CHAPTER 1

INTRODUCTION

Serious concerns were expressed when yields of cotton (*Gossypium hirsutum*) in the Macquarie valley, New South Wales (Figure 1.1) in the 1976/77 season were 40% lower than the average attained over the previous five years (Figure 1.2). The low yields were harvested from stunted plants grown in a

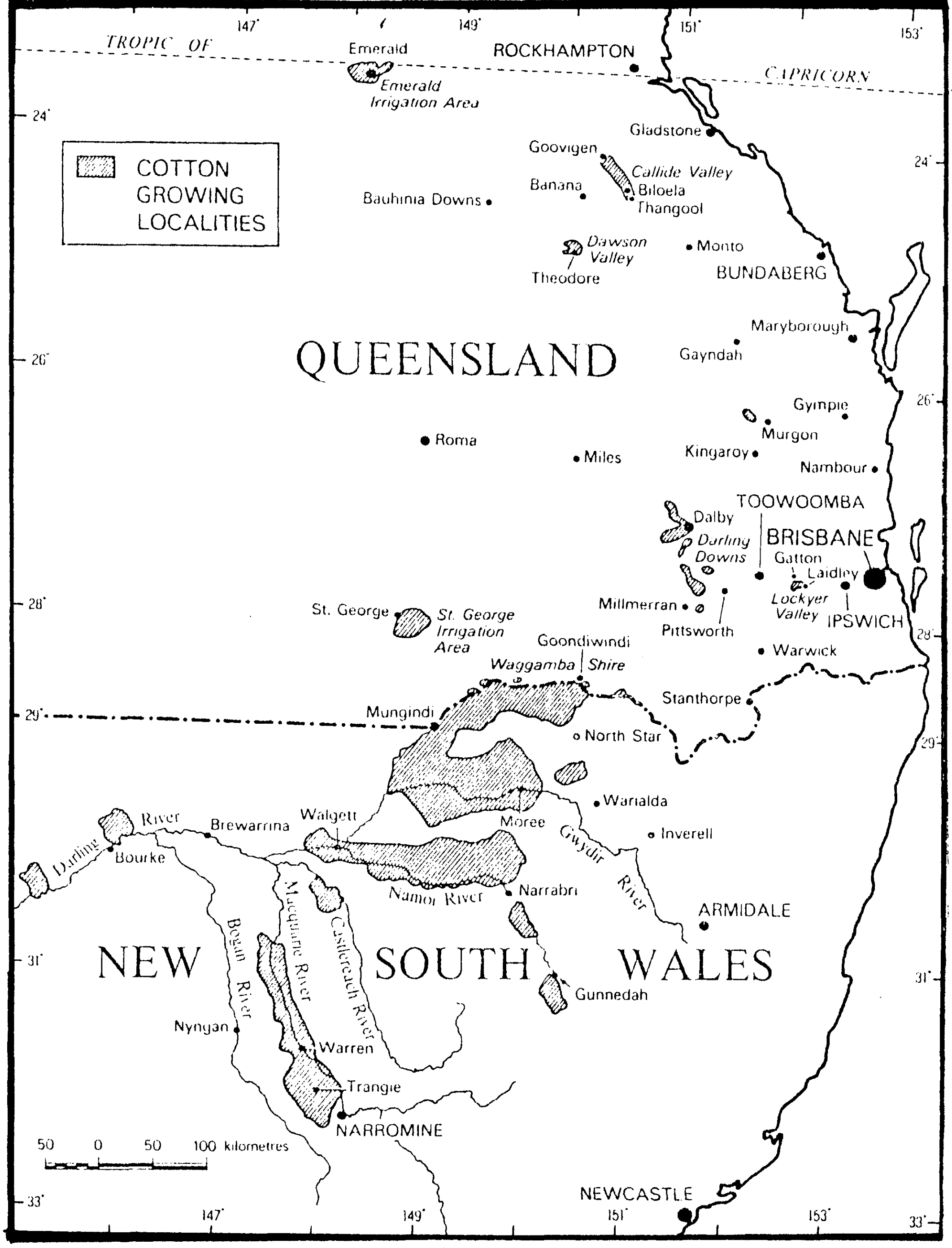

Figure 1.1 Cotton growing localities of Queensland and New South Wales (J. Loveday and R.C. McDonald, unpublished).

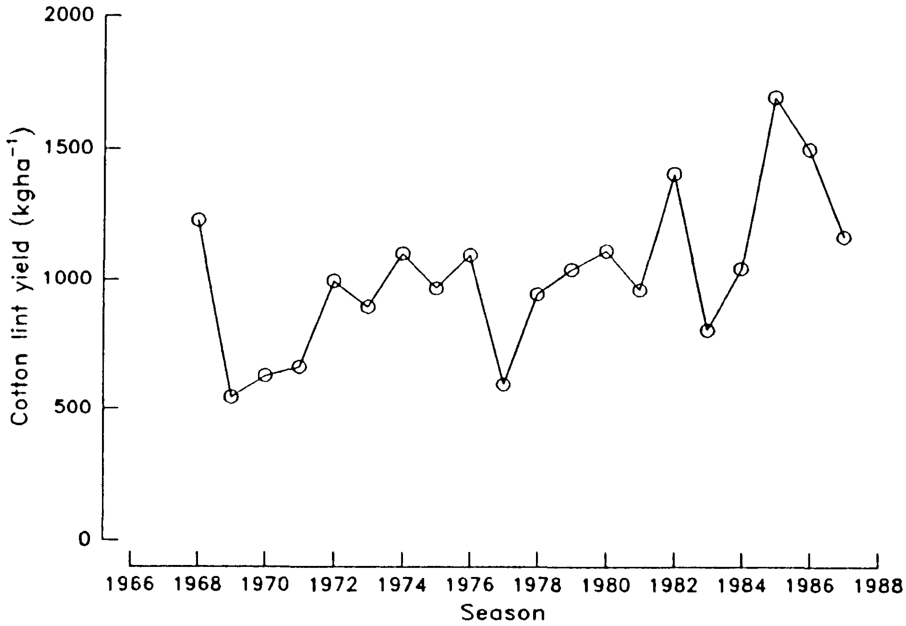

Figure 1.2 Average cotton yields, Auscott Ltd., Warren farm.

favourable growing season with adequate water, but after very wet conditions during seedbed preparation and planting (J. Beale, personal communication). Plant symptoms were inconsistent with common pathogenic diseases, and nutrient application gave little response (D. Anthony, personal communication). Degradation of soil structure was then, by default, implicated as the cause of the poor growth. A research programme to find reasons for the poor cotton growth, and to improve cotton yields and profitability by developing a better soil management system, was established in 1979 by NSW Department of Agriculture and Auscott Ltd. (McKenzie *et al.* 1984b).

The first stage of the programme was to verify that irrigated cropping degraded soil structure. McKenzie *et al.* (1984b) did this in a comparison of soil properties at a site which had been under irrigated cropping for 15 years with those at a nearby site under native pasture. Their conclusion that irrigated cropping caused a decline in soil physical fertility in vertisols was verified by McGarry and Chan (1984), who conducted a field trial in the Namoi valley in 1979. On the basis of a perceived decline in structure, farmers consider that it is necessary to rectify this damage by carrying out such operations as deep tillage to break up compacted zones.

The second stage of the research programme was to ascertain the best way to ameliorate structural degradation in soils used to grow irrigated cotton. Farmer experiments had shown yield improvement when the soil was deep tilled with a tined implement (ripped) after a rotation crop of wheat (*Triticum aestivum*), or safflower (*Carthamus tinctorius*) had been used to dry the soil (Beale, 1982). A tillage experiment was established near Warren in the Macquarie valley (Figure 1.1) in 1981 to evaluate the effectiveness of tillage at depths of 0·15 to 0·7 m, gypsum application, and the frequency of tillage at 0·25 and 0·5 m depths in ameliorating poor structure in a degraded sodic grey vertisol. McKenzie *et* *al.* (1984c) observed little difference in physical properties in response to imposed treatments after one year. In a second cotton crop grown on the same site under wetter conditions, McKenzie *et al.* (1984a) found that the highest cotton yield was associated with the 0·25 m cultivation depth and, although they observed that cultivation at 0·5 m depth before this season had depressed yield, they did not relate yield differences to soil physical properties. An economic analysis by McKenzie *et al.* (1984a) after these two cotton crops showed that ripping once to 0·7 m without gypsum was the most profitable treatment, that reimposition of tillage was profitable at 0·25 but not 0·5 m, and that gypsum application increased profit only for 0·15 m, the shallowest tillage depth studied.

The aims of the third stage of the research programme, including the study described in this thesis, are to improve knowledge of managing the soil to minimize structural degradation, and refine knowledge of amelioration of poor soil structure. The finding of McKenzie *et al.* (1984a) that reimposition of deep tillage was unprofitable, combined with the assertion of Beale (1982) that ripping may be unnecessary after thorough drying of the profile by a crop, raises the main question addressed by the current project of whether "permanent beds" can be used for a number of years whilst maintaining a structure which does not restrict cotton growth. A second question addressed by the current study, is to determine how deep tillage can cause yield depression compared to areas subjected to shallow tillage, such as that observed by McKenzie *et al.*.(1984a) . A third, longer term, aim is to incorporate the results of this and other projects to establish guidelines to predict which soil management practices are best suited to a given situation.

A study of the effect of a range of depths of soil disturbance on soil physical properties and cotton growth was undertaken to meet these aims. An understanding of structural degradation, plant response to measured soil physical properties, and the influence of management on soil physical properties and cotton growth are essential for the interpretation of a soil management experiment; the literature on these topics is reviewed in Chapter 2. Swelling is central to the physical behaviour of vertisols, the main soil type used for cotton production in Australia, but dispute continues about the most appropriate means of measuring volumetric properties in swelling soils, such as density, porosity, and even depth; these aspects are reviewed in Chapter 3. Fears were held that short range variability in the physical properties of vertisols, evident when large cracks occur in dry soil, would lead to high long range variability and mask the effect of tillage treatments. A number of statistical techniques to describe and account for this variability are described in Chapter 3.

Description of experiments commences in Chapter 4 with an outline of the tillage treatments imposed - ripping to 0·45 m depth and chiselling to 0·25 m, both followed by discing and listing, and permanent beds formed by direct listing. Factors relevant to all subsequent chapters such as cultural practices, climate, and a general soil description are also included in Chapter 4. The neutron moisture meter was used for most measures of soil water content for depths of 0·2 m and greater. Calibration of the neutron moisture meter is described in Chapter 5 together with a study of soil shrinkage in the water content range between cotton crop irrigations, the results of which were used in the neutron moisture meter calibration. Soil and plant measurements obtained during the 1984/85 cotton season are presented in Chapter 6, along with a concurrent study of the vertical and areal distribution of the variability of soil water content.

Few differences between soil physical properties of tillage treatments were measured in the 1984/85 season, leading to a search for more sensitive indicators of soil physical condition. A number of these were tested in two studies described in Chapter 7 and were applied during the second cotton season in 1986/87. The results for this season are combined with measures used in the first season to differentiate between tillage treatments. An economic analysis of the tillage treatments is given in Chapter 9, followed by a general discussion divided into two sections. In the first, findings applicable to the management of and characterization of soil physical condition in experiments similar to the current project are discussed, including suggestions for future research. Second, findings of the project directly applicable to commercial cotton production are combined with findings of related studies to formulate guidelines for management of vertisols for irrigated cotton production.

To reduce confusion regarding a number of terms describing cotton growing machinery and management practices in this thesis, glossary of these terms has been included in Appendix 2.

CHAPTER 2

SOIL STRUCTURE MANAGEMENT AND COTTON PRODUCTION IN VERTISOLS

2.1 INTRODUCTION

Vertisols, in common with other clay soils, possess many properties favourable to crop production. Favourable properties may include high natural chemical fertility, high plant available water capacity, high potential infiltration rates when dry, an ability to self mulch, lack of specific restrictions to root penetration, and an ability to rejuvenate structure (Smith *et al.*, 1984). With these favourable properties may come the disadvantages of poor internal drainage, low infiltration rates when cracks are closed, a narrow range of water contents optimal for tillage, high draught requirement when dry, and instability to wetting. The properties of clayey soils described depend to a large extent on the characteristics of the pore space in the soil. Fluxes of water, gases and nutrients occur in the pores, and the friable condition of the soil results from its separation into structural units (Warkentin, 1982).

In the following sections, the mechanisms of structural degradation will be outlined, along with the effect of degradation on cotton growth, and methods of avoiding and reducing degradation in an irrigated cotton growing system.

2.2 STRUCTURAL DEGRADATION

Soil structure is the arrangement of the solid phase of the soil and the pore space located between its constituent particles (Marshall and Holmes, 1979); structural degradation involves a modification to the pore volume and pore structure of the soil. Small scale examination of the soil may reveal a reduction in the size and number of macropores, together with changes in the shape and continuity of pores (Soane *et al.*, 1981a). Physical forces causing structural degradation arise from wheel traffic, tillage implements, wetting, and in clay soils,which remain saturated to large water potentials, even drying of the soil (Mullins and Panayiotopolous, 1974).

2.2.1 Influence of soil water content on structural degradation

Chancellor (1976) considered that water content was the dominant factor influencing the amount of compaction which results from the passage of machinery over agricultural soils. Soil water content mediates the effect of a given stress on soil structure through changes in soil strength and plasticity, which combine to determine soil consistency. Consistency is the extent a soil body can maintain its shape when subjected to forces tending to cause deformation (Hillel, 1980), and is defined by Atterberg limits.

Detailed procedures for determining Atterberg limits are given by Sowers (1965); a summary of their relationship to soil behaviour, based on Hillel (1980), is given here:

Upper plastic limit (UPL): The mass wetness at which the soil-water system changes from a viscous liquid to a plastic body.

Lower plastic limit (LPL): The mass wetness at which the soil stiffens from a plastic to semirigid and friable state. It characterizes the lower end of the range over which the soil is in a plastic state.

Shrinkage limit : The mass wetness at which the soil changes from a semirigid to a rigid soil with no additional change in specific volume as drying proceeds.

A second rheological (flow) property of the soil that depends on water content is thixotropy. Thixotropy is a process affecting the clay fraction of the soil, is isothermal, reversible and time dependent, and occurs under conditions of constant composition, whereby a material softens or liquefies when remoulded (Mitchell, 1960). Thixotropy of clay is normally associated with suspensions which are more or less flocculated (van Olphen, 1963). It is also observed in soil if the net interparticle force balance is such that the soil will flocculate if given a chance, but the flocculation tendency is not so strong that it cannot be overcome by mechanical action, such as shearing or stirring the soil (Utomo and Dexter, 1981).

Thixotropy can be observed at field water contents when soil masses are sheared by swelling, shrinking, surface tension and, most importantly, tillage tools. Any of these disturbances would be analogous to stirring of clay suspensions, and as such would leave a weak soil, in which stability through aging might follow (Blake and Gilman, 1970). For three field soils with different clay contents and mineralogies, Utomo and Dexter (1981) found that the maximum thixotropic effect occurred between lower and upper plastic limits.

Water content also affects the degree to which a soil can be compacted. Changes in density for a constant stress at varying water contents are approximated by the Proctor compaction test (Raghavan *et al.*, 1976). For a given compactive effort, the Proctor compaction test indicates an optimum water content to obtain a maximum density (Figure 2.1). The optimum water content for compaction can be near the lower plastic limit (Weaver and Jamison, 1951). In this context, optimum refers to achieving the maximum density for engineering purposes, the exact opposite of that for good structural conditions for plant growth. This optimum water content is related to the lubricating action of water films below the optimum, and the limited air voids available for displacement above the optimum (Soane *et al.*, 1981a). Above the optimum water content, the water in soil pores prevents close packing of the soil particles, and limits the maximum bulk density attained in the Proctor compaction test to that equivalent to 85 to 90% saturation (Hillel, 1980).

Considerable structural degradation may occur at water contents above the optimum for maximum density. Boone (1986) has stated that soil deformation plays an important, even dominating, role in compaction under wet conditions. In laboratory studies on vertisols used for cotton growing in Australia, Kirby (1987) has shown that shear, rather than volume change, is the main mechanism of structural degradation. These soils are generally either dry enough to be too strong to be compacted by agricultural machinery, or near saturation, allowing deformation, but not compression.

Soil water content is also important in determining the extent of structural degradation caused by rapid wetting of the soil during irrigation. Because irrigation damages structure by rapid wetting of the soil, the higher the initial water content the less is the damage caused (Section 2.2.4).

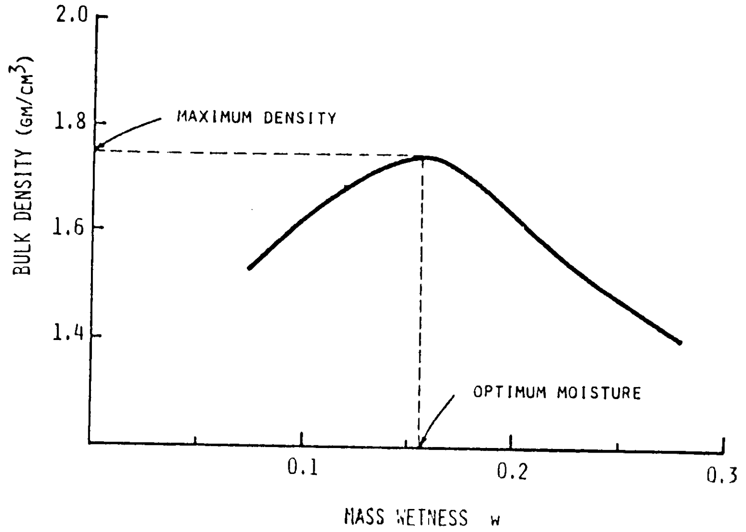

Figure 2.1 Typical moisture-density curve for a medium textured soil, indicating maximum density obtainable with a particular compactive effort (from Hillel, 1980).

2.2.2 Wheel passage

Incidental structural degradation of soils by vehicles engaged in cultural practices or transportation is a serious problem in many parts of the world (Taylor and Gill, 1984). The importance of wheel passage in structural degradation is related to the large proportion of a field traversed by wheels in conventional tillage systems. Soane *et al.* (1982) listed studies where 75 to 91% of the surface of fields was covered by tractor wheelings during land preparation (Figure 2.2). The proportion of the field covered by tractor wheelings can be reduced by the use of controlled traffic (Section 2.4.3).

A serious conflict in the management of wheel traffic is that soil conditions required for good root growth are nearly opposite to those required for high performance of tyres. High soil strength is associated with reduced sinkage and thus reduced rolling resistance of tyres. Soil strength also largely determines the tractive force a tyre can produce (Dwyer, 1984). Conversely, high soil strength restricts plant emergence and limits root growth (Section 2.3.4)

Consideration of the effect of wheel parameters on structural degradation will lead to the establishment of criteria to minimize structural degradation, while maintaining tractive efficiency.

Factors affecting static ground pressure

For a given set of soil conditions, Soane *et al.* (1981b) listed three parameters, namely load, tyre width, and tyre inflation pressure, which can be varied to alter average ground pressure under tyres. The average ground pressure is a function of deformation of both the soil and tyre. If the tyre pressure is low, and the soil firm, most deformation will occur in the tyre. Conversely, a combination of high tyre pressure and soft soil will lead to high soil deformation (Dwyer, 1984). In agricultural situations, both extreme cases outlined above may occur, but deformation of both the soil and tyre is much more common.

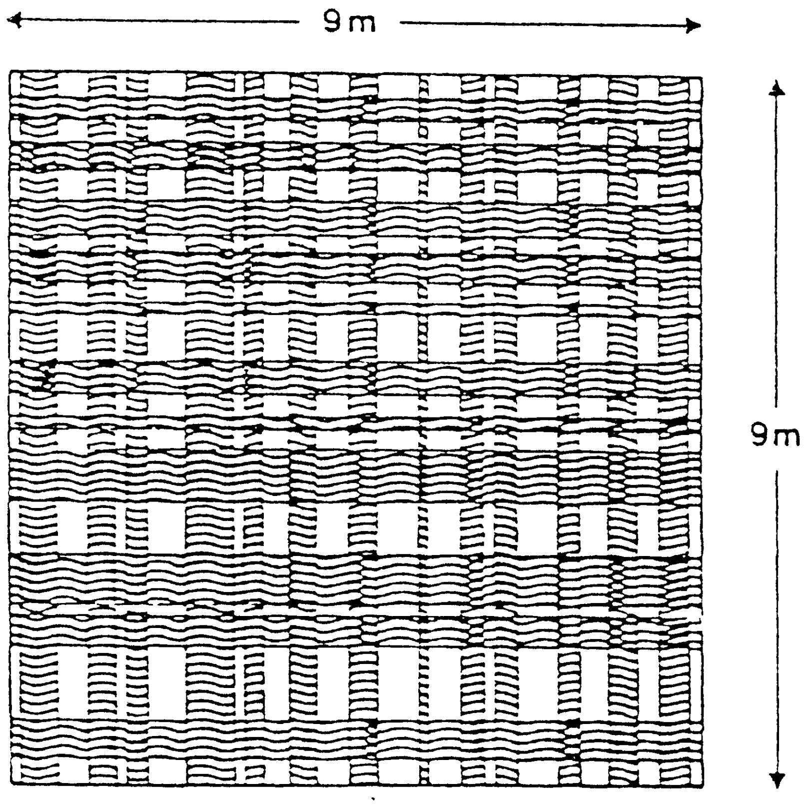

Figure 2.2 Example of pattern of tractor wheel tracks over an area during traditional seedbed preparation (fertilizer distribution, harrowing twice, sowing and rolling; 91% coverage including overlap) (from Soane, 1975).

Pressure is not evenly distributed under most tyres. A tyre with relatively stiff sidewalls will have higher pressure at the edges of the contact area than in the middle. High ground pressure occurs beneath lugs, but, because of the discontinuity of lugs, this effect is not as damaging to root growth as the high pressure under sidewalls (Dwyer,1984). Although the average ground pressure under tracks is lower than under tyres, Soane *et al.* (1981b) pointed out that higher than average pressures occur under sprockets and rollers, and that an increase in draught will concentrate the load towards the rear of the track.

Constraints to tyre selection are that tyres should prevent excessive rolling resistance for the terrain conditions, and that an appropriate tread pattern should be used to obtain maximum drawbar pull (Muro, 1982). In addition, Soane *et al.* (1981b) recommended that average contact pressures should be less than 200 kPa, and preferably below 100 kPa.

Axle load and depth of degradation

While structural degradation near the soil surface is strongly correlated with surface pressure, Taylor and Gill (1984) stated that high total axle load was the basic cause of structural degradation in the subsoil. This relationship between axle load and subsoil stress was predicted by Soehne (1958), and has been verified under laboratory conditions (Taylor *et al.*, 1980; Blackwell and Soane, 1981).

Subsoil structural degradation has been shown by Voorhees *et al.* (1986) to extend to 0·5 m in response to 18 Mg axle loads. This degradation persisted for four years despite soil freezing in winter each year. Subsoil degradation can be reduced under heavy loads by the use of tandem axles or long, narrow tracks rather than dual tyres (Carpenter *et al.*, 1985; Smith, 1985). Carpenter *et al.* (1985) further recommended that axle loads in highly compactible soils be restricted to a maximum of 6 Mg. Structural degradation caused by heavy loads can be minimized by restricting the passage of heavy loads to dry soils.

Wheelslip

Wheelslip imposes a shear stress near the soil surface, and occurs to varying degrees during the passage of all wheels and tracks. The amount of shear strain during wheel passage increases with the draught exerted through the wheels, and with decreasing soil shear strength (Soane *et al.*, 1981b).

Davies *et al.* (1973) have shown that excessive slip is likely to damage the soil more than high wheel loading. This effect becomes more pronounced as tractor power increases. Wheelslip can be reduced by increasing ballast or speed, reducing draught, or using tractors of higher power. For a given draught, tracked vehicles have less slip than similarly powered tyred vehicles because they have a larger soil contact area and greater weight (Koolen and Kuipers, 1983).

Number of passes and speed

The relationship between the degree of degradation and number of wheel passes varies with initial soil strength. In freshly tilled soil, Taylor *et al.* (1982) recorded that three-quarters of the total change in density and 90% of total sinkage occurred in the first of four passes over the soil. At the other extreme, Raghavan *et al.* (1976) found that bulk density increased linearly with the number of passes, but the initial state was undefined. From these and other reports, it can be concluded that density of a tilled soil increases greatly during the first of many passes, but that each additional pass increases density still further. Further research is needed to fully clarify the soil response to multiple wheel passes, including thixotropic effects (Section 2.2.1).

Increased speed is associated with reduced soil stress (Soane *et al.*, 1981b), but the effects are often small. Stafford and de Carvalho Mattos (1981) stated that the speed effect is larger at lower densities, and is relevant to field traffic in loose, soil such as found at crop establishment with conventional cultivations. However, the effect of speed is minimal in stronger soils.

Conclusions

Some structural degradation in response to agricultural traffic is inevitable. This degradation can be minimized by restricting axle load, minimizing wheelslip, ground pressure and the number of passes across the soil, increasing travel speed where applicable, and restricting passage on wet soil.

2.2.3 Tillage

Tillage can be used to improve soil physical conditions (Section 2.4.1). However, tillage is also responsible for a major proportion of structural damage. Larson and Osborne (1982) described the adverse effects of tillage on structure as the oxidation of organic matter by exposure of soil surfaces, mechanical dispersion by puddling due to the compaction and shearing action of implements, and by rainfall impact on bare soil.

Tillage of wet clay soils leads to smearing of aggregates, which can smooth over and seal pores and fissures (Batey, 1975). McGarry (1987) has presented strong circumstantial evidence that shearing of wet soil by steel tillage tines caused zones of oriented clay in a structurally degraded cotton-growing soil. Although little work has been done on the relationship between orientation of clay particles and structural degradation, Aitchison and Holmes (1953), Stirk (1954), and Chang and Warkentin (1968) have all related increased orientation of clay particles to indices of structural degradation.

Because it is a major factor in structural degradation water contents above a critical limit, should be avoided when making tillage decisions.

2.2.4 IRRIGATION

Rapid wetting of soil during flood irrigation has been widely reported as causing the breakdown of surface structure in clay soils (Collis-George and Laryea, 1971; Kemper *et al.*, 1975; Mathieu and Hmamou, 1979; Blackwell and Green, 1986). Structural degradation in swelling clay soils with an adsorbed cation composition not conducive to the dispersion of clay colloids is restricted mainly to the formation of microaggregates by slaking. Clay dispersion contributes to the movement of clay particles into the subsoil and the infilling of macropores by the clay. This natural process is speeded by the weakening of bonds between particles as a result of cultivating the soil when wet (Emerson, 1983) and by the more rapid flow of water through the soil profile under irrigated than rainfed regimes (Greenland, 1977).

Emerson (1972) outlined two reasons for the slaking of aggregates. First, exchangeable cations on the surface of the clay rapidly complete their hydration shells forcing clay particles apart, and this leads to differential swelling of the aggregate. Second, pressures can build up in air filled pores isolated by the wetting front when water displaces nitrogen and oxygen adsorbed on mineral surfaces (Kemper *et al.*, 1985).

The extent of slaking increases with the rate of wetting, as a high water content gradient in the aggregate increases the amount of swelling-induced displacements. These displacements are the primary factor in causing shear stresses in aggregates at right angles to the direction of wetting (Kemper *et al.*, 1975). The water content of the aggregates prior to wetting also influences the amount of swelling and hence slaking (Mathieu, 1982).

In flood irrigation, the rate of wetting of seedbed soil can be reduced by using corrugation or furrow, rather than border check irrigation (Mathieu, 1982). Furrow irrigation has the added advantage that surface drainage of beds is improved, and hence waterlogging of the surface soil is reduced (Luthin, 1982).

2.3 EFFECT OF SOIL PHYSICAL PROPERTIES ON COTTON GROWTH

In an agricultural cropping system the most important short term indicator of the condition of soil structure is crop performance. The plant integrates the effects of soil physical properties, direct tillage effects such as root pruning, and weather (Whisler *et al.*, 1982). A drawback of the use of crop growth as an indicator of soil physical conditions is that results are site specific, and crop response to a given set of soil physical conditions varies from year to year with the influence of weather on crop growth. Despite this problem, much research effort has been devoted to relating soil physical status to crop growth. In the following sections soil physical properties important to plant growth are discussed, with the plant response to these properties illustrated mainly by cotton growth.

2.3.1 Bulk density

Much data, such as that of Carter and Tavernetti (1968) have been collected relating density of non-swelling soils to cotton growth. Rosenberg (1964) described the relationship between bulk density and plant growth over a wide range of densities as parabolic. Density increase is associated with a decrease in the volume of large pores, especially those with diameters greater than 1·5 μm (Hill *et al.*, 1985).

The relationships between bulk density and crop growth are difficult to measure in swelling soils. In studies on the effect of soil water content during seedbed preparation on cotton growth, neither McGarry (1984) nor Daniells (1984) were able to detect density differences between treatments which showed cotton yield decline in response to structural degradation. However, degradation arising from the different seedbed preparation techniques was manifested by differences in clod shrinkage and structural properties. Abbott and Daniells (1987) measured differences in clod shrinkage characteristics between the treatments. McGarry (1987) observed coarser structure and fewer peds with polished surfaces in the seedbed prepared at water contents above the lower plastic limit (LPL), compared with that prepared drier than the LPL.

McKenzie *et al.* (1984b) observed differences in bulk density between two sites, one uncultivated and the other under irrigated crops for 15 years. However, McGarry and Chan (1984) did not record significant density differences between six sites at which cotton yield declined by 30% as time under irrigated crops increased from 1 to 17 years.

From this evidence, bulk density *per se* appears to be of limited use as a measure of the physical status of swelling soils. This is attributed to difficulties of sampling (Chan, 1981; Section 3.2.1), and the influence of water content on density. Also, it is pore size distribution, through its influence on air and water relations, which more directly affects plant growth.

2.3.2 Porosity

Porosity is the best physical measure of structural condition (Greenland, 1981). The plant root environment, as well as the successful manipulation of the physical condition of clayey soils by tillage, depends on the soil pores as they control the fluxes of water, gases and nutrients.

Pore size distribution

Pore size distribution is the major determinant of soil water content at a given matric suction and, along with pore continuity, controls aeration for a given suction. Negi *et al.* (1981) claimed that the ability of the soil to hold sufficient water at moderate suctions (5 to 50 kPa), and yet possess reasonable conductivity, should be the criterion for favourable physical conditions. Newman and Thomasson (1979) stated that the formation of pores in the size range 0·2 to 30 μm is important in structural regeneration of swelling clays.

Pore volume in swelling soils varies as the soil volume changes with water content. The relationship between soil water content and soil volume is shown in Figure 2.3. The volume of air is constant during the normal shrinkage phase, as changes in soil water content are associated with equal changes in soil volume. Changes in soil volume are less than changes of soil water content in both structural and residual phases, hence the volume of soil air increases with decreasing soil water content.

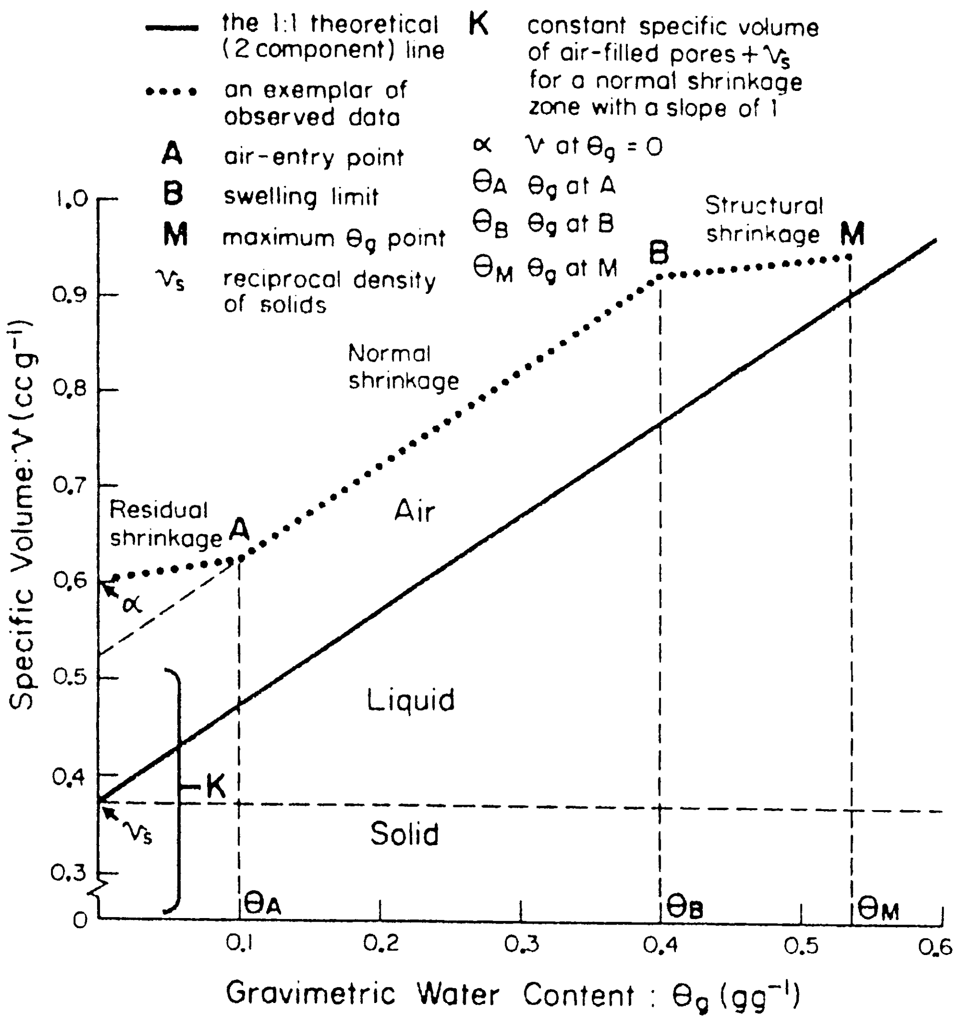

Figure 2.3 Plots of theoretical and exemplar shrinkage lines using the coordinates of specific volume (v) and gravimetric water content (θ_g) (from McGarry and Malafant, 1987).

Structural shrinkage is important in attaining a desirable pore size distribution in swelling soils. If no structural shrinkage occurs as a soil dries, contraction of soil occurs almost entirely by shrinkage of individual peds and formation of interpedal cracks (Reeve and Hall, 1978). Contraction of the ped may reduce internal pore size, and rapidly increase ped density and strength, which hinder root penetration and increase draught when tilling. However, a soil with structural shrinkage would allow more air to enter during drying, thus maintaining a more favourable pore size distribution, and would have a slower density increase.

Although optimal pore size distributions for water storage, and air and water transfer can be defined, volume changes of swelling soils mean that the pore size distribution will vary with water content. Creation of structural pores by tillage and plants, discussed in Section 2.4, combined with management of soil water content, can be used to attain optimal pore size distributions.

Aeration

Variation of pore size with water content complicates the study of air flow in swelling soils. Greacen and Gardner (1982) stated that air transfer between heavy textured subsoils and the atmosphere is one of the least understood processes in these soils. The presence of shrinkage cracks means that large volumes of soil need to be instrumented to study aeration, and that complex models are needed to simulate aeration status.

Despite these problems, Australian researchers have obtained good correlations between a range of indices of aeration status and cotton yield. Constable and Hearn (1981), Hodgson (1982), McGarry and Chan (1984) and Hearn (1986) associated waterlogging with reduced cotton lint yields. Hodgson and Chan (1982) were able to account for 77% of the variation in lint yield by the time taken for the surface soil to recover to 10% air filled porosity (ε_a). Hearn and Constable (1984) claimed, that each day of waterlogging, when the water content was above that needed to give an ε_a of 10%, reduced cotton lint yield by 33·2 kg ha^{-1}. Characterization of the aeration status of vertisols has been improved by Hodgson (1986), who found that oxygen flux density (OFD) was a highly sensitive indicator of structural degradation in an irrigated vertisol.

Poor aeration limits cotton root growth. Huck (1970) observed that cotton root elongation ceased within two to three minutes of all oxygen being removed from the soil, and that meristem death occurred after three hours without oxygen. Waterlogging stress primarily causes a direct reduction in active (energy requiring) root processes such as nutrient uptake (Reicosky *et al.*, 1985). Hodgson (1982, 1986) measured reduced nitrogen uptake of waterlogged cotton plants, and overcame the cotton yield decline due to short term waterlogging by foliar application of nitrogen. This indicates that the main means by which poor aeration limits cotton growth in these soils is lower nitrogen uptake. Organic compounds produced in the soil under reduced conditions, such as ethylene and volatile fatty acids and detrimental to root function are less important than nitrogen nutrition because of the low level of organic matter, the substrate for production of these compounds, in the surface of soils used for cotton growing in Australia (McKenzie *et al.* 1984a), and the.relatively short duration of each waterlogging event.

Cotton plants can adjust to waterlogging. Reicosky *et al.* (1985) found physiological acclimatization during the second of two waterlogging events. Hodgson (1986) used acclimatization as the rationale for using a decay function to describe the relationship between the duration of waterlogging throughout a cotton season and cotton lint yield.

Poor aeration may also limit cotton yields by promoting denitrification. Craswell (1978) has shown that measurable denitrification occurs in well structured vertisols only when the soil is very wet (absolute pressure potential: $|\psi_p| < 10$ kPa), and soil temperatures are above 20°C. These conditions would be common after cotton irrigation as waterlogging of the above magnitude is well documented, and soil temperature in the lower Macquarie valley is 20°C and higher from November to March (Cooper and Harris, 1985).

Poor aeration has been shown to limit cotton yields in irrigated swelling soils in Australia. Thus an important aim of soil and water management in these soils is to reduce the duration of waterlogging.

2.3.3 Plant available water content

In recent publications, plant available water content (PAWC) has superseded available water content (AWC) in describing water holding capacity of swelling clay soils. AWC is the difference between field capacity (-33 or -10 kPa water potential) and wilting point (-1500 kPa water potential) water contents summed over rooting depth (Ritchie, 1981), whereas PAWC is the difference between the field-measured upper and lower storage limits summed over rooting depth (Gardner *et al.*, 1984). When measuring PAWC, the lower storage limit is measured by allowing plants to grow to their maximum vegetative size without stress, then drying the soil by growing the plants on stored soil water until they are visibly distressed (Ritchie, 1981). Greacen and Gardner (1982), discussing the weaknesses of the AWC concept in swelling soils, draw attention to the inapplicability of field capacity to poorly drained soils, and doubts about the effectiveness of roots at withdrawing all water held at tensions above the wilting point level of -1500 kPa. A third weakness is that the soil water store may be determined by water entry rather than water retention properties. This is supported by observations of Chan and Hodgson (1981) that flood irrigation did not fully replenish soil water storage in a swelling grey clay.

PAWC has been defined by Gardner *et al.* (1984) as :

$$PAWC = \sum_{Z=0}^{Z = \text{rooting depth}} (\theta_{g_{max}} - \theta_{g_{dry}})\rho_{b\theta gmax} \quad \text{......... 2.1}$$

where Z is depth, $\theta_{g_{max}}$ and $\theta_{g_{dry}}$ are wettest and driest gravimetric water contents respectively, and $\rho_{b\theta gmax}$ the field bulk density at the wettest water content. All three properties are measured during field studies using crops, and irrigation and drying regimes appropriate to the cropping system under investigation.

Factors affecting plant available water content

PAWC is affected by root profile, clay content, subsoil salinity, drainage characteristics (Venkatsewarlu, 1984) and soil strength. Processes determining PAWC include infiltration, water movement to roots, and plant water uptake (Smith, 1984).

Infiltration in cracking clays is a complicated process consisting of three phases (Greacen and Gardner, 1982). The first is an initial filling of cracks, which usually lasts less than 30 minutes, makes up about 70% of the irrigation increment of flood irrigated soils, and is referred to as instantaneous infiltration. The second consists of absorption of water by the peds from cracks, during which time infiltration rate decreases linearly with the square root of time. The third process occurs when the peds are saturated and the rate is equal to the saturated hydraulic conductivity. The saturated hydraulic conductivity of grey clays is very low. Van der Lelij (1984) recorded a median saturated hydraulic conductivity in 32 Murrumbidgee valley (NSW) grey clays as 2·3 mm day^{-1} with a range of 1 to 17 mm day^{-1}. Prolonged water application in these soils thus does little to increase water infiltration.

Soil water storage is controlled by the water retention curve, so factors which change the pore size distribution, such as tillage and increasing bulk density, will alter soil water storage.

Plant water uptake will be restricted by any factor, such as poor aeration or high soil strength, which restricts root growth. Greacen and Gardner (1982) stated that water uptake by roots is determined by the geometry, density and distribution of roots, and the hydraulic properties of roots and soil. McGarry and Chan (1984) noted that water uptake by cotton was less in structurally degraded soils than in soils of good structure. These observations were supported by Hodgson and Chan (1984) for wheat and safflower.

PAWC in swelling soils can be altered by management of factors which affect infiltration, soil water storage, and root growth. This can be achieved by modification to the size and continuity of pores by tillage, promoting shrinkage, and structural degradation.

Cotton responses to soil water availability

Unlike most crop plants, cotton has no clearly defined life cycle or seasonal cycle to complete. The important unit in the cotton plant is a segment of the fruiting branch consisting of an internode, flower bud and leaf (Hearn, 1980). It is then not surprising that simple attempts to relate water regime to cotton yield give inconsistent results (Hearn, 1980). However, more detailed experiments have given sensible relationships.

Hearn and Constable (1984) defined a water stress day as being one when the minimum leaf water potential is less than -1.8 MPa up to 90 days after emergence, and less than -2.4 MPa thereafter. They found that stress reduced lint yield by up to 40 kg ha^{-1} day^{-1}, with the greatest sensitivity at 80 to 140 days after planting, coinciding with the period of maximum water uptake.

The most important processes affected by crop water deficit are those associated with cell growth and stomatal behaviour (Hearn, 1980). The effects of water deficit on cell growth are expressed in rates of leaf elongation and plant height increase, and in the abrupt cessation of node and square production. The rate of cotton photosynthesis is affected less than transpiration and leaf extension by mild water deficit stress (Leopold and Kriedmann, 1975).

An important response of cotton plants to water deficit stress is the shedding of squares (floral buds) and bolls (fruits). Hearn (1980) postulated that shedding occurs when seed growth decreases as internal competition for carbohydrate increases. This reduces the production of a growth substance that inhibits development of the abscission layer. The effect of water deficit stress on boll retention is complicated by time lags, and the influence of other plant factors, such as boll load. Guinn and Mauney (1984a) observed that flowering continued unabated during monitored stress periods, but once flowering rate declined, it did not recover until about three weeks after stress was relieved by irrigation. The yield decline in response to water deficit stress was attributed in part to decreased flowering and in part to decreased boll retention. Water deficit stress thus tends to limit boll load by reducing boll setting and retention.

Reduced PAWC as a result of structural degradation can be counteracted by more frequent irrigation. However, more frequent irrigation can reduce water use efficiency by increasing the risk that the soil will be too wet to permit utilization of natural rainfall (Cull *et al.*, 1981). For a given duration of irrigation, more frequent irrigation also increases the duration of waterlogging, leading to reduced cotton yield (Section 2.3.1).

2.3.4 Soil strength

Structural degradation is associated with an increase in soil strength at a given water content. Soil strength is strongly affected by both density and water content (Figure 2.4). As density increases, soil shear strength increases because of an increase in the interlocking soil particles. Increasing soil water tension increases cohesion, and decreases the lubricating effect of soil water.

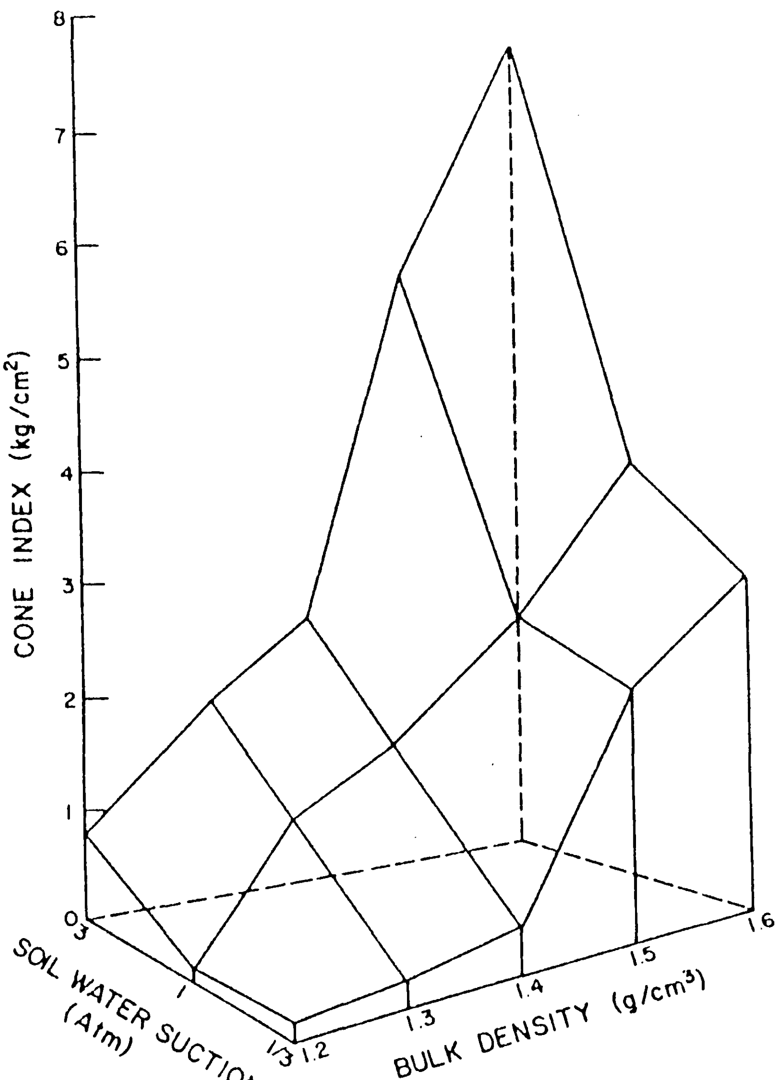

Figure 2.4 Effect of bulk density and soil water suction on penetration resistance of a loam soil (after Singh and Ghildyal, 1977).

Surface crusts

Soils with low organic matter content, and high proportions of silt, clay and monovalent cations exhibit the greatest tendency to form soil crusts (Goyal, 1982). The soils rich in fine sand frequently show a tendency to slake on wetting and to form a crust on drying. Crust formation is related to the stability of aggregates, and is positively correlated with the rate of wetting (Osborne, 1984). Although crusting as a major problem normally occurs on medium textured soils,its adverse effects have been reported for Australian vertisols.Its reduction of the emergence of wheat has been shown by Doyle *et al.*, (1979) and of clovers (*Trifolium* spp.) by Loveday and McIntyre (1966) and Bridge and Tunny (1982).

The presence of surface crusts has been shown by Bilbro and Wanjura (1982) to reduce the total emergence and emergence rate of cotton seedlings. Wanjura (1982) observed that delaying cotton emergence by between 33 and 100% can reduce yield from 10 to 56% because of lower plant survival and reduced plant productivity.

Subsurface strength

Subsurface strength directly affects plant root growth through physical limitations to root expansion. Arkin and Taylor (1981) listed worldwide studies relating root growth of many crops, including cotton, maize (*Zea mays*), sorghum (*Sorghum bicolor*), sugar cane (*Saccharum officinarum*) and wheat, to soil strength. Dexter (1987) found that root elongation rate decreases from a maximum value in an exponential manner with increasing soil strength.

Root growth through the soil matrix is dependent on soil failure. Barley (1968) has stated that the chief deformations caused by root growth are a result of shear failure, often with appreciable elastoplastic strain and tensile failure. The forces necessary to cause the above types of soil failures, and thus permit root growth, can be measured separately. Shear strength, which is dependent on soil cohesion and angle of internal friction, can be measured in a triaxial shear test, or by translational or torsional devices. Tensile strength can be measured by loading a bar shaped sample with tensile force. However, penetrometer cone index, which integrates these properties in a poorly defined way, is a more widely used measure to link soil strength to crop growth, as it is more rapidly, easily, and cheaply measured than shear strength (Soane *et al.*, 1981a).

A number of studies linking cotton root growth to soil penetration resistance have been undertaken at Auburn University, Alabama, USA, in medium to coarse textured soils. From these studies, Taylor *et al.* (1966) showed that almost all cotton roots penetrated soil cores with low resistance, but that the proportion decreased with increasing resistance until no roots penetrated soil with over 3 MPa resistance (Figure 2.5). Taylor and Gardner (1963) observed a much stronger correlation of cotton root penetration with penetration resistance than with either water content or bulk density. These observations are supported by Taylor and Ratliff (1969) who observed that soil matric suction between 17 and 700 kPa did not affect the relationship between root elongation rate and penetration resistance, over the range from 0·006 to 2 MPa. Pearson *et al.* (1970) observed, for a given penetration resistance, that root elongation rate increased with temperature to an optimum at 30 to 34^{o}C, then declined with increasing temperature.

In addition to the direct effects of soil structure on penetration resistance outlined above, poor soil structure can lead to increased strength if structural degradation reduces water infiltration (Dexter, 1979). Lower infiltration causes a decrease in soil water content, leading to higher soil strength.

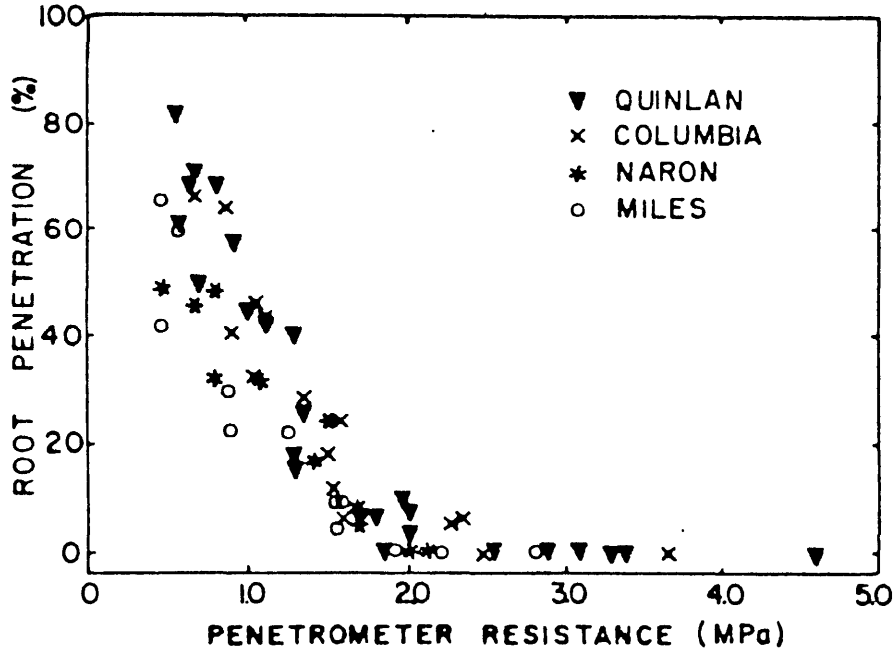

Figure 2.5 The effect of penetrometer resistance on the percentage of cotton tap roots that penetrated through 0·025 m thick cores of four soils (redrawn from Taylor *et al.*, 1966).

Conclusions

Seedling emergence and root growth can be limited directly by zones of high soil strength, which develop as a result of structural degradation. Although penetration resistance is not a direct measure of the soil physical properties which limit crop root growth, strong negative correlations between root extension rate and penetration resistance have been widely reported. Penetration resistance is thus a useful indicator of soil resistance to root growth.

2.4 MANAGEMENT TO MINIMIZE THE EFFECT OF STRUCTURAL DEGRADATION ON CROP PRODUCTION IN VERTISOLS

The main causes of structural degradation in irrigated cropping, and their effects on plant growth have been outlined in Sections 2.2 and 2.3. Despite the documented limitations of poor structure to plant growth, Greenland (1981) claimed that proper management of soil structure is secondary to plant nutrition in limiting crop yield. Thus, optimum management of soil structure will improve crop production only in the absence of other constraints to crop growth. In irrigated cotton production systems, where large inputs of fertilizer and pesticides are used, physical restrictions to root growth, water supply and nutrition absorption are the factors which most commonly prevent achievement of potential yields, and realization of the benefits of these inputs.

2.4.1 Amelioration of structural degradation

If poor soil structure limits crop growth, amelioration of the structural degradation is the first step in improving crop production. Techniques of improving soil structure may be either mechanical (tillage), biological (root growth, soil fauna, organic matter), or chemical (gypsum, lime, polyelelectrolytes) (Arkin and Taylor, 1981).

2.4.1.1 Tillage

Tillage can improve soil structure, in addition to causing the negative effects considered in Section 2.2.1. The effects of tillage on soil physical properties are not uniform, but vary at different locations throughout the profile (Cassel, 1982). Plant responses to the new soil physical conditions are strongly influenced by soil temperature, nutrient supply, composition of the soil atmosphere, soil strength and plant type (Larson and Osborne, 1982) in addition to climatic conditions, particularly water regime (Kuipers, 1984).

The complex relationships between tillage, resultant soil physical conditions, and plant growth have to be borne in mind when assessing the effects of tillage.

Effects of soil water content on soil physical conditions resulting from tillage

Application of mechanical forces to the soil during tillage results in soil failure. Schafer and Johnson (1982) listed, in terms of soil behaviour, four types of failure observed in response to tillage: shear, compression, tension and plastic flow. The relative magnitudes of the different types of failure during tillage are highly dependent on soil conditions before tillage, particularly soil water content.

Spoor (1975) outlined the influence of water content on soil failure as follows. In well structured soils at water contents below the shrinkage limit, the bulk strength is not particularly high, but the clod strength is exceptionally high (Figure 2.6). In this condition, little damage can be done to soil structure, and any work done on the soil simply rearranges clods without breaking them. In dry, poorly structured soils, the bulk shear strength is equivalent to the clod shear strength, and working in these conditions is like tearing up a concrete path. Kuipers (1984) stated that, despite the resulting clods and large amount of energy used to cultivate a dry, poorly structured soil, the internal structure of clods is unchanged, and only a few holes are introduced into the soil.

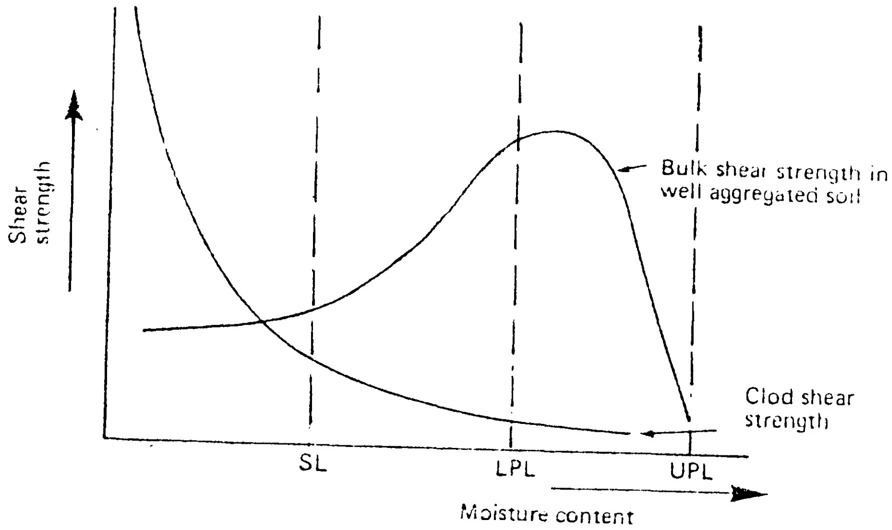

Figure 2.6 Variation in shear strength with moisture content (SL is sticky limit, LPL and UPL are upper and lower plastic limits) (from Spoor, 1975).

As water content increases above the shrinkage limit, the soil becomes friable, with the bulk shear strength increasing and the clod strength rapidly decreasing (Figure 2.6). It is in this condition that the soil is most workable. At the shrinkage limit end of the friable range, the risk of structural damage is minimal, and the soil can be manipulated with relatively little effort. In this range, bulk shear strength exceeds clod shear strength, allowing the clods to be broken naturally along their weakest cleavage planes.

Once the lower plastic limit is reached, the water content is adequate for the water to behave like a lubricant, the clod strength is low and the bulk shear strength is high. Therefore, clods and aggregates can be broken along any plane, and the risk of puddling, smearing and structural degradation increases.

Tillage implement selection and operation

Tillage implement selection is dependent on the desired soil conditions, relative bulk and clod shear strengths, and soil consistency (Table 2.1). Tillage implement design has also been influenced by studies of soil behaviour. An example of this type of study is that of Tupper (1974) who found that the draught of an exponentially shaped shank was 25% less than the draught of a vertical shank.

Table 2.1 Soil consistency and basic cultivation operations (from Spoor, 1975)

Operation	Objective	Bulk shear strength --Relative	Clod shear strength values---	Soil consistency	Direction of resultant implement force on soil	Conventional implement
Disintegration	Reduce clod size by breaking along cleavage planes	High	Low	Friable	Downwards	Roll, rotary cultivator
Clod formation	Compact particles into clods	Low	Low	Plastic	Downwards or sideways	Mouldboard plough
Rearrangement	Increase soil unit weight by filling larger pores with smaller aggregates	Low	Low	Friable	Sideways	Spike or oscillating harrow
Puddling	Increase soil unit weight by destroying all structure and	High	Very low	Plastic	Downwards or sideways	Disc harrow
	compacting	Very low	Very low	Liquid	Any direction	Rotary cultivation
Loosening	Reduce soil unit weight either generally or locally	Low	High or low	Friable Cemented	Upwards	45° rake angle tine
Inversion	Invert soil completely complete burial	High	High or low	Friable Plastic		Mouldboard plough
Mixing		Low	High or low	Friable Plastic		Rotary cultivation, Disc harrow, 45° tine
Smoothing	Leave smooth soil surface	Low	High or low	Friable		Leveller
Moling	Permanent channel with smeared sides at depth	High	Low	Plastic (below)		Mole plough 45° leg
	Loosening above	Low	High or low	Friable (above)	Upwards	
Smearing	Increase unit weight of thin layer by destroying structure	High	Low	Plastic		Slipping wheel
Cutting and Movement	Conditions depend upon other requirements					

An understanding of soil behaviour affects tillage implement operation. For example, Wismer and Luth (1972) stated that the draught of a mouldboard plough increases with the square of speed because of inertia effects, whereas chisel plough draught increases linearly with speed. Spoor and Godwin (1978) have determined that tines have a critical depth of operation, below which soil flows forwards and sideways rather than upward, and causes compaction at depth. Under given soil conditions, the wider the tine tip, the smaller the rake angle for a given lift height, and the looser the soil surface, the greater is the critical depth. The wetter and more plastic the soil, the shallower is the critical depth. When using tined implements to decompact the soil, it is desirable to operate the tine shallower than the critical depth. On the other hand, when forming mole drains, in which a continuous, stable, channel is desired, it is preferable to operate deeper than the critical depth (Spoor and Ford, 1987).

Effect of tillage on soil physical properties

Tillage normally results in an initial increase in porosity, creating a bimodal pore size distribution from an initially unimodal pore size distribution (Klute, 1982). In the cultivated layer this will result in large changes in hydraulic conductivity with soil water tension. Due to the formation of macropores, saturated hydraulic conductivity and water retention at low suctions will be increased by tillage, but as macropores are drained hydraulic conductivity and water content decrease rapidly (Klute, 1982). Tillage also interacts with the soil water regime to modify the amount of gas-filled pores, as well as the tortuosity and continuity of pores (Erikson, 1982).

The porosity changes resulting from tillage are often transient. Reconsolidation of surface soil, mainly caused by wetting, is affected by texture, with coarse soils undergoing more rapid reconsolidation than fine soils (Kouwenhoven, 1985). Simpson and Gumbs (1985) postulated that the porosity changes to a clay surface soil disappeared as quickly as 23 days after tillage. Subsoil porosity created by deep tillage is lost less rapidly than near surface porosity. Loveday *et al.* (1970) observed an increased porosity in response to deep ripping of a clay soil but Muirhead *et al.* (1970) found that it had disappeared after 18 months.

Measurement of density changes after tillage is complicated by spatial and temporal variation. Wolf and Hadas (1984), Hill and Cruse (1985), and Simpson and Gumbs (1985) reported that tillage treatments caused no statistically significant effect on bulk density measured during crop growth. McKenzie *et al.* (1984c) reported some decreases in oven-dry bulk density in response to deep ripping of a vertisol. Loveday *et al.* (1970) also reported a transient density decrease in response to deep ripping, while Soane *et al.* (1986) have shown that machinery passage for seedbed preparation after deep tillage quickly recompacted loosened soil. Cassel (1982) claimed that the detection of changes in bulk density in response to tillage can be increased by careful location of sample sites with respect to tillage tines and wheel traffic lanes.

In non-swelling soils, the pattern of soil strength reflects the disturbance created by tillage. Carter and Tavernetti (1968) presented isoimpedance profiles, which show that widely spaced tines are characterized by an inverted triangular zone of low soil strength within an originally uniform profile. Similar profiles have yet to be produced for swelling clay soils.

In conclusion, positive changes to soil physical properties resulting from tillage include increased macroporosity and reduced mechanical impedance and density. However, these improvements are transient if the soil is recompacted by subsequent machinery operations.

Cotton yield response to tillage

Cotton yields are poorly correlated with the amount of tillage performed on a field. In a survey of Israeli cotton management practices, Wolf *et al.* (1984) showed that cotton lint yield was much more strongly correlated with plant available water than energy input from tillage (Figure 2.7); an increase in PAWC of only 40 to 60 mm was found between the most and least intensively tilled areas.

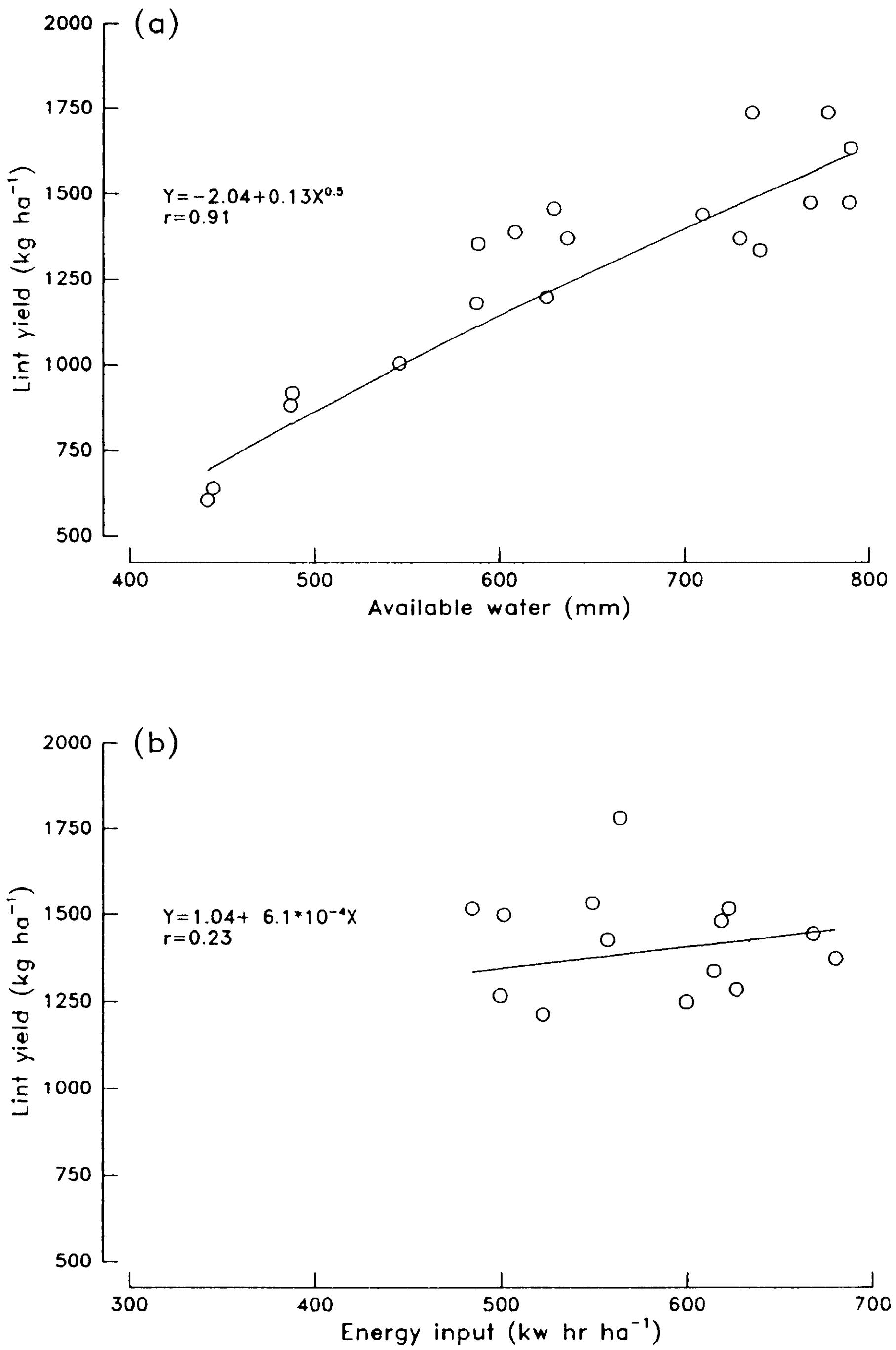

Figure 2.7 Lint yield of irrigated cotton as a function of a) available water (irrigation and rainfall) and b) energy input by tillage (after Wolf *et al.*, 1984).

Cotton yields have not been consistently increased by deep tillage. McKenzie *et al.* (1984c) reported a 28% increase in cotton yield in response to deep ripping compared to shallow cultivation. In the same experiment, reripping two years later led to a 10% yield reduction compared to the same shallow cultivation treatment (McKenzie *et al.*, 1984a). El-Araby *et al.* (1987) recommended that deep tillage to 0·65 m be abandoned in Egyptian vertisols used for cotton production because of naturally abundant cracks in the soil, the high cost of deep tillage, and the small or negative yield responses. In non-swelling soils, Colwick (1979) concluded that the success of deep tillage in increasing cotton yield in silty clay loams was dependent on the presence of a soil barrier to cotton root growth, and minimizing recompaction of loosened soil.

The transient nature of soil structure makes it difficult to relate growth of a particular crop to soil physical characteristics (Osborne, 1984). As previously stated, soil water content during the growing season has a dominant effect on plant response to soil physical conditions. Consequently, intensive measurement of soil physical conditions during growth of the crop are needed to identify the effect of tillage on growth.

2.4.1.2 Crops

Plant roots can improve soil structure by penetrating through pans in both non-swelling and swelling soils. Pan shattering by plants such as lucerne (*Medicago sativa*), sweet clover (*Melilotus alba*), guar (*Cyamopsis tetragonolobus*) and bahiagrass (*Paspalum notatum*) is widely reported (Arkin and Taylor, 1981). Such reports associate yield increases in succeeding crops with these plants, but are often not clear about the exact mechanisms involved, such as increased root penetration, nitrogen supply, aeration, or infiltration (Arkin and Taylor, 1981).

Plants can also improve soil structure by reducing the decline of total organic carbon often associated with tillage, such as that observed by McKenzie *et al.* (1984a) in their comparison of a soil under irrigated cotton with one under native pasture. Total organic carbon is, however, a poor indicator of the influence of organic matter on structure. The main effect of cropping compared to native pasture is that the return of organic residue to the soil is very much lower than for native pasture. The significance of fresh additions of organic matter is the production of organic polymers, such as polysaccharides, which stabilize structure (Arkin and Taylor, 1981).

Blackwell *et al.* (1985) claimed that clay soils which shrink and swell may recover porosity and pore continuity after structural degradation by agricultural machinery, particularly if a large proportion of the shrinkage is in the structural phase. Although they measured porosity increases in a degraded soil after drying by wheat, they point out that the plants suffered yield-reducing stress before structural damage was overcome. In a study of the effect of crop growth on the continuity of a subsoil pan, McGowan *et al.* (1983) observed that the regeneration of structure was greater under barley (*Hordeum vulgare*) than fallow.

In the quest for high yields from irrigated crops on vertisols water deficit stress is avoided by frequent irrigation, and the soil may not be dried to depth for a number of crop cycles. Structural regeneration from soil shrinkage does not occur under this water regime. Where the soil is allowed to dry out, it has been shown that crops such as wheat and safflower can penetrate, dry and crack degraded subsoils (Hodgson and Chan, 1982; Douglas, 1985). On the grey clay studied by Douglas (1985), McKenzie *et al.* (1987) measured better structure after wheat and safflower crops compared to a cultivated fallow 14 months after harvest of the crops.

By drying the soil and causing shrinkage, crop plants have thus been found to be successful in overcoming structural degradation in clay soils. However the plant is subjected to a certain amount of moisture stress to achieve this, so that deep tillage, as well as cracking from drying of the soil by the plants, may be needed in badly degraded soils (McGowan *et al.*, 1983).

2.4.1.3 Gypsum

Gypsum has been successfully used to improve soil physical conditions of some Australian clay soils. By inhibiting dispersion through increasing electrolyte concentration of the soil solution, and replacing adsorbed sodium by calcium and reducing clay mineral swelling, gypsum can improve soil tilth, reduce dry soil strength, increase water infiltration and storage, and improve drainage and leaching (Loveday, 1980).

As gypsum responses occur only under some soil conditions, a means of predicting gypsum response is desirable. Loveday (1974) found that a combination of dispersion index, and percentage exchangeable sodium and magnesium gave the highest prediction of gypsum response for a range of soils used in NSW for irrigated cropping. However, a combination of dispersion index and pH was only a slightly less sensitive indicator of gypsum response. Rengasamy *et al.* (1984) developed a classification system measuring only total soluble salts (TSS) and sodium adsorption ratio (SAR) to predict a range of soil properties, including gypsum responsiveness, for a narrower range of soils, all classified as red-brown earths. Rengasamy *et al.* (1986) showed that gypsum application rates needed to be increased in soils where magnesium rather than calcium was the dominant divalent cation.

Gypsum was the only profitable chemical ameliorant out of gypsum, organic matter, polyvinyl alcohol and potassium sulphate tested by Doyle *et al.* (1979) in a study of wheat growth in a cracking clay soil in northern NSW. They observed 80% wheat yield increase following application of 12·5 t gypsum ha^{-1}, and a 50% yield increase for 2·5 t gypsum ha^{-1} to soils with a surface exchangeable sodium percentage (ESP) of 5 to 11%. So and McKenzie (1984) also obtained economic wheat yield improvements following gypsum application to soils with a surface ESP > 6·5 at 2·5 but not 12·5 t gypsum ha^{-1}. When gypsum was applied to an irrigated cotton soil with surface ESP of 5% increasing to 10% at 0·1 m, Muirhead *et al.* (1970) obtained a 25% yield increase in response to 25 t gypsum ha^{-1}. However, McKenzie *et al.* (1984c) obtained only a 10% yield increase when they applied 7·5 t gypsum ha^{-1} to a soil with surface ESP of 5% increasing to 10% at 0·5 m. In all four experiments above, yield increases were attributed mainly to an increased PAWC of the soil, as gypsum improved water infiltration.

In summary, gypsum has led to substantial yield improvement on suitable soils. Because of the high gypsum rates required for these yield increases, gypsum application is only profitable if high value crops, such as cotton, are grown, or if gypsum is used at low rates to rectify surface structural problems.

2.4.2 The development of tillage management systems

Techniques available to ameliorate soil structural degradation should be applied with care. Neither tillage nor gypsum always improve soil physical properties or crop yield. The use of plants to improve soil physical structure is ineffective in badly degraded soils.

In management of soil physical properties, it is preferable to avoid soil structural degradation rather than to be constantly faced with the task of ameliorating soil structural degradation. The development of tillage management systems is claimed by Johnson *et al.* (1982) to be necessary, as there is no universal prescription for effective and efficient tillage. The degree of soil breakup optimal for plant growth depends on seed size, crop type and weather conditions (Gupta and Larson, 1982). In addition, as seen in Section 2.4.1.1, prior soil conditions affect soil response to tillage.

Development of tillage management systems relies on the accumulation of a data base of soil and plant responses to a management practice under given soil physical conditions. Wide application of tillage management systems is dependent on inexpensive, reliable measurements of soil physical conditions, and a quick, easy means of applying the decision-making process. Computer models, although expensive to develop and maintain, provide a suitable tool for applying this decision-making process. Shaffer *et al.* (1984) outlined a computer-based coordinated farm and research management system (COFARM). COFARM collects and stores information in a form suitable for making soil-crop management decisions regarding nitrogen, phosphorus and potassium fertilizer needs, manure, tillage, crop residues, soil erosion, drainage and crop yields.

Recommendations of the most suitable tillage management system may take the form of an index, which takes into account soil, climatic, topographical, and biological factors. Lal (1985) has developed such an index to determine the optimal tillage system for a wide range of soil and climatic conditions in the tropics. A more dynamic management system is Custom Prescribed Tillage (CPT) outlined by Johnson *et al.* (1982) and illustrated in Figure 2.8. CPT is claimed by Johnson *et al.* (1982) to be a dynamic control system that responds to forces imposed on the agricultural system, and covers a broad spectrum from extensive to zero mechanical manipulation.

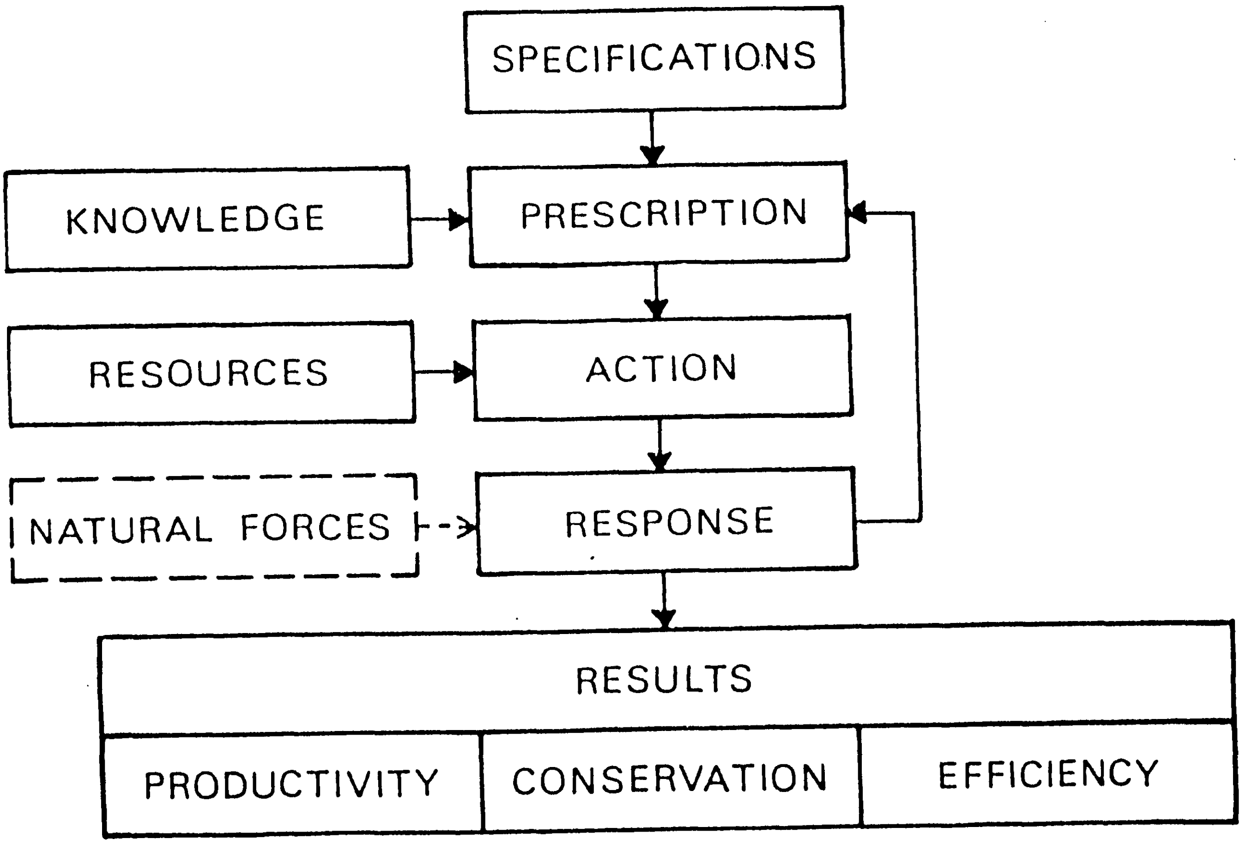

Figure 2.8 Custom Prescribed Tillage (CPT) (from Johnson *et al.*, 1982).

If soil structure management practices on farms are bad, and soil and climate fairly uniform, advances in soil structure management can be achieved by the development of tillage systems which can be applied with little change over a wide area. These systems would be developed after consideration of the physical limitations to crop production, and the system designed to minimize these restrictions.

A number of such systems have either been developed or are being developed for red-brown earths and transitional red-brown earths in southern Australia. Cockroft and Tisdall (1978) have developed a system for management of peach orchards which has been adapted by Tisdall and Adem (1986) to irrigated row crops. Jayawardane and Blackwell (1985) presented a favourable preliminary evaluation of gypsum-enriched slots in a transitional red brown earth.

Research into improved tillage management systems for cotton production has concentrated on non-swelling soils and the controlled traffic concept. This concept separates the soil into three major zones : (i) root development zone, (ii) water infiltration area, (iii) traffic support area (Carter and Colwick, 1971). Ideally, the root development zone and the traffic support area are distinct and permanently separated. Traffic lanes are not deep tilled, and are used for wheel paths year after year (Taylor, 1983). Dumas *et al.* (1973) and Williford (1980) have reported that controlled traffic was associated with improved soil conditions and higher cotton lint yields compared with conventionally tilled areas.

A potential limitation to the adoption of controlled traffic is the possibility of structural degradation developing next to wheel furrows, and the roots being "boxed in" to a shallow zone under the plant row (Trouse, 1983). Dumas *et al.* (1973), Trouse (1983), and Mogilevets and Khalyyev (1977) have shown that post-planting wheel traffic can suppress cotton yields in plant rows adjacent to the wheeled furrows. Under a controlled traffic system, structural degradation beneath the plant row can be overcome by running a tine beneath the centre of the plant row, a practice described by Trouse (1979) as under-the-row subsoiling.

The controlled traffic concept, combined with under-the-row subsoiling, appears to limit structural degradation of non-swelling soils during row crop production. This system should have similar advantages in swelling clays.

2.4.3 Conclusions

Use of our knowledge of soil response to tillage and wheel passage, and of the effects of soil structure on plant growth has enabled the development of soil management regimes which, when applied, should arrest the structural degradation in Australian cotton fields described in Section 2.1.

Structural degradation in vertisols can readily occur in response to inappropriate tillage, wheel traffic, or irrigation management practices. Consideration of soil physical behaviour can minimize the degradation of soil physical conditions during cropping. In addition, vertisols can regenerate structure as they dry and crack, a property beneficial where tillage is limited. However, there is currently no information on the longevity of a controlled-traffic system for irrigated cotton growing on vertisols, and little detail on the mechanism of plant response to deep tillage in these soils. The experiments described in this thesis will compare soil physical properties during growth of cotton crops, for which the seedbed has been prepared with and without deep tillage.