-catchment is less than 7 m² and in total only about 20% of the land area is cultivated. Sorghum and millet yields equivalent to 250 to 600 kg ha⁻¹ were achieved. Trials focussed on millet and sorghum but demonstration crops of bambara groundnut and okra were also successful. This work is notable in that it specifically addressed eroded crusted soils and brought into cultivation land that had been abandoned. An advantage of the small scale approach is that micro-catchments can be developed by individual farmers as and when labour is available. However, it was noted that although water harvesting to varying degrees includes some nutrient harvesting due to transmission of plant litter and other wastes in the run-off waters (Nabhan, 1984), the increased infiltration through the relatively light soils would lead to soil degradation unless fertility was maintained by fertilization and addition of organic materials. The study suggested that good sub-surface soil characteristics are essential for high yields and consistency of results. Unless the soil physical characteristics are known, it was proposed that only crusted area that had formally been productive should be considered for development.

Reij *et al.* (1996) describe further case studies and explore the various factors that influence the adoption of soil and water conservation techniques in dryland areas. The 27 case studies considered demonstrate the wide range of soil and water conservation techniques that are available (e.g. earth bunding, stone bunding, mulching, bench terracing, microbasins) at the same time as demonstrating the fundamental need for the techniques to be attuned to the end-users needs, the local environmental conditions and the local farming systems.

Small-scale irrigation

Irrigation requires diversion or bringing of water to a cultivated area, but usually implies some control of the timing and quantities of water inputs. There are many irrigation techniques, large and small scale with differing degrees of control over water applications, and differing success in terms of water use efficiency. Irrigation inputs usually wet the soil surface (e.g. flood irrigation, overhead irrigation) and there is an inevitable water loss due to soil evaporation. An alternative approach is to focus the water input by using surface or sub-surface drip irrigation, or other subsurface irrigation methods, and so reduce water wastage due to evaporation from the soil surface.

Relatively low cost, small scale, low head drip irrigation systems, are effective in terms of improving plant water use, but are sensitive to poor management. Schemes in Sri Lanka that irrigated areas of about 1 hectare, to enable farmers to produce vegetables in addition to rainfed crops, were considered too large because the whole area had to be irrigated at once which meant planting to a single crop, or irrigating different crops at the same time (Batchelor *et al.*, 1996). In Zimbabwe smaller areas were irrigated using oil-drums to provide the water head;

irrigation applications were much more controllable, but, to prevent drip lines becoming blocked and unusable, good standards of filtration and chlorination are always required.

Simpler sub-surface systems using pitchers and sub-surface clay pipes have been demonstrated to be effective alternatives (Batchelor *et al.*, 1996). Pitcher irrigation is an ancient method still practised in several countries including India and Brazil (Mondal, 1974). However, experiments in Zimbabwe with locally made pitchers (unglazed clay pots) of about 2 l capacity showed that although the irrigation had significant benefits in terms of yield, water use efficiency was less than obtained when using subsurface pipes. This was because soil around the neck of the pitcher is wetted and early in the season, water is lost by evaporation. Subsurface pipe irrigation has many of the attributes of drip schemes without the need for filtration. Locally made pipes, of about 0.24 m length and 0.075 m internal diameter, were laid at a depth of 0.1 to 0.2 m depth. Water enters the soil through the joints between the pipes as well as through the unglazed walls. To allow filling, at one end a pipe with an angle is used into which water can be poured from buckets or hoses. The other end of the pipeline is blocked with a stone, a piece of wood or similar. Yield improvements relative to production of the same crops using the same water inputs applied by flood irrigation were good for most crops (Table 5). The yield and water use efficiency improvements were least for the tomato crops which established a full canopy cover early in the season so limiting soil evaporation losses. Batchelor *et al.*, 1996, concluded that subsurface pipe irrigation techniques involve relatively low risk, and even if poorly managed are likely to result in no yield or other improvements rather than having detrimental effects, and can be very effective in improving water usage and hence yields relative to flood irrigation. Table 6 summarizes the advantages and disadvantages of different small scale irrigation techniques.

TABLE 5

Percentage improvement in yield and water use efficiency for crops irrigated using subsurface pipes, relative to the same crops with flood irrigation. Data from Batchelor *et al.* (1996).

Year	Crop	Average improvement		Best improvement	
		Yield %	WUE %	Yield %	WUE %
1991	Maize	64.4	64.2	94.3	95.6
1992	Tomato	5.5	8.2	5.6	8.9
1992	Rape	8.6	27.5	17.1	45
1993	Okra	5	-1.1	17.8	8.6
1993	Tomato	-0.9	4.8	9.7	10.9
1993	Rape	8.6	14	22.2	43.7
Mean		15.2	19.6	27.8	35.5

TABLE 6
Advantages and disadvantages of small scale irrigation techniques for low-cost crop production
(From Batchelor *et al.* (1996))

Irrigation method	Advantages	Disadvantages
Flood irrigation	Traditional and well known. Easy to perform. Good crop establishment. Minimal additional inputs	Poor water use efficiency. No inherent control against over-irrigation. Labour intensive
Low-head drip irrigation	Improved water use efficiency. Good uniformity of wetting. Reduced drudgery and effort of carrying water	Cost and availability of materials. Degree of management skills required. Water filtration necessary No inherent control against over-irrigation.
Subsurface pipe irrigation	Improved water use efficiency. Pipes can be made locally. Robust method. Low labour requirement. Some inherent control against over-irrigation. Good uniformity of wetting. Low cost, simple and easy to learn. Once installed pipes can be used over several seasons.	Initial labour and skill requirement for pipe manufacture. Crop establishment can be poor if initial irrigation only via pipes.
Pitcher irrigation	Improved water use efficiency. Inherent control against over irrigation. Can position pots next to individual plants as well as in very small plots or undulating land.	Initial skill and labour requirement for pot manufacture. Pots less robust than clay pipes. More labour intensive as pots have to be filled individually. Difficult to cope with high water requirement.
Flood irrigation with mulching	Improved water use efficiency. Low skill requirements and easy to carry out. Good crop establishment. Protects fruit from damp soil. Prevents crusting and reduces erosion.	Potential for increase in pests and diseases. material suitable for mulching not always readily available.

Tillage and mulching to reduce water loss

Loss of water by evaporation from the soil surface can be reduced through the use of mulches or by tillage. The effect of tillage is variable. The aim is to achieve a coarser layer with large pores at the top of the soil profile. Generally the soil has already lost a substantial amount of water before its condition is suitable for tilling. The loosening and opening up of the surface layer will expose damp soil and so tend to speed its drying initially but may reduce upward water movement from lower layers. Thus tillage may have little effect on water loss from bare soil. It is most likely to be beneficial in the case of clay soils which shrink and crack appreciably on drying. Soil water loss also occurs via the cracks in such soils and can result in very dry hard soil. Tillage of the surface before drying can prevent serious cracking by reducing the amount of drying. Tillage can also be useful if it removes weeds and so cuts water wastage by weed transpiration. Tillage systems are considered further in Chapter 6.

A mulch is a cover to the soil surface. It may be comprised of plant residues from the previous crop, or imported for the purpose, e.g. straw and wood bark, gravel, or plastic sheeting. The effect of a mulch is complex. Any reduction in soil water loss occurs not only because the mulch acts as a barrier preventing loss; the soil radiation balance and its thermal regime are usually altered too, thus influencing the evaporation rate at the surface. The most usual mulch material is plant residues. They may be ineffective at reducing evaporation rates if present only as a thin layer. Usually very rapid evaporation from wet soil is prevented but slow drying may continue thereafter. The effect of the mulch may therefore be beneficial only where frequent wetting occurs. The advantages of mulching for preserving soil water have to be weighed against the disadvantages. The surface of a plant residue mulch is usually more reflective than the soil surface and therefore the soil remains cooler than in the absence of the

mulch. Mulches of plant residues may harbour pests and weed seeds which will cause problems later (see Chapter 6 for further discussion).

Drainage

In certain agroclimatic regions, there are periods of excessive water, which can be detrimental to crop production if the soil is not drained. Excessive soil water diminishes gas exchange between the soil and the atmosphere, often resulting in oxygen deficiency that retards root respiration, reduces total root volume, and also causes the formation of certain toxic compounds in soils. The major objectives in drainage are removal of excess water and salinity control. Surface drainage of excess water on land may be achieved with open ditches (interception drains), lateral drains, and waterways that convey the water at non-erosive velocities to be discharged onto nearby grasslands or woodlands, or into nearby streams. Internal drainage of excess soil water in the profile is usually achieved with a system of open ditches and buried tube drains into which water seeps by gravity (tile drainage system) (Donnan and Schwab, 1974). A tile drainage system is usually installed to cover a large farm or numerous small farms. In many instances, both surface and subsurface drainage may be required to effectively prevent waterlogging.

In agriculture, the main function of internal drainage is to lower the water table fast enough after rainfall or irrigation to avoid damage to crops. The design of the drainage system, therefore, is usually based on falling water table criterion, which specifies the rate of fall of water table at a certain water table position and at a certain time. This criterion is used as input for equations or models that express the rate of fall of water table as a function of system geometry and certain soil parameters, in order to estimate the drain spacing (Bouwer, 1974). Many research results (e.g., Williamson and van Schilfgaarde, 1965; Gilbert and Chamblee, 1959; Goins *et al.*, 1966; Williamson and Carreker, 1970) indicate that coarse-textured soils require a shallower water table depth (60 to 90 cm) for optimum crop yields than do fine-textured soil (100 to 150 cm) and that the specific water table depth that reduces yield drastically depends on soil type, crop, and climatic conditions.

Sometimes drains are installed in agriculture to improve trafficability of the soil in order to permit earlier planting of crops or to ensure that crops can be machine-harvested in areas that are plagued with rains during the harvesting period. In such cases, tile lines are installed to drain as many low areas or wet spots as possible. Such systems are often designed based on local experience. However, the rational design of a drainage system for trafficability will be to relate water content (or suction) of topsoil, rainfall, and evaporation for various drain spacings, and then selecting the appropriate spacing based on water content (or suction) in the topsoil and traction (or cone penetrometer readings)(Bouwer, 1974).

MEASUREMENT OF SOIL WATER PROPERTIES IN THE FIELD

Soil water content and soil water potential are the properties which are most useful to measure in the field. Individually both are useful. If measured simultaneously they can be used to determine the soil water retention characteristic and the hydraulic conductivity of the field soil at a series of depths in the soil profile. In addition, the direction and magnitude of water fluxes through a growing season can be measured.

Soil water content can be determined with relative ease by oven drying and weighing of samples taken from the field. However, there are two shortcomings to this approach. First,

water content expressed on a volumetric basis (m^3 water m^{-3} space) is considerably more useful than that expressed on a weight basis (kg water kg^{-1} soil). Multiplication of volumetric water content by the depth of profile generates the equivalent depth of water in that profile, a figure compatible with the depth measurements used to quantify rainfall and irrigation inputs. Volumetric water content can be calculated from water content measured on a weight basis if the dry bulk density of the soil is known. Ideally, the dry bulk density of the soil sample in question should be determined but often a value from some other source, or an averaged value must be used with a consequent loss in accuracy. The second shortcoming is the impossibility of repeating measurements at the same place and the consequent error introduced due to the need for repeated sampling.

Alternative procedures, the neutron probe method and techniques based on measurement of soil dielectric properties, are available but require investment in expensive instrumentation (Gardner *et al.*, 1991). Both approaches permit *in situ* measurements of volumetric water content. The recently developed dielectric methods (Time Domain Reflectometry - TDR, and capacitance) are suitable for permanent installations and automatic monitoring and logging at one or several depths/locations, as required. The small hazard associated with the presence of the radioactive sources in neutron probes precludes permanent installation. However, advantages over dielectric methods are the possibility of monitoring to depths of several metres, and the ability to measure in saline and other electrically conductive soils without difficulty (Gardner *et al.*, 1991).

Hydraulic potentials in the range 0 to -85 kPa are measured using tensiometers. A water filled porous cup attached to a pressure sensor is installed at the required depth in the soil. If the soil is saturated, the water within the porous cup will be in equilibrium with the water in the soil around it. If the soil is unsaturated, water will be drawn out of the porous cup until equilibrium between the two water bodies is reached. The pressure of the water in the porous cup will then fluctuate in response to water potential changes in the soil about it. The pressure sensor may be a manometer, a vacuum gauge or a pressure transducer. For research purposes, mercury manometer tensiometers and pressure transducer systems are most accurate. For farm purposes such as irrigation scheduling, vacuum gauge tensiometers have conventionally been used but the recent development of cheaper pressure transducers for use with septum seal tensiometers has provided a simpler alternative (Marthaler *et al.*, 1983). Irrigation water is applied sufficient to maintain water potentials in the root zone greater than a given threshold, e.g. -15 kPa. Reviews of soil water potential measurement techniques have been provided by Cassell and Klute (1986) and Mullins (1991).

Chapter 4

Soil crusting

A soil crust is a thin, dense, hard layer at the soil surface. Crusts are characterized by greater density and shear strength, but finer pores and lower saturated hydraulic conductivity, than the underlying soil (Shainberg, 1992). Soil crusts interfere with seedling emergence, hamper gas exchange between soil and the atmosphere, reduce infiltration and encourage runoff and hence erosion. Because of their role in sealing the soil surface to water infiltration, crusts are often referred to as seals when wet but there is no clear morphological or developmental reason for distinguishing between crusts and seals.

The prime cause of crusting is breakdown of soil structure at the soil surface due to water drop impact and soil wetting, and the consequent re-organization of the soil particles. Two main types of crust are recognized: structural crusts which develop *in situ*, and depositional crusts which are formed predominantly of material that has been transported from its original location. Salty crusts, developed generally as a consequence of deposition of salts - chlorates, chlorides, sulphates and carbonates - are not considered here. Such crusts may occur as a consequence of evaporation of saline waters at the soil surface, or result from erosion removal of the surface soil layer to reveal saline or sodic subsoil material.

The development of hard-setting conditions in surface soil horizons, noted especially in Australia, can often be associated with crusting. Hard-setting has been defined as "a compact, hard, apparently apedal condition which forms on drying" (McDonald *et al.*, 1984). The surface of a hard-setting soil is hard enough to prevent disturbance by finger pressure. Due to their dense packing and low porosity, hard-setting soils have slow infiltration rates and low hydraulic conductivities, similar to crusted soils. The distinction between crusting and hard-setting is that the whole of the A horizon hardens as the soil dries downward from the surface and so the mechanical strength is not limited to the uppermost 5 mm or so. Also hard-setting can occur purely as a consequence of sudden wetting and hence slaking; raindrop impact is not necessary (Mullins *et al.*, 1987).

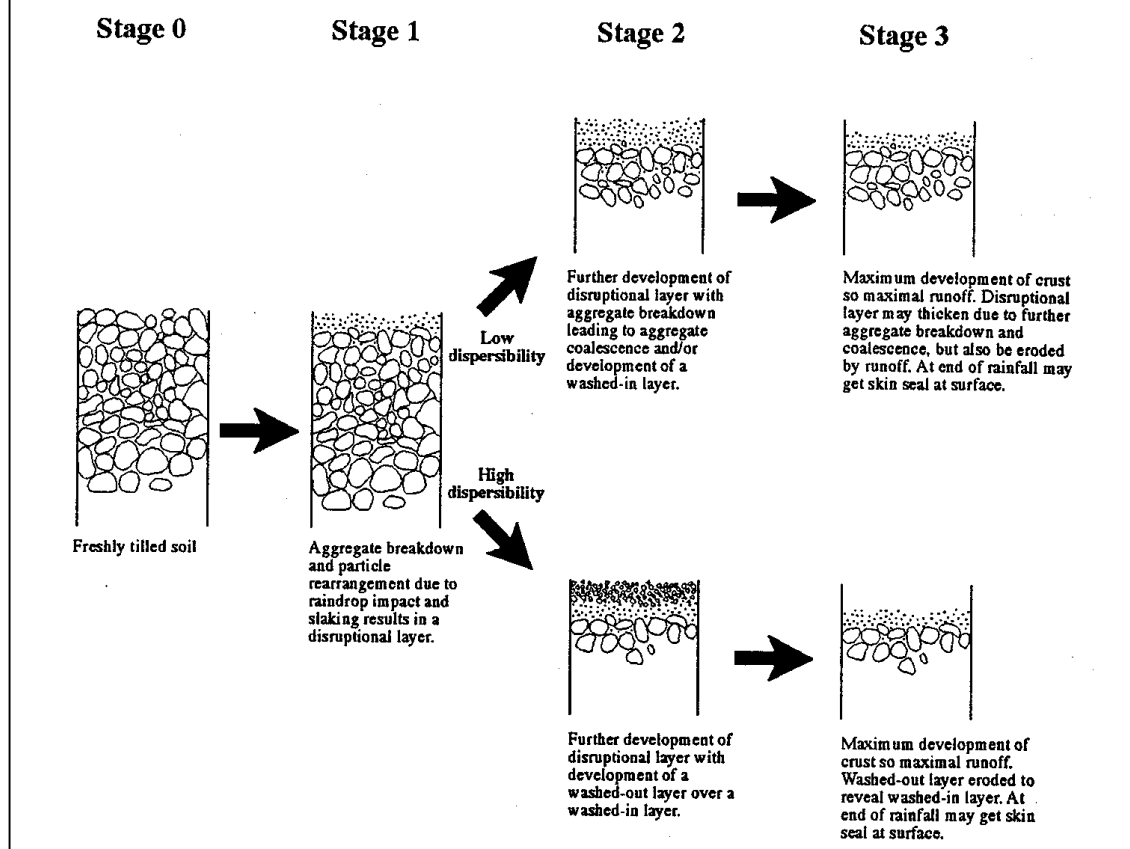
The development of soil crusts has been studied in detail at the field and plot scale, under natural conditions and using rainfall simulators, as well as in the laboratory. The physical and chemical processes which cause crusting have been reviewed in the text edited by Sumner and Stewart (1992). As yet the comprehensive research required to fully understand the relationships between dispersibility, other soil chemical and physical properties, rainfall conditions and crust formation, has not been conducted.

Structural crusts

These range from <1 mm to >10 mm in depth. West *et al.* (1992) proposed a general model for structural crust development (Figure 13) having distinguished three types of microlayer within structural crusts. It is unusual to find all the types of microlayer present together. The model

FIGURE 13

Schematic representation of the general model for surface crusting proposed by West et al. (1992)



recognizes that crusting is a dynamic process, the character of the crust changing in the course of a rainfall event and as a result of subsequent rainfalls, and it permits different end points.

Disruptional layer

Frequently the surface layer of a crust is more dense than the material below, and thicker than layers beneath. Particles and microaggregates released on aggregate breakdown as a consequence of raindrop impact and/or slaking, fill pores resulting in reduced porosity. Aggregate coalescence due to mechanical compaction by raindrops, when their consistency is plastic, probably also reduces porosity (Bresson and Boiffin, 1990). It is notable that formation of disruptional layers as a consequence of slaking alone has been observed in a sandy loam protected by a mulch from raindrop impact (Valentin and Ruiz Figuero, 1987).

Skin seal

Skin seals are generally dense layers, about 0.1 mm thick, comprised predominantly of oriented clay materials. They result from deposition of suspended material from surface water at the end of a rainfall event. A skin seal is fragile and readily ruptured by raindrop impact, and prone to cracking on drying. They are of minor importance for plant growth (Mualem and Assouline, 1992).

Washed-out/washed-in layers

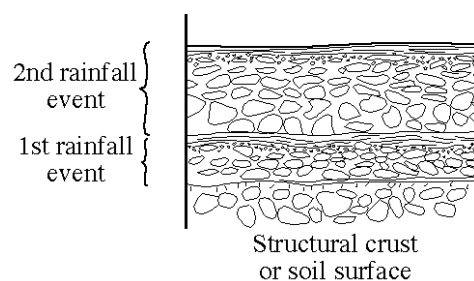
The role of fine disaggregated material washing down into and blocking pores just below the surface of crusts, and hence reducing infiltration rates, has long been recognized. Washed-in layers are thin, generally <1 mm thick. A washed-out layer of loose sand and silt sized material often remains above the washed-in layer, but may occur in the absence of a washed-in layer as fine material may be removed laterally in runoff. Washed-out layers are generally thin (<1 mm) though may be up to 5 mm thick. Valentin (1993) called these features sieving crusts and suggested that they are most prevalent in sandy and sandy-loam soils. It is probable that soil dispersion is a dominant mechanism in their development but no clear relationship between exchangeable sodium percentage and soil susceptibility to this form of crusting has been found (West *et al.*, 1992).

The thickness, porosity and hydraulic characteristics of structural crusts has been considered by West *et al.* (1992) who report from the literature, and present results from their own work in the USA. Reductions in porosity of between 30 and 90% have been reported when structural crusts develop. In addition a reduction in the mean pore diameter appears usual e.g. Valentin and Ruiz Figuero (1987) found pores of 0.075 to 0.3 mm in a crust over soil where the pore diameters ranged from 0.15 to 0.4 mm. Infiltration rates are very low, generally between 0 and 6 mm h⁻¹ (West *et al.*, 1990; Casenave and Valentin, 1989, 1992). However, no evidence of straightforward relationships between soil properties and the thickness and porosity of structural crusts is as yet forthcoming. Despite careful research effort, the hydraulic behaviour of structural crusts, whether measured as saturated hydraulic conductivity, or infiltration rate, cannot be simply described as a function of crust thickness or porosity.

Sedimentary crusts

Lateral transport of primary soil particles and microaggregates by water, and their subsequent deposition, causes the development of sedimentary crusts. The distance travelled may be small, <100 mm from a clod surface to an adjacent depression where temporary ponding may occur, or great, >5 m when material is entrained by rill or sheet flow. Thus sedimentary crusts may cover extensive areas, or be developed in a discontinuous patchwork between microtopographic highs such as clods, ridges, and areas where structural crusts have developed. Repeated rainfall events may reduce the microtopographic highs in time so that the extent of the sedimentary crusting increases. Sedimentary crusts occur over undisturbed soil and over structural crusts. They vary in thickness from <1 mm to 20 mm or greater, a thickness of 3 to 5 mm being usual for extensive crusts.

FIGURE 14
Particle sorting according to size within the microbeds of a sedimentary crust



Sedimentary crusts often exhibit in microscale the features of particle size sorting, bedding and fining upwards within beds typical of sedimentary deposits such as flood plain formations (Figure 14). During and after a rainfall event, large particles are deposited when the velocity of the surface water flow decreases. This is followed by settling of particles of decreasing size as ponding, slow infiltration and/or evaporation of the surface water occurs.

Several beds may be deposited in sequence upon one another as a result of a series of rainfalls. The presence of spherical voids (vesicles) just below the surface of sedimentary crusts has often been observed. They are thought to arise as a result of air entrapment below the clay lenses and ponded water.

Sedimentary crusts will be deposited only if the rainfall intensity is greater than the soil infiltration rate, and the lateral water flow is insufficient to remove entrained soil particles from the site. The formation of a structural crust and consequent reduction of infiltration rates may frequently initiate the surface water flow that results in sedimentary crust formation for both types of crust occur in association, and sedimentary crusts overlying structural crusts have been observed (West *et al.*, 1992, Bresson and Boiffin 1990.)

The porosity of sedimentary crusts arises mainly as a result of the packing of primary particles and is related to the particle sizes present and the sorting within the microbeds. In general coarser material provides greater porosity than fine particle size. The presence of vesicles within sedimentary crusts increases the total porosity. However, there is little connectivity between these voids and the porosity of the crust matrix so that their contribution to the hydraulic properties of the crust are probably unimportant. Infiltration rates of between 0 and 30 mm h⁻¹ have been reported for sedimentary crusts (Falayi and Bouma, 1975; Casenave and Valentin, 1989,1992). Fattah and Upadhyaya (1996) observed very low infiltration rates through thick wet depositional crusts, but noted that the crust cracking which occurred on drying considerably improved infiltration rates.

FACTORS IN CRUST FORMATION

Whether crusting occurs, and the nature of the crust that develops is influenced by soil properties including particle size distribution and aggregate stability, the nature of the incoming rainfall or irrigation, antecedent moisture conditions and local topography both at the microscale (e.g. ridge and furrow relief) and larger scale. A crust may form in the course of a single rainfall event. The development process may continue during succeeding rainfall events, depending on rainfall character and the degree of drying which takes place in the intervening period. Prolonged drying may result in cracking of a crust and development of new aggregates. Repeated cycles of drying and wetting by gentle rain will encourage weakening of a crust and soil aggregation. The intensity of crust formation may be measured in terms of final infiltration rate, crust strength or thickness.

Rainfall characteristics

Crusting is initiated by aggregate breakdown and slaking as a result of raindrop impact and sudden wetting. The impact forces associated with rainfall depend upon the size distribution of the raindrops, their velocities and intensities. During a light rainfall (intensity 0.1 mm h⁻¹) drops of median diameter 1.25 mm, velocity 4.8 m s⁻¹ falling at a rate of 280 m⁻² s⁻¹ were recorded (Lull, 1959, in Morin, 1993). The associated kinetic energy measured per unit area and time was 12 J m⁻¹ h⁻¹. Heavy rainfall of 15 mm h⁻¹ was associated with larger drops, 2.05 mm median diameter, greater fall velocity 6.7 m s⁻¹, fell at a rate of 495 drops m⁻² s⁻¹ with a kinetic energy of 340 J m⁻² h⁻¹. During a cloudburst intensities of 1100 mm h⁻¹ may occur which, depending on the drop diameter can give rise to a kinetic energy of 3300 J m⁻² h⁻¹ or greater.

Different studies have employed different measures of rainfall impact forces including kinetic energy, momentum, intensity and combinations of these, e.g. 30 minute intensity of kinetic energy. It is clear that both rates and intensity of crust formation, increase with increase in raindrop impact energy, whether the latter is

due to greater intensity or greater drop diameter. For example, Bradford *et al.* (1987) found that doubling the average drop size of a 60 min rainfall of intensity 64 mm h⁻¹ from 2.3 to 4.6 mm resulted in crusts with lower infiltration rates (Table 7). Final crust infiltration rates declined asymptotically with increasing raindrop energy to a threshold beyond which no further aggregate breakdown occurred, despite greater raindrop energy. The final strength of the crust was also much greater as a result of the higher energy rainfall.

TABLE 7

Effect of drop size on crust infiltration rate and strength (from Bradford *et al.*, 1987)

Soil	Drop size mm	Infiltration mm h ⁻¹	Strength kPa
Coarse silt loam (Vicksburg)	2.3	11.0	13.1
	4.6	6.5	48.0
Silty clay (Brooksville)	2.3	51.6	-
	4.6	9.8	24.5

Soil texture and aggregate stability

The relationship between soil texture and crusting arises firstly from the implications that textural characteristics influence aggregate stability, and secondly, the mobility of different particle size fractions when soil is dispersed. Crusts occur on most soils except coarse sands with very little silt and/or clay present. Soils with a high silt content are prone to crusting due to their susceptibility to dispersion. And, for the same reason, crusts are more likely to occur on sandy loams than clay loams.

Bradford and Huang (1993) have demonstrated the influence of silt and clay content on crust formation for soils with low sand content (<10%) (Table 8). Increasing silt content while reducing clay content resulted in development of much stronger crusts but final infiltration rates were greater in soils with the higher clay content. Stern *et al.* (1991) investigating crust formation in South African soils with sand contents ranging from 19 to >70%, found no correlation between silt and/or clay content and final infiltration rate. However, clay mineralogy was important. Mermut *et al.* (1995) reported that the mineralogy of clay particles is one of the major factors that determines the properties of the soil crust. The presence of smectites led to increased dispersion and lower final infiltration rates.

TABLE 8

Indices of crust formation resulting from a simulated rainstorm of 64 mm h⁻¹ (from Bradford and Huang, 1993)

Soil	Sand 2000-50 µm %	Silt 50-2 m %	Clay <2 µm %	Infiltration mm h ⁻¹	Strength kPa
Silty clay (Brooksville)	4	51	45	39.0	12.5
Silty clay (Sharkey)	4	53	43	25.4	19.2
Silt loam (Memphis)	4	73	23	35.2	32.2
Silt loam (Grenada)	6	80	14	11.6	74.2
Silt loam (Vicksburg)	8	84	8	12.0	84.0

Antecedent soil water content

The water content of an aggregate influences its susceptibility to raindrop impact and slaking on wetting. Aggregates which are initially dry collapse mainly due to slaking when wetted. In contrast it is the mechanical impact of raindrops which is most important in the breakdown of

aggregates with a high water content (e.g. water content at 0.5 kPa.) Consequently, under wet conditions the degree of aggregate breakdown and crust development depends on rainfall energy and duration. In dry conditions, aggregate breakdown depends more on initial rainfall intensity (Table 9).

TABLE 9

Infiltration and soil strength following 60 min of simulated rainfall with intensity 71 mm h on < 20 mm soil materials under laboratory conditions (from Bradford and Huang, 1993)

Soil	Antecedent water content	Aggregate stability	Final infiltration mm h ⁻¹	Final strength kPa
Clay (Brooksville)	Dry	Good	21.0	17.7
	Wet	Good	28.6	24.5
Clay (Heiden)	Dry	Good	15.7	27.3
	Wet	Good	21.7	26.7
Clay (Broughton)	Dry	Good	20.1	17.9
	Wet	Good	44.2	21.4
Sandy loam (Cecil)	Dry	Poor	15.5	32.7
	Wet	Poor	6.5	37.4
Silt loam (Vicksburg)	Dry	Poor	8.00	33.3
	Wet	Poor	5.46	40.2
Silt loam (Miami)	Dry	Poor	21.2	16.2
	Wet	Poor	12.4	24.5

Slope and microtopography

Crusting is less likely on steeper slopes because rainfall intensity is reduced and the greater runoff velocity of runoff is likely to remove disaggregated material, and may erode any crust that does develop. The microtopography of the soil surface due to the presence of large aggregates or clods after tillage, and/or ridging, may encourage depositional crust formation in microtopographic lows. Larger aggregates and clods are more resistant to breakdown under raindrop impact than smaller ones of the same soil, due to the increased negative water potential at the top of the clods and so greater cohesion. Also the sloping sides of clods and ridges are subject to reduced raindrop impact. Soil microtopography will decline and associated crusting will increase in the course of a rainfall and repeated rainfall events. Therefore the initial improvement of infiltration after tillage is likely to decline with time. Biielders *et al.* (1996) observed that on a coarse textured soil, crust distribution was related to the initial soil microtopography, resulting from cultivation, not the final topography.

THE AGRONOMIC EFFECTS OF CRUSTING

The effects of soil crusting can be divided into those that directly influence plant growth, in particular seedling emergence, those which have an indirect impact on crops through the change in infiltrability of the soil surface, and those such as erosion which have consequences for the cropped area generally, and areas further away. Comprehensive reviews of the agronomic effects of soil crusting in Africa, Australia, South America and different regions of the United States, with research results, have been provided in the volume devoted to soil crusting published by Sumner and Stewart (1992).

Seedling emergence

Crusts can prevent seedling emergence to the extent that a substantial amount of seed may be wasted and resowing may be necessary if production of a crop is to be worthwhile. This occurs because the mechanical strength of a crust maybe too great for seedling shoots to penetrate so that emergence is impossible. Until a seedling emerges and photosynthesis can commence, it is

entirely dependent upon the reserves of the seed for growth. Thus there is only limited potential for the shoot to grow before emerging. Seed weight and emergence from crusting soils are closely related, emergence of crops grown from larger seeds being more successful than for fine seeded crops, in conditions where crusting occurs (Graven and Carter, 1990; Heather and Sieczka, 1991). Williams (1956) found that seed weight and the lifting capacity of a seedling are closely correlated. Soman *et al.* (1992) observed that apparently crust tolerant cultivars of sorghum had longer mesocotyls with faster growth rates, indicating that the mechanism involved in crust tolerance was avoidance by faster shoot growth. Townend *et al.* (1996) noted similarly that the faster initial rates of cowpea root and shoot growth, combined with the greater shoot size, enabled it to overcome mechanical impedance in hard-setting Tanzanian soils resulting in emergence of 56% or greater, compared with emergence of 0 to 30% for sorghum on the same soils.

Seedling emergence in crusted conditions may be delayed due to the greater time required for shoots to penetrate the crust with possible consequences for subsequent crop development. In addition, the emergent seedlings are often smaller and weaker than those from comparable but uncrusted soil (Sale and Harrison, 1964), again with possible consequences for crop development and ultimate yields.

Several studies have indicated that it is crust strength rather than crust thickness that is most important in impeding seedling emergence. The mechanical strength of a dry crust is influenced by the drying history, slow drying resulting in stronger crusts (Gerard, 1965). It is usually assumed that the emergent force of the shoots of monocotyledons such as grasses and cereals is exerted at a point. The pressure exerted on a crust by the coleoptiles of maize seedlings is of the order of 200 kPa and Souty *et al.* (1992) suggest that emergence results from a penetration mechanism rather than bending and fracturing of crusts. Dicotyledonous species such as cotton or sugar beet are expected to exert a force over a small area of soil crust. Oil seed rape seedlings have been observed to penetrate crusts with a resistance exceeding 230 kPa (Boem and Lavado, 1996). A negative linear relationship between crust strength and seedling emergence for several crops in different soils has been demonstrated by Bennet *et al.* (1964), Hanks and Thorp (1957) and Joshi (1987). However, crust strength depends on water content, being greatest when dry if the crust remains intact on drying. Therefore crusting may only be a problem for seedling emergence on a given soil in those seasons where rainfall and/or water for irrigation are scarce or absent.

The potential effect of a dry crust on emergence can be ameliorated by wetting. The method of wetting used can be significant; Fapohunda (1986) found the gentle wetting associated with trickle irrigation resulted in much better seedling emergence than furrow or rapid flooding irrigation of crusted soils. Intense overhead irrigation similarly could exacerbate the situation by increasing the crusting rather than wetting the crust. Drying of crusts in certain soils may lead to cracking so that the impact on seedling emergence is diminished. The degree of cracking will depend upon the clay content and clay mineralogy of the soil, as well as the immediate drying history of the crust.

The significance of vertical seedling placement with respect to emergence in crusted soil is uncertain. However, horizontal placement can be significant. Morin (1993) suggests planting seeds on ridges, or furrow sides where crust formation is weaker. Alternatively, seeds may be planted in groups so generating a greater penetrating force to breakthrough a crust (Hanegreefs and Nelson, 1986).

Many studies have demonstrated the effectiveness of gypsum additions in reducing crusting on sodic and generally non-acid soils by improving the aggregate stability of the surface soil (e.g. Grierson, 1978; So *et al.*, 1978). However, gypsum additions to a red acid kaolinitic soil resulted in stronger crusts which did not crack as much on drying, as untreated areas, and therefore hindered seedling emergence (Borselli *et al.*, 1996a). This was attributed to greater clay contents in the crusts of the treated soil. The gypsum reduced clay dispersion such that less dispersed clay was washed-out of the surface layer, which encouraged stronger crust development in the kaolinitic soil. However, crust infiltration rates did not decline as rapidly during rainfalls on the treated soil (Borselli *et al.*, 1996b).

Water infiltration

The significance of reduced infiltration rates due to crusting varies according to the farming system and importance of rainfall and/or irrigation for maintaining adequate soil water for crop growth. In irrigated agriculture, any reduction in infiltration limiting the farmers ability to replenish soil water reserves is undesirable. Plant stress and reduced yields are likely whilst loss of irrigation water through evaporation from the soil surface is a cost without benefit.

Productivity of cropping systems which rely on rainwater to replenish the soil water reservoir may be severely limited if crusting occurs. Unfortunately the heavy rainfall which can initiate crusting is characteristic of regions where rainfall amounts are small and erratic and water loss due to runoff may be a common occurrence. This is particularly serious on soils which have small amounts of plant available water.

In dryland farming, crust formation in certain circumstances, may be a benefit, depending on the farming aims. Crusting may result in runoff concentration in particular localities where the accumulated water infiltrates, stimulating growth of vegetation which can be grazed. According to the local topography it may be possible to exploit this water by cropping (see Chapter 3).

Another possible benefit of reduced infiltration due to crusting has been noted by Roth and Pavan (1991). Under experimental conditions they collected much greater concentrations of Ca, K, NO₃ and NH₄ in leachate from mulch protected soil subjected to simulated rainfall, than from bare soil. In soils with inherently low nutrient absorption properties prevention of such leaching may be beneficial to cropping.

Chapter 5

Other physical constraints to soil productivity

This chapter brings together details of soil aeration, soil temperature, mechanical impedance and soil erosion and their impact on crop growth. Each of these facets of soil physical behaviour is strongly influenced by soil structure and soil hydrology. They are also inter-related, thus soil aeration has relevance to soil temperature but temperature conditions also influence the degree of aeration.

In certain soils, aeration, temperature conditions, impedance to root growth or erosion are dominant factors in plant growth, and for successful crop production, management must be tailored to allow for these constraints. For many soils, improvements in the understanding and management of soil structure and water supply for plants, and of plant nutrient requirements, make it possible to optimize crop production. Consequently attention is being focussed on other factors which formerly were considered less important and not regarded as limiting.

As in the case of soil hydrology, research effort in each aspect of soil physical constraints covered here is directed towards development of physically based models. The aim is to simulate soil conditions accurately, improving our understanding of them and ultimately to develop models which can be used in practical applications. Modelling of soil erosion is fairly well advanced. This is a reflection in large part of practical necessity. Severe erosion problems, particularly in the USA, led to the early field study of erosion processes and development of predictive models to assist decision making in soil conservation management. Although the theory of the principles governing soil behaviour with respect to temperature, aeration and mechanical impedance has been known for many years, modelling is not nearly as well progressed.

SOIL AERATION

The air in the pore spaces of a well structured, drained soil is composed of about 20% oxygen by volume; this is similar to the amount of oxygen in the atmosphere, 20.5%. Under anaerobic soil conditions the amount of oxygen present may be negligible. In general, the amount of carbon dioxide present in soil is always greater than in the atmosphere (0.03%). Concentrations as great as 3% can occur where anaerobic conditions have persisted for some time. Whereas the relative humidity of the atmosphere changes with the weather, that of the soil air is usually close to 100% except in the surface after extended drying.

The oxygen and carbon dioxide composition of the soil air fluctuates more than that of the atmosphere. It depends on the rate of use of oxygen, and carbon dioxide production, by roots and soil organisms, and on gaseous exchange between the soil air and the atmosphere. The latter tends to re-dress any imbalance due to the former. Factors such as the time of year,

soil water content, soil temperature and the level of activity of soil organisms, especially the micro-organisms, are therefore all important in determining the composition of the soil air.

Root and soil respiration

Roots require oxygen to respire and grow. In most plants it is essential that oxygen can be supplied from the soil atmosphere. This is because the transfer of oxygen from the aerial parts of the plant, to roots, is too slow for satisfactory root growth in most species. In a soil with zones of poor aeration, oxygen transfer along short distances through roots may occur. However growth at the root tips will be slowed if the distance reduces the rate of oxygen. The net result is that root systems "avoid" anaerobic zones in soils. It is probable that decreasing aeration with increasing depth often restricts the rooting depth of crops.

Oxygen is used by the soil flora and fauna for respiration, as well as by roots. They, and roots, produce carbon dioxide as a result of respiration. In a well aerated soil, the ratio of the volume of carbon dioxide which they produce, to the volume of oxygen consumed, is about one. The ratio rises above one where anaerobic zones are present. The amount of

oxygen used by a bare soil, i.e. by the soil organisms, can amount to half of the soil oxygen usage when a crop is present (Table 10). The total quantity of oxygen respired in the course of a day may represent a substantial proportion of all the oxygen present in the soil. If oxygen supply to the soil from the atmosphere above is prevented, that in the soil may only be sufficient to meet the needs of the roots and organisms for 2 or 3 days in a warm moist soil. Maintenance of pathways from the soil surface to depth, to permit inward movement of oxygen, is therefore essential. This is true when a soil is cropped. It is also important at other times if the benefits of the activity of soil organisms in improving soil structure are to be accrued, and the detrimental effects of denitrification avoided.

Effect of anaerobic soil conditions

When the availability of oxygen is reduced, several biochemical pathways in plant roots and soil organisms are altered. Under oxygen stress, roots may produce substances such as ethylene and acetaldehyde, which are toxic if allowed to accumulate. However, in rice, ethylene stimulates root production under water-logged soil conditions. Similarly, under anaerobic conditions, some soil organisms produce toxins on decomposition of soil organic matter. Various chemical and biochemical reducing reactions are induced which produce toxic substances such as sulphides and nitrites. Denitrification, in which nitrite production is one stage, results in loss of plant available nitrogen as elemental nitrogen.

Different plant species, and varieties of species, show different tolerances to temporary anaerobic conditions. The development stage which a plant has reached when transient anaerobic conditions occur will also influence the degree to which crop production is affected. The impact of waterlogging on crops during cool seasons is generally less because the requirement of soils and roots for oxygen decreases with decreasing temperature.

TABLE 10

Oxygen consumption and carbon dioxide use from a bare soil and a soil with a kale crop in southern England ($\text{g m}^{-2} \text{d}^{-1}$) (from Payne and Gregory, 1988)

Soil temperature 0.1 m	July (17°C)		January (3°C)	
	cropped	bare	cropped	bare
Oxygen consumption	24	12	2.0	0.7
Carbon dioxide production	35	16	3.0	1.2

Movement of air in soil

Movement of air within soil, and exchange between the soil and the atmosphere, takes place by two processes: convection and diffusion. As with the transmission of water through soils, pore size and pore continuity, as well as water content, influence movement of the soil air. Air movement takes place preferentially through the larger pore spaces and cracks between aggregates. The importance of convective flow to soil aeration is still uncertain and it is often assumed to be negligible (Jury *et al.*, 1991). It is induced by gradients of total gas pressure in soil; the air mass flows from zones of higher pressure to zones of lower pressure. Total pressure gradients may be introduced as a result of soil temperature changes, water infiltration into the soil surface, or due to barometric pressure changes, temperature differences and wind effects in the atmosphere above the soil surface.

Diffusion is the more significant process for soil aeration. The individual constituents of the soil air move in response to concentration (partial pressure) gradients; e.g. when the concentration of oxygen in the soil air is spatially variable, oxygen molecules will migrate from zones of high oxygen concentration to zones where the concentration is lower. Diffusion is important for exchange between the soil and the atmosphere, and between different zones within soil. Diffusion of both oxygen and carbon dioxide also occurs in the soil water and is very important at the interfaces between the soil and roots and soil organisms. Most oxygen uptake and carbon dioxide release occurs via water films and mucilages which surround the roots and micro-organisms.

Micro-organisms within aggregates create zones of lower oxygen concentration in the aggregates. Oxygen gradients, causing diffusion from cracks and pores between aggregates into aggregates, therefore develop. However, any restriction to that diffusion due to either the water content of the aggregate, or low pore continuity within the aggregate, leads to anaerobic zones developing within the aggregates although the inter-aggregate pore space is well aerated (Horn *et al.*, 1994).

Diffusion of gases through soil can be modelled by combining the theories of gas conservation and gas diffusion through porous media. Jury *et al.* (1991) explain how such models have been developed to describe oxygen uptake and carbon dioxide evolution, and their success in simulating the changing composition of the soil air.

Effect of soil structure and tillage on aeration

The oxygen concentration in soil at a given matric potential increases as pore size increases and pore tortuosity decreases. This is because fewer zones within the total soil volume are inaccessible to oxygen diffusion. Consequently the finer the structure of a soil, the lower the oxygen concentration at a given matric potential. As aggregation of a soil of given texture increases, so the oxygen concentration of the soil air declines at a given matric potential, due to slower diffusion within aggregates. This means that lower matric potentials are necessary for adequate aeration in clay or poorly structured soils. A detailed review of oxygen diffusion and consumption in and around soil aggregates, and the role of micro-organisms and organic substances, has been provided by Horn (1994).

While tillage operations improve soil aeration, the effect is often only temporary. For example, Khan (1996) found that use of a mouldboard plough was more effective than use of other equipment in terms of increasing oxygen diffusion ratios in a sandy loam lateritic soil cultivated for peanut. However, the diffusion ratios declined during the growing season. Under

no-tillage systems, the general finding is that the increase in earthworm and other soil faunal populations, and improvement in soil structure, result in improved aeration (Baker *et al.*, 1996).

SOIL TEMPERATURE

Temperature conditions within a soil are continually changing. The system attempts to come to an equilibrium state but is continually perturbed by heat inputs (predominantly solar radiation) and heat sinks including cooler soil at depth, cool air at the surface and water phase changes, especially evaporation. Diurnal and seasonal variations in the solar radiation input prevent uniform soil temperature conditions ever being attained. Hillel (1980a) has emphasized the formidable task which quantifying and simulating the soil temperature regime presents, and the difficulty of predicting the effects of attempts to modify and control soil temperature conditions. Theoretical explanations of soil thermal properties, the soil temperature regime, interactions with other soil properties and soil temperature modelling have been provided by Buchan (1991) and Jury *et al.* 1991. Payne and Gregory (1988) have reviewed the effect of soil temperature on plant growth.

Effect on plant development

The range of soil temperature conditions which a plant will tolerate is often quite broad, 25 °C, or more. However, optimal conditions for plant development are generally towards the middle of the range. Decreasing soil temperatures progressively reduce growth rates. Temperatures above the optimum have less of an impact until a maximum is reached when growth ceases. In hot climates, the living root mass of established pasture crops may vary through the season, declining during the hottest months due to high soil temperatures. In many species, the seed must be exposed to temperatures below a certain threshold before germination is triggered. Germination success is then best under optimal temperature conditions which may differ to those for later growth stages. New crop cultivars in which germination and seedling emergence are not restricted by excessive soil temperatures (25 to 40 °C) continue to be evaluated (e.g. Kasalu *et al.*, 1993). Other soil conditions, such as water content and aeration can exacerbate or ameliorate the impact of sub-optimal temperatures on plant growth.

As with plants, root growth also requires favourable temperature conditions. Better root growth improves the size of the root system and its capacity to provide the above ground parts of the plant with water and nutrients. The rate at which water, and at least some nutrients, are taken up by roots is also influenced by temperature. For example, Wei *et al.* (1994) monitored the differential effects of soil temperature on iron-deficiency chlorosis in various species and cultivars of clovers. Responses to low temperature differed between clovers but nodular activity and shoot dry weight was always greater at moderate temperatures. In those species where the shoot meristem remains at or within the soil surface, cereals in particular, soil temperature in the upper 5 cm directly effects rates of leaf development (Payne and Gregory, 1988).

It is important to appreciate that soil temperature varies with time and depth. Too frequently studies of crop development which include a soil temperature element have failed to monitor temperature regularly and throughout the soil profile. Any conclusions about the role of temperature based on such incomplete data are dubious.

Indirectly soil temperature influences plants through its impact on soil physical processes, particularly the rate of water loss through evaporation at the soil surface to the atmosphere, and the rate of exchange of oxygen and carbon dioxide between the soil air and the

atmosphere. The rate of most chemical soil processes increase with temperature increase, but the relative importance of different chemical pathways may change with temperature. Finally, the activity of soil organisms, large and small, is influenced by temperature. The role of larger fauna in soil structural development is often severely diminished at low temperatures. As with plants, the activity of soil micro-organisms reaches a maximum at some optimal temperature range but decreases at temperatures above and below that. Organic matter decomposition and mineralization are therefore strongly temperature dependent as is the biodegradation of pesticides and other organic chemicals. The activity of crop pests which live in soil is also influenced by soil temperature conditions. For example, populations of nematodes which affect potato production in the sub-tropics, vary in size with soil temperature and crop timing (Greco, 1993).

Heat exchange at the soil surface

Radiant, thermal and latent heat exchange processes, primarily at the soil surface, are responsible for soil temperature fluctuations. Their impact effects the deeper soil profile due to heat transport via a series of processes. Heat exchange at the surface, and heat transport are both affected by time and spatially variable soil properties including water content and soil structure.

Part of the sun's radiant energy reaching the soil surface is reflected and scattered; the rest is absorbed. About 10 to 40% of incoming radiation is reflected by soils, thus the reflectivity coefficient, or albedo, ranges from 0.1 to 0.4. Dark surfaces including wet soil have low albedos, whereas light ones such as dry or pale coloured soil, are more reflective and have high albedos. Where vegetation is present, the amount of radiant energy reaching the soil surface is reduced by reflection from, and absorption by the vegetation canopy. The effect is approximately proportional to the degree of shading of the soil surface.

Four mechanisms are responsible for dissipation of the energy absorbed at the soil surface:

- radiation back to the atmosphere as longer wavelength energy (back radiation);
- dissipation as latent heat on the evaporation of soil water. Much of the energy will be used for evaporation if the surface soil is wet. As the surface dries, increasing amounts of energy are available for the following processes;
- increase in the temperature of the surface soil and heat dissipation to the air above (sensible heat loss);
- conduction to lower depth increasing soil temperature there.

The temperature of soil at greater depth in the profile therefore depends on the amount of heat available for conduction and the soil's thermal properties. At night and during cooler seasons, there is a net flow of heat out of soils, as the balance of these processes alters.

Soil thermal properties

The thermal properties of soils which influence the soil temperature regime are specific heat capacity, thermal conductivity and thermal diffusivity. Heat movement is induced in soils by temperature gradients; heat moves from zones of high temperature to zones where the temperature is lower at rates determined by the thermal conductivity. However, as heat movement takes place, so the temperature gradient changes. The amount of heat required to

change the temperature per unit of soil is known as the specific heat capacity. If heat is moving between soil zones with different specific heats, the rate of temperature increase of the initially cooler soil will differ from the rate of temperature decline in the soil supplying the heat. The ratio of the thermal conductivity to the volumetric heat capacity is known as the thermal diffusivity. The thermal diffusivity therefore expresses the combined effect of heat gain or loss on temperature and thermal conductivity change in a volume of soil.

The volumetric heat capacity and thermal conductivity properties of a soil depend on the relative proportions of solid, liquid and air present, and the composition of the solid phase (Table 11). Since the volumetric heat capacity of air is very small relative that of water, increase in soil water content increases the heat capacity markedly and so wet soil requires more heat to warm up than dry soil. Therefore, in spring, the surface of a wet soil usually will take longer to warm up than that of an adjacent dry soil of the same type. However, warming is also influenced by the albedo, and thermal conductivity properties of the soil.

The ratio of the thermal conductivities of air, water and quartz is 1:23:352 (Table 11). Therefore structural changes which reduce porosity result in an increase in thermal conductivity. In a soil of fixed structure, thermal conductivity increases significantly with water content. The thermal conductivity values of whole soils, when wet and dry, depends on their texture: sand>loam>clay>peat, reflecting the associated water retention and structural characteristics.

TABLE 11
Thermal properties of the principal soil constituents (solids at 10 °C, ice at 0 °C) (after Buchan, 1991)

Material	Volumetric heat capacity MJ m ⁻³ °C ⁻¹	Thermal conductivity W m ⁻¹ °C ⁻¹
Quartz	2.0	8.8
Clay minerals	2.0	2.9
Organic matter	2.5	0.25
Water-liquid	4.2	0.57
Ice	1.9	2.2
Air	1.25 x 10 ⁻³	0.025

If values for these thermal properties are available, they can be used in heat equations and models to simulate heat flow in soils. However, heat flow cannot be divorced from water movement as temperature gradients influence water flow which can carry heat. For effective simulation of the soil thermal regime, it is necessary to incorporate the surface energy balance into models. In addition water phase changes below the surface, particularly evaporation at depth in drying soils, but also condensation and freezing must be allowed for.

Altering soil temperatures

Attempts to manipulate soil temperature throughout the growing period of a crop are only practical in glass house situations, and are very costly. Soil temperature is therefore one of the elements in crop selection - a crop can only be grown in a climate where soil temperatures are within a range which it can tolerate. Most often the need is to improve soil temperature conditions at the time of seed germination and early growth. In cooler climates, raising soil temperature in spring even marginally, may allow earlier germination so extending the growing season by a week or two. In hot countries, soil temperatures may need to be depressed to achieve germination at the time required. Frequently the soil temperature regime is modified as a consequence of other cultivation practices, in particular the use of tillage systems involving residue retention, or mulching. Because the detailed thermal behaviour of soils is not well understood as yet, most attempts to improve field soil temperature conditions are based on empirical experience (Hillel, 1980a).

Tillage to produce a seedbed will modify the thermal properties of a soil through the increase in porosity and change to the behaviour of the soil water. Most often drainage or tillage operations to reduce water content of otherwise wet soils in springtime is beneficial in raising temperatures for early germination and growth. Kaune *et al.* (1993) conducted a comprehensive study of the effect on thermal properties of different soil structures modified by tillage, but concluded that their results might not be applicable to other soils. Horn (1994) has reviewed the effect of structural modifications on thermal properties from a more theoretical view point.

Surface application of pale materials e.g. kaolin or ash, increases the albedo of the soil surface and can be effective in reducing temperatures and use of a dark material such as coal dust or charcoal, can have the opposite impact. Shade plants can be used to lower soil temperatures to suit a particular crop. However, the benefits have to be balanced against the possible competition for water and nutrients between the two crops.

Soil temperatures under mulching and reduced-tillage systems

Management options such as reduced or no-tillage, to conserve soil water and/or prevent soil erosion, or use of mulches for the same purposes, have implications for soil temperature conditions which may be neglected at the time of decision making. The presence of residues at the soil surface generally reduces radiant energy inputs so cooling the soil, but also reduces heat loss from the soil surface and so diurnal soil temperature fluctuations are reduced. These effects are well documented (e.g. Alam *et al.*, 1993; Azooz *et al.*, 1995; Dwyer *et al.*, 1995) but methods for prediction of soil temperature in response to such management are limited. Knowing the initial soil temperature profile, the mass of the residue and its apparent thermal diffusivity, Brar and Unger (1994) simulated soil temperature satisfactorily from air temperature measurements at 2 m height above the plot. Bussiere and Cellier (1994) managed to quantify and model the influence of mulches of uncropped residues, such as those used widely in the tropics, on water and energy exchanges between soil and the atmosphere. Their experiments showed that a mulch having a leaf area index of 1 intercepted less rainfall and was preferable for soil water optimization, whereas a mulch with an equivalent leaf area of 4 provided better soil insulation and reduced soil temperatures.

In tropical climates the soil temperature reduction due to residue retention or mulching, is often beneficial. For example, Gajri *et al.* (1994), in North-West India, attributed distinct increases in leaf area in young maize plants grown with residues present, to soil temperature differences early in the growing season. Temperature in bare soil were 26 °C compared with 23 °C under residues. In cooler climates temperature reductions of this order may restrict early springtime germination in which case use of strip tillage systems may be advantageous. For example, Azooz *et al.* (1995) grew maize in 30 cm wide tilled strips in an otherwise untilled area where residues were retained, and observed increased early season soil temperatures in the seedbed, relative to untilled areas, and this improvement was reflected in early growth of the crop. Dwyer *et al.* (1995) similarly noted that lower soil temperatures where all residues were retained in no-tillage systems delayed early maize growth to the 12-leaf stage, the effect of which was evident in yields. Partial removal of residues was advantageous in terms of early development and subsequent yield.

MECHANICAL IMPEDANCE

Mechanical impedance occurs where soil is lacking in pores of appropriate size for roots or shoots to grow through, and/or is too hard for the growing root or shoot to push out of the way. The shoot from a seed has to force its way through the overlying soil to the surface. A root must be able to enlarge existing pores, or create new pores, to elongate through the soil. It seems probable that root hairs (which are involved in nutrient uptake) can only grow into pre-existing pores which are of the same or greater diameter than they, i.e. $\geq 10 \mu\text{m}$ diameter.

Shoot growth and seedling emergence

The effect of mechanical impedance on shoot growth is limited to the short period between seed germination and shoot emergence at the soil surface, and restricted to the shallow soil layer between the seed and the surface. The impact of mechanical impedance on seedling emergence is examined in Chapter 4 in the context of soil crusting but such impedance can also arise due to poor structure at the surface, hardsetting of the surface layer, surface compaction due to traffic over the seedbed, or as a result of overdeep seed placement.

Where tillage is used to create a seedbed, the aim is to create a fine porous tilth. However, wet weather conditions may preclude or delay appropriate operations resulting in a coarse, cloddy surface. Conversely dry conditions may result in a powdery tilth susceptible to wind erosion. Rainfall after tillage but before seedling emergence can cause structural collapse at the soil surface in soils of low aggregate stability. This is the beginning of crust development but even incipient structural collapse may hinder shoot emergence. Hardsetting conditions can be difficult to ameliorate with tillage if the soil is dry. Where drying after seed sowing leads to hardsetting in the layer above the seeds, emergence will be hindered as if a crust had developed.

Root growth

Roots are geotropic, i.e. they grow downward under gravity unless obstructed by stones or other mechanical impedance. Mechanical impedance to root growth arises if the soil presents insufficient pores and failure zones for the growing root system to make use of. Rooting is therefore inhibited or re-directed for more successful root growth will occur wherever more porous and structured soil is present. Horizontal growth will dominate until further vertical growth is possible. For example, in the subsoil of a clay, roots will exploit the shrinkage cracks and weaknesses that develop during the dry season. But, there may be little penetration into the prismatic clay structures between the cracks which comprise most of the soil volume (Figure 15). Water and nutrient extraction is therefore confined to the soil at the faces of the prismatic structures.

Where roots encounter a more continuous compacted layer such as a plough pan, horizontal growth will dominate and can result in a dense root mat (Figure 15). However, the effect of such a compacted layer on rooting is often more complex. The reduced porosity is likely to restrict drainage resulting in poor aeration and possibly waterlogging above the pan. This will reduce root growth rates and may cause root death.

The maximum pressure which roots can exert on soil to enlarge or create pores is about 3 MPa, and so the energy used by a plant to overcome soil strength is very small. Any restriction to root growth reduces the volume of soil from which the plant can obtain water and nutrients and may result in water stress and nutrient deficiencies which restrict crop growth and development. In a fertile soil, the effect of impedance may vary between seasons due to

different rainfall. In a dry season, the effects of restricted root growth are likely to be more serious than when soil water is plentiful due to wetter weather.

The impact of soil compaction on yield of vegetable crops of different rooting habit is similar (Stone, 1988). Differences in root architecture and mean root diameter were found to be of little benefit in overcoming adverse soil structural conditions. It is possible that the relationship between root elongation rate and soil strength is similar for most crop species. Greacen (1987) provides a review of the subject of mechanical impedance to root growth.

Causes of mechanical impedance to root growth

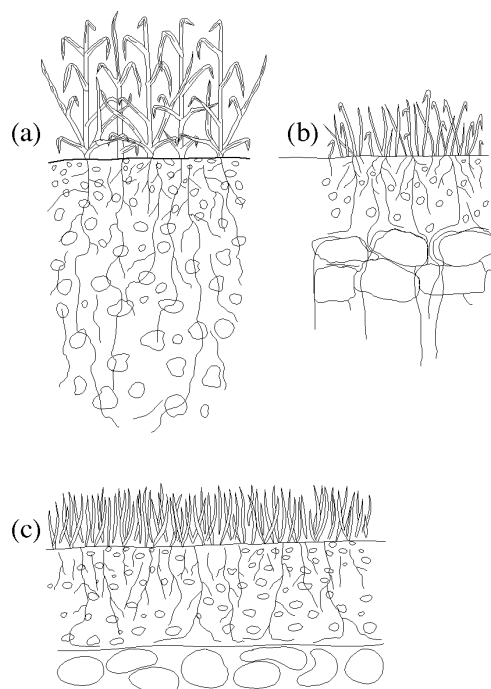
Poor soil structural conditions causing mechanical impedance may be due to inherent soil properties, or a consequence of past or present farm operations, or a combination of all of these. Cohesive soils where structural development is poor, perhaps due to low levels of organic matter and faunal and microbial activity, or a low clay content, are susceptible to problems of mechanical impedance. The condition of such soils can be exacerbated by repeated tillage to loosen them without organic additions. Soils in which hardsetting occurs are very difficult to manage if prolonged drying occurs early in the season before the roots have reached a depth of 20 cm.

Tillage operations over several years may lead to compacted layers in field soils. Plough pans develop in clayey soils, at the base of the plough layer, due to smearing under the plough blade as it passes if ploughing is conducted when the soil is too wet. Ploughing at the same depth year after year re-inforces the pan development. The combination of weather conditions and soil type may mean that pan development is inevitable. Occasional subsoiling i.e. extra deep ploughing, may be the only way to break up a pan.

Passage of any machinery across a field is likely to cause some compaction where the wheels have passed. Where mechanized farming is the norm, usual practice is to re-use the same tracks for all post-seeding operations e.g. fertilizer applications, pest and herbicide spraying. This limits damage to the crop itself and means that the compacted zone is restricted. The effect of the repeated wheeling depends on the soil type, the weight of the equipment used and the soil water conditions at the time of the operation. Sinkage of the soil in the tracks is likely, but the compression may extend to 60 cm or deeper. At the end of the season, careful tillage will allow structural recovery in the surface soil but it is difficult to ameliorate the

FIGURE 15

a. Root growth in a soil with no mechanical impedance problems; b. Root growth in a soil with prismatic structured sub-horizons. Vertical root extension is restricted to the cracks between the clay structures; c. Root growth above a compacted subsoil. Vertical extension is hindered due to mechanical impedance but restricted drainage causing aeration problems may also be a factor



effects on soil structure at greater depth. Root growth in the vicinity of tracks developed in previous years may therefore be inhibited.

Soil structural degradation due to animal traffic, particularly under wet soil conditions, can also result in mechanical impedance to root growth. However, where severe trampling has occurred, the reduction in drainage rates from the soil and poor aeration will compound any problems due to mechanical impedance.

Measurement of mechanical impedance to root growth

Approaches to assessing the effects of mechanical impedance on rooting range from observing rooting patterns in soil, to monitoring the effect of impedance on plant growth and yield. The soil impedance is usually quantified with some measure of soil strength although bulk density measurements can be useful too. Soil strength can be measured directly using tensile and shear strength tests. However these do not lend themselves to application to bulk soil in the field. Penetrometers are more usually used. A penetrometer is a device that when forced into soil allows the resistance to penetration to be measured. In the context of roots and penetrometers, the term resistance refers to the force exerted by the penetrometer or root, divided by its cross-sectional area. Bengough (1991) recommended the use of small diameter "needle" penetrometers as "probably the best indirect method of estimating soil resistance to root growth". Good relationships between root elongation rate and penetrometer resistance have been found for particular soil and crop combinations (e.g. Ehlers *et al.*, 1983), elongation rate decreasing with increasing penetrometer resistance.

SOIL EROSION

Soil erosion by wind and water occurs in all environments (Hudson, 1995). It takes place particularly in situations where at times the soil surface is not protected by a cover of vegetation. Removal of soil takes place by detachment of small soil particles from the soil surface and their transport, by wind or water, to another location. The greater the wind or water velocity, the greater the likelihood of particle detachment and the size of particle which can be transported. In the case of wind erosion, particles of up to 0.5 mm diameter (i.e. up to medium to fine sand size) can be entrained by turbulent air and carried short distances. Particles of less than about 0.1 mm diameter (very fine sand and silt size and smaller) tend to be carried higher and transported much greater distances. Water erosion will entrain particles of similar size, but again the smallest are susceptible to being carried greater distances. In both cases, removal of fine particles may cause some movement of larger material, due to undercutting and creep.

Complete degradation of land for agricultural purposes is always a risk in erosion prone areas. However, considerable problems for crop production can arise even where erosion is less severe. Effects may be direct, for example: removal of soil from around the shallow parts of the root system causing instability as well as water and nutrient uptake problems; complete uprooting of seedlings or plants; removal of soil from around seeds. In the case of both wind and water erosion, the pressure and abrasive action exerted around the base of the plant due to moving soil particles may cause damage. Weesies *et al.* (1994), for example, report yield reductions of from 9 to 18% for maize, and of 17 to 24% for soybean, on three soils subject to severe water erosion, compared with yield from the same soils with only slight erosion. Reduction of soil depth and of available water capacity were particularly important in influencing yield from the severe erosion sites. In the longer term soil erosion is harmful in removing the upper layer of soil which is generally the most nutrient rich, and nutrient and

water retentive part of the soil profile. Preferential removal of the finer soil particles, particularly clay and organic matter, exacerbates that effect.

Soil erosion studies tend to emphasize the removal of soil from fields. Deposition of the products of erosion can equally cause problems. Partial submergence of growing plants and the soil surrounding them, by deposition of wind or water transported material can occur. Problems are likely to be more acute if this happens early in plant development when the plant shoot is more fragile. Depending on the nature of the deposited material, and the conditions of deposition, the porosity of the surface layer may be reduced therefore decreasing infiltration rates and aeration of the soil. Material that is transported by water from a field may cause siltation of drains, stream channels or reservoirs further down stream and consequent problems for water supply, flooding or other difficulties for the wider region.

However, because it is the finer soil particles which are most susceptible to soil erosion, and as these are the most useful from a plant nutrient point of view, deposition has benefits. The fertility of the soils of some regions is maintained due to deposition of suspended sediment in the course of periodic flooding. On a smaller scale, deposition of eroded material in the lower part of a field may enhance soil fertility there if soil structure and soil water conditions are favourable.

Soil structure is intimately involved in soil erosion because it determines the size and strength of the aggregates at the soil surface that are exposed to erosion processes. The particles which are transported by wind or water may be primary particles, micro-aggregates or fragments of aggregates. If a soil presents a well structured surface where the particles are predominantly greater than 0.5 mm in diameter, water infiltration is not limited by poor conductivity and the aggregates are stable, erosion will be minimal.

Currently most research emphasis and conservation practice is placed on understanding and preventing water erosion of soils, because of its prevalence. The following account reflects this giving only brief attention to wind erosion.

Wind erosion

Wind erosion problems were recognized earlier than water erosion due to cultivation, for the wind transport of dust from fields is so much more visible. Wind erosion often has been induced by cereal monoculture and/or removal of field boundaries which previously acted as effective wind breaks. Wind erosion can be controlled through the use of measures to:

- reduce ground level wind velocity, e.g. use of windbreaks or strip tillage oriented across the direction of the prevailing wind, keeping soil covered with plants or plant residues;
- maintaining large sized stable particles at the soil surface.

Aggregate strength as well as size is important, for to remain large, aggregates must be strong enough to withstand abrasion when dry and collapse on wetting. In general, the aggregate strength of sandy soils is less than those with a greater clay content and so they are more prone to wind erosion. Moistness considerably reduces the susceptibility of a soil to wind erosion because of the enhancement of aggregate strength due to surface tension forces within the water filled pores. Wind erosion is therefore mainly confined to low rainfall areas. Soil crusting may enhance or hinder wind erosion depending on the state of the crust, and the particle size distribution of the material at the immediate surface.

Water erosion

The damage caused by water erosion ranges from almost insignificant to very severe. Wischmeier (1970) suggested that rates of soil removal of between 7 and 11 t ha⁻¹ a⁻¹ can be tolerated, at least under soil and farming conditions in the USA. Large quantities of soil may be removed from a field, and irregularities at the soil surface may induce channelling of water flow and gully formation. Gullies incise into a field surface and can ultimately preclude future mechanized cultivation if the field surface is cut up badly. Areas bordering deeply incised stream valleys, and at the perimeter of existing badlands (i.e. highly gullied topography), are susceptible to badland development which will preclude future use for crop production.

Water erosion is usually initiated by raindrops. If the soil is dry, the drops will be absorbed wetting up the surface soil. The wetting can dilute the soil suspension causing a change in electrolyte concentration sufficient to disperse some clay material. Rapid wetting may compress air in closed soil pores within aggregates to the point that the air pressure exceeds the aggregate strength. If that occurs, the aggregates fracture along zones of weakness and smaller particles are released. If the drops are large, their mechanical impact may also cause aggregate collapse. The effect of raindrops can therefore be to break down the structure of the soil surface bringing finer particles into suspension.

If at a later stage of the rainfall, or during subsequent rainfalls, the rainfall intensity exceeds the infiltration rate, ponding of water will be initiated and flow down at any slope. The greater the rainfall intensity, and the steeper the slope, the greater the velocity of the surface flow and its potential for entraining soil particles and transporting them. When the flow velocity decreases, usually due to reduced slope, larger particles will be deposited, and if flow ceases, particles will sediment out overtime, the smallest ones taking longest. Erosion can arise purely as a consequence of water flow over a soil surface, or due to the combined effect of rainfall and water flow. The balance of the relative importance of raindrop detachment and runoff entrainment changes with soil type and condition, and slope as well as rainfall and runoff intensity (Profitt and Rose, 1991).

Modelling soil erosion

Appreciation and prediction of soil water erosion in many parts of the world has until recently been dominated by the Universal Soil Loss Equation, USLE, developed by Wischmeier and Smith (1965) of the United States Department of Agriculture. It predicts the mass of soil lost per unit area, per time period due to water erosion. The calculation includes six factors which are:

- the erosive character of the rainfall (its characteristic intensity and hence kinetic energy)
- the erodibility of the soil (the amount lost from a standardized plot in given rainfall conditions);
- a slope length factor;
- a slope steepness factor (slope curvature can be allowed for, convexity increasing and concavity decreasing soil loss);
- a cropping management factor; and
- a factor allowing for erosion control practices.

The USLE became widely known and used because it is simple to understand and easily applied. However, it is an empirical rather than a process based model and so unable to incorporate advances in the understanding of erosion processes. A revised version of the USLE, RUSLE, was recently released by USDA but it too has limitations. For example, the benefits for soil structure derived from no-till farming are not allowed for (Glanz, 1994). RUSLE will be superseded by a new process based erosion prediction system (Lane *et al.*, 1992). A great variety of other process based models are available for erosion prediction. In the European Community, the process based erosion research and experience of several countries is being brought together in EUROSEM - the European Soil Erosion Model (Morgan *et al.*, 1994). Manrique (1993) has reviewed the technology available for erosion assessment in the Tropics noting the data requirements of a selection of empirical and physically based models. As models become more sophisticated, so they tend to become more data hungry but appreciation of their sensitivity to poor quality data input becomes more difficult. For example, the finite difference model of Sharda *et al.* (1994) for simulating runoff and soil erosion requires data on antecedent soil water conditions, saturated hydraulic conductivity, surface roughness, slope, as well as crop and climate parameters and information as to conservation works that have been carried out.

Much current research effort in soil erosion is looking more and more closely at the detail of the processes involved with a view to modelling. Examples are research into the development of canopy structure of different plant species so that the canopy effect on the erosivity of raindrops, or the erosive force of wind, can be simulated as a crop develops (Armbrust and Bilbro, 1993), and understanding of the effect of clod size distribution on soil erodibility (Ambassakiki and Lal, 1992).

The benefits of long-term studies of soil erosion are now being realized. In particular, plots which have been subject to no-till treatments for several years, have recently been cultivated to permit direct comparison of the effects of structural improvement on erodibility with that of conventionally tilled plots. It has been found that generally the erosion benefits of no-till procedure largely accrue from the presence of plant residues at the soil surface rather than the improvement of soil structure, although the latter is a contributory factor (Bradford and Huang, 1994; Auerswald *et al.*, 1994). An overview of irrigation induced erosion in the United States has shown that furrow irrigation can result in soil losses ranging from 20 to 100 t ha⁻¹ a⁻¹ while rates are less from overhead irrigated fields e.g. only up to 33 t ha⁻¹ a⁻¹ under centre pivot type irrigation. It is estimated that in Southern Idaho crop yield potentials have been reduced by 25% due to 80 years of irrigation induced erosion (Koluvek *et al.*, 1993).

Conservation measures advocated by FAO (1983, 1984, 1987) are very relevant. A range of possibilities has opened up with the development of equipment and herbicides so that no-till options are much more favourable. Baker *et al.* (1996) preface their book on no-tillage with the statement that "No technique yet devised by mankind has been anywhere near as effective at halting soil erosion and making food production truly sustainable as no-tillage". The following Chapter describes these techniques. The use of soil conditioners to improve soil structure and reduce erodibility is also viable though costly (Levy *et al.*, 1992).

Chapter 6

Soil management through tillage/no-tillage

Production of all crops involves the use of some type of tillage system. On the one hand, the tillage system may be very simple, involving either digging or punching holes to sow seeds. On the other hand, it may be a complex system comprised of primary tillage and several secondary tillage operations before and after crop establishment, with different machines and equipment.

Benefits from tillage include (a) improvement of the soil environment by imparting desirable soil-air-water relations in seedbeds, (b) control of weeds, and (c) reduction of the mechanical impedance to root growth. Regardless of whether it is done using a hoe or machines, tillage invariably cuts, loosens, and, in some cases, mixes and inverts the soil. Depending on the objectives, it may also smooth or shape the soil surface. In some tillage systems, large clods created during primary tillage may be pulverized during secondary operations, thus exposing soil aggregates and particle surfaces to the atmosphere with the resultant oxidation of organic matter. The loss of organic matter through oxidation, may exacerbate the structural instability of some soils following continuous cultivation. Because of this deleterious effect on soil structure, a number of scientists (e.g., Phillips and Phillips, 1984; Lal, 1990a) have, during the last two decades, questioned the logic in following certain conventional tillage practices (e.g., those that remove or bury crop residue, invert the soil, and pulverize large clods through several disk harrowing operations).

The current trend in many developed countries is to replace "clean tillage" (defined later), which may accelerate organic matter decline and increase erosion potential, with conservation tillage systems. This is because conservation tillage systems reduce the detrimental effects of the ever-present soil degradation processes. However, there are two schools of thought on the appropriateness of tilling soils. Some researchers believe that tillage has beneficial effects on soils because it is necessary for weed control, for loosening compacted and crusted soils, and for increasing the rooting depth of shallow soils. Others believe that by cutting, mixing, pulverizing, and inverting, tillage in the long run does more harm than good to soils and should therefore be discontinued.

The protagonists of both schools of thought have experimental evidence to support their arguments. A closer examination of the available experimental evidence, however, appears to indicate that tillage is not very necessary for soils with clay content exceeding 20 percent and whose clay mineralogy is dominated by the swelling 2:1 clay minerals, e.g., smectites. In these soils, the swelling and shrinking processes and their resultant inversion of the soil as it wets and dries, regenerate a good and desirable structure and so tillage may either not be required or can be reduced considerably (Nicou and Charreau, 1985). For soils having less than 20 percent clay or whose clay mineralogy is dominated by the non-shrinking clay minerals (e.g., kaolinite and illite), some form of tillage reportedly is necessary to loosen the compact, hard soils, thus providing an adequate and desirable soil-air-water ratio for growth and easy movement of both crop roots and soil organisms. In the section that follows, we examine the different types of tillage systems and indicate their suitability to different conditions.

"CLEAN" TILLAGE

Clean tillage may be defined as "a process of ploughing and cultivation which incorporates all residues and prevents growth of all vegetation except the particular crop desired during the growing season" (SSSA, 1987). Although this definition emphasizes residue incorporation, clean tillage also includes systems in which all residues are either removed and burned before sowing, or removed for other purposes (livestock feed or bedding, building or fencing material, etc.). In this system, most of the soil surface is left bare especially at seeding and during the initial crop growth stages until a full crop canopy is established. The clean tillage system has been adopted in the past because it reduces competition between crops and weeds for water, nutrients, and sunlight. In developed countries, weeds and residues are incorporated using inversion tillage (e.g., mouldboard, disk, or lister ploughs) and subsequent disk harrowing to break up large clods. One operation with such inversion-type equipment usually incorporates about 90 percent of surface residues (Table 6.1). During crop growth, weeds may be controlled by cultivation, hoeing or using herbicides. Clean tillage in most developing countries of the arid and semi-arid tropics is achieved manually with either a cutlass and hoe, or with an animal-drawn plough consisting of a carved wooden log with an attached iron blade. In these countries, residues are first collected into heaps and burned before tillage with either the hoe or the animal-drawn equipment. Because of the limited draft power, animal-drawn ploughs have very little inversion action when compared with mouldboard or disk ploughs. Use of hoes also results in little soil inversion.

Not only does clean tillage involve inversion of soil, it also involves soil mixing using implements such as disk harrows, tandem disks, one-way disks, and rotary tillers. These implements usually incorporate about 50 percent of the surface residues at each operation (Table 12). Whereas soil inversion and mixing equipment loosen, mix, and invert soil, other equipment (e.g., chisels, sweep and blade ploughs, and some harrows) loosen the soil without inverting or mixing. However, even these implements, result in some losses of residues. Therefore, repeated operations often leave the soil devoid of residues at planting time, particularly in situations where initial residue amounts on the soil surface are low.

By effectively incorporating residues in the soil, clean tillage eliminates or minimizes the interference of residues with sowing, cultivating, and weed control. It also facilitates the incorporation of fertilizers, lime, and pesticides. Other advantages of clean tillage include (a) breaking soil crusts to enhance water infiltration and (b) increasing soil surface roughness to increase temporary surface water storage. Thus it facilitates infiltration of water that would otherwise be lost as runoff and reduces susceptibility to wind erosion. Clean tillage also loosens condensed and impermeable soil horizons that restrict or prevent root penetration, movement of fluids, and activities of soil organisms. It buries residues to control the proliferation of pathogens and insect pests that reside in and/or live on the residues during the off-season period for crop production.

The main disadvantage of clean tillage is that it leaves the soil surface devoid of residues and it renders most soils vulnerable to soil erosion by water and/or by wind. This is because residues are no longer present to reduce the impact of raindrops, retard overland flow of water, and reduce wind speeds at the soil surface.

Clean tillage also results in the decline of soil organic matter content (Hobbs and Brown, 1957, 1965; Johnson, 1950; Johnson and Davis, 1972; Johnson *et al.*, 1974; Unger, 1968; Unger *et al.*, 1973), which decreases soil aggregate stability (Johnston *et al.*, 1943; Mazurak and Ramig, 1962; Kemper and Koch, 1966) and results in deterioration of soil quality (Johnston *et al.*, 1943;

TABLE 12
Residue remaining following different operations^a

Implement	Non-fragile ^b	Fragile ^b
PLOUGHS:	--- % Remaining ---	
Mouldboard plough	0-10	0-5
Disk plough	10-20	5-15
MACHINES WHICH FRACTURE SOIL:		
Paratill/paraplow	80-90	75-85
"V" ripper/subsoiler		
30 to 35 cm deep, 50 cm spacing	70-90	60-80
Subsoiler + chisel	50-70	40-50
Disk + subsoiler	30-50	10-20
CHISEL PLOUGHS WITH:		
Sweeps	70-85	50-60
Straight chisel spike points	60-80	40-60
Twisted points or shovels	50-70	30-40
COMBINATION CHISEL PLOUGHS:		
Coulter chisel ploughs with:		
Sweeps	60-80	40-50
Straight chisel spike points	50-70	30-40
Twisted points or shovels	40-60	20-30
Disk chisel ploughs with:		
Sweeps	60-70	30-50
Straight chisel spike points	50-60	30-40
Twisted points or shovels	30-50	20-30
UNDERCUTTERS:		
Sweep, "V"-Blade > 75 cm wide	85-95	70-80
Sweeps, 50-75 cm wide	80-90	65-75
DISKS HARROWS:		
Offset or tandem		
Heavy ploughing > 25 cm spacing	25-50	10-25
Primary cutting > 23 cm spacing	30-60	20-40
Finishing, 18-23 cm spacing	40-70	25-40
Light tandem disk after harvest	70-80	40-50
One-way disk with:		
30-40 cm blades	40-50	20-40
45-75 cm blades	20-40	10-30
Single gang disk	50-70	40-60
FIELD CULTIVATOR + levelling attachments:		
As the primary tillage operation:		
Sweeps 30-50 cm	60-80	55-75
Sweeps or shovels 15-30 cm	55-75	50-70
Duckfoot points	60-70	35-50
As a secondary operation:		
Sweeps 30-50 cm	80-90	60-75
Sweeps or shovels 15-30 cm	70-80	50-60
Duckfoot points	60-70	35-50
FINISHING TOOLS:		
Combination finishing tools with:		
Disks, shanks, & levelling attachments	50-70	30-50
Spring teeth & rolling basket	70-90	50-70
Harrows:		
Springtooth (coil tine)	60-80	50-70
Spike tooth	70-90	60-80
Flex-tine tooth	75-90	70-85
Roller harrow (cultipacker)	60-80	50-70
Packer roller	90-95	90-95
Rotary Tiller:		
Secondary operation 8 cm deep	40-60	20-40
Primary operation 15 cm deep	15-35	5-15

TABLE 12 Cont'd

Implement	Non-fragile ^b	Fragile ^b
RODWEEDERS:		
Plain rotary rod	80-90	50-60
With semi-chisels or shovels	70-80	60-70
STRIP TILLAGE MACHINES:		
Rotary tiller, 30 cm tilled on 100 cm rows	60-75	50-60
ROW CULTIVATORS: > 75 cm spacing		
Single sweep per row	75-90	55-70
Multiple sweeps per row	75-85	55-65
Finger wheel cultivator	65-75	50-60
Rolling disk cultivator	45-55	40-50
Ridge till cultivator	20-40	5-25
UNCLASSIFIED MACHINES:		
Anhydrous applicator	75-85	45-70
Anhydrous applicator + closing disks	60-75	30-50
Subsurface manure applicator	60-80	40-60
Rotary hoe	85-90	80-90
Bedders, listers, & hippers	15-30	5-20
Furrow diker	85-95	75-85
Mulch treader	70-85	60-75
DRILLS:		
Hoe opener drills	50-80	40-60
Semi-deep furrow drill or press drill (18-30 cm spacing)	70-90	50-80
Deep furrow drill with > 30 cm spacing	60-80	50-80
Single disk opener drills	85-100	75-85
Double disk opener drills	80-100	60-80
No-till drills and drills + attachments		
In standing stubble:		
Smooth no-till coulters	85-95	70-85
Ripple or bubble coulters	80-85	65-85
Fluted coulters	75-80	60-80
In flat residues:		
Smooth no-till coulters	65-85	50-70
Ripple or bubble coulters	60-75	45-65
Fluted coulters	55-70	40-60
ROW PLANTERS:		
Conventional planters with:		
Runner openers	85-95	80-90
Staggered double disk openers	90-95	85-95
Double disk openers	85-95	75-85
No-till planters with:		
Smooth coulters	85-95	75-90
Ripple coulters	75-90	70-85
Fluted coulters	65-85	55-80
Strip till planters (20-35 cm strip) with:		
2 or 3 fluted coulters	60-80	50-75
Row cleaning devices	60-80	50-60
Ridge-till planter	40-60	20-40
DECOMPOSITION: ^c		
Warm humid	65-85	60-80
Warm dry	70-90	65-85
Cool humid	70-90	65-85
Cool dry	75-95	75-90

^a Adapted from Steiner et al. (1994).

^b Non-fragile crops include: Alfalfa or legume hay, barley, buckwheat, corn, cotton, forage silage, grass hay, millet, oats, pasture, rice, rye, sorghum, triticale, and wheat. Fragile crops include: Canola, dry beans, dry peas, fall-seeded cover crops, grapes, green peas, guar, lentils, peanuts, potatoes, safflower, soybeans, sugar beats, sunflowers, and vegetables. If a straw chopper or shredder is used to cut straw or other residue materials into small pieces, then the residues should be considered fragile.

^c Loss of cover due to decomposition is highly variable during fallow periods, depending on length of the fallow, climate, crop material, and initial amount of residue.

Mazurak *et al.*, 1955; Ramig and Mazurak, 1964; Unger, 1975). Other disadvantages of clean tillage include the need for larger tractors and equipment, and a larger assortment of equipment.

CONSERVATION TILLAGE

Conservation tillage as defined by the Conservation Technology Information Center (CTIC, 1993) in Indiana, USA, is "any tillage and planting system in which at least 30 percent of the soil surface is covered by plant residue after planting to reduce erosion by water. Where soil erosion by wind is the primary concern, at least 1000 lbs of flat small grain residue per acre (1120 kg ha⁻¹) should be put on the surface during the critical erosion period". The CTIC identifies four main conservation tillage systems, viz., no-tillage (also known as no-till, zero-tillage, slot planting, sod planting, ecofallow, chemical fallow, direct drilling), reduced tillage, stubble mulch tillage, and ridge tillage (Parr *et al.*, 1990).

The productivity of soils under any tillage system appears to be related to whether residue is retained on the soil surface. This, particularly in the tropics, is due in part to the intense rainfall that disrupts the surface soil aggregates. For example, in a study to assess the effects over seven years of three tillage treatments (viz., disk, blade, no-tillage) and crop residue management (i.e., with or without stubble) on a Vertisol in the semi-arid subtropics of central Queensland, Australia, Thomas *et al.* (1990) found that stubble retention on the soil surface consistently gave significantly ($P < 0.05$) higher grain yields than stubble removal in no-tilled plots.

TABLE 13

Runoff and sediment yield from maize watersheds at Coshocton, Ohio (USA), during a severe rainstorm (from Harrold and Edwards 1972)

Tillage	Slope (%)	Rainfall (mm)	Runoff (mm)	Sediment yield (Mg/ha)
Ploughed, clean tilled sloping rows	6.6	140	112	50.7
Ploughed, clean tilled contour rows	5.8	140	58	7.2
No-tillage contour rows	20.7	129	64	64.0

The success of conservation tillage depends largely on herbicides, crop residues on the soil surface, and, in the case of no-tillage, planting equipment to permit precision sowing through trash. One of the problems sometimes encountered with conservation tillage is the toxic effect of substances (phytotoxicity or allelopathy) from residues on subsequent crops (Elliott *et al.*, 1978). It has been most severe when subsequent crops are planted into large amounts of residue. Phytotoxicity may also be related to type of residue, crop grown, and soil environment. Conservation tillage may increase, decrease, or have no effect on plant diseases. Under certain conditions, crop residues from conservation tillage systems may provide an excellent source of overwintering inoculum for diseases of many field crops, thus increasing the overwintering survival rate of pathogen propagules. Crop residues may increase the activity of organisms that are antagonistic to pathogens, or may modify the soil environment to favour selected organisms. Residues may also affect the survival of pathogen vectors or may decrease soil pH, which will in turn affect survival of some pathogens in soil (Boosalis *et al.*, 1981; Sumner *et al.*, 1981; Kirby, 1985).

No-tillage

This is a method of crop production that involves no seedbed preparation other than opening the soil for the purpose of placing seed at the desired depth (SCSA, 1982). Sowing is done by cutting small slits or by punching holes in the soil. Weed control is achieved with herbicides. If the previous crop's residue is not removed, burnt, or grazed by animals roaming freely as happens in many developing countries, the absence of tillage leaves the soil surface covered by the residues. Some residue losses occur as a result of decomposition, wind dispersal, ingestion and/or incorporation by soil organisms, etc. However, large quantities of residues often remain to provide cover and to protect the soil against erosion until the canopy of the next crop is well developed.

If adequate residue amounts are present, they promote environmental conditions conducive to prolific growth of fauna and flora in the soil beneath the litter. There is often an enhancement of the predatory and saprophagous soil arthropod community as well as that of crop damaging herbivores in continuous no-tillage cropping systems (House and Parmelee, 1985). Ground beetles (*Coleoptera: Carabidae*) (House and All, 1981), spiders (Blumberg and Crossley, 1983), and decomposer fauna such as earthworms (Edwards, 1975; Barnes and Ellis, 1979) have been found to occur in higher numbers in no-tillage than in clean-tilled systems. The burrowing activities and incorporation of decomposed organic matter into soil by earthworms improve the structure, aeration, drainage, and water regime of soil. Therefore, increased faunal activity by arthropods and earthworms in soil under no-tillage will, in the long-term, improve the soil quality and thus have beneficial effects on crops.

By increasing the reflection of incoming global irradiance (i.e., increasing the albedo), residues in no-tillage systems reduce net radiation at the soil surface (Shen and Tanner, 1990). In no-tillage systems having crop residues, the roughness length on the soil surface is also increased, thus affecting the latent and sensible heat fluxes through changes in the aerodynamic boundary layer (Van Bavel and Hillel, 1976). Also, the heat flux at the soil surface is modified by the crop residues in no-tillage systems because the thermal conductivity of surface residue is generally lower than that of a mineral soil (Hillel *et al.*, 1975). The sum total of all these effects is that the presence of residues on the surface in no-tillage systems affects the energy and water balances at the soil surface. Therefore, the water and temperature regimes in clean tillage where the soil remains bare will be different from those at the surface in no-tillage. In cold or cool regions, the change in the energy balance in no-tillage systems may be disadvantageous because, in reducing net irradiance at the surface and also modifying heat flux due to low thermal conductivity, residues may delay soil warming at planting time in spring (Triplett and Van Doren, 1977) and thus delay germination, emergence, and crop establishment. As a consequence, frost may occur before crops reach maturity (Swan *et al.*, 1987). Delay in crop establishment of up to 7 days in the northern USA occurred on no-tillage fields compared with fields that had been cleanly tilled (Unger and Stewart, 1976). However, in hot climates the depression of soil temperature in no-tillage systems may be advantageous by avoiding high temperatures that may be detrimental to root growth and soil faunal activities.

The presence of adequate residue on the soil surface in no-tillage systems provides excellent control of erosion by water (Osuji, 1990; Dickey *et al.*, 1983, 1990; Sidiras *et al.*, 1983) and by wind (Finkel, 1986; Woodruff, 1972). The performance of no-tillage compared with other tillage systems in terms of the percent erosion reduction, is given in Table 14. Because of its effectiveness in controlling erosion, no-tillage makes crop production possible on sloping lands that would under clean tillage result in enormous erosion problems. No-tillage systems also ensure significant increases in water conservation (Tables 15 and 16). Higher soil

profile water content in conservation tillage systems is beneficial to crops grown in seasonally-dry arid and semi-arid regions.

TABLE 14

Measured surface cover, cumulative soil loss, and erosion reduction from mouldboard plough, due to application of simulated rainfall for various tillage and planting systems in Nebraska (USA).^a

Residue type, slope & soil texture. Tillage and planting operations	Residue cover %	Soil loss Mg/ha	Erosion reduction %
Corn residue, 10% slope, silt loam ^b			
Mouldboard plough, disk, disk, plant	7	17.5	--
Chisel plough, disk, plant	35	4.7	74
Disk, disk, plant	21	4.9	72
Rotary-till, plant	27	4.3	76
Till-plant	34	2.5	86
No-till plant	39	1.6	92
Soybean residue, 5% slope, silty clay loam ^c			
Mouldboard plough, disk, disk, plant	2	32	--
Chisel plough, disk, plant	7	21.5	32
Disk, plant	8	23.7	26
Field cultivate, plant	18	17	46
No-till plant	27	11.4	64
Wheat residue, 4% slope, silt loam ^d			
Mouldboard plough, harrow, rod weed, drill	9	9.4	--
Blade plough three times, rod weed, drill	29	2.7	72
No-till drill	86	4.5	96
Oat residue, 10% slope, silt loam ^e			
Mouldboard plough, disk, harrow, plant	4	56	--
Disk, disk, harrow, plant	5	46.2	24
Blade plough, disk, harrow, plant	10	47	16
No-till plant	39	11.2	80

^a From Dickey *et al.* (1990).

^b 51 mm water in 45 minutes.

^c 51 mm water in 45 minutes.

^d 70 mm water in 75 minutes.

^e 64 mm water in 60 minutes.

TABLE 15

Tillage effects on water storage during fallow after wheat harvest, sorghum grain yields, and water use efficiency in an irrigated winter wheat-fallow-dryland grain sorghum cropping system, Bushland, Texas, 1973-1977.^{a,b}

Tillage method	Water storage (mm)	Grain yield (Mg/ha)	WUE ^c (kg/m ³)
No-tillage	217 a	3.14 a	0.89 a
Sweep	170 b	2.50 b	0.77 b
Disk	152 c	1.93 c	0.66 c

^a From Unger and Wiese (1979).

^b Values followed by different capital letters are significantly different at the 5% level, based on Duncan's multiple range test.

^c Water use efficiency based on grain yields, growing seasons precipitation, and soil water changes.

On poorly-drained soils or clay soils that are often slowly permeable, reduction of both overland water flow and soil water evaporation by crop residues aggravates the inundation problems (Amemiya, 1977; Griffith *et al.*, 1977). Wet soil conditions under no-tillage may enhance rapid movement of nitrates through macropores, thus leading to losses due to leaching (Blevins *et al.*, 1985) and denitrification (Rice and Smith, 1982). On hard-setting soils and/or sandy soils in arid regions where residues may not be sufficient to cover the soil, the inherent

high bulk density and frequent development of surface crusts after rainstorms may increase runoff from subsequent storms. As a consequence, no-tillage may not enhance infiltration. In such circumstances ploughing with precision implements has usually given best results (Nicou and Chopart, 1979; Huxley, 1979; Willcocks, 1988). Also, addition of adequate quantities of residues to the soil surface may decrease evaporation losses so that the overall soil water balance may be favourable for crop production.

TABLE 16

Effect of tillage method on average soil water storage during fallow after irrigated winter wheat and on subsequent rainfed grain sorghum yields at Bushland, Texas, 1978-1983.^{a,b}

Tillage method	Water Storage ^c (mm)	Grain yield (Mg/ha)	WUE ^d (kg/m ³)
Mouldboard	89 b	2.56 bc	0.71
Disk	109 b	2.37 cd	0.65
Rotary	85 b	2.19 d	0.61
Sweep	114 ab	2.77 b	0.72
No-tillage	141 a	3.34 a	0.83

^a From Unger (1984a).

^b Fallow duration of 10-11 months. Values followed by the same capital letters are not significantly different at the 5% level based on Duncan's multiple range test.

^c Measured to 1.8-m soil depth.

^d Water use efficiency based on grain yield, growing season precipitation, and soil water changes.

The major constraints to adoption of no-tillage practices by farmers, particularly in the semi-arid tropics, are inadequate amount of residues, the farmers' demand for residues as animal feed, fencing, and for household fuel. Unger *et al.* (1991) discussed some possibilities of overcoming these constraints. These include limited or selective residue removal, substitution of high value forages for residue, alley cropping, utilization of wastelands for forage production, and control of livestock numbers.

Reduced tillage

As its name implies, this tillage system (also called minimum tillage) attempts to minimize or reduce the many tillage operations, often involving primary ploughing and four or more secondary tillage operations using disk harrows, chisels, sweep implements etc., that characterize clean tillage. The major objectives for reduced tillage are to conserve soil and water by retaining crop residues on the surface for as long as possible and particularly during periods of the year when the soil is prone to erosion. Unger (1984a) briefly described the various types of reduced tillage systems that are summarized in the following section.

Autumn (fall) plough, field cultivate system

This system is used widely on clay and clay loam soils of the east central Corn Belt in the USA. Primary tillage is usually done with a mouldboard plough followed by secondary tillage consisting of one shallow cultivation with a sweep implement at the time of sowing. In a variant form called autumn (fall) chisel, field cultivate system, mouldboard ploughing is replaced by 20- to 25-cm deep chiselling. This is achieved with a chisel plough having 40-cm sweeps on 38-cm centres for primary tillage. No secondary tillage is done but a modified planter is used to facilitate sowing in heavy residues. The chiselling may also be done with a chisel plough having straight or twisted points, followed by secondary tillage involving either disking and harrowing or field cultivation and harrowing. In some cases a coulter-chisel or disk-chisel is used for primary tillage. This is followed by either a disk-chisel (sweeps), disk-harrow, or field cultivation and harrow for secondary tillage. Alternatively, chiselling may be done in fall (autumn) after soybeans, followed by mouldboard ploughing in the subsequent fall after a

maize crop. In this case, cultivating and harrowing or disking and harrowing would be done as a secondary tillage practice.

Spring plough, wheel-track planting system

In this system, residues from the previous season's crops are retained on the soil surface until ploughing that is followed within 12 to 24 hours by sowing on strip seedbeds. Seedbed preparation and sowing are accomplished in the same operation. This way, the soil does not lose a lot of water before planting. Consequently, the soil water content at planting time is such that the planter wheels break the clods to ensure a firm seedbed.

Disk and plant

Primary tillage in this system is done usually in autumn using either tandem disks set at 8 to 10 cm deep, heavy disks set at 15 to 20 cm deep or a combination of the two. This is followed in the spring by one or more diskings before planting. In order to retain residues on the surface for as long as possible, disking should be delayed and preferably be done with a tandem disk, which does not penetrate as deeply as heavy disks and also incorporates less residue in the soil than heavy disks.

Till-plant system

Tillage and planting are both done in one operation in this system. In some places, tilling the previous season's ridge 5 to 8 cm deep with wide sweeps provides a trash-free zone for planting because the implement is constructed in such a way that it moves old stalks and root clumps into the zone between rows. With compact soils, the implements used for tilling first loosen the compact layer, enabling the seed to be sown directly in the loose soil. Other types of equipment, e.g., subsoiler-planter or "ripper-hipper," will in one operation loosen the compact layer, firm the loose soil in slits with treading wheels, and sow the seed with unit planters.

Combination of tillage and herbicides

An alternative weed control method to tillage is the use of herbicides, which allows more crop residues to be retained on the surface. In situations where residue amounts are normally inadequate, erosion is endemic, and persistent weeds cannot be controlled individually by either tillage or herbicides, a combination of tillage and herbicides has been found to be very effective in controlling weeds, controlling erosion, conserving water and increasing crop yields (Smika and Wicks, 1968; Phillips, 1969; Papendick and Miller, 1977). In this system the soil may be tilled to control existing weeds, loosen compact layers, and/or incorporate some of the residues. Herbicides are then used for subsequent weed control. Alternatively, herbicides may be applied in order to retain more residues on the surface, especially during periods of the year when the soil is prone to erosion. The soil will be tilled later to prepare seedbeds as close to the planting time as possible. Another practice is to use tillage for one crop and herbicide for the other in a two-crop rotation system.

Other systems

These include strip tillage, in which a narrow band (usually 20 cm wide) of soil is tilled using rotary tillers with some of the blades removed, lister ploughing followed by planting, rotary tilling followed by planting, and sweep ploughing followed by planting. All these systems can retain residues on the soil surface for a considerable part of the crop production cycle.

Notable among the advantages of reduced tillage are that they (a) conserve soil and water more effectively than clean tillage, (b) maintain or increase crop yields when compared with clean tillage, (c) involve fewer cultural operations, thus reducing fuel and oils required for crop production and also reducing the labour and machinery time. Major disadvantages include

lower soil temperature, which may delay seed germination, emergence, and crop establishment; poor seed placement because of the presence of residues on the surface; and possible pest problems.

Stubble mulch tillage

This tillage system (also known as mulch farming, trash farming, mulch tillage, or ploughless farming) is defined as tilling the soil so that plant residues or other materials are retained to cover the soil surface (SSSA, 1987). By this definition then, any soil disturbing tillage that retains residues on the surface could be classified as stubble mulch tillage. However, we restrict stubble mulch tillage to tillage that undercuts the soil surface to control weeds and prepares the seedbed in such a way that most crop residues are retained on the surface. Subsurface tillage implements (e.g., sweeps that are 60 cm or wider, rodweeders with or without semi-chisels or small sweeps, straight-blade machines, and chisel ploughs) are used for this purpose. By undercutting the soil surface, residues remain anchored in the surface soil, thus holding the soil *in situ* and also trapping some wind- and water- transported sediments. Although stubble mulch tillage was originally designed to control erosion by wind, it conserves water if and when weeds are effectively controlled. The residues may also enhance infiltration and reduce soil water evaporation. Because of the necessity to control weeds effectively, tillage operations may be performed as frequently as required. Among the main disadvantages of stubble mulch tillage are difficulties in performing tillage operations in the presence of large amounts of residues, difficulties in tilling because of high soil water content due to reduction of evaporation by residues, and poor weed control when precipitation occurs soon after tillage.

Ridge tillage

Ridge tillage has been defined as "a method of land preparation whereby the topsoil is scraped and concentrated in a defined region to deliberately raise the seedbed above the natural terrain" (Lal, 1990b). Mounds and hillocks are also raised seedbeds. Although they are discontinuous in space, they will be used synonymously with ridge tillage in this section. Crops are usually grown on the ridges in rows, with one or more rows per ridge, even though in some cases crops may be grown in the furrows to take advantage of the wetter condition of the soil under the furrows. Ridge tillage is adapted to a wide range of conditions including diverse soils, crops, rainfall regimes, ecological environment, socio-economic and cultural conditions (Lal, 1990b). It is an effective water management and erosion control practice when the system is established on the contour and the slope of land is less than 7 percent (Moldenhauer and Onstad, 1977). On clay soils, ridge tillage can be used to safely dispose of excess surface water (Kampen *et al.*, 1981). However, if it is not properly designed and constructed, breaching of the ridges can cause severe erosion damage as most of the overland flow concentrates in the breached section of the ridge.

Ridge tillage is very effective in conserving water in the root zone in semi-arid to subhumid regions, particularly when ridges have cross ties in the furrows (known either as tied-ridging, furrow blocking, or basin tillage). A series of basins created by the tied-ridge system allows more time for infiltration of surplus water that would otherwise be lost as runoff. However, in allowing more water to infiltrate, the system of tied-ridges may enhance leaching of soil nutrients beyond the root zone.

As noted by Lal (1990b), "Crops are grown with ridge tillage on shallow soils to increase the effective rooting volume; on poorly-drained soils to grow upland crops in well-aerated seedbed; in nutrient-deficient soil to heap up the fertile ash-rich topsoil; on steep slopes to provide drainage channels up and down the slope for safe disposal of surplus water to avoid

risks of land slides; on sloping lands to control erosion; and in dryland farming to conserve water."

TILLAGE EFFECT ON SOIL PROPERTIES AND PROCESSES

The major soil property that is normally affected by tillage is soil structure. This in turn influences water movement into (infiltration), out of (evaporation, drainage), or within (hydraulic conductivity) a soil. Therefore, tillage controls the water regime (water conservation) of the soil profile (Tables 15, 16 and 17). Tillage effect on soil structure also influences heat movement in soil. Consequently, it affects the temperature regime and thus the rate of soil chemical reactions and biological activities. Tillage effects on soil structure also affects soil aeration (Table 18). By influencing structure, tillage affects the hydrological characteristics, particularly overland flow of water (runoff) and sediment transport (erosion). Through its effect on movement of water within the soil, soil structure also influences movement of agrichemicals, including chlorides, nitrates and pesticides, through the soil profile to contaminate groundwater.

TABLE 17
Effect of tillage-induced plough layer porosity and surface roughness on cumulative infiltration of simulated rainfall^a

Tillage treatment ^c	Surface conditions		Cumulative infiltration ^b		
	Pore space ^d (cm)	Roughness (cm)	To initial runoff (cm)	To 2.5 cm runoff (cm)	To 5.0 cm runoff (cm)
Untilled	8.1	0.8	0.9	2.1	2.4
Plough	13.7	5.0	17.1	21.7	23.0
Plough-disk-harrow	12.4	2.5	5.3	7.3	8.4
Cultivated	9.7	2.9	5.7	8.3	9.1
Rotovated	11.7	1.5	2.4	3.8	4.1

^a From Burwell *et al.* (1966)

^b Water applied at a 12.7 cm h⁻¹ rate

^c Ploughing and rotovating performed to 15 cm depth; cultivating to 7.5 cm depth on otherwise untilld soil.

^d Measured to the tillage depth.

There have been conflicting reports on the effect of conservation tillage practices, principally no-tillage, on soil structure. Some indicate that addition of mulches to Alfisols in no-tillage systems improves soil porosity, soil structure and water transmission (e.g., Lal, 1976). Others, e.g., Blevins *et al.* (1985), also indicate that on medium-textured soils in Kentucky, USA, no-tillage has no effect on bulk density (an attribute of structure) while Gantzer and Blake (1978) reported significantly higher bulk density with no-tillage treatments compared with conventional tillage on fine-textured soil. On an Alfisol at the ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) centre in Patancheru, India, the effects of tillage (i.e., no-till, and 10- and 20-cm deep tillage), amendments (i.e., bare soil, rice straw mulch applied at 5 t ha⁻¹ yr⁻¹, and farmyard manure at 15 t ha⁻¹ yr⁻¹), and three perennial species (e.g., *Cajanus cajan*, *Cenchrus ciliaris*, and *Stylosanthes hamata* alone or in combination) were investigated. Tillage produced variable responses during the cropping season in that for a short time (approximately 6 weeks) after tillage, runoff was

TABLE 18
Mean oxygen flux over 60 days in pasture grown under rainfall on a ridge or flat bay on a fine sandy loam at Knoxfield, Victoria^a

Depth mm	Mean oxygen flux (10 ⁻⁵ g m ⁻² s ⁻¹)	
	Ridge	Flat
50	1.72	0.63
100	1.67	0.21
150	1.38	0.08
200	1.2	0.05

^a From West and Black (1969).

reduced from plots that had been tilled compared to the untilled plots. Thereafter, tilled plots had more runoff than no-till plots during the remainder of the cropping season (Smith *et al.*, 1992).

The presence of residues at the soil surface in different types of tillage systems has a tremendous effect on runoff and erosion (Tables 13 and 14). The residues also have an effect on soil temperature, soil reaction, nutrient distribution and availability, population and activities of soil fauna, and, therefore, on soil organic matter content. Clean tillage increases the rate of organic matter decomposition while soils that have been under conservation tillage for several consecutive years have a higher organic carbon content, with a build-up occurring mostly in the surface 0- to 8-cm layer (Blevins *et al.*, 1985; Unger 1991). Other changes that occur in the chemical properties of soil under conservation tillage include lower pH and exchangeable calcium and magnesium, higher levels of exchangeable aluminium and manganese, lower nitrate concentrations, and higher levels of available phosphorus and potassium (Blevins *et al.*, 1985).

TABLE 19

Abundance of soil fauna in ecosystems on the Georgia Piedmont^{a,b}.

	Forest	Meadow	No-till ^c	Ploughed ^c (High soil Organic Matter)	Ploughed (Low soil Organic Matter)
Prostigmata	96,270	51,380	63,860	25,980	7,550
Mesostigmata	6,020	510	6,800	2,650	610
Oribatid	78,380	8,160	33,270	5,100	360
Astigmata	0	0	100	3,490	1,380
Collembola	21,230	1,170	12,490	7,730	23,270
Others	6,820	660	2,600	1,070	0
Microarthropod Totals	208,730	61,890	119,110	46,000	33,170
Earthworms	ND ^d	190	970	150	130

^a From Hendrix *et al.* (1990).

^b Values are numbers of organisms per square metre to a depth of 5 cm for microarthropods and to 15 cm for earthworms.

^c Microarthropod data from House and Parmelee (1985).

^d ND=not determined

A number of changes in soil microbial population and activities occur when an undisturbed soil is tilled. The changes are due largely to the effect tillage has on temperature, water, and organic matter content of soils. Different tillage systems have different effects on these factors because of the varying degrees of reduction of surface residues (Table 12) and the resultant reduction of the mulch effect of the residues left after tillage. Ploughing also pulverizes soil aggregates and disrupts the continuity of soil pores. Soil conditions after tillage may favour soil micro-organisms with short life cycles, have rapid dispersal, high metabolic activity, and unspecialized food and habitat requirement. As a result, there will be changes in microbial species composition, which may alter the nutrient cycling dynamics. Alternatively, by enhancing conditions of the habitat and/or resource availability, tillage and other soil management practices may increase the abundance and diversity of soil organisms. Thus, ploughing may loosen compacted soils to improve soil aeration, while irrigation and drainage may optimize soil water content for microbial growth and activities. As shown in Table 19, the abundance of dominant micro-organisms (e.g., Prostigmata and Oribatid) generally follows the organic matter content of soils (i.e., forest > no-tillage > meadow > ploughed (high organic matter) > ploughed (low organic matter)(Hendrix *et al.*, 1990).

TILLAGE EFFECTS ON CROP YIELD

A number of factors (e.g., weather, incidence of pests and diseases, drainage, etc.) regulate crop growth and yield response. As a result, tillage may have a positive, negative, or no effect on crop yield. Under conditions of favourable precipitation, adequate soil water, good drainage, and adequate available nitrogen, grain yield is not greatly affected by the type of tillage (Al-Darby and Lowery, 1986; Christian and Miller, 1986; Maurya, 1986; Gerik and Morrison, 1984; Locke and Hons, 1988). Alternatively, increased grain yields in conservation tillage systems, particularly no-till, compared with clean tillage, have been reported from areas having limited precipitation and soil water (e.g., Musick *et al.*, 1977; Unger and Wiese, 1979; Jones, 1981; Baumhardt *et al.*, 1985). Lower crop yields with conservation tillage have been obtained in areas receiving adequate to excessive precipitation, low temperatures, poor drainage, and poor weed control (Griffith *et al.*, 1977; Papendick and Miller, 1977; Costamagna *et al.*, 1982; Touchton and Johnson, 1982; Hargrove and Hardcastle, 1984; Gallaher, 1984; Thurlow *et al.*, 1984).

Chapter 7

Research considerations for study of soil physical constraints to crop production

Accurate modelling of soil physical processes and crop yield response to these must be a priority for all areas of soil physics research. The potential of good simulation models for aiding policy decisions at the field, regional and even wider scale is enormous. In soil hydrology and erosion studies, modelling is particularly well advanced but effective model use is often restricted by the absence of the necessary data input e.g. values for saturated hydraulic conductivity, the water retention characteristic or rainfall amounts. The mis-match between the sophistication of soil physical models and the quality of the data available to use with them is often extreme. Better techniques are required for measuring soil parameters *in situ*, at an appropriate scale so that use of theoretical equations or values published in the literature, to obtain values for model parameters, is unnecessary.

Soil physics research suffers from a great diversity of on-going and published work in which results from experiments with the same focus are often difficult to compare precisely. This occurs in other disciplines in the agricultural and environmental sciences too. It arises because different methodologies were used, or the results pertain only to a limited range of soils, and in particular because field experimentation is subject to the variable weather conditions.

Although innovation and ingenuity are essential in research, circumstances do arise where repetition of work on different soils, with different crops, or in otherwise different environments, is valid and will add substantially to the body of knowledge about soil behaviour and crop response. Long term, well thought out, field experiments are especially useful for soil and crop response to seasonal variation year-to-year can be monitored. And, slow processes such as structural change need to be recorded over long periods. In addition, such experiments generate datasets which have enormous potential utility for calibrating and validating simulation models. Their usefulness demands confidence that the experimental work was conducted to a high standard throughout and that the methodology used and experimental results have been fully documented. Hillel (1991) emphasized the need to tackle the difficult task of comprehensive experimentation at realistic scales in the field, for the purpose of validating theories and models. Practical application of soil physics knowledge has been hampered, and still is to an extent, by the publication of unsubstantiated theory based on simple well defined systems unlike field soils.

The discussion of soil physical properties in the foregoing chapters has been underlain by an assumption that soil is a one-dimensional phenomena. In some studies of crop and soil physical features, not even that is assumed - a point measurement of temperature or bulk density, for example, is assumed to characterize the entire plot with no regard for variation in 3-

dimensional space, and in some cases, time. Appreciation of the scale dependence of soil physical properties is growing. For example, some research results reported in earlier chapters focus on the differences between properties of aggregates of different size. Field scale variation of physical properties needs to be understood and methods for coping with these, based on geostatistics, are available. However, the spatial variability of processes tends to differ from the spatial variability of physical properties because of the tendency for the soil system to adjust to reduce gradients of water potential and temperature, for example. This is why consideration of the soil system as 1-dimensional is successful up to a point. Soil management techniques which introduce spatial inhomogeneity, such as drip or furrow irrigation and inter-row cropping, require monitoring which recognizes that, if the system is to be properly assessed.

The main soil factors which influence soil structure and structural stability have been identified. But, full understanding of their interaction with one another and external factors such as water content in the course of tillage, and the maintenance of stability, as yet eludes soil scientists. It is still not possible to predict accurately the soil condition that will result from a particular tillage operation. Research effort is required to understand the conditions under which soils fracture and crumble in response to tillage.

Dexter (1988) identifies the properties of micro-aggregates in the size range 2 - 100 μm as a neglected research area. Their neglect is because they are too small to be seen readily, yet too large for consideration by colloid chemists. Aggregates of this size are very important because the pore spaces between them store much of the water that plants can make use of and are major pathways for water transmission in unsaturated soil.

Research at the field scale into soil hydrology and soil-plant water systems is increasing, taking advantage of the benefits of recent developments in equipment for *in situ* and regular monitoring of soil water potential and water content in particular. In areas where the climatic conditions are such that soil water is in the main non-limiting, the research need is more for methods to maximize use of this resource through, for example, improvements to soil structure to minimize impedance to root growth and maximize aeration.

Where water is limiting, application of a combination of soil hydrological research with agronomy enables objective assessment of the advantages and disadvantages of fallowing or mulching for water conservation, for example. The techniques are available to conduct experiments which measure all aspects of water use and wastage in irrigation projects, and so to clearly determine the most efficient irrigation options. Research of this type needs to be further extended to low technology water conservation and irrigation practices,

The better the comprehension of the response of individual crops to water shortage, the better farmers can be advised as to how and when to use limited water supplies to best effect. Detailed physiological study of the principal cereal crops, and others such as potatoes and sugar cane have brought great benefits to their production in many parts of the world. For example the most drought sensitive periods of these crops are known and their response to water after different drought intensities. A similar level of information is required for many less well known crops. Research to obtain it will be aided by the experience gained from work on more conventional crops and advances in instrumentation. Much potential lies in the careful study of the behaviour of different genotypes of crop species to adverse soil water conditions, and their future use.

The present level of understanding of soil temperature is unsatisfactory. As methods to ameliorate other adverse soil conditions improve, so the importance of soil temperature comes sharper into focus. The components of the energy balance at the soil surface are well known because of their interest to atmospheric physicists. However, much effort is yet required to generalize models of heat fluxes so that temperature change in response to a given intervention, perhaps use of a mulch, can be predicted. As yet little information is known about temperature differences between soils of different texture in the same locality. Much more needs to be known about the values of the thermal properties of different soil types, and how variations within a soil profile interact to generate the temperature conditions at any one time.

Management techniques to ameliorate soil temperature conditions for seed germination are in the main based on empirical experience. Comprehensive evaluation of techniques will permit better informed choices to be made. Improved understanding of soil temperature would aid research into its effect on crop yields and future selection of plant varieties to suit particular conditions more closely. Similarly better understanding of soil aeration and its impact on crop production will permit crop varietal selection to make the most of conditions where aeration is a problem which cannot be ameliorated by drainage or tillage operations.

The effects of mechanical impedance on root development and hence crop yields, are quite well understood and the role of agricultural machinery in causing compaction, and hence impedance is well recognized. However impedance may arise as a result of the presence of natural hard pans or as a result of hard-setting conditions. Methods to ameliorate such conditions and improve soil structure without introducing other problems such as increased erodibility are required.

The move in soil erosion studies away from empiricism to process oriented approaches is to be welcomed. However there are still missing links such as the effect of different crop canopies on raindrop size. Research on soil crusting, which often is the first stage of soil erosion by water, requires more effort. An area worthy of further attention is that of the influence of crusting on seed germination and seedling emergence. Related to this, the whole topic of hard-setting soils deserves greater attention than hitherto.

The inter-linkages between different aspects of soil physics such as aeration and water content, water content and temperature, and especially structure and virtually all other physical phenomena cannot be denied. Researchers tend to compartmentalize their efforts into, for example soil temperature, soil hydrology or soil erosion "boxes". But as emphasized repeatedly here, one cannot be divorced from the others. Recognition of this is essential when it comes to evaluating the impact of management techniques such as mulching and no- or low-tillage operations. For example, the mechanistic linkages between crusting, infiltration and surface management practices are not fully understood. Similarly the influence of mulches used perhaps to prevent soil evaporation, reduce soil temperature or counter soil erosion, on other soil physical behaviour and in achieving the desired aim, deserves more attention.

The foregoing discussion has emphasized the gaps in understanding of the physics of soils yet the main principles governing soil physical behaviour are well established. And, there is a wealth of information regarding the success/failure of applying different management practices in various situations. Familiarity with the underlying processes of soil physical behaviour, and soil management research results, coupled with understanding of local soils and farming practices, provides a good basis for determining how land can be brought into production, and/or yield improvements achieved. There is much scope for the development of

simple, useable models to aid advisors and producers with soil management decisions. Combining research and local experience can produce effective decision support systems as, for example, Daniells *et al.*, (1996) have demonstrated

There is in some cases a wide gap between the yield potential of land and the yields which are attained by local farmers. For example, this may occur in irrigated areas as a result of poor irrigation scheduling practice. Research into how best to implement new techniques, or adapt old ones, is necessary to look at the socio-economic structure within which cropping is conducted. Policy makers and advisors need to recognize what impact, beyond the field, proposed changes to long established practices may have, and the repercussions for crop yields. In many parts of the world, traditional farming practices have served very well without causing degradation problems. Pressure to improve productivity has various origins. Advice on how to achieve this may or may not be welcome or effective. However, the most sophisticated prediction of yield benefits will be worthless if the grower in the field is unable to implement the necessary changes through mis-understanding or economic constraint.

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