Chapter 5

Soil Water Properties

Abstract

Chapter 5 investigates the effect of soil horizon mixing and compaction on the plant available water content range and saturated hydraulic conductivity. Soil water storage and transmission are aspects of soil physical fertility which control penetration resistance and soil aeration. Water storage and transmission are determined by pore size distribution, which is modified by compaction and soil texture.

The aim of work reported in this chapter is to model the effect of soil horizon mixing and soil compaction on water retention and saturated and unsaturated hydraulic conductivity. Water retention between matric potential values of -0.2 and -150 mH_2O, and saturated hydraulic conductivity are measured in the laboratory for A and B horizon soil, and the range of soil horizon mixtures studied previously. Soil cores were compressed to different void ratios with a uniaxial compression testing instrument.

Transmission porosity is removed by compaction. This results in lower saturated and unsaturated hydraulic conductivities in compacted soil. Soil horizon mixing does not increase soil water storage. Soil horizon mixing appears to enhance soil water transmission because of an increase in the tendency of soil to form aggregates during preparation.

Critical water transmission and storage properties are determined for inclusion in the compaction management model (Chapter 7). A critical void ratio of 0.70 m^3 m^{-3}

for rapid water intake is determined from saturated hydraulic conductivity data. Also, the upper and lower limits of plant available water are determined at matric potential values of -1 m and -150 mH_2O for each soil horizon and soil mixture.

5.1 Introduction

The water holding and transmitting properties of soil are factors which affect the growth of plants. The plant available soil water content and the soil drainage rate are affected by void ratio and soil texture because these properties determine the proportions of pores which retain water and conduct flow under gravity. Consequently, there are compaction conditions, for different textured soils, which optimise soil water behaviour for crop production.

The proportion of pores which retain water between the drained soil water potential (field capacity) and the lowest potential extractable by plant roots (wilting point) tends to increase as the clay content increases from sandy to loamy textured soil. At higher clay contents the plant available water content may decline because of a proportional increase in pores retaining water at potentials less than the wilting point. The proportion of pores conducting water flow between soil saturation and the upper drained potential decreases as the pore size distribution becomes finer.

Soil compaction produces a finer pore size distribution and tends to remove the larger pores responsible for drainage. The desired soil structure should provide for rapid soil drainage and as well as adequate water retention for irrigated agriculture. Consequently, it may be possible to optimise soil water conditions for plant growth by selecting a particular soil texture and by managing soil compaction.

The aims of this chapter were to,

- characterise the effect of compaction on water retention, available water storage and water flow for natural soil as well as artificial mixtures of A and B horizon material,
- derive a suitable management model to predict plant available water and drainage rate as a function of soil void ratio.

5.2 Literature Review

5.2.1 Water Retention

The water retention curve, determined in a drainage cycle, relates the amount of water in soil to the energy of interaction between the water and the soil matrix (matric potential). This relationship is commonly used in evaluating soil–water conditions important to plant growth (Rose 1976, pp121-151; Childs 1969, pp120-124; Groenvelt and Bolt 1972). The drainage curve, determined by measuring water retained at several matric potentials in the range 0.5 m H_2O to 150 m H_2O, covers most edaphic requirements in soil–water–plant studies (Loveday 1974). The range from 0 to -1 m H_2O is important for characterising water movement in soil.

Campbell (1974) modelled water retention in the range from saturation to a matric potential of -1 m H_2O using the relationship

$$\psi_m = \psi_e \left(\frac{\theta}{\theta_s}\right)^{-b} \tag{5.1}$$

where ψ_m is the matric potential, the amount of work per unit mass of water required to transport an infinitesimal quantity of soil solution from the soil matrix to a reference pool of the same soil solution at the same elevation, pressure and temperature (Campbell 1985). θ_s is the saturated soil water content and ψ_e and b are intercept and slope parameters fitted by regression. ψ_e estimates the air– entry potential, the matric potential at which continuous air–filled porosity develops.

ψ_e is a function of the largest pore size class and decreases as soil is compacted. b is the slope of the water retention curve and indicates the shape of the pore size distribution. A large b indicates a narrow range of pore sizes which drain over a narrow range of matric potentials. The effects of compaction and soil texture on drainage can be modelled from their effects on these two parameters (Campbell 1985).

Compaction

Campbell (1985) used an empirical Equation to correct ψ_e for soil compaction

$$\psi_e = \psi_{es} \left(\frac{\rho_b}{1.3}\right)^{0.67b} \tag{5.2}$$

where ψ_{es} is the air–entry potential for a standard bulk density (1.3 Mg m^{-3}), b is from Equation 5.1 and ρ_b is bulk density (Mg m^{-3}). Equation 5.2 predicts an increase (less negative) in ψ_e when bulk density increases.

Compaction increases the slope of the water retention function (b) (Gupta and Larson 1979). Compaction has a decreasing effect on water retention as matric potential decreases (becomes more negative). This effect is slight and difficult to quantify from existing data (Campbell 1985).

Texture

The effect of soil texture on the water retention function depends on the correlation between particle size and pore size. ψ_e will decrease as mean pore diameter (d_g) decreases, and b will increase (become less negative) as the standard deviation of mean pore diameter (σ_g) increases. Campbell (1985) deduced approximate relationships for soil at a standard bulk density

$$\psi_{es} = -0.5 d_g^{-\frac{1}{2}} \tag{5.3}$$

$$b = -2\psi_{es} + 0.2\sigma_g \tag{5.4}$$

where d_g is in mm and ψ_{es}, the air entry potential at a standard bulk density of 1300 kg m^{-3}, is in J kg^{-1}. Dividing by g gives ψ_{es} in metres of water.

$$\frac{\psi_{es}}{g} = \psi_w(mofwater) \tag{5.5}$$

5.2.2 Available Water Storage Capacity

Plant available soil water can be estimated as the water held between an upper free drained water content and a lower water content at which plants can no longer physically extract water. The upper limit, termed *field capacity*, was defined by Rich (1971) as "the percentage of water remaining in a soil two or three days after having been saturated, and after free drainage has practically ceased". The definition implies that there is no impediment to free drainage.

Approximations of field capacity are used in laboratory studies. The amount of water retained in a soil sample that has been thoroughly saturated and drained to equilibrium with a known matric potential is used as an approximation to field capacity. A matric potential of -1 m H_2O approximates the drained water potential in the field for different textured soils (McIntyre and Loveday 1968; Loveday 1974).

The lower limit of available water, the permanent wilting point, is the water content at which a plant will permanently wilt. The permanent wilting point is substantially the same for different plants in the same soil. It is the soil water content at which the plant at a certain stage of development wilts, and does not recover turgor when placed in a dark humid chamber overnight. Richards and Weaver (1943) found the permanent wilting point to be closely matched by the water content at -150 m potential. This potential is commonly used to approximate permanent wilting point. It is affected only slightly, if at all, by the structural condition of the sample (Elrick and Tanner 1955).

Available water storage (field capacity – permanent wilting point) is a useful concept in well drained soils. In soils that do not drain freely beyond the rooting depth, water available to the plant after irrigation or rainfall is the amount that enters while water is being added at the surface, i.e. the amount available is controlled by the infiltration rate, not its water retention properties (Loveday and McIntyre 1966).

Compaction

Compaction can increase or reduce the amount of soil water held between field capacity and wilting point. To increase plant available soil water, compaction must reduce drainage pores to form pores that retain water for plant use. The effect of compaction on available soil water varies with soil texture and soil horizon (Reeve *et al.* 1973). Archer and Smith (1972) recommended managing soil density to optimise water storage without impairing drainage and aeration processes. Compaction may increase the proportion of pores holding water in the plant available range, but usually reduces the transmission porosity.

Texture

Increasing fineness of soil texture implies that the mean effective pore size will be reduced and that more water will be stored at lower soil water potentials. Some studies of the effect of mixing clay textured B Horizons with sandy textured surface soils have shown that increasing the percentage of subsoil does increase available soil water (Brown *et al.* 1985). Part of the effect in the field is through increased plant rooting depth, as mixing techniques require deep loosening of the soil profile. Jamison and Kroth (1958) found that available water content decreased with increased clay and increased with increased silt and organic matter for 127 dominantly silty soil samples collected from northwestern, central, western and southwestern Missouri. The clay tended to block pores between silt particles for soils with low organic matter contents.

5.2.3 Pore Size Distribution

The pore size distribution can be estimated from the water retention curve for non–swelling soils. The water potential under a curved air–water interface, such as exists in a soil pore, is given by the capillary rise equation,

$$\psi_m = \frac{-2\sigma\cos\alpha}{r\rho_w g} \tag{5.6}$$

where r is the radius of curvature of the interface, σ is the surface tension of water in contact with air (7.27×10^{-2} J m^{-2} at 20^o C), g is acceleration due to gravity in m s^{-2}, and ρ_w is the density of water (998 kg m^{-3} at 20^o C), and α is the contact angle — usually assumed to be zero, (Marshall and Holmes, 1979, p194), but dependent on the amount of adhesion between water and the capillary wall. Equation 5.6 has been used to determine the size distribution of soil pores (Childs 1940).

The radius, r, of the largest pores remaining full when water is displaced from a non–shrinking material by negative potential is given by Equation 5.6 for a drying soil. The water retention curve can be expressed in terms of relative saturation ($\frac{\theta}{\theta_s}$) as a function of pore radius, r. The pore size distribution can be expressed by the distribution of the slope of this relationship as a function of r.

Compaction

Soil compaction reduces pore space per unit volume and increases the frequency of finer pores. Compaction occurs at the expense of inter–aggregate porosity and the largest voids are excluded first (Braunack *et al.* 1979). Greenland (1977) divided interaggregate porosity into transmission pores (50 – 500 μ m) and fissures ($\geq 500\mu$ m). Transmission pores are important for internal soil drainage and root growth (Goss *et al.* 1984).

When roots encounter pores which are smaller than their own diameter, continuing extension is possible only if they are able to expand the pores (Wiersum 1957). Mechanically restricted seminal roots produce a dense system of laterals and thicken radially to relieve pressure ahead of the elongating tip (Gerard *et al.* 1972). Lateral root growth occurs at the expense of deep seminal root growth in compact soils.

Tillage of topsoil creates transmission pores but simultaneously reduces pore continuity between top and subsoil (Goss *et al.* 1984). Transmission porosity, continuous with the subsoil , maximises unrestricted seminal root growth and has a positive effect on yield (Whitely and Dexter 1982).

Soil Texture

Soil pore size distribution rather than particle size distribution determines soil water behaviour. Pore and particle size distributions are correlated (Gupta and Larson 1979). However, particle packing, shape and orientation affect pore size distribution. Consequently, correlations between pore size distribution and particle size distribution are only accurate for the soil for which they are established (Campbell 1985).

5.2.4 Hydraulic Conductivity

Water flows in response to a hydraulic potential gradient according to Darcy's Law for steady state, one dimensional, saturated flow:

$$J = -K_{sat}\frac{\partial\psi}{\partial x} \tag{5.7}$$

where J is the water flux density (kg m^{-2} s^{-1}), $\frac{\partial\psi}{\partial x}$ is the hydraulic potential gradient that drives the flow and K_{sat} is the saturated hydraulic conductivity.

At water contents less than saturation, hydraulic conductivity values will be lower than K_{sat} because of the smaller crossectional area available for liquid flow. Unsaturated flow generally predominates in the field. The unsaturated hydraulic conductivity, $K(\theta)$, can be estimated from the water retention function, since this function relates the pore size distribution to the pore size classes filled with water.

Theory linking the water retention function with unsaturated flow was developed by Campbell (1974)

$$K(\theta) = K_{sat}\left(\frac{\theta}{\theta_s}\right)^{2b+3} \tag{5.8}$$

where $K(\theta)$ is the steady–state unsaturated hydraulic conductivity, $\frac{\theta}{\theta_s}$ is the relative volumetric water saturation and b is the slope of the water retention function from Equation 5.1. Equation 5.8 is similar to several unsaturated conductivity functions which have been used (Hillel 1971, p108). Combined with Equation 5.1, Equation 5.8 becomes

$$K(\theta) = K_{sat}\left(\frac{\psi_e}{\psi}\right)^{2+2/b} \tag{5.9}$$

Equations 5.8 and 5.9 indicate that the hydraulic conductivity of soil is determined by three soil properties, θ_s, ψ_e, and b, all of which are affected by soil pore space.

Compaction

Compaction reduces saturated and unsaturated conductivity by reducing the cross sectional area of soil drainage pores. Compaction in fact eliminates a whole class of pores, the transmission pores, which are important in terms of the Poiseuille equation (see Marshall and Holmes 1979, p84). This effect of compaction can be quantified by analysing its effect on ψ_e, b, θ_s and K_{sat}, the parameters of the hydraulic conductivity model (Equation5.8).

Texture

Finer soil textures correlate with fine pore size distributions. Consequently, K_{sat} typically decreases as silt and clay content increase (Israelsen and Hansen 1962). The relationships between texture and saturated hydraulic conductivity do not account for large cracks, root channels and worm holes which will cause actual conductivities to be larger than those predicted. Unsaturated hydraulic conductivity of fine textured soils is higher than that of coarse textured soils, even though coarse textured soils have higher saturated conductivity (Campbell 1985). Clays, because of their smaller mean particle diameter, have lower (more negative) air–entry potentials and larger b values than sandy soils. The hydraulic conductivity of a sand therefore decreases more rapidly with decreased matric potential than does that of a clay (Equation5.9). Also the higher ψ_e causes $K(\theta)$ to start decreasing at higher potential in sand than in clay.

5.3 Materials and Methods

5.3.1 Water Retention

Soil cores (25 mm high) were prepared from each soil horizon mix, described in Chapter 2 at high, intermediate and low levels of compaction after the soil had been equilibrated at the lower plastic limit water content (DCPL). The compaction method is described in Section 4.3.2.

Soil cores were equilibrated on ceramic plates at pressures of 0.2, 0.5, 1.0, 3.0, 10.0, 100, and 150 m H_2O in pressure chambers (Soil Moisture Equipment Company, California USA). Equilibration was attained when outflow from the chamber became zero. Soil cores were then weighed and dried to constant mass at 105°C. Some cores were used for saturated hydraulic conductivity determination prior to oven drying.

Problems were encountered with equilibration on the 15 bar plates. Cores did not attain the desired water potential when checked with a thermocouple hygrometer (DECAGON, Washington State, USA), even when outflow had stopped. A -150 m H_2O potential was attained by drying the soil in a microwave oven on low power for 1 minute and measuring potential with a thermocouple hygrometer. The hygrometer measured osmotic plus matric potential. Osmotic potential values at these water contents were low (1.78 m of water) for the A horizon (A. Cass personal communication). The comparability of hygrometer measurements with pressure chamber measurements of matric potential was checked visually by plotting the water retention curve comprising data from both techniques (using the thermocouple hygrometer data ranging from -150 m to -30 m water potential).

The coefficients, b and ψ_e, of the water retention model (Equation 5.1) were determined by linear regression. ψ_e is the intercept and b the slope of the relationship between $\ln \psi$ and $\ln\left(\frac{\theta}{\theta_s}\right)$.

5.3.2 Available Soil Water

The upper drained limit water content, analogous to field capacity, was assumed to be the water retained at a matric potential of -1 m H_2O. The lower plant available water limit, or wilting point, was determined as the water retained at a matric potential of -150 m H_2O, measured with a thermocouple hygrometer.

5.3.3 Saturated Hydraulic Conductivity

Soil cores for saturated hydraulic conductivity determination were selected from those used in the water retention study. Cores were chosen to provide a range of compaction conditions for each soil mixing treatment. After equilibration in the pressure chambers the cores were removed, weighed and allowed to air dry.

Saturated hydraulic conductivity (K_{sat}) was measured with a solution of 10 mmol p^+ $CaCl_2$/l as described by Loveday (1974). Soil air was displaced by CO_2 gas prior to commencement of the test. Flow rates were measured over a time period of 1 minute at 1 hour intervals until steady state flow was attained.

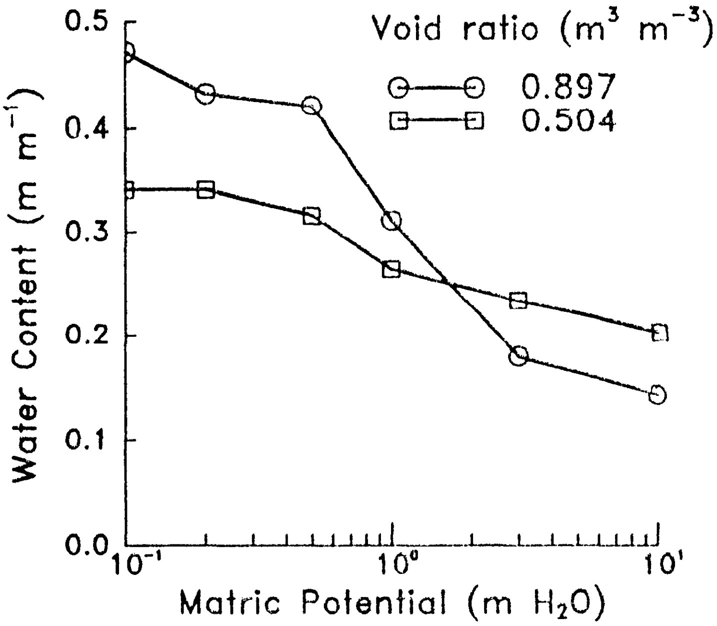

Figure 5.1: The relationship between water content and absolute value of matric potential for the A horizon of Trangie red–brown earth at high and low levels of compaction

5.4 Results

5.4.1 Water Retention

Compaction

Soil compaction reduced the amount of water retained at high water potentials, i.e. that retained in large pores (Figure 5.1). Large diameter pores ($> 30\mu m$) are the first to be removed by compaction. The same effect was found for the other mixtures and B horizon soil.

Compaction decreased (made more negative) the intercept (ψ_e) and decreased (made more negative) the slope (b) of the water retention function (Equation 5.1) for each of the soil horizon mixtures (Table 5.1). Significant empirical correlations with the data were,

$$\psi_e = \psi_{es} \times 13.8 \left(\frac{n}{0.75}\right) \quad (P = 0.02); \quad r^2 = 0.66 \tag{5.10}$$

$$b = b_s(1.63 - 0.58 \left(\frac{n}{0.75}\right)) \quad (P = 0.1); \quad r^2 = 0.47 \tag{5.11}$$

where, ψ_{es} and b_s are determined from Equation 5.1 for a standard void ratio of 0.75 m^3 m^{-3}. Equation 5.10 and 5.11 imply that compaction reduces ψ_e and makes b more negative.

Table 5.1: Coefficients of the water retention model $\psi = \psi_e \left(\frac{\theta}{\theta_s}\right)^{-b}$.

Horizon Mass Fraction	Void Ratio (m^3 m^{-3})	ψ_e (m H_2O)	$\sigma_{\psi e}$ (m H_2O)	b	σ_b	r^2
100 A 0 B	1.04 ± 0.17	-0.26	.03	2.60	0.167	97.2
100 A 0 B	0.80 ± 0.10	-0.25	0.03	3.12	0.22	93.7
100 A 0 B	0.64 ± 0.08	-0.32	0.04	3.45	0.20	94.0
91 A 9 B	1.05 ± 0.17	-0.23	0.04	2.90	0.29	92.4
91 A 9 B	0.80 ± 0.10	-0.21	0.03	3.96	0.24	97.2
91 A 9 B	0.64 ± 0.08	-0.41	0.06	4.00	0.27	89.3
75 A 25 B	0.81 ± 0.10	-0.24	0.03	3.39	0.47	87.8
75 A 25 B	0.65 ± 0.08	-0.38	0.06	5.41	0.43	92.7
50 A 50 B	1.07 ± 0.17	-0.18	0.02	3.83	0.36	
50 A 50 B	0.80 ± 0.10	-0.24	0.06	6.19	0.633	87.9
50 A 50 B	0.65 ± 0.08	-0.43	0.06	5.72	0.362	94.3
25 A 75 B	1.08 ± 0.17	-0.21	0.04	4.14	0.54	86.5
25 A 75 B	0.83 ± 0.10	-0.29	0.03	4.68	0.373	89.7
0 A 100 B	1.09 ± 0.17	-0.21	0.02	3.73	0.346	91.3
0 A 100 B	0.84 ± 0.10	-0.40	0.05	5.53	0.351	93.5

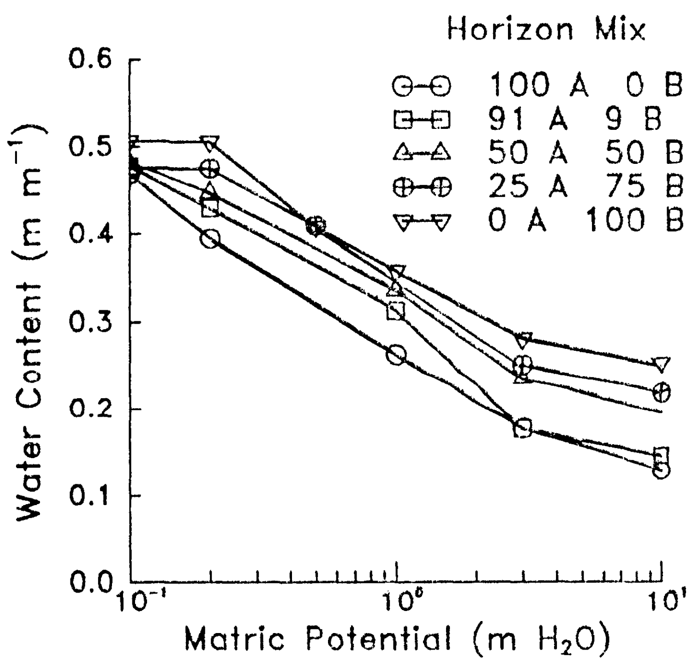

Figure 5.2: The relationship between water content and absolute value of matric potential of Trangie red-brown earth A horizon (100 A 0 B), B horizon (0 A 100 B) and A:B horizon mixtures at a void ratio of 0.98±0.05 m^3 m^{-3}.

Soil Horizon Mixing

Soil horizon mixing increased the amount of water retained at matric potentials greater than -10.0 m H_2O (Figure 5.2). This potential range corresponds to transmission pores with diameters greater than 30 μm. Increasing the proportion of B horizon soil in the mixture increased the volume of pores in this size range for soil that is only slightly compacted (void ratio 0.98±0.05m^3 m^{-3}).

The increase in water content with an increase in the proportion of B horizon at the highest matric potential (-0.2 m H_2O) shows an increase in the volume of pores remaining filled at potentials above -0.5 m H_2O. Increasing the proportion of B horizon in the mixture increased ψ_e and increased b, based on comparisons at similar void ratios for the different mixtures in Table5.1. Both these effects indicate an increase in large pores in a narrow size range and may be related to an increase in interaggregate pore space brought about by mixing B horizon soil with A.

5.4.2 Total Plant Available Water Content

There was no significant relationship between the mass water content at field capacity and void ratio. Mass water contents are used in Table 5.2 rather than volumetric water contents because void ratio and volumetric water content are not independant variables. It was assumed that wilting point water content did not vary with void ratio. Consequently, total plant available water content (TPAWC) was not increased by compaction. The mean field capacity water content for each mix from Table 5.2 is used to represent the upper limit to the plant available water range.

TPAWC was not increased by soil horizon mixing (Table 5.2). Soil horizon mixing increased the wilting point and field capacity water contents such that the plant available water content did not change. The B horizon has a similar plant available water content to the A horizon soil.

5.4.3 Pore Size Distribution

Transmission porosity ($\geq 30\mu$ m diameter) was reduced by compaction (Table 5.3). This confirms that the drop in soil water content at high matric potentials (Figure 5.1) results from the removal of transmission pores.

Soil horizon mixing tends to increase the void ratio at which a particular transmission porosity is attained in compacted soil. This can be shown by examining Table 5.3 for the void ratios for each soil horizon and soil horizon mixture at which transmission porosity decreases below 0.10 m^3 m^{-3}. For 100 A 0 B, 91 A 9 B and 75 A 25 B horizon soil this occurs at void ratios between 0.7 and 0.8 m^3 m^{-3}. For the 50 A 50 B, 25 A 75 B and 0 A 100 B horizon soil the transmission porosity decreases below 0.10 m^3 m^{-3} at void ratios between 0.8 and 0.9 m^3 m^{-3}. At low levels of compaction (at the highest void ratio) there is no trend in transmission porosity variation with soil horizon mixing (Table 5.3).

Table 5.2: Total plant available water content for the A and B horizons and soil horizon mixtures of Trangie red–brown earth.

Horizon mass fraction	Field capacity (kg kg^{-1})	Void ratio (m^3 m^{-3})	Mean field capacity (kg kg^{-1})	Wilting point (kg kg^{-1})	TPAWC (kg kg^{-1})
100 A 0 B	0.21	0.694	0.20±0.01	0.06	0.14±0.01
100 A 0 B	0.21	0.699			
100 A 0 B	0.19	0.885			
100 A 0 B	0.19	0.964			
100 A 0 B	0.19	0.838			
100 A 0 B	0.20	0.578			
100 A 0 B	0.20	0.677			
100 A 0 B	0.20	0.612			
100 A 0 B	0.21	0.742			
91 A 9 B	0.23	0.936	0.20±0.03	0.06	0.14±0.03
91 A 9 B	0.23	0.962			
91 A 9 B	0.23	0.672			
91 A 9 B	0.22	0.696			
91 A 9 B	0.22	0.679			
91 A 9 B	0.22	0.908			
75 A 25 B	0.21	0.746	0.19±0.01	0.06	0.13±0.01
75 A 25 B	0.20	0.718			
75 A 25 B	0.20	0.743			
75 A 25 B	0.19	0.836			
75 A 25 B	0.19	0.762			
75 A 25 B	0.19	0.607			
75 A 25 B	0.19	0.700			
75 A 25 B	0.18	0.606			
75 A 25 B	0.18	0.555			
50 A 50 B	0.25	0.981	0.23±0.02	0.12	0.11±0.02
50 A 50 B	0.25	1.047			
50 A 50 B	0.25	0.987			
50 A 50 B	0.24	0.812			
50 A 50 B	0.23	0.678			
50 A 50 B	0.23	0.806			
50 A 50 B	0.23	0.692			
50 A 50 B	0.23	0.691			
50 A 50 B	0.22	0.662			
25 A 75 B	0.24	1.069	0.23± 0.01	0.1	0.11±0.01
25 A 75 B	0.23	1.093			
25 A 75 B	0.23	0.844			
25 A 75 B	0.23	0.854			
25 A 75 B	0.23	0.745			
25 A 75 B	0.22	0.896			
25 A 75 B	0.22	0.843			
25 A 75 B	0.22	0.730			
25 A 75 B	0.22	0.854			
0 A 100 B	0.27	1.030	0.26±0.02	0.12	0.14±0.02
0 A 100 B	0.27	1.184			
0 A 100 B	0.26	0.811			
0 A 100 B	0.26	0.748			
0 A 100 B	0.26	0.848			
0 A 100 B	0.21	1.051			

Table 5.3: Transmission porosity as a fraction of total porosity for different soil horizon mixtures of Trangie red–brown earth compacted to different void ratios.

Horizon mass fraction	Void ratio (m^3 m^{-3})	Transmission pores $\geq 30\mu m$ diam. as a fraction of total porosity
100 A 0 B	0.964	0.23
100 A 0 B	0.886	0.20
100 A 0 B	0.838	0.18
100 A 0 B	0.740	0.12
100 A 0 B	0.699	0.08
100 A 0 B	0.694	0.08
100 A 0 B	0.677	0.08
100 A 0 B	0.612	0.05
100 A 0 B	0.578	0.03
91 A 9 B	0.962	0.18
91 A 9 B	0.936	0.17
91 A 9 B	0.908	0.16
91 A 9 B	0.696	0.06
91 A 9 B	0.679	0.05
91 A 9 B	0.672	0.04
75 A 25 B	0.836	0.18
75 A 25 B	0.762	0.14
75 A 25 B	0.746	0.11
75 A 25 B	0.743	0.11
75 A 25 B	0.718	0.10
75 A 25 B	0.700	0.11
75 A 25 B	0.607	0.06
75 A 25 B	0.606	0.07
75 A 25 B	0.555	0.04
50 A 50 B	1.047	0.18
50 A 50 B	0.987	0.16
50 A 50 B	0.981	0.16
50 A 50 B	0.812	0.09
50 A 50 B	0.806	0.10
50 A 50 B	0.692	0.04
50 A 50 B	0.691	0.04
50 A 50 B	0.678	0.03
50 A 50 B	0.662	0.04
25 A 75 B	1.093	0.22
25 A 75 B	1.069	0.21
25 A 75 B	0.897	0.15
25 A 75 B	0.844	0.12
25 A 75 B	0.854	0.13
25 A 75 B	0.854	0.14
25 A 75 B	0.843	0.13
25 A 75 B	0.745	0.07
25 A 75 B	0.730	0.08
0 A 100 B	1.184	0.21
0 A 100 B	1.051	0.23
0 A 100 B	1.030	0.15
0 A 100 B	0.848	0.08
0 A 100 B	0.811	0.06
0 A 100 B	0.748	0.03

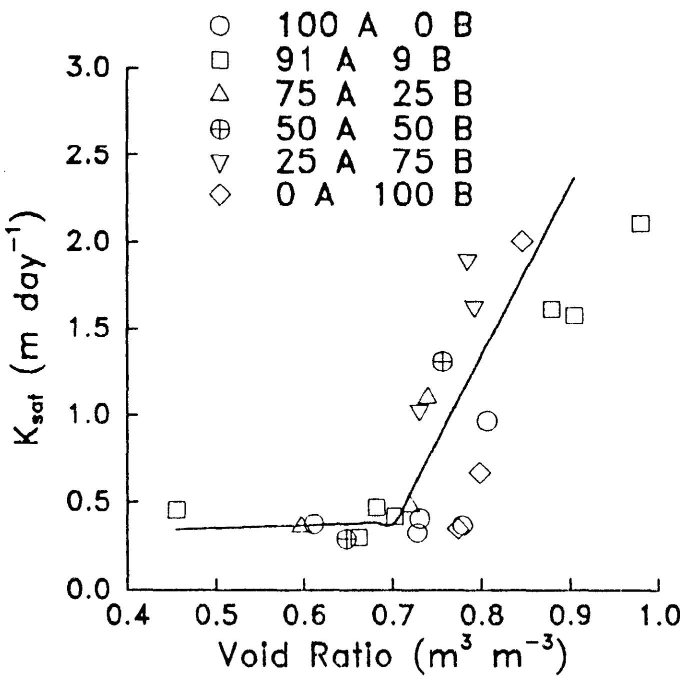

Figure 5.3: Saturated hydraulic conductivity as a function of void ratio for Trangie red–brown earth A and B horizons and A:B horizon mixtures.

5.4.4 Saturated Hydraulic Conductivity

Compaction

Measurements of saturated hydraulic conductivity (K_{sat}) at different levels of compaction indicate that K_{sat} varies in two stages with respect to void ratio (n) (Figure 5.3). At high levels of compaction (low n) K_{sat} is low ($\leq$ 0.5 m day^{-1}) and increases slowly with increasing void ratio until some critical void ratio (n_c) above which K_{sat} increases more rapidly. This critical void ratio was estimated to be 0.70 ± 0.01 m^3 m^{-3} from the point of inflection in a two stage linear function

$$K_{sat} = a + b_1((n - n_c) - \mid n - n_c \mid) + b_2((n - n_c) + \mid n - n_c \mid) \tag{5.12}$$

Soil Horizon Mixing

There is no obviously consistent textural effect on K_{sat} (Figure 5.3). The predominantly B horizon mixtures have higher K_{sat} values than the predominantly A horizon mixtures. However, the B horizon soil (0 A 100 B) has similar K_{sat} values to the A horizon soil (100 A 0 B).

5.4.5 Unsaturated Hydraulic Conductivity

Unsaturated hydraulic conductivity (K) was modelled for different void ratios, and A and B horizon soil using Equation 5.9. Values of ψ_e and b were determined from Equation 5.1 for void ratios presented in Table 5.1.

The conductivity of uncompacted A horizon soil was higher than that of compacted A horizon soil, over the range of drainage soil matric potentials (Figure 5.4). This reflects the change in pore size distribution induced by compaction. Compaction reduced the volume of transmission pores (Table 5.3).

Soil Horizon Mixing

The unsaturated hydraulic conductivity of the B horizon was higher than that of the A horizon (Figure 5.5) at a similar level of compaction. This reflects the larger transmission porosity of the clay B horizon, which is attributed to greater structural aggregation. The mixtures of A and B horizon soil were similar to the A horizon soil.

5.5 Discussion

5.5.1 Water Retention

Compaction

Compaction reduces the size of the largest pores (Figure 5.1) and consequently, reduces the amount of water retained over the range of matric potentials attained during free drainage. The effect of compaction on water retention and flow can

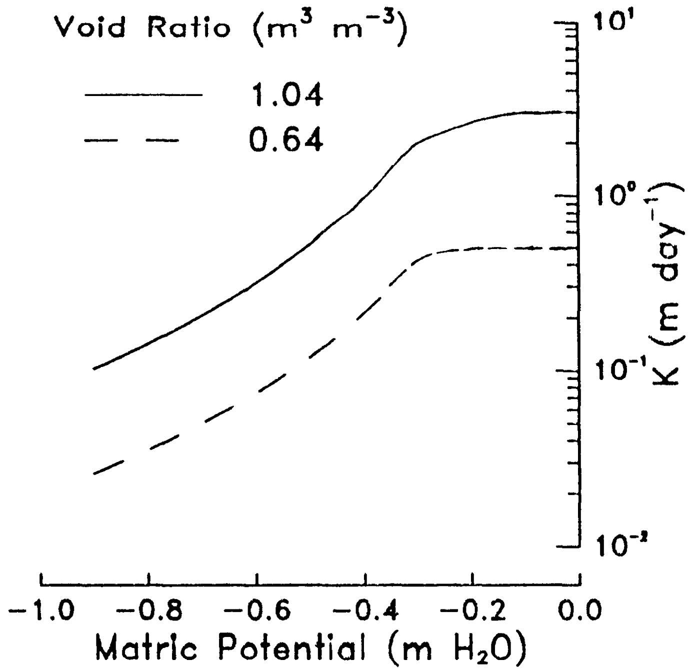

Figure 5.4: Predicted unsaturated hydraulic conductivity ($K(\theta)$) for the A horizon of Trangie red–brown earth at two levels of compaction, modelled from Equation 5.9

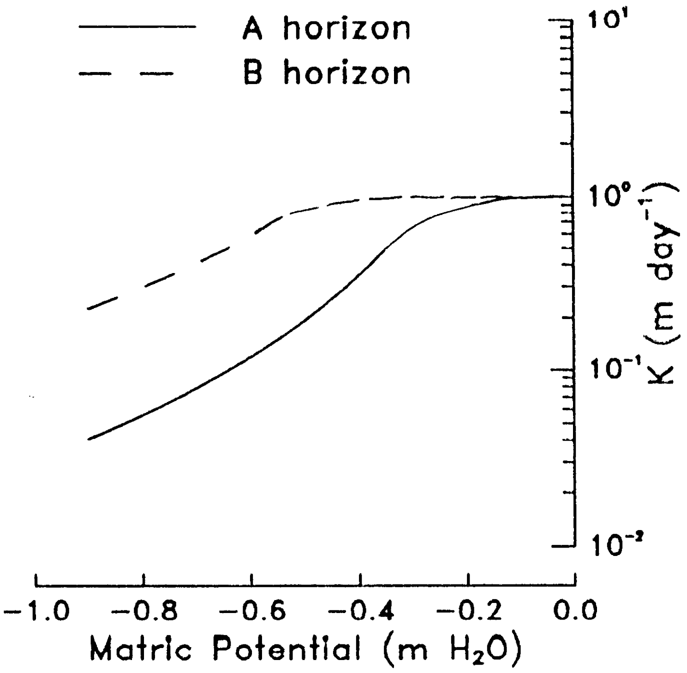

Figure 5.5: Predicted unsaturated hydraulic conductivity ($K(\theta)$) for A and B horizon of Trangie red–brown earth at similar levels of compaction (0.80 m^3 m^{-3} A horizon; 0.84 m^3 m^{-3} B horizon), modelled from Equation 5.9.

be predicted from the intercept (ψ_e) and slope (b) of the drainage water retention function (Equation 5.1).

Compaction reduces ψ_e and increases b (Table 5.1). The compaction effect can be modelled from measurements of ψ_e and b at a standard level of compaction using Equations 5.10 and 5.11. Predictive accuracy is greatest for ψ_e for reasons discussed in Section 5.2.1.

Soil Horizon Mixing

Increasing the proportion of B horizon in the horizon mixture increased the volume of transmission pores (Figure 5.2). This implies that the pore space for water transmission is increased. A finer texture (Table 2.3) would be expected to produce a finer pore size distribution (Campbell 1985). However, increasing the proportion of B horizon in the mixture also increased soil plasticity index (Table 2.4) and thus the tendency of soil to remould into aggregates during the mixing. Horizon mixing created a more structurally aggregated soil and this is reflected in the increase in the volume of large pores between aggregates. Presumably this would occur to some extent in the field during deep tillage and subsequent cultivation.

5.5.2 Total Plant Available Water Content

The transmission pore space removed by compaction (Figure 5.1) does not result in increased water storage (Table 5.2). Thus, the storage pores created by compaction do not necessarily contribute to plant available water. An explanation could be that the storage pores produced by compaction tend to be discontinuous and hence do not fill with water when the soil is initially wet at zero matric potential.

Texture modification had no effect on TPAWC. Consequently, there is no positive effect of soil horizon mixing by deep mouldboard tillage on the plant available water store. Any increases in the plant available water store attributed to deep mouldboard tillage (Harrison *et al.* 1984) are probably a result of deep soil loosening which allows more extensive root growth.

5.5.3 Pore Size Distribution

Compaction

Compaction reduces the proportion of transmission pores (Table 5.3)resulting in a drop in soil water content at high matric potentials (Figure 5.1). Kuipers (1984) calculated that soil transmission porosity, as a fraction of total porosity, needed to be greater than 0.1 to permit root growth unrestricted by mechanical impedance. This figure allows for pore discontinuity.

Fractional soil transmission porosity is reduced below 0.1 at void ratios less than approximately 0.70 m^3 m^{-3} (Table 5.3). The field soil approaches and exceeds this limit in the top 200 mm of the profile (D. Hall , personal communication). Roots expand cylindrically behind the growing tip to penetrate pores of smaller diameter than the elongating tip (Richards and Greacen 1986), thus root growth in this soil depends on the strength of the soil matrix over the range of plant available soil water contents.

Evidence that the void ratio at which a transmission porosity of 0.10 m^3 m^{-3} is attained is increased by soil horizon mixing may be explained by the change in texture that is produced. The finer textured soil produced by soil horizon mixing is expected to have a finer pore size distribution, thus at a particular void ratio the volume of transmission pores would be less in a mixture than in the unmixed A horizon soil. At low levels of compaction the volume of transmission pores will be affected by soil preparation as well as soil texture. The tendency for aggregates to form as a result of soil preparation would increase transmission porosity and reverse the effect of creating a finer soil texture on pore size distribution. This may explain the lack of a consistent effect of soil horizon mixing on pore size distribution at all levels of compaction.

5.5.4 Saturated Hydraulic Conductivity

Compaction

Saturated hydraulic conductivity (K_{sat}) is sensitive to the reduction in transmission porosity caused by compaction. Compaction to a void ratio less than 0.7 m^3 m^{-3} will reduce K_{sat} to below 0.5 m day^{-1} (Figure 5.3). This K_{sat} is indicative of degraded structure in red–brown earths (Greacen 1981). Compaction to void ratios less than 0.7m^3 m^{-3} also reduced soil transmission porosity to a level critical for unrestricted root penetration (Section 5.5.3). Both these findings highlight the contribution of transmission pores to soil fertility and the need to maintain transmission porosity in the cultivated soil.

Soil Horizon Mixing

Soil horizon mixing has no obvious effect on the relationship between K_{sat} and void ratio (Equation 5.12). The results indicate that the critical void ratio (n_c) from Equation 5.12 may be lower for the soil horizon mixtures than for the A and B horizons, however more data at high levels of compaction is needed to investigate variation in n_c between mixtures.

Reduction in n_c with increased B horizon mixing would conform with the conclusion that mixing increases structural aggregation in disturbed soil (Section 5.5.1). The soil mixing treatment caused remoulding of soil aggregates. This needs to be prevented to investigate the effect of texture independent of structure on K_{sat}. For structurless soil, creating a finer texture should create a finer pore size distribution and, since K_{sat} is directly related to the square of the pore radius (Campbell 1985), should decrease K_{sat} at any void ratio.

5.5.5 Unsaturated Hydraulic Conductivity

Compaction

Reduced hydraulic conductivity ($K(\theta)$) during drainage (Figure 5.4) reflects the loss of transmission pores caused by compaction (Figure 5.1). This is further evidence that drainage rate is impared by compaction rather than water storage. The practical consequences of reduced $K(\theta)$ are impared drainage leading to the persistence of anaerobic conditions after irrigation or rainfall.

Soil Horizon Mixing

Hydraulic conductivity, measured by $K(\theta)$, is higher for the B horizon than the A horizon soil(Figure 5.5) for reasons relating to structural differences caused by soil mixing (Section 5.5.1). Water transmission into the B horizon is not considered to be a problem in the field soil (D. Hall , personal communication) and this correlates with the results obtained in this study. However, sporadic bleaching of the A2 horizon (Table 2.1) suggests that reducing conditions, brought about by restricted water movement into the B horizon, probably do occur (Loveday 1981).

The confinement of the subsoil clay means it will swell slightly rather than disperse. Any tendency of the subsoil clay to swell will reduce interaggregate porosity and hence water intake. Dispersion was prevented in the laboratory measurement of K_{sat} (used to model $K(\theta)$ in Equation 5.9) by adding $CaCl_2$ to the permeating water. In the field trial, adding gypsum was shown to increase steady state infiltration rate (D. Hall , personal communication), presumably because it also reduced dispersion of B horizon clay.

5.6 Conclusions

- Compaction changes the water release curve. The effect of compaction can be modelled from estimates of the slope and intercept of the water retention function.

- Soil horizon mixing tended to increase the water retained at high matric potentials, reflecting an increase in structural aggregation caused by moulding aggregates during soil preparation.

- Compaction does not increase the total range ofplant available water contents.

- Texture modification brought about by soil horizon mixing does not increase the range of plant available soil water contents.

- The compactness of field soil is such that transmission porosity is suboptimal for root penetration and root exploitation of soil water will depend on soil strength properties (Section 4.5).

- Saturated hydraulic conductivity measurements indicate that compaction removes transmission pores essential for rapid water transmission. Field soil compactness is suboptimal in terms of the critical void ratio (0.7 m^3 m^{-3}) for rapid flow determined from the laboratory study.

- The hydraulic conductivity of the soil mixtures is greater than that of the A horizon soil at low levels of compaction. This reflects the the more aggregated structure of the horizon mixtures. Soil management should aim to create stable structural aggregation to improve infiltration and drainage.

Chapter 6

Soil Aeration

Abstract

Chapter 6 investigates soil aeration and the level of compaction critical for unrestricted oxygen supply to plant roots for the soil horizons and soil horizon mixtures. Plant root respiratory demand for oxygen is met by oxygen diffusing from the atmosphere, through the soil to the root surface. The supply of oxygen through the soil may be reduced by compaction.

Air–filled porosity was measured on disturbed soil cores at different void ratios. The cores were equilibrated at different matric potentials in pressure chambers. Transmission porosity is defined as the air–filled porosity at a matric potential of -1 m H_2O and represents the pore size fraction greater than 30 μ m diameter. Void ratio is used as the index of soil compactness. The relative diffusion coefficient and oxygen flux density were calculated from oxygen concentration measured in a diffusion chamber using a polarographic electrode.

Compaction reduces transmission porosity, while creating a finer soil texture by soil horizon mixing tends to shift the relationship between transmission porosity and void ratio to higher void ratios. The relative diffusion coefficient is less sensitive than the oxygen flux density to changes in oxygen partial pressure gradient during the measurement period. Thus, the relative diffusion coefficient is used to model the oxygen transmission properties of the soil rather than the oxygen flux density. A two part linear function is used to relate the relative diffusion coefficient to transmission

porosity.

Critical void ratios for adequate oxygen supply to respiring roots are determined from the relationships between relative diffusion coefficient and transmission porosity, and transmission porosity and void ratio. The critical void ratio for adequate oxygen supply is 0.68±0.01 $m^3\ m^{-3}$ for the A horizon and 0.86±0.02 $m^3\ m^{-3}$ for the B horizon soil. Soil horizon mixing tends to increase the void ratio critical for unrestricted oxygen supply. The critical void ratios for unrestricted aeration are calculated for inclusion in the nomograms of soil physical fertility in Chapter 7.

6.1 Introduction

Plant roots need oxygen to respire. The solid and liquid components of soil act as impediments to oxygen diffusion from the atmosphere through the soil to the root surface. Hence, oxygen supply to the root is affected by soil compactness and the relative proportion of air and waterfilled pore space.

Compaction removes the transmission pores which conduct water over the range of drainage matric potentials. Thus, compaction reduces the volume of continuous air–filled pores at the upper end of the range of plant available water contents. Continuous air–filled pore space is essential for rapid gas diffusion at rates comparable to the root respiratory demand for oxygen. Soil oxygen flux may be modelled as a function of air–filled pore space at a particular void ratio and matric potential. Consequently, the level of compaction critical for the supply of oxygen to plant roots can be estimated from oxygen diffusion and air–filled porosity measurements.

A study of the effect of compaction on soil oxygen transmission is made for different soil horizon mixtures of Trangie red–brown earth. Oxygen diffusion is modelled as a function of air–filled pore space and critical values of transmission porosity for adequate aeration in different mixtures of A and B horizon are established. These values are used in nomograms of the effect of compaction on soil physical fertility in Chapter 7.

6.2 Literature Review

Erickson (1982) categorised soil aeration status in terms of: capacity, intensity and rate. Aeration capacity is the volume fraction of bulk soil occupied by gas (air–filled porosity). Aeration intensity is the oxygen concentration in the gas–filled pores or in the soil solution. The rate factor is the velocity of oxygen diffusion through gas–filled pores or liquid films.

6.2.1 Transmission Porosity

Air capacity, the soil volume fraction occupied by gas, is the parameter that has been most used to describe aeration. Often it is designated as the air volume at some matric potential that seems reasonable or at the formerly respectable field capacity (Erickson 1982). The matric potential of soil water is a function of the diameter of soil pores (Equation 5.6). Consequently, air capacity at a matric potential of -1 m H_2O, used to approximate field capacity (Chapter 5, Section 5.4.2) represents the volume of transmission pores greater than 30 μm diameter as a fraction of the total soil volume. The volume fraction of transmission pores is represented by the symbol E_T.

Soil transmission porosity is responsible for rapid drainage of water and hence has a major influence on soil aeration. Compaction reduces E_T, i.e. air–filled porosity at a drained matric potential is reduced as pore space is reduced (Grable and Siemer 1968). Consequently, soil compaction reduces E_T and soil drainage rate thus prolonging limiting soil aeration conditions following irrigation or rainfall. Structural aggregation increases soil transmission porosity (Grable and Siemer 1968). Soil aggregation creates inter–aggregate pores with diameters which are directly related to the diameter of the soil aggregate. Grable and Siemer (1968) found that critical air–filled porosities for adequate oxygen diffusion may not be attained for soils with a mean aggregate diameters of less than 0.5 mm.

Pore size distribution is correlated with soil texture. However, the effect of soil aggregation reduces the generality of the relationship (Section 5.2.3). Consequently, relationships between pore size distribution and soil texture only apply accurately to the soils for which these relationships have been developed (Campbell 1985). In non-aggregated soils, the pore size distribution should become finer for finer textured soils causing a reduction in transmission porosity.

6.2.2 Aeration Intensity

Soil oxygen concentration ($[O_2]$) is a function of gaseous disequilibrium between the soil and atmospheric air. The disequilibrium is caused by two factors — impedance to diffusive mixing through the soil matrix, and consumption of O_2 by biological processes in soil. The relationship between $[O_2]$ and soil compactness is not predictable because of the variability in soil biological activity (Erickson 1982). Also, roots are surrounded by a water film which forms a barrier to plant oxygen uptake irrespective of soil oxygen concentration. Consequently, soil oxygen concentration measurements do not provide a good indication of aeration status following irrigation and drainage.

6.2.3 Aeration Rate

Diffusion Process

Gas diffusion is the principle process causing gaseous interchange between the soil and the atmosphere (Penman 1940a,b). Consequently, oxygen diffusion is measured to characterise oxygen supply.

Fick's law describes diffusion of oxygen in soil:

$$OFD = \frac{J_G}{A} = -D \times \frac{dc}{dz} \tag{6.1}$$

where OFD is the oxygen flux density (μg m^{-2} s^{-1}), J_G is the mass flux (μg s^{-1}) across cross sectional area A (m^2), D is the diffusion coefficient for a soil medium (m^2 s^{-1}), c is the concentration of O_2 (μg m^{-3}) and z is diffusion distance (m). Equation 6.1 can be integrated to give

$$OFD = D \times (c_1 - c_2)/z \tag{6.2}$$

where $(c_1 - c_2)/z$ is a concentration gradient between two locations z distance apart. Thus for steady state conditions, where the concentration gradient is constant, OFD is proportional to D. The diffusivity of oxygen through soil is usually expressed as relative diffusion coefficient $(\frac{D}{D_0})$ where D_0 is the diffusion coefficient of oxygen through air, without any intervening soil.

$\frac{D}{D_0}$ and OFD have different relevance in soil aeration studies. The ratio $\frac{D}{D_0}$ is, within broad limits, independent of the nature of the diffusing gases; it is a measure of the ability of the soil material to allow transit of gases by diffusion, and integrates the effects of air content, pore continuity and tortuousity (Currie 1984). $\frac{D}{D_0}$ is dimensionless and directly proportional to OFD for steady state diffusion. OFD is used as a measure of soil oxygen supply to plants. It is convenient because oxygen supply can be expressed in the same form as respiratory consumption of oxygen by plant roots (Blackwell and Wells 1983).

OFD and $\frac{D}{D_0}$ are exponential functions of air filled porosity E_a, multiplied by a factor describing pore tortuousity (Currie 1984; Wilson *et al.* 1985). The relationship between oxygen diffusion and air-filled porosity is in two parts — at low air–filled porosities slow diffusion through fine intra–aggregate pores occurs while at some higher air–filled porosity rapid diffusion through larger inter–aggregate, or transmission pores, accounts for most of the diffusion taking place (Currie 1984). The relationship can be approximated by a two part linear model in which OFD increases rapidly above a critical E_a (Hodgson 1986).

OFD and $\frac{D}{D_0}$ can be measured rapidly in the laboratory. Hodgson (1986) described a method (based on Taylor 1949) in which oxygen diffusing from the atmosphere through a soil core into a chamber is sensed by a polarographic electrode. For steady state conditions $\frac{D}{D_0}$ will relate directly to the OFD towards the respiring root surface. The method described by Hodgson (1986) approximates steady state diffusion during the initial stages of oxygen diffusion through soil and into a chamber evacuated of oxygen.

Direct measurement of OFD can be made with a bare platinum electrode inserted in the soil. The bare electrode closely approximates a plant root and the technique is generally accepted as giving the most accurate indication of oxygen supply to a respiring root surface in the soil (Gliński and Stępniewski 1985). The original technique proposed by Letey and Stolzy (1964) had major faults which caused overestimation of OFD in unsaturated soils (McIntyre 1970). These faults have since been corrected (Blackwell 1983).

Comparisons between oxygen flux measured by the bare electrode and that calculated from steady state diffusion into a chamber may be misleading. The oxygen flux within soil aggregates is usually much smaller than that between soil aggregates (Blackwell 1983). A bare electrode is much smaller than a soil structural unit and will most likely measure oxygen flux within structural units, while the diffusion chamber technique measures oxygen diffusing through the interaggregate pore space. Soil respiration will tend to reduce oxygen diffusing through the soil core into the chamber. Soil sterilization can be used to overcome the measurement bias caused by soil respiration (Melhuish *et al.* 1974). However, Hodgson (1986) found that soil respiration did not have a significant effect on the oxygen diffusion rates he measured using the diffusion chamber technique. Hodgson used published respiration rates, ranging from 54 to 270 μ g m^{-2} s^{-1} to test the accuracy of his technique.

6.2.4 Compaction

Compaction reduces the rate of oxygen diffusion through soil by reducing the fractional volume of soil transmission pores thereby reducing the volume of air filled pores as the soil drains. Compaction which reduces air filled porosity (E_a) to a value critical for oxygen diffusion will create problems for respiring roots. Wesseling and van Wijk (1957) suggested a tentative lower limit of 0.10 m^3 m^{-3} for E_a for the growth of plants. The critical E_a for loam soils is more like 0.12 to 0.15 m^3 m^{-3} (Grable and Siemer 1968) and may be as high as 0.20 m^3 m^{-3} for loose packed soil. This seemingly anomalous effect of compaction relates to soil desorbtion behaviour. At a low value of air–filled porosity the less compact the soil, the less intra–aggregate pore space and the greater the fraction of the soil water volume likely to be in the inter–aggregate pores blocking pore necks. In two cores at the same E_a and different void ratios, water in the more compact core will be at a lower (more negative) matric potential. Consequently, water in the less compact core will be more likely to block transmission pores essential for rapid oxygen diffusion (Currie 1984). If compared at the same matric potential the less dense soil will always be better aerated. Thus, the effect of compaction on soil aeration status should be determined by comparing diffusion in soils for different levels of compaction at the same matric potential using E_T instead of E_a.

Soil Horizon Mixing

A fine pore size distribution is correlated with the fineness of soil texture. Consequently a clay soil will have a higher oxygen flux through the surface than a sand, if compared at the same E_a (Skopp 1985) for the same reasons that a compacted soil has a higher oxygen flux at a low E_a than an uncompacted soil. However, the sand is likely to drain more rapidly than the clay and at the same matric potential the sand will be better aerated.

Soil structure modifies pore size distribution and transmission porosity independently of soil texture. Root channels, worm holes, cracks and interaggregate pores form conduits for rapid drainage and the attainment of a transmission porosity above the value critical for unrestricted oxygen supply. The effect of texture on oxygen flux through the soil surface has been modelled by Skopp (1985). However, the theory does not account for the secondary effect of soil structure on oxygen diffusion. There is no general relationship between soil texture and soil aeration for the same reason there is no general relationship between soil texture and water retention (Campbell 1985), i.e. soil structure may modify the pore size distribution independently of soil texture.

6.2.5 Aeration Limits to Plant Growth

Plant roots and seeds in the soil are surrounded by water films. Water is a barrier to diffusion because the oxygen diffusion coefficient in water is four orders of magnitude less than that in air (Erickson 1982). Thus, water film thickness controls oxygen uptake from the soil.

Water film thickness is reduced as matric potential becomes more negative. Root elongation rate increases rapidly as matric potentials fall below the air–entry potential (Grable and Siemer 1968). Therefore water film thickness at the air–entry potential should represent the maximum diffusion path length through water for unrestricted root growth. The air–entry potential represents the highest matric potential for which root growth is not restricted by oxygen supply.

Compaction

Compaction reduces the air–entry potential (Campbell 1985). Consequently, the air–filled porosity for optimal root elongation in compacted soil may occur at a matric potential 4 to 5 times the matric potential in uncompacted soil (Grable and Siemer 1968). Because compaction reduces soil drainage rate these potentials take longer to attain. Thus, critical E_a values determined from diffusion measurements need to be interpreted with matric potential measurements to determine whether compaction is critical to plant oxygen uptake from the soil. An obvious criterion for compaction damage is the value of transmission porosity (E_T) at which oxygen diffusion is just equal to root respiratory consumption.

Soil Horizon Mixing

Fine texture is correlated with a fine pore system (Gupta and Larson 1979) and thus lower air–entry potentials and slower drainage than for coarse textured soil (Campbell 1985). As with compacted soils, comparison of different textured soils using air–filled porosity is misleading (Section 6.2.4). Again, it is neccessary to relate oxygen diffusion to the E_a at a relevant matric potential such as the -1 m H_2O potential.

6.3 Materials and Methods

The soil used in this study included A and B horizon material as well as mixtures in the ratio 91:9, 75:25, 50:50 and 25:75 A:B. Soil preparation is described in Section 2.3.2. Soil cores (75 mm high and 73.6 mm diameter) were manufactured by uniaxial compaction at the plastic limit (DCPL) water content (Section 4.3.2). The degree of compaction was varied to provide cores in three bulk density ranges, 1200 to 1300, 1450 to 1550 and 1600 to 1700 kg m^{-3}. These bulk density ranges correspond to light, medium and heavy compaction.

Cores were saturated by imbibition on ceramic porous plates, then equilibrated to a particular matric potential in a pressure chamber (Section5.3.1). The pressures used were 0.2, 0.5, 1.0, 3.0, 10.0, 30.0, 100.0 and 150 m H_2O. Two replicate cores were used for each pressure. The total number of cores was 6 mixtures x 3 bulk densities x 7 pressures x 2 replicates = 252 cores.

Transmission porosity (E_T) was calculated for cores equilibrated in the -1 m matric potential chamber using:

$$E_T = (\theta_{sat} - \theta_g)\frac{\rho_b}{\rho_w} \tag{6.3}$$

where θ_g is the mass water content (kg kg^{-1}), ρ_b is bulk density (kg m^3) and ρ_w is the density of water at 20° C.

Diffusion of oxygen through the soil cores was measured with a Beckman Oxygen Analyser (Model 0260) and the diffusion chamber shown in Figure 6.1. The method and apparatus were obtained from Hodgson (1986) who modified the technique of Taylor (1949). The oxygen analyser electrode was inserted through a port in the wall of the chamber. Two other ports, an inlet and an outlet port, were used to flush the chamber with N_2 gas prior to all measurements. Completion of air removal was assumed when the oxygen meter gave a zero reading.

Diffusion measurments were made by placing a soil core on the slide (Figure 6.1), sealing all possible points of oxygen leakage with petroleum jelly and flushing the sealed chamber with N_2 gas. At the start of the test the chamber was opened to the atmosphere via the soil core by sliding the soil core housing over the main port

Figure 6.1: Oxygen diffusion measurement apparatus

of the chamber (Figure 6.1). O_2 partial pressure was measured over a period of 15 minutes at one minute intervals and the temperature recorded at the start and end of the test. All tests were carried out in a constant temperature laboratory (20 ± 1^oC).

Two possible sources of error in the measurements were development of O_2 gradients in the chamber and respiratory consumption of O_2 as it diffused through the soil core. O_2 gradients were in fact assumed to be negligible. Respiratory consumption of O_2 was tested by flushing the chamber with O_2 and monitoring O_2 change in the chamber with a soil core in place (-0.5 m H_2O matric potential) on the chamber, but with the top of the core sealed from the atmosphere with plastic film.

Oxygen flux density (OFD) was calculated from the O_2 partial pressure measurements between 5 and 15 minutes after the start of the test, using

$$OFD = \frac{(P_{15} - P_5)\frac{VM}{RT}10^6}{At} \tag{6.4}$$

where P_{15} and P_5 are the oxygen partial pressures in the chamber at 15 and 5 minutes (kPa O_2/kPa TOTAL),
V is volume of the chamber (m^3),
M is the molecular mass of O_2 (0.032 kg mol^{-1}),
R is a gas constant (8.312 m^3 K^{-1} mol^{-1}),
T is thermodynamic temperature (^oK),
A is crossectional area of the soil core (m^2) and
t is time of diffusion (600 s). OFD is expressed in units of μg m^{-2} s^{-1}. Equation 6.4 is a restatement of Equation 6.1 with the measured partial pressure gradient converted to mass flow units by the factors V, M, R and T.

The oxygen diffusion coefficient (D) was calculated from the oxygen partial pressure measurements at one minute intervals between 5 and 15 minutes after the start of the test, using

$$\ln\left(\frac{P_0}{P_0 - P}\right) = D \times t \tag{6.5}$$

where P_0 is the partial pressure of oxygen in air at 20°C (0.209 (kPa O_2 / kPa TOTAL) and P is the partial pressure of oxygen in the chamber at t seconds after diffusion has begun. $\ln\left(\frac{P_0}{P_0-P}\right)$ is the partial pressure gradient at time t. The diffusion coefficient of oxygen through soil relative to through air was calculated as $\frac{D}{D_0}$, where D_0 is the diffusion coefficient calculated using equation6.5 without soil in the system. The theoretical basis for Equation 6.5 was presented by Taylor (1949).

6.4 Results and Discussion

6.4.1 Transmission Porosity

The decrease in transmission porosity as void ratio decreases (Figure 6.2) represents a decrease in non–capillary pore space. Transmission pore space per unit volume of soil is directly proportional to void ratio. Similar relationships can be determined from the data of Grable and Siemer (1968) for a silty clay loam soil.

Transmission porosity is zero at a finite void ratio (n) (Figure 6.2). Since the -1 m H_2O matric potential can be converted to the pore size class greater than 30μm diameter using Equation 5.6, transmission porosity represents the volume fraction of pores in this size class. Compaction removes pores greater than 30μm diameter as transmission porosity decreases to zero.

Analysis of covariance shows that the slopes of the relationships in Figure 6.2 decreased as the proportion of B horizon in the mixture is increased. There is no consistent trend in the intercepts of the relationships with mixing. The effect of soil horizon mixing on the rate of decrease of transmission porosity with decreasing void ratio (Figure 6.2) may be related to the textural changes produced by mixing. This textural effect may arise from differences in pore size distribution between soil horizon mixtures.

The void ratio at which transmission porosity was reduced to zero did not vary consistently as progressively more B horizon was mixed with A horizon soil. However, there was a shift in the value to higher void ratios for the B horizon soil compared with the A. Some of the variation between mixtures may have resulted from the soil preparation method (Section 5.5.1) which affected the pore size distribution differences between mixtures (Figure 5.2).

6.4.2 Aeration

Diffusion Process

Soil respiration did not cause a significant change in the partial pressure of oxygen in the chamber. Oxygen partial pressure (p) in the chamber increased at a constant rate (Figure 6.3a). Thus steady state diffusion is occurring over the measurement period and oxygen flux density (OFD) can be calculated using Equation 6.4.

The slope of the curves in Figure 6.3b gives the oxygen diffusivity, D (Taylor 1949). D divided by oxygen diffusivity through air gives relative diffusivity $\frac{D}{D_0}$ against which OFD is plotted in Figure 6.4. OFD is proportional to $\frac{D}{D_0}$ (Figure 6.4), as is predicted from diffusion theory (Equation 6.2).

The relationship between OFD and $\frac{D}{D_0}$ is not linear at high OFD (Figure 6.4). The oxygen partial pressure gradient decreases rapidly at high oxygen fluxes and, from Equation 6.1, OFD begins to decrease. $\frac{D}{D_0}$ on the other hand depends only on the properties of the soil medium for a particular combination of conditions and is not affected by the oxygen partial pressure gradient from the atmosphere to the diffusion chamber. Thus, the relative diffusion coefficient ($\frac{D}{D_0}$) of oxygen through soil reflects the transmission properties of the soil medium rather than the effect of decreasing oxygen concentration gradient at high OFD. Consequently, $\frac{D}{D_0}$ is used as an index of the ability of the soil to transmit oxygen, in gas phase, in this study.

Compaction

When $\frac{D}{D_0}$ is plotted against E_a at different void ratios (n) a family of curves are obtained (Figure 6.5). The E_a critical for oxygen diffusion increases as void ratio increases. This effect is also reported by Currie (1984) and Grable and Siemer (1968) and is discussed in Section 6.2.4. The decrease in the air-filled porosity critical for oxygen diffusion with increased compaction relates to the water in the more

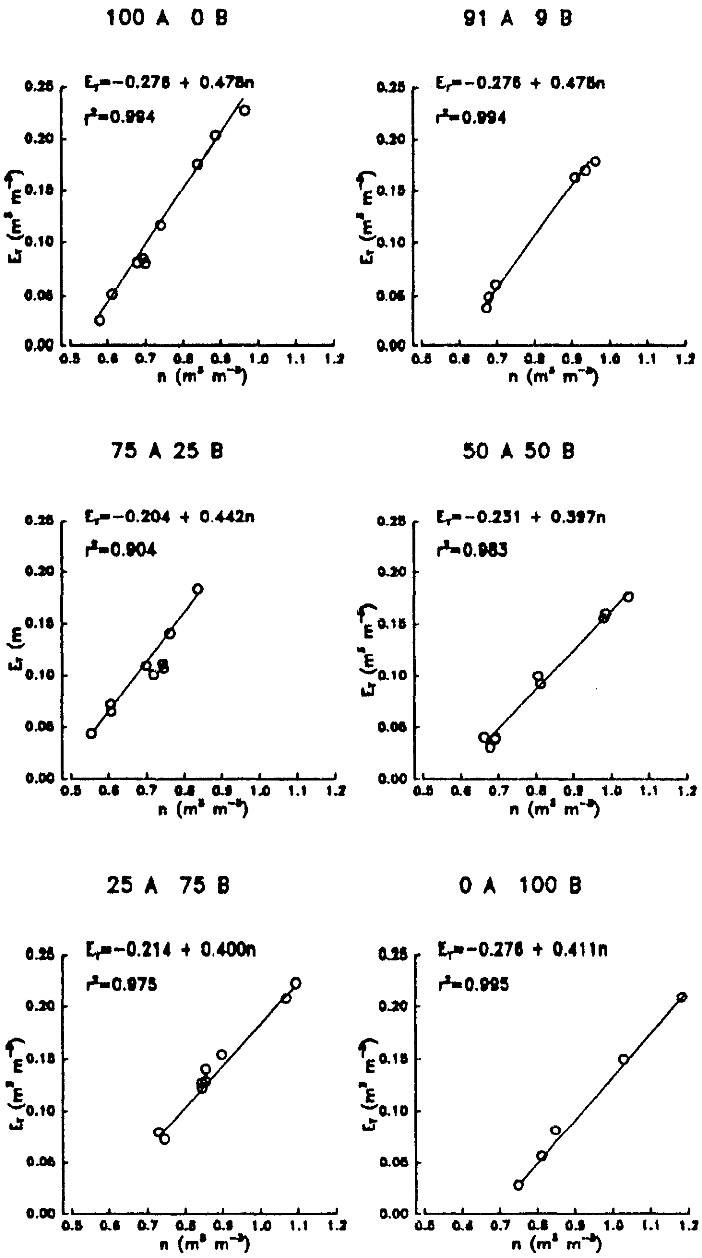

Figure 6.2: Transmission porosity (E_T) versus void ratio (n)for A and B horizon mixtures for A and B horizon mixtures of Trangie red-brown earth.

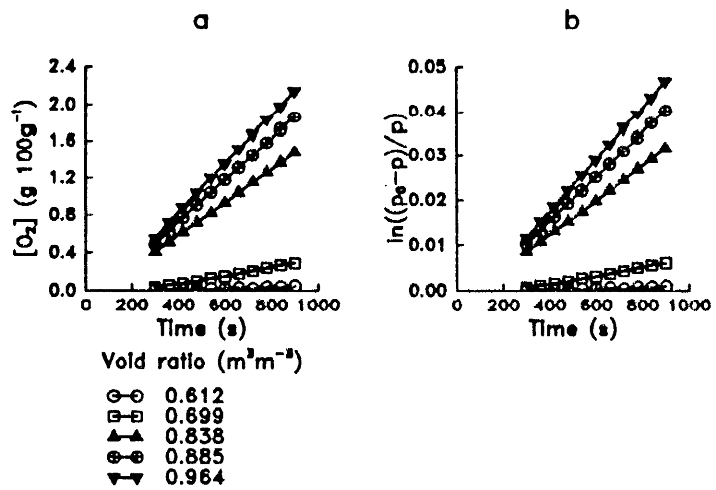

Figure 6.3: (a) Oxygen partial pressure in the diffusion chamber every 60 s after diffusion had begun, and (b) the effect of diffusion time (s) on oxygen partial pressure gradient in the diffusion chamber, resulting from diffusion through cores of Trangie red–brown earth A horizon at a matric potential of -1 m H_2O and 5 levels of compaction.

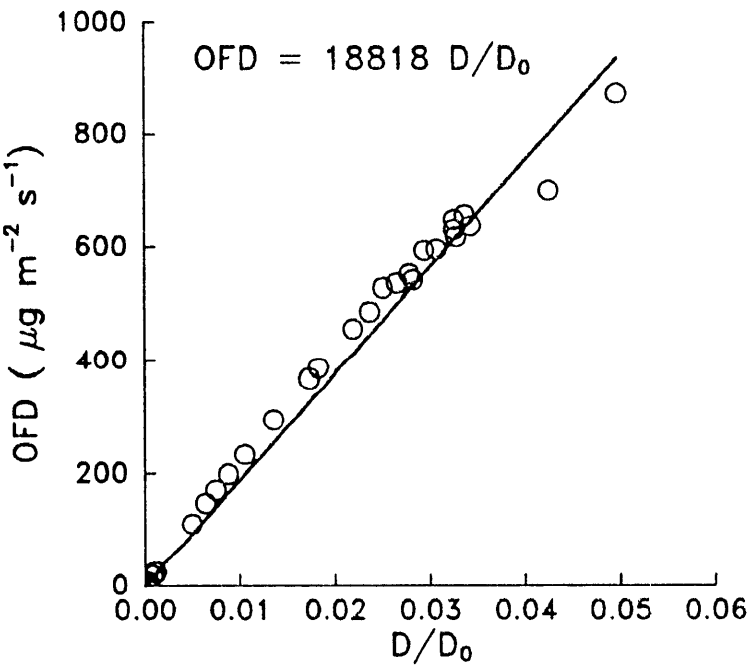

Figure 6.4: The relationship between oxygen flux density (OFD) and relative diffusion coefficient ($\frac{D}{D_0}$) for Trangie red-brown earth A and B horizons and horizon mixtures.

compacted soil being at a lower matric potential, thus occupying smaller pores and being less likely to block necks in the transmission pores which are responsible for rapid oxygen diffusion. Even in compact soils the small volume of transmission pores allows some oxygen movement to occur.

The effect of matric potential variation between soils at the same air–filled porosity, but different void ratios, on oxygen diffusivity should be removed when $\frac{D}{D_0}$ is plotted against the air–filled porosity at a particular matric potential. Thus when $\frac{D}{D_0}$ is plotted against transmission porosity (E_T) the family of curves is reduced to a single relationship (Figure 6.6), which can be described by a two part linear equation,

$$\frac{D}{D_0} = 0.0007 + 0.03((E_T - 0.08) + \mid E_T - 0.08 \mid + 0.007((E_T - 0.08) - \mid E_T - 0.08 \mid) \tag{6.6}$$

Compaction reduces transmission porosity (Figure 6.2) and reduces soil aeration rate. Hence, below the point of inflection in Figure 6.6 transmission pores become less effective for conducting oxygen. This may be because most of the air–filled pores remaining are not continuous between either end of the soil core. The relative diffusion coefficient is zero at a positive value of transmission porosity (Figure 6.6) because of non–continuous transmission pore space in the soil. The impairment of oxygen diffusion at transmission porosities less than 0.08 m^3m^{-3} is corroborated by reduced yields reported by Erickson (1982) at similar transmission porosities in the field.

Soil Horizon Mixing

The relative diffusion coefficient ($\frac{D}{D_0}$) data from all the soil horizon mixtures, and different levels of compaction, are a simple function of transmission porosity (Figure 6.6). This relationship may be described by a two part linear model (Equation 6.6). There was no single relationship between the relative diffusion coefficient and air–filled porosity for the different soil horizon mixtures. Increasing the proportion of B horizon in the mix reduced the air–filled porosity at which diffusion began in a manner similar to that attributed to compaction (Figure 6.5).

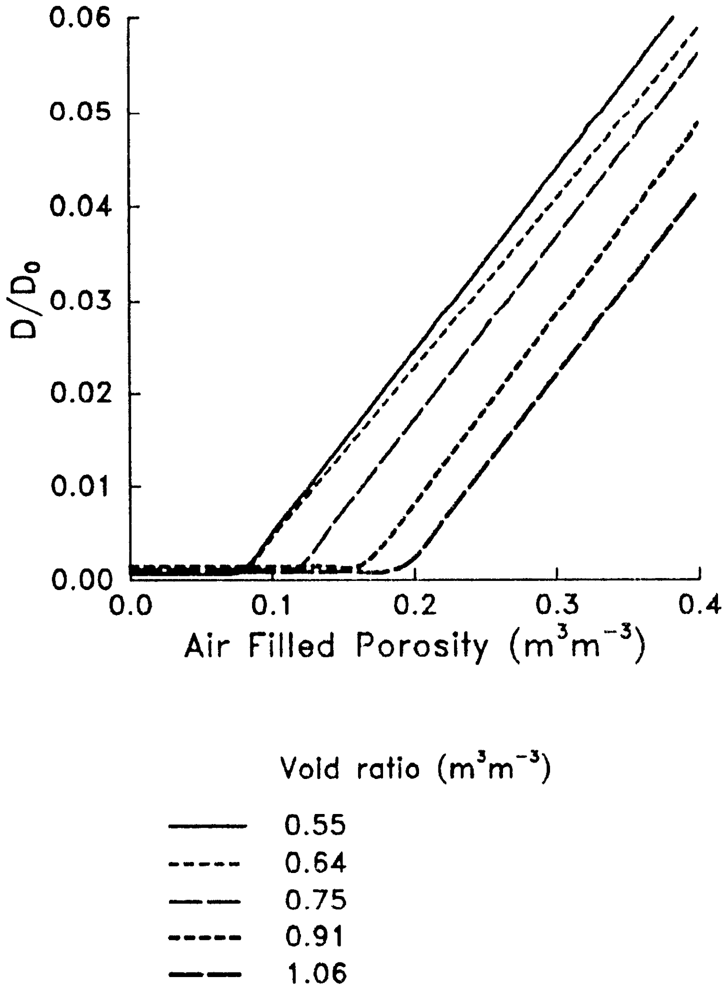

Figure 6.5: Relative diffusion coefficient $\frac{D}{D_0}$) versus air–filled porosity (E_a) at different void ratios for Trangie red–brown earth A horizon.

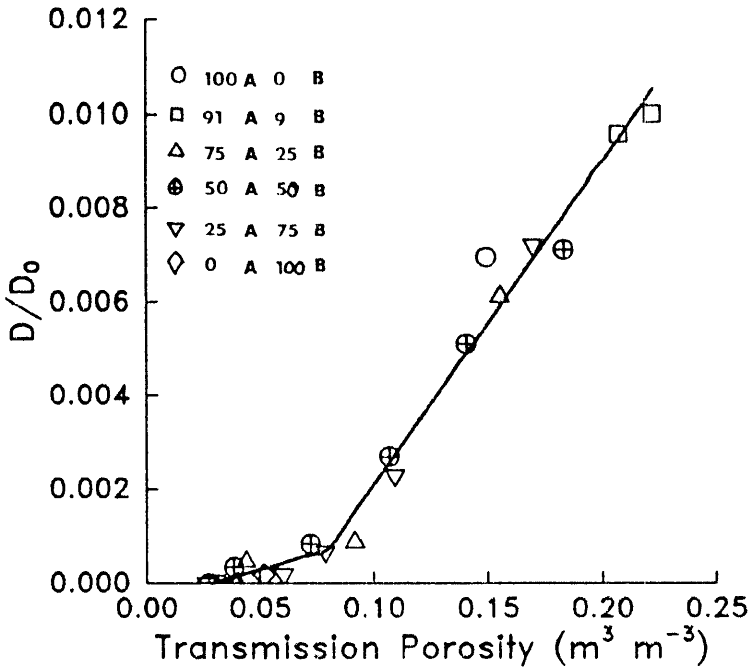

Figure 6.6: Relative diffusion coefficient ($\frac{D}{D_0}$) versus transmission porosity (E_T) for Trangie red–brown earth A and B horizon soil and for soil horizon mixtures.

6.4.3 Aeration Limits for Plants

The critical OFD for unrestricted root growth depends on the amount of oxygen needed for unrestricted root respiration. Root respiration rate increases with increased temperature and at the highest temperature reported by Blackwell and Wells (1983) (25°C) OFD is approximately 23 μg m^{-2} s^{-1}. This corresponds to a $\frac{D}{D_0}$ of 0.001 (Figure 6.4), which must be supplied through the soil to satisfy respiratory oxygen demand under most soil temperature conditions.

In terms of oxygen supply, this peak demand is satisfied close to the point of inflection in Figure 6.6 ($\frac{D}{D_0}$ of 0.0007±0.00004 at E_T of 0.08 m m^{-1}). Thus the void ratios in Table 6.1 indicate the level of compaction conditions critical for unrestricted root respiration. The point of inflection in Figure 6.6 occurs at a E_T of 0.080±0.008 m^{3}m^{-3}. The inflection point represents a marked change in the effectiveness of transmission pores for conducting oxygen diffusion. This void ratio was substituted into the relationships between transmission porosity and void ratio for each soil horizon mixture (Figure 6.2) to calculate the void ratios presented in Table 6.1.

Table 6.1: Void ratio (n) corresponding to an transmission porosity of 0.080 m^3 m^{-3} for Trangie red-brown earth A and B horizons and soil horizon mixtures.

Horizon mass fraction	Void ratio (m^3 m^{-3})
100 A 0 B	0.677±0.013
91 A 9 B	0.746±0.019
75 A 25 B	0.647±0.026
50 A 50 B	0.783±0.015
25 A 75 B	0.735±0.025
0 A 100 B	0.864±0.019

These critical void ratios indicate compaction which reduces E_a to a critical level for oxygen movement at the maximum plant available water content (1 mH_2O matric potential). At void ratios less than the critical value the transmission porosity is likely to be too low to allow oxygen diffusion at a rate adequate for unrestricted root respiration. The variation in critical void ratios for different mixtures relates to the different relationships between E_T and void ratio (Figure 6.2).

Soil Horizon Mixing

The critical void ratio for oxygen supply is higher in the B horizon than the A horizon soil (Table 6.1). This arises from variation in the relationship between E_T and n for the different soil horizons (Figure 6.2), the basis of which was discussed in Section 6.4.1. It was expected that creating a finer soil texture by B horizon mixing would create a finer pore size distribution and consequently increase the void ratio critical for oxygen supply. This effect would have been reversed by the tendency for structural aggregation to increase, because of remoulding during soil preparation, as the soil texture became finer (Section 5.5.1).

6.5 Conclusions

- Soil compaction reduces soil transmission porosity — the volume fraction of air–filled pores at a matric potential of -1 mH_2O.

- Soil horizon mixing tends to increase the proportion of fine pores, not drained at a matric potential of -1 mH_2O, consequently increasing the void ratio at which a particular transmission porosity is attained.

- Steady state oxygen diffusion theory describes the diffusion process addressed in this study. Oxygen flux density and relative diffusion coefficient are proportional to each other except at high fluxes where the steady state assumption is not accurate. Relative diffusion coefficient is a more consistent indicator of the properties of the soil medium affecting oxygen diffusion to respiring roots as it is not affected by the oxygen concentration gradient.

- Compaction decreases the air–filled porosity critical for oxygen diffusion. This does not mean that compaction improves oxygen supply. A greater proportion of water will be at lower matric potentials in compact soils compared to less compact soils. Consequently, oxygen supply is closely linked to water desorbtion.

- The relative diffusion coefficient of oxygen through soil is a function of the air–filled porosity at a drained matric potential of -1 mH_2O (the transmission porosity) independent of soil compactness. The critical transmission porosity for oxygen diffusion is 0.080 ± 0.008 $m^3\ m^{-3}$. This value is used as a critical limit for calculating critical void ratios for the nomogram model of soil physical fertility (Chapter 7).

- Soil horizon mixing does not affect the relationship between relative diffusion coefficient and transmission porosity.

- The critical void ratio for oxygen diffusion in the A horizon is 0.68 ± 0.01 $m^3\ m^{-3}$ and in the B horizon soil is 0.86 ± 0.02 $m^3\ m^{-3}$. There is no systemmatic effect of soil horizon mixing on the critical void ratio for oxygen supply.

Chapter 7

Soil Management

Abstract

The aim of Chapter 7 is to model the effects of compaction and soil horizon mixing on the physical fertility of Trangie red–brown earth soil. The model is used to interpret the effect of deep mouldboard tillage on the soil physical fertility. The results of uniaxial compression testing (Chapter 3) are used to model soil compaction caused by vertical pressure attributed to traffic. Soil penetration resistance (Chapter 4), saturated hydraulic conductivity (Chapter 5) and oxygen diffusivity measurements (Chapter 6) are used to characterise soil physical fertility at different levels of compaction for the range of water contents from -150 to -1 m of water, representing the range of plant available water contents.

The model of soil fertility can be used to determine soil physical conditions limiting to crop production and to guide tillage management so as to minimise compaction degradation caused by traffic. It can be seen from the model that soil compaction by a 200 kPa surface pressure at the plastic limit water content will mechanically impede root growth and restrict soil water availability. This is a reduction in the soils physical fertility. Greater surface pressures and/or traffic at higher water contents are needed to create restriction to water intake or soil aeration. Consequently, soil penetration resistance is the primary limiting factor to soil physical fertility in compacted soil.

The model indicates that the mouldboard–tilled soil following sowing was not sufficiently compacted to cause restriction to root growth, while the disc–harrowed soil was. This, combined with evidence that soil horizon mixing attainable by deep mouldboard tillage does not reduce soil resistance to compaction damage, suggests that the beneficial effect of the deep mouldboard technique is temporary and related to soil loosening.

In conclusion, penetration resistance is the primary limitation to root growth and is not affected by gypsum application. Maintaining topsoil at void ratios greater than 0.75 m^3m^{-3} (bulk density less than 1500 kg m^{-3}) should prevent compaction restriction to root growth and crop yield. Compaction by wheel pressures greater than 100 kPa at the plastic limit water content may cause compaction damage. Wheel pressures should be kept below 100 kPa and wheel traffic should be confined to water contents less than the plastic limit. Also, there is evidence that the beneficial effect of deep mouldboard tillage is temporary and depends on thorough soil loosening, and not on an increase in the soil's resistance to compaction damage brought about by soil horizon mixing. Any observed beneficial effects of deep mouldboard ploughing appear to be attributed to soil loosening, and aggregate formation, neither of which were investigated.

7.1 Introduction

The aim of this chapter is to model the effects of soil compaction and soil horizon mixing on the physical fertility of Trangie red–brown earth soil. A nomogram model of soil physical fertility is used which combines the strength (Chapter 4), water storage and transmission (Chapter 5) and oxygen supply (Chapter 6) limits to root growth with soil compaction behaviour (Chapter 3) and soil consistency behaviour (Chapter 2). The nomogram is used to evaluate deep mouldboard tillage and as a rational tool for deciding on the need for loosening tillage. Management of tillage aimed at improving rather than degrading red–brown earths will need to be based on such models, which combine a diversity of research information in a form intelligable to primary producers.

7.2 Literature Review

Water, oxygen and penetration resistance conditions which impair seedling emergence or root growth all directly affect plant growth. Water content is the dominant controlling factor. Penetration resistance and oxygen movement are affected by water content. Soil pore size distribution, which changes with soil texture and compactness, affects the relationship between water and both aeration and penetration resistance. Thus, developing a model of the soil physical conditions optimal for root growth requires that the interrelationships between these conditions are described. Soil penetration resistance, oxygen diffusion, water storage and water transmission constraints to soil fertility, as a function of soil compactness, are reviewed in previous chapters. This review investigates the interrelations between these factors as the basis of a compaction management model for physical fertility management. The relationship between soil physical conditions and the management of red–brown earths is also discussed.

7.2.1 Soil Physical Factors

Root Penetration

Plants can be directly affected by the mechanical resistance of the soil to root growth (Section 4.2.3). Mechanical resistance refers to the impedance that a root encounters in growing into a dense compact soil layer or the impedance a seedling encounters in emerging through the soil surface. Since both cases are approximately represented by a "probe" being extended through the soil, penetrometers have been used to measure soil mechanical resistance as it affects plants (Taylor 1971).

The penetration resistance at which root growth effectively ceases varies according to plant species and soil type and has been found to average 2.5 MPa (Greacen *et al.* 1969). The growth and yield of cereal crops in soils similar in texture to red–brown earths may be restricted when cone penetration resistances are above 2.5 MPa. Thus, 2.5 MPa is a reasonable indicator of soil physical restriction to plant growth. Soil compaction increases soil penetration resistance and penetration resistance increases as the soil dries, hence compaction and water content conditions which produce penetration resistances greater than 2.5 MPa may restrict plant growth.

Soil Water

The optimum range of water content for plant growth has generally been assessed on the basis of plant water availability. The upper limit is usually associated with the minimum drained soil water content or "field capacity" and the lower limit is associated either with permanent wilting point or the lowest water potential which will not reduce plant growth (Loveday 1974). However, the non–limiting water range may be affected either by aeration or penetration resistance, particularly in poorly structured compacted soils (Letey 1985). Possibly oxygen diffusion is limiting for root growth at field capacity and a lower water content is required for adequate oxygen diffusion or, at the other end of the available water range, mechanical resistance which restricts root growth may occur at a water content higher than the value which would be considered limiting to plants on the basis of water availability determination. Thus, the freely available range of water contents can be reduced by either poor aeration or high penetration resistance in some soils. As soil compaction increases the freely available water range becomes more restricted.

Water intake rate is a soil property which can be reduced by compaction to levels critical for efficient irrigation. Compaction reduces the volume of soil transmission pores and hence the rate of water transmission at high water potentials. Greacen (1981) considers that a laboratory measured saturated hydraulic conductivity of 0.5 m day^{-1} indicates compaction restriction to irrigation efficiency for red–brown earth soils. This indicator of compaction damage depends only on soil compactness and is independent of soil water content.

Oxygen Diffusion

As soil compactness increases beyond a critical level the rate of oxygen diffusion in soil at the lowest drained soil water potential may be inadequate to supply root respiratory needs. Thus, at the upper limit of the plant available water range root growth may be restricted by low oxygen status of the soil. Root respiration rate increases with increased soil temperature, and at a relatively high temperature of 25°C root respiration rates of approximately 20 $\mu g\ O_2\ m^{-2}\ s^{-1}$ can occur (Blackwell and Wells 1983). Thus, the level of compaction which reduces the oxygen diffusion rate to below 20 $\mu g\ O_2\ m^{-2}\ s^{-1}$ at a matric potential corresponding to the lower drained water content may reduce the upper limit of the plant available water range and reduce soil productivity. The oxygen diffusion constraint to soil fertility depends on soil compactness and soil water content to the extent that soil water restricts oxygen diffusion at a matric potential of -1 m H_2O used to approximate the upper limit to the available water range.

Tillage Management

Management has clear objectives to optimise soil structure for crop production. Tillage objectives were reviewed by Blake (1963), Kuipers (1963), Greenland (1981), Greacen (1983), Kuipers (1984). The aim of tillage management is to produce a soil porosity that is optimal for root growth, i.e. one in which mechanical impedance, water content and aeration are non–limiting to root function over the range of plant available soil water contents.

Greacen (1983) and Osborne (1984) maintained that the answer to optimising soil disturbance using tillage was in a modelling approach. Greacen (1983) concluded that the critical physical properties to be measured are the water retention properties, hydraulic conductivity and mechanical strength as functions of soil water content. By using a soil water balance simulation as a basis for extrapolation in time, limitations to any of these processes can be located using a simulation study, and corrected by tillage. Because of the complexity and variability of the system such models have little predictive accuracy.

Gupta and Larson (1982) also used soil strength, aeration and water retention properties as the basis of an agrophysical model, in this case a nomogram, summarising limitations to plant performance over a range of water contents and levels of compaction. The nomogram model is useful for making field management decisions, i.e. whether the soil may be trafficked without reducing soil physical fertility and whether soil loosening is needed to increase soil physical fertility.

7.2.2 Soil Loosening

Crop Management

A pasture phase between successive wheat crops is effective in restoring the structure of red–brown earths (Greenland 1977; Clarke and Russell 1977). The growth of plant roots (Clarke *et al.* 1967) and the activities of soil fauna (Barley 1961) restabilise soil porosity under pasture. In a similar way the root systems of previous crops maintain soil porosity under minimum and no–till farming. Adem and Tisdall (1984) achieved increased water stable aggregation by retaining residues and maintaining permanent beds on a fragile, irrigated red–brown earth double cropped for four years. Successful tillage management depends on an open soil structure that permits unrestricted root growth in a cropped soil.

Deep Mouldboard Ploughing

A dense soil layer beneath the tilled horizon may restrict root development. Deep ripping may shatter such a horizon when dry but upon rewetting it may return to the initial condition. Deep tillage with an implement that inverts and mixes the soil (such as a mouldboard plough) can distribute clods of the dense horizon into the sandy surface horizon and alleviate the problem (Erickson 1982). Also, more thorough soil loosening is possible with a mouldboard plough than with a tyned implement. However, Harrison *et al.* (1984) recorded more cotton growth in response to deep mouldboard ploughing of a red–brown earth soil than to chisel ploughing. They ascribed this response to the mixing of swelling clay subsoil with topsoil thereby preventing the formation of strong surface crusts by imparting a degree of self–mulching to the surface.

There is evidence to suggest that subsoil mixing increases the water retained by a sandy topsoil underlain by clay textured B horizons (Brown *et al.* 1985). Sodium content of the B horizon may be a problem. Deep tillage of solonetzic soils in Canada has been successful, depending on the relative calcium–sodium concentration in the subsoil, and the depth to and clay content of the subsoil (Lavado and Cairns 1980; Alzubadi and Webster 1982). Thus the sodicity, water table depth and amount and type of subsoil being mixed affect the suitability of using deep mouldboard tillage.

7.2.3 Conclusions

Subsoil physical conditions affecting plant growth can be represented in a nomogram which depicts the compactness resulting from traffic over the range of trafficable soil water contents, with compaction constraints to penetration resistance and oxygen diffusion superimposed. Compaction damage is identified by the nomogram when the range of plant available water contents is restricted by either of these two physical fertility factors. Compaction restriction to irrigation efficiency can be included in the nomogram by determining the level of compactness which reduces saturated hydraulic conductivity below a minimum acceptable rate.

The nomogram model is useful to primary producers in scheduling their traffic according to soil water content and in deciding on the need for soil loosening below the normal tillage depth, either by crop rotation or by deep tillage. The nomogram model is not useful for evaluating tillage systems as it only gives a point in time indication of physical conditions affecting plant growth.

7.3 Methods

Soil compactness (void ratio m^3 m^{-3}) was modelled as a function of vertical stress (kPa) and soil water content (kg kg^{-1}) from the results of confined uniaxial compression tests (Chapter 3). Compaction models were developed for A horizon soil (100 A 0 B), B horizon soil (0 A 100 B) and A/B horizon mixtures (91 A 9 B, 75 A 25 B, 50 A 50 B, 25 A 75 B). The model parameters (Chapter 3, Table 1) were used to plot isostress lines of 100, 200 and 400 kPa on a compaction nomogram for each soil mixing treatment.

Soil penetration resistance (cone index, MPa) was modelled as a function of void ratio and soil water content for each soil mixing treatment. The model and the coefficients were presented in Chapter 4, Table 1. A critical void ratio for root penetration was calculated from the penetration resistance models for each soil mix based on a cone index limit to root penetration, for silt loam soil, of 2.5 MPa, and plotted on the nomogram for each mix.

Results presented in Chapters 5 and 6 show that adequate soil transmission porosity needed for rapid water intake and adequate root aeration. A critical void ratio for a water transmission rate of 0.5 m day^{-1} was determined from saturated hydraulic conductivity measurements to be 0.70 m^3 m^{-3} (Section5.5.4). This limit is shown on the nomograms for each mix to represent the level of compaction that is restrictive to efficient irrigation. The void ratio corresponding to an oxygen diffusion rate critical for unrestricted root respiration (20 μ g m^{-2}s^{-1}) at a matric potential approximating field capacity (-1 m of water) (Section 6.4.3) is plotted on the nomogram to indicate levels of compaction which restrict root oxygen supply.

The upper and lower limits of available water (arbitrarily chosen as -1 and -150 m of water, and referred to as WP and FC respectively) (Table 5.2) are similarly shown on the nomograms for each mixture. The plastic (DCPL) and liquid limits (DCLL) are plotted on the nomograms to indicate the upper water content recommended for tillage and the water content at which the soil behaves as a liquid.

7.4 Results and Discussion

7.4.1 Compaction

Resistance to soil compaction decreases as soil water content increases, i.e. soil is compacted to a lower void ratio by the same pressure as soil soil water content increases (Figure 7.1). The plastic limit (DCPL) and the liquid limit (DCLL) in Figure 7.1 represent the maximum water content recommended for tillage and the maximum trafficable water content respectively (Archer 1975). It is possible but not desirable to traffic the soil between these two water contents.

The 100 kPa, 200 kPa and 400 kPa lines in Figure 7.1 represent uniaxial pressures which are an approximation of the loading beneath tyres. Koolen and Kuipers (1983, p42) maintain that an agricultural tyre can be simulated by a uniaxial compression test with a maximum pressure of 400 kPa. Carpenter *et al.* (1985) found that mean surface contact pressures beneath tyres should not exceed pressures of 100 kPa for individual wheel loads which exceed approximately 30 kN if compaction beneath the tilled layer is to be avoided. These loading conditions are attainable by using low floatation tyres and increasing the number of wheels and/or axles to reduce the wheel load. The vertical compressive stress in the subsoil is shown by Carpenter *et al.* (1985) to approach the mean surface contact pressure above individual wheel loadings of 30 kN. Vertical stresses of 200 kPa in the subsoil are possible with single tyre axle arrangements (Carpenter *et al.* 1985). Thus, the applied uniaxial loads used in my study are of similar magnitude to the vertical pressures in the subsoil and the mean surface loading applied by traffic.

The rate at which void ratio declines as soil water content increases is increased as the applied pressure is increased from 100 to 200 to 400 kPa in Figure 7.1. Soil compaction at an applied load of 100 kPa is relatively insensitive to soil water content. This finding relates to soil which is laterally confined, i.e. beneath the tilled soil layer, and soil compaction is predominantly uniaxial. Consequently, the need to restrict traffic to a limit less than the plastic limit to manage compaction in the subsoil may be reduced if applied pressures can be limited to less than 100 kPa by vehicle design changes.

Penetration Resistance

Penetration resistance decreases as water content increases (Figure 4.3). Hence, the 2.5 MPa line, which represents the compaction conditions limiting to root elongation, in Figure 7.2 is independent of void ratio at high water contents, but is dependent on void ratio as soil water content decreases. A void ratio of approximately 0.9 m^3 m^{-3} will not restrict root growth over the available water range. However, soil at void ratios greater than 0.75 m^3 m^{-3} does not develop penetration resistances greatly exceeding 2.5 MPa (Figure 4.2). Thus, while soil at void ratios

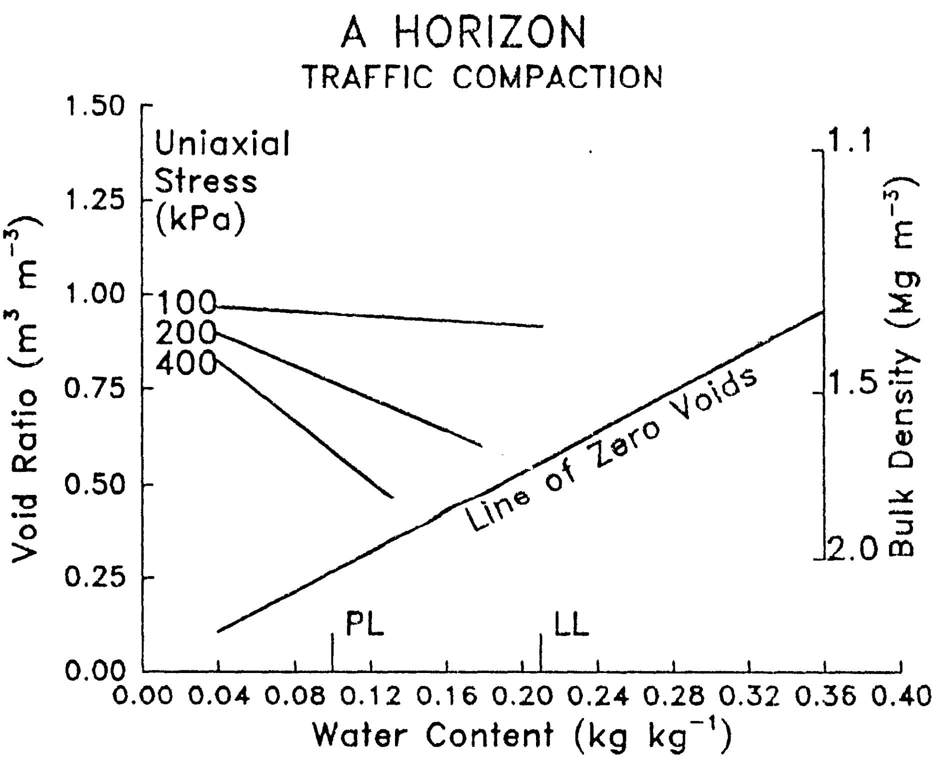

Figure 7.1: Soil compaction model for Trangie red-brown earth. The void ratios resulting from static vertical loads of 100, 200 and 400 kPa are plotted with a zero air filled voids line indicating the minimum void ratio attainable by compaction at a particular water content.

as low as 0.75 $m^3\ m^{-3}$ may cause slight restriction to root growth at the lower end of the available water range it will not develop the "hard setting" character of a more compacted soil as it dries. A void ratio of 0.75 $m^3\ m^{-3}$ should be the minimum void ratio that is tolerated by compaction management.

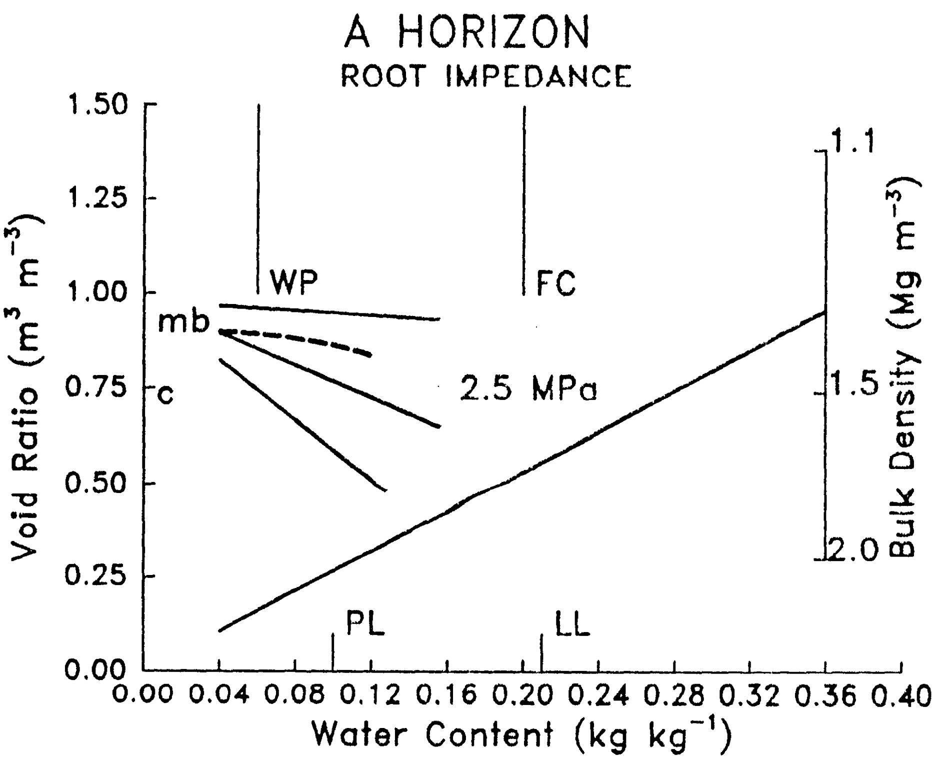

Figure 7.2: Soil penetration resistance model for Trangie red–brown earth A horizon soil. Wilting point (WP), plastic limit (DCPL), field capacity (FC) and liquid limit (DCLL) marked on the water content axis. Shaded areas indicate conditions restrictive to root growth. mb and c indicate the void ratios in the top 150 mm of the mouldboarded and conventionally tilled plots repectively. The 2.5 MPa line represents the void ratio below which soil penetration resistance limits root growth.

Void ratios below the 2.5 MPa line correspond to compaction conditions which restrict root growth. A static vertical load of 200 kPa at the plastic limit water content will reduce the void ratio of Trangie red–brown earth soil to a value such that penetration resistance will be below the critical limit of 2.5 MPa over most of the range of available water contents from wilting point, WP, to a water content approximating the lowest drained water content, FC (Figure 7.2). The same load at water contents above the plastic limit greatly increases the range of plant available water contents for which penetration will be critical for root growth. A static vertical load of 400 kPa well below the plastic limit causes penetration resistances greater than 2.5 MPa to develop over most of the range of plant available water contents (Figure 7.2). Loads in excess of 200 kPa should be avoided.

Crop exploitation of soil water is impaired when root growth is restricted in the range of water contents between field capacity and wilting point. This mechanical restriction to soil water availability should be prevented if maximum vertical loads beneath agricultural traffic do not exceed 100 kPa. Vertical loads up to 100 kPa over the range of trafficable water contents do not appear to restrict root penetration and water availability. Trafficking the soil at the plastic limit may cause slight restriction to soil water availability when the maximum vertical stress is 200 kPa. Surface soil is also subjected to high lateral loads and these vertical load limits for compaction damage may not be accurate. However, soil beneath the tilled layer will be laterally confined and vertical loads will predominate. Thus, mechanical impedance to root growth beneath the tilled layer should be prevented by limiting vertical loads in the soil to the values mentioned above.

Soil compaction did not alter the total plant available water range defined by WP and FC in Figure 7.2. It has been suggested that judicious use of compaction can increase the plant available water range by increasing FC (Archer and Smith 1972) but this is not the case for this soil as indicated by a single value of field capacity for all levels of compaction.

Water Transmission

Traffic pressures greater than 200 kPa at the lower plastic limit (DCPL) reduce void ratios to below the 0.5 m day^{-1} line (Figure 7.3). Void ratios less than 0.5 m day^{-1} are critical for efficient water intake in irrigated red–brown earth soils (Greacen 1981). At this critical void ratio there is insufficient transmission pore space to conduct water at rates of more than 0.5 m day^{-1}. The level of compaction which restricts water transmission is greater than that which restricts root penetration.

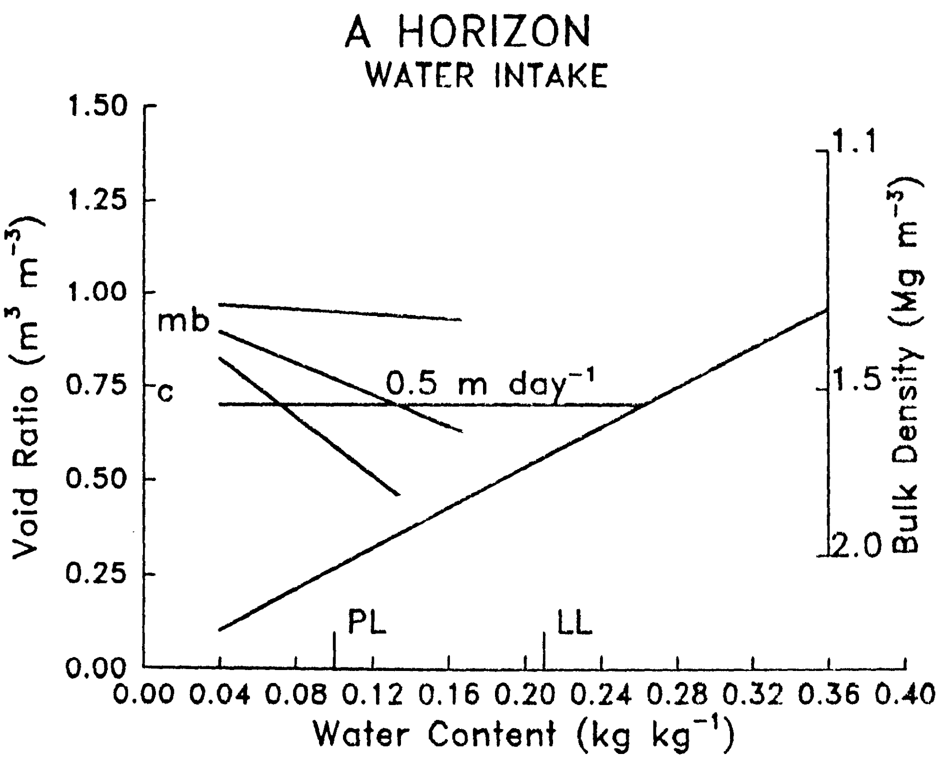

Figure 7.3: Water transmission model for Trangie red–brown earth A horizon soil. Wilting point (WP), plastic limit (DCPL), field capacity (FC) and liquid limit (DCLL) are marked on the water content axis. Shaded areas indicate conditions restrictive to root growth. The 0.5 m d^{-1} line represents the void ratio below which soil water transmission limits irrigation efficiency.

The soil loading limit required to maintain non–critical water intake rates is higher than the loading limit which ensures non–critical penetration resistance (Section 7.4.1. Thus, non–critical water intake rates will be maintained by managing traffic loads to prevent compaction causing soil penetration resistances critical for root growth.

Oxygen Transmission

Compaction to void ratios less than 0.68 $m^3\ m^{-3}$ in the A horizon creates an oxygen supply constraint to root respiration (Figure 7.4). At 0.68 $m^3\ m^{-3}$ there is insufficient transmission pore space to meet the oxygen requirements of a respiring root in soil at FC (Section 6.4.3). The 0.68 $m^3\ m^{-3}$ line intersects with the DCPL line at a pressure between 200 and 400 kPa (Figure 7.4). The pressure needed to cause an aeration constraint to root growth seems to be higher than that needed to cause a water transmission constraint to irrigation management.

Figure 7.4 shows that compaction causing inadequate soil aeration is brought about by similar pressures in A and B horizon soil. Void ratios $< 0.86\ m^3\ m^{-3}$ in the B horizon create an oxygen diffusion constraint to root respiration (Figure 7.4). For the B horizon soil critical oxygen diffusion line intersects the DCPL line at a pressure slightly greater than 400 kPa (Figure 7.9). So, similar levels of stress create an aeration constraint in the B and A horizon. Water transmission data, based on saturated hydraulic conductivity measurements, indicates that higher pressures are needed to restrict water transmission in the B horizon than in the A horizon. However, both oxygen and water transmission at low air–filled porosities depend on transmission pore space.

The reason for this discrepancy may be that the saturated hydraulic conductivity data set was incomplete for individual soil horizon mixtures and the B horizon; consequently the critical void ratio for rapid water movement was determined from the combined data set (Figure 5.3). The aeration data indicates that the critical void ratio for oxygen and water transmission is different for A and B horizons. The mean of the critical void ratios for oxygen transmission in each horizon is not significantly different to the critical void ratio for water transmission.

The finding that transmission pore space is critical at a higher void ratio in the B horizon than in the A horizon is consistent with the difference in textures. The finer B horizon texture correllates with a finer pore size distribution, i.e. at any void ratio there will be a lower volume of transmission pores in the B than the A horizon. The aeration data indicate the variation in critical transmission

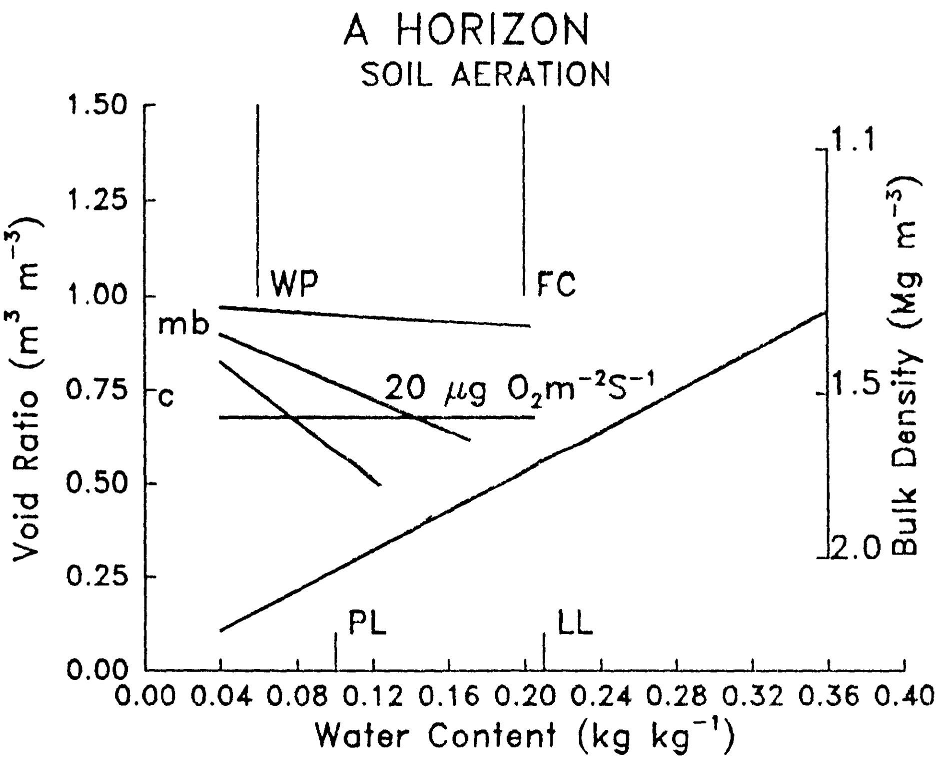

Figure 7.4: Oxygen diffusion model for Trangie red-brown earth A horizon soil. Wilting point (WP), plastic limit (DCPL), field capacity (FC) and liquid limit (DCLL) are marked on the water content axis. Shaded areas indicate conditions restrictive to root growth. mb and c indicate the void ratios in the top 150 mm of the mouldboarded and conventionally tilled plots repectively. The 20 μg m^{-2} s^{-1} line represents the void ratio below which oxygen diffusion through the soil may limit root growth at FC.

porosity between the A and B horizons, while the saturated hydraulic conductivity data indicate the mean transmission pore space needed for rapid oxygen and water movement through the A and B horizons.

It is important that similar surface pressures are critical for oxygen transmission in both A and B horizon soil. This means that the relationship between transmission pore space and compaction at the plastic limit (DCPL) depends only slightly on soil texture. The same tyre pressure recommendations to prevent suboptimal aeration and drainage should apply to different textured red–brown earths and for mixed soil horizons.

7.4.2 Soil Horizon Mixing

Penetration Resistance

For the soil horizon mixtures and the B horizon, pressures between 100 and 200 kPa at the plastic limit (DCPL) reduce void ratio to below the 2.5 MPa line critical for unrestricted root penetration (Figures 7.5–7.8). Thus the 100 kPa maximum pressure recommendation for the A and B horizons also applies to the soil horizon mixtures. Soil horizon mixing does not appear to alter the resistance of the soil to compaction damage.

Soil horizon mixing increases the void ratio at any point on the 2.5 MPa line. This increase in penetration resistance is accompanied by an increase in the void ratio at any point on the 100, 200 and 400 kPa maximum pressure lines. Thus any increase in penetration resistance is balanced by an increase in soil resistance to compaction.

Soil horizon mixing does not increase the freely available soil water range if the soil is compacted by a pressure of 200 kPa at the DCPL (Figures 7.5—7.9). Figure 7.7 represents a level of mixing attributable to deep mouldboard tillage to 400 mm on the Trangie red–brown earth soil. The shaded area between WP and FC represents the freely available water range for soil compacted by a 200 kPa pressure at the DCPL. The position of lines on the nomograms approaches that of the B horizon nomogram as the proportion of B horizon in the soil horizon mix is increased. Consequently, an increase in the level of mixing above that produced by deep mouldboard tillage will not increase the resistance of the soil to compaction degradation.

Gypsum application at a rate of 5 t ha^{-1} improved water intake, root growth and crop yield on field mouldboard tillage plots (D. Hall, personal communication). However, no effect of gysum on penetration resistance was found in my laboratory study (Chapter 4, Section 4.4.4). Adding gypsum to the soil surface may increase the stability of surface clay by increasing the electrolyte concentration of the soil solution when the soil is wet. The response to gypsum in the field can be related to the increase in the stability of surface structure leading to a reduction in the strength of surface crusts which form when the soil is wet rapidly by rainfall or irrigation (Greene and Ford 1985).

Water Transmission

For the B horizon, surface pressures greater than 400 kPa at the lower plastic limit (DCPL) water content will reduce void ratios to below the 0.5 m d^{-1} line critical for rapid drainage and water intake (Figure 7.9). Transmission porosity appears to be more resistant to compaction in the B horizon than A horizon.

The intersection between the vertical line drawn at the DCPL water content and the 0.5 m d^{-1} line occurs at higher pressures as the proportion of B horizon in the mix is increased (Figures 7.6–7.8). However, the 0.5 m d^{-1} line was determined from the combined data for all the soil mixtures (Section 5.5.4) and represents an average minimum void ratio for acceptable infiltration and drainage rates.

Oxygen Transmission

Critical void ratios for oxygen transmission in a drained soil did not vary systematically as soil horizon mixing was increased (Table 6.1). The intersection of the vertical line drawn at the DCPL and the critical void ratio lines for the dominantly A horizon mixtures occurs at pressures between 200 and 400 kPa (Figures 7.6 and 7.7), while for the dominantly B horizon mixtures this intersection occurs at pressures greater than 400 kPa. The finer pore size distribution produced by mixing B horizon soil has a transmission pore space slightly more resistant to compaction.

7.4.3 Field Conditions

Some indication of the accuracy of the compaction model determined by uniaxial compression tests is gained by comparing the void ratio predicted by Figure 7.5 for a compressive stress attributable to a single wheel per axle tractor (200 kPa) at the maximum water content recommended for tillage (DCPL) (0.75 m^3 m^{-3}) with soil densities after sowing measured by Barrett (1985) of 0.71±0.03 m^3 m^{-3} on the non–mouldboard ploughed treatments from 0 to -100 mm depth. The modelled void ratio is just outside the standard error of the field measurement, however Barrett (1985) suggests that soil density may have been increased by trampling around the sampling site during sample collection. Thus, the compaction model used in the nomogram appears to give useable predictions, based on the available field data. Field measurements of vertical stress and soil volume change beneath a tractor tyre are needed to confirm the laboratory determined compaction model used in the nomogram.

The topsoil in the field (0 to -100 mm) was at a void ratio of 0.90 m^3 m^{-3} for mouldboarded and 0.71 m^3 m^{-3} for non–mouldboarded tillage treatments (Barratt 1985). From Figure 7.5 a line drawn at a void ratio of 0.90 m^3 m^{-3} does not intersect with any of the lines indicating physical constraints to root growth, between wilting point (WP) and field capacity (FC) water contents. Thus, physical conditions were probably non-limiting initially in the mouldboard ploughed tillage treatments. Barratt (1985) found that root limiting penetration resistances developed between irrigations on non–mouldboarded tillage treatments but not on the mouldboard ploughed treatments.

A line drawn on Figure 7.5 at a void ratio of 0.71 m^3 m^{-3} intersects with the 2.5 MPa line at a water content of 0.16 kg kg^{-1}. Thus, between 0.16 kg kg^{-1} and the wilting point (WP) at 0.06 kg kg^{-1} root growth is likely to be restricted by high penetration resistance for non–mouldboarded soil. This line is also above the 0.5 m day^{-1} line critical for rapid water transmission at low air–filled porosities. Consequently, water penetration during irrigation is a problem on the non–mouldboard ploughed plots. This conclusion was supported by observed water penetration differences between the mouldboard ploughed and non–mouldboard ploughed tillage treatements in May 1985 while collecting soil samples for the laboratory study.

By the third year of the tillage trial the topsoil void ratio had decreased to 0.61 m^3 m^{-3}, with mouldboard ploughed plots not being insignificantly less compact than mouldboarded plots (D. Hall, personal communication). A line drawn at a void ratio of 0.61 m^3 m^{-3} on Figure 7.5 representing the non–mouldboarded topsoil and Figure 7.7 representing the mouldboarded topsoil intersect with the 2.5 MPa penetration resistance line at water contents of 0.18 and 0.21 kg kg^{-1} respectively. Both these water contents are close to field capacity (FC), hence by 1986 penetration resistance was restricting root growth over most of the range of plant available water contents on both mouldboard ploughed and non–mouldboarded tillage plots. The 0.61 m^3 m^{-3} void ratio is also less than the void ratio critical for water and oxygen transmission.

Figure 3.8 suggests that the mouldboarded topsoils will be less dense since soil horizon mixing increased void ratio for any pressure at the plastic limit water content. However, this soil may also be compacted by settling processes unrelated to agricultural traffic. The closeness of the DCLL and FC water contents on Figure 7.2 and Figure 7.7 indicates that non–mouldboarded and mouldboarded topsoil may flow or slump under the effect of the negative matric potentials which develop as the soil drains from saturation to FC. According to effective stress theory (Terzaghi 1943) the negative potentials which develop in unsaturated soil act as an isotropic compressive stress. The liquid limit, DCLL, represents a point on the critical state line of approximately 1 kPa (Greacen and Sands 1980). Thus, shear pressures greater than 1 kPa will compact the soil. FC is the water content at a matric potential of -10 kPa and so it is likely that the soil will slump over the range of potentials less than -1 kPa during drainage.

The soil strength differences between the A horizon and the B horizon are indicated by the higher liquid limit (DCLL) for the B horizon than the A horizon (0.36 as opposed to 0.21 kg kg^{-1}), while the field capacity (FC) increased only slightly (0.26 compared to 0.20 kg kg^{-1}) (Figures 7.5 and 7.9). Consequently, the A horizon soil will display low bearing strength at water contents close to field capacity.

A surface pressure of 400 kPa at the plastic limit is needed to compress the soil to a void ratio restrictive to oxygen diffusion in Figures 7.5 and 7.7. Such pressures can be applied by the wheels of crop harvesting equipment and driven wheels when wheelslip contributes to compaction. However, much of the compaction over time may be attributed to soil settling. When the topsoil has drained to FC it is in the upper end of the plastic soil consistency range and tends to flow in response to applied pressure. Consequently, the pressures applied by water films during drainage can cause an initially decompacted soil to slump into a compacted mass. The soil horizon mixing performed by deep mouldboard tillage does not reduce the tendency of soil to slump during drainage.

7.4.4 Management Strategies

Compaction

The maximum recommended traffic pressure of 100 kPa predicted in this study is corroborated by other compaction management studies. Blackwell *et al.* (1986) studied the effect of varying levels of wheeltrack compaction on soil conditions and yield of direct drilled winter wheat on a silt loam soil. They found that axle loads greater than or equal to 5 t and tyre inflation pressures greater than or equal to 100 kPa created a topsoil macroporosity of less than 5 % and axle loads of 13 t (simulating a combine harvester) decreased porosity to to less than 5 % to a depth of 50 cm. The 5 % macroporosity restricted oxygen supply in wet and warm periods of spring and summer. The growth limits in wheeled soil were related to high soil strength and poor aeration.

Tractor wheel loads range from 67 kN to 220 kN. From the findings of Blackwell *et al* (1986) and from this study, these wheel loads will inevitably cause compaction damage. Increased wheel load (or axle load) increases the pressure at depth so that large wheel loads create a subsoil compaction problem (Carpenter *et al.* 1985). Individual wheel loads can be reduced by designing heavy equipment with more axles while surface contact pressures are reduced by high flotation tyres. Carpenter *et al.* (1985) showed that the design load for high flotation tyres caused relatively high subsoil stresses. They also showed that individual wheel loads of 20.7 kN (2.07 t) did not produce critical subsoil stresses and could be achieved by designing machinery with tandem rather than dual wheels and low ground pressure tyres.

Low Ground Pressure Vehicles (LGPV) have been designed for vegetable cropping. Rowse and Goodman (1984) found that a Turner Ranger LGPV (900 kg, 30 kW) did not produce serious compaction when the soil had dried sufficiently for drilling (drier than the plastic limit) but that a Massey Ferguson 550 (2083 kg, 35 kW) did. Vehicles designed to minimise compaction have clear advantages in conventional cultivation systems.

Alternatively the compaction problem can be addressed by reduced tillage and confining traffic to lanes between permanent beds without radical equipment modifications. The increased bearing capacity of the uncultivated wheelings should permit greater vehicle access and increase the number of days available for drilling and harvesting. Rowse and Goodman (1984) found that compaction from wheelings did not spread appreciably across beds to reduce yield.

Red–brown earths are naturally compact and there is an initial benefit from deep loosening with a mouldboard plough (McKenzie *et al.* 1984). Tillage and traffic management has been shown to preserve the benefits of initial loosening tillage (Adem and Tisdall 1984). Once soil macroporosity has been established by tillage it needs to be maintained biologically. Thus the nomogram developed for this soil would be used to recommend initial tillage required to optimise soil physical conditions. This would be followed by reduced tillage and traffic management to stabilise soil structure through the growth of extensive root systems and increased soil faunal activity.

Such a system of "biological cultivation" was suggested by Cockroft and Martin (1981) to improve red–brown earths and has been developed in detail for irrigated row cropping of red–brown earths at Tatura in northern Victoria (Adem and Tisdall 1984). Penetration resistance and soil compactness tend to increase over time with minimum tillage (Ehlers *et al.* 1983; Adem and Tisdall 1984). However, this will not restrict root growth if sufficient continuous macropores have been established by earthworms and previous root systems (Ehlers *et al.* 1983).

Soil water supply is critical for seed germination and seedling establishment. Thus, loosening around the seed in direct drilled soil should remove the mechanical restriction to water supply. Penetration resistance, restricting the freely available water range, is the main factor limiting root growth (Figures 7.5 —7.9). The strength problem can be removed when crops are direct drilled into an uncultivated seedbed by making a slot under the row (Whiteley and Dexter 1982). Whiteley and Dexter found that unrestricted seminal root growth in cracks beneath direct drilled seeds improved crop yields in a non-tilled red–brown earth to a level comparable with tilled treatments. The design of direct drilling equipment for minimum tillage management needs to account for soil strength restriction to root establishment and provide some loosening of the soil beneath the depth of sowing.

Crop plants vary in their ability to penetrate compact soils. Whiteley and Dexter (1982) considered that the relative suitability for growth in non–tilled soil of the following crops was wheat > safflower > sunflower and soybean. A fine and extensive seminal root system allowed the more suitable crops (Whiteley and Dexter 1981b) to penetrate naturally occurring soil pores.

Cotton is the highest value crop grown in the Lower Macquarie Valley. A rotation crop such as wheat would be an important part of minimum tillage management of cotton. Adem and Tisdall (1984) used barley grown in winter with a summer crop of sunflowers in minimum tillage management of an irrigated red–brown earth in northern Victoria. It is difficult to find a crop with a short enough growing season to double crop with cotton and more attention should be given to double cropping with other high value crops such as vegetables and oilseeds.

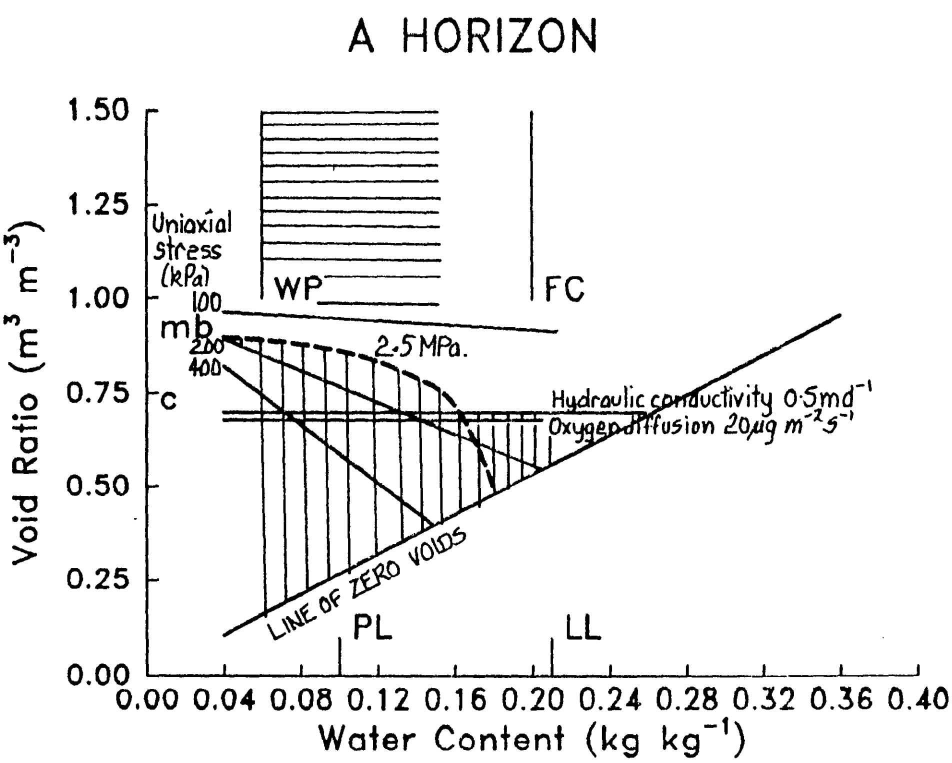

Figure 7.5: Compaction nomogram for the A horizon of Trangie red-brown earth with wilting point (WP), plastic limit (DCPL), field capacity (FC) and liquid limit (DCLL) marked on the water content axis. Shaded areas indicate conditions restrictive to root growth. The 2.5 MPa line, the 0.5 m day^{-1} line and the 20 μg m^{-2} s^{-1} line represent the void ratios below which soil strength, soil drainage and soil aeration respectively limit root function.

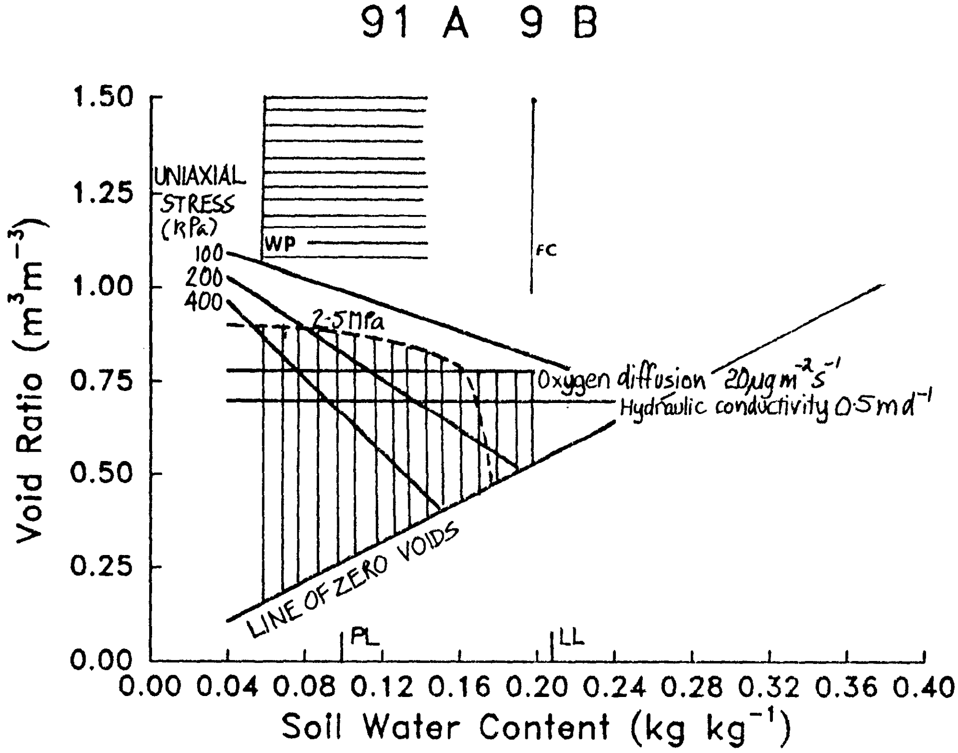

Figure 7.6: Compaction nomogram for the 91 A 9 B horizon mix of Trangie red–brown earth with wilting point (WP), plastic limit (DCPL), field capacity (FC) and liquid limit (DCLL) marked on the water content axis. Shaded areas indicate conditions restrictive to root growth. The 2.5 MPa line, the 0.5 m day^{-1} line and the 20 μg m^{-2} s^{-1} line represent the void ratios below which soil strength, soil drainage and soil aeration respectively limit root function.

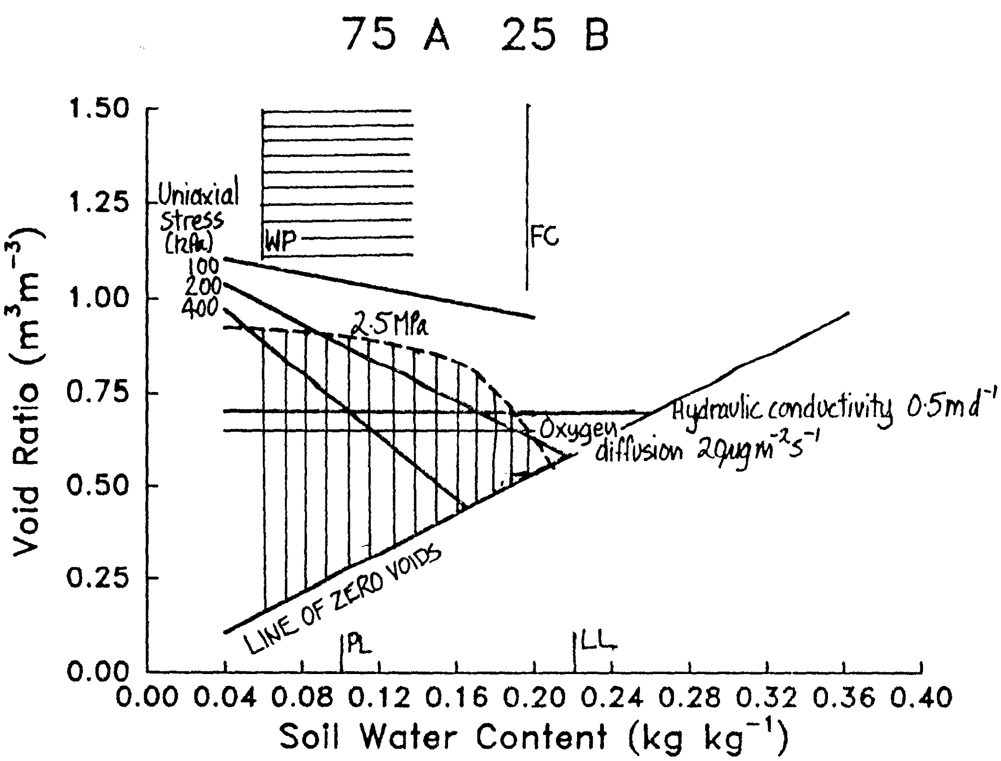

Figure 7.7: Compaction nomogram for the 75 A 25 B horizon mix of Trangie red–brown earth with wilting point (WP), plastic limit (DCPL), field capacity (FC) and liquid limit (DCLL) marked on the water content axis. Shaded areas indicate conditions restrictive to root growth. The 2.5 MPa line, the 0.5 m day^{-1} line and the 20 μg m^{-2} s^{-1} line represent the void ratios below which soil strength, soil drainage and soil aeration respectively limit root function.

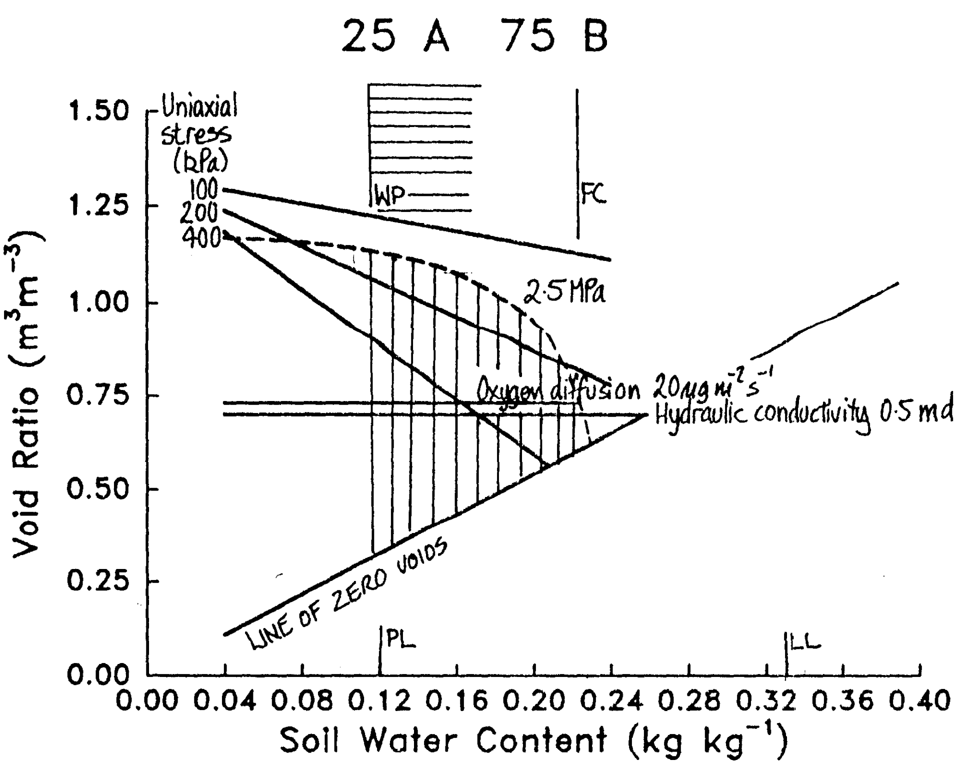

Figure 7.8: Compaction nomogram for the 25 A 75 B horizon mix of Trangie red–brown earth with wilting point (WP), plastic limit (DCPL), field capacity (FC) and liquid limit (DCLL) marked on the water content axis. Shaded areas indicate conditions restrictive to root growth. The 2.5 MPa line, the 0.5 m day^{-1} line and the 20 $\mu g\ m^{-2}\ s^{-1}$ line represent the void ratios below which soil strength, soil drainage and soil aeration respectively limit root function.

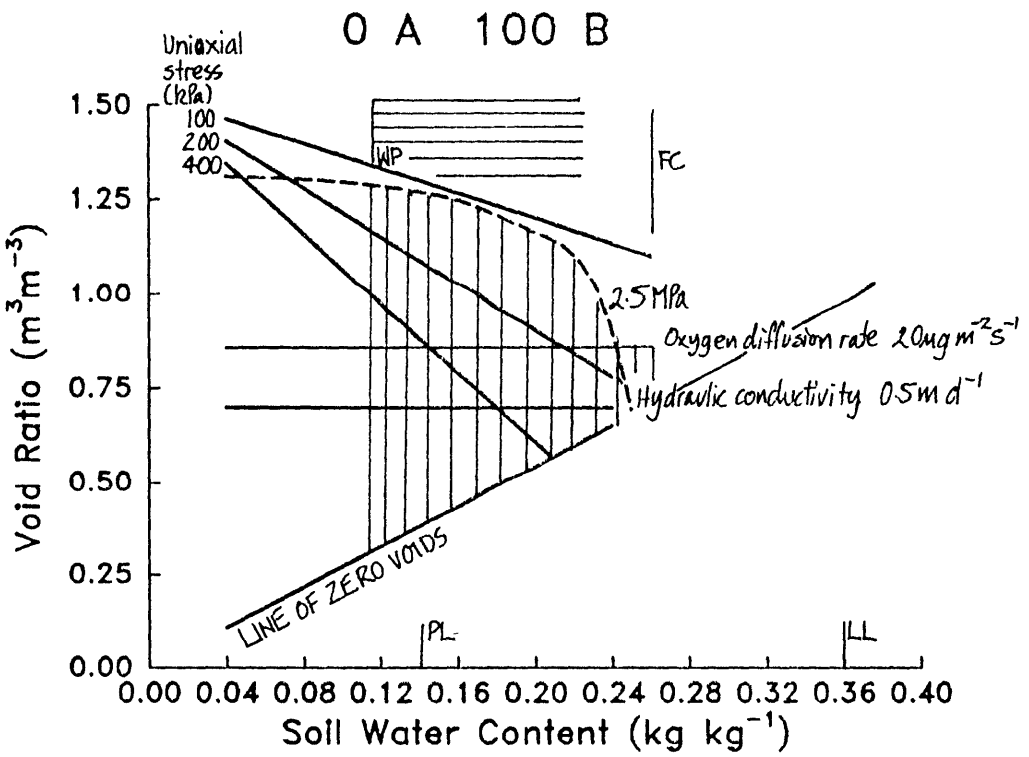

Figure 7.9: Compaction nomogram for the 0 A 100 B horizon mix of Trangie red–brown earth with wilting point (WP), plastic limit (DCPL), field capacity (FC) and liquid limit (DCLL) marked on the water content axis. Shaded areas indicate conditions restrictive to root growth. The 2.5 MPa line, the 0.5 m day^{-1} line and the 20 μg m^{-2} s^{-1} line represent the void ratios below which soil strength, soil drainage and soil aeration respectively limit root function.

7.5 Conclusions

7.5.1 Compaction

Soil penetration resistance is the main limitation to root growth in compaction damaged soil. Soil aeration and drainage will not restrict root growth at void ratios which allow unrestricted root penetration. Hence, management should be constrained by conditions relevant to managing penetration resistance.

Non–limiting soil physical conditions can be maintained by limiting ground pressures to less than 100 kPa for the whole range of trafficable soil water conditions. If the maximum ground pressure is 200 kPa then traffic should be restricted to water contents below the lower plastic limit. Where maximum ground pressures are 400 kPa traffic should be restricted to water contents at or below the permanent wilting point.

Soil water availability is restricted where penetration resistance restricting root growth occurs at a water content higher than the permanent wilting point content. This mechanical restriction to soil water availability can be identified from the nomogram model of physical restriction to root growth.

Soil compactness should be maintained at void ratios greater than 0.75 m^3 m^{-3} to prevent high soil strengths developing as the soil dries. At this void ratio penetration resistance does restrict soil water availability at low water contents, however the soil strengths which develop are only slightly higher than the 2.5 MPa critical limit for root elongation. At void ratios less than 0.75 m^3 m^{-3} very high penetration resistances develop as the soil dries, soil water intake rate becomes critical for flood irrigation and restricted oxygen diffusion begins to restrict water availability at the upper end of the plant available water range.

7.5.2 Soil Horizon Mixing

The beneficial effect of deep mouldboard tillage on the Trangie red–brown earth soil seems to depend on the removal of physical restrictions to root growth by loosening the soil. The hypothesis that soil horizon mixing performed by deep mouldboard tillage increases the resistance of soil to compaction damage is not supported by the finding that resistance to soil penetration increased as resistance to soil compaction increased with increasing proportions of B horizon in the soil horizon mix.

Soil horizon mixing may increase the resistance of tilled soil to structural collapse as it drains after flood irrigation. This is indicated by an increase in soil cohesiveness at a water potential approximating the the lower drained water content. The level of soil horizon mixing required to substantially increase soil cohesiveness is beyond that achieved by deep mouldboard tillage on the Trangie red–brown earth soil. Further work is being done at the University of New England by Mr. S. Gusli, Dr. A. Cass and Dr. D. MacLeod.

7.5.3 Management Strategies

Soil management should aim to establish a system of stable and continuous macropores by:

- initially removing any physical impediments to root growth with deep tillage followed by
- a permanent bed system where traffic compaction is restricted and the macroporosity created by plant root systems is conserved as a soil resource by reduced tillage of the beds,
- combining tillage operations and using low ground pressure vehicles,
- using decompacting tillage techniques based on the compaction nomogram — if soil factors are suboptimal in the rooting zone, as determined by the nomogram, then deep tillage would be recommended.

The positive response to gypsum application which was recorded in the field tillage trial may be related to an ameliorative effect on soil surface conditions. The gypsum response in the field trial was not supported by a laboratory study of soil penetration resistance with and without an equivalent gypsum application of 5 t ha^{-1}. It is possible that the beneficial effect of gypsum is confined to the soil surface. Even a low concentration of gypsum at the soil surface could counter the processes of slaking and dispersion of the surface clay and the formation of an impediment to water intake and seedling emergence at the soil surface.

7.5.4 Further Research

Because of the greater macroporosity and the pore structure differences between cultivated and minimum tilled soil, soil physical limits to plant growth on minimal tilled soil are likely to be different from those presented in the nomogram. The strength, water retention, aeration responses of minimally tilled soil to compaction need to be studied. The stable macroporosity established by root systems will be more important for root growth than bulk soil strength properties measured with standard penetrometers.

Research into the soil physical constraints to production on minimally tilled soil should concentrate on measurements of the nature and extent of macropores. Penetration resistance measurements should closely resemble the resistance encountered by elongating roots either by using fine penetrometers of similar dimensions to roots (Groenvelt *et al.* 1984) or plant roots under standard conditions in undisturbed soil cores.

In the opinion of producers (Maynard and Muir 1984), who used double cropping and permanent beds on an irrigated grey clay, research is needed into:

- documenting the chemical and physical changes in direct drilled soil,
- machinery for sowing and harvesting using wide traffic lanes,
- broad–leaved weed control in double cropping,
- pest and disease build up with permanent beds, and
- the compatability of different crops in rotation.

The first two points are being addressed, for red–brown earth soils, by the Victorian Department of Agriculture at Tatura (Adem and Tisdall 1984). However, there is potential use in a modelling approach to tillage management decisions with the techniques applied in my study.