Changes in soil physical properties under raised bed cropping

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ABSTRACT

Winter cropping often does not realise its full potential in south-western Victoria, where waterlogging is a major problem on the poorly drained soils of conventional cultivation (CC) systems. Consequently, cropping has been undertaken on raised beds (RB) to reduce the risk of waterlogging. Initial reports on the yields of RB were encouraging. It was hypothesized that an improvement in soil properties of RB may account for their better performance compared to CC systems.

The aim of the thesis was to evaluate selected soil physical properties of RB and to make comparisons with other treatments (CC and pasture). The specific objectives were to: 1) evaluate plant growth and crop yield; 2) quantify soil water dynamics; 3) assess changes in the soil water retention characteristic (SWRC), soil strength and soil hydraulic properties; 4) describe pore pathways from solute transport; and 5) quantify soil macropore structure.

Measurements of volumetric water content ($\theta_v$) were taken at 20, 40, 60 and 80 cm and at the soil surface. These data allowed the determination of the profile soil water deficit (SWD), which was found to be greater under the RB than the CC, although at times the pasture had the largest SWD. The RB mostly remained drier than the CC, but the response to rainfall in the surface $\theta_v$ was similar between treatments. Below average rainfall was received during the whole study period which resulted in drier than normal conditions.

There was no consistent difference in plant growth between crops on the RB and CC; e.g. in 2004 periods of waterlogging resulted in greater dry matter production on the RB; while drier conditions in 2003 saw better crop growth on the CC. Grain yield varied annually according to rainfall, and overall the treatment yields were similar. Analysis of regional yield data showed that there was no yield difference in years with average or below average rainfall, but years with higher rainfall favoured RB.

Little difference was found in the laboratory-derived SWRC, but in the field the RB were consistently drier at all depths and at 60 cm depth the CC had a saturated zone. The RB were found to have a lower soil strength characteristic within the surface 24 cm
compared to the CC. The air-filled porosity (AFP) was higher in the RB while for long periods the CC were <10 per cent AFP. There was no significant difference between the treatments in unsaturated hydraulic conductivity ($K_{us}$) in the soil surface. Saturated hydraulic conductivity ($K_s$) in the subsoil was very small, although the RB had significantly greater $K_s$ than the CC.

A solute transport experiment investigated the movement of a solute in large soil cores of the RB and CC treatments. Derived parameters from a transfer function model were used to assess the solute transport characteristics. This showed that under nearly saturated conditions the CC had significantly greater solute spreading than the RB. Furthermore, the transport volume ($\theta_{st}$) to $\theta_v$ ratio was smaller in the RB which indicated a greater proportion of preferential flow. These and other data suggested that the RB had a better connected and more stable pore network.

Soil macropore structure was quantified using image analysis of resin-impregnated soil. Samples were taken twice; the first samples showed that the RB had improved pore connectivity, slightly greater porosity and a pore network with smaller sized pore components than the CC. In comparison, at the second sampling time the structural parameters of the two treatments were similar.

Uncertainty exists in the scenario of higher rainfall or of the longer-term changes of soil properties under RB cropping. Nevertheless after three years of measurements, this thesis concludes that most soil physical properties of RB are distinctly better for cropping than under CC systems.
DECLARATION

This is to certify that:

i. the thesis comprises only my original work,

ii. due acknowledgement has been made in the thesis to all other material used,

iii. the thesis is less than 100,000 words in length, exclusive of tables, references and the appendix.

Much of the work in chapter nine was presented at Supersoil, the 3rd Australian and New Zealand Soil Science Conference in Sydney, December 2004.

Results from chapter eight and nine have been accepted for presentation at the World Congress of Soil Science to be held in Philadelphia, USA in July 2006.

______________________________
Jonathan E. Holland
Soli Deo Gloria.

In thanks for the loving support of my parents – Peter and Elisabeth.
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The collection of experimental data became a herculean task at times. Fortunately though there were a number of people from different organisations who kindly supported me. Stephen Cattle and Simon Speirs at the University of Sydney introduced me to resin-impregnated image analysis. Stephen and Simon also looked after me and got me interested in quantifying soil structure. I was also taken care of by Anthony Ringrose-Voase and Inars Salins of CSIRO, Canberra. I am most grateful to Anthony for allowing me to work in the thin section facility of the Butler Laboratory and for the stimulating discussions we had. I am grateful to Graham Higgerson (CSIRO, Geelong), for allowing me to use Optimas software. The measurement of soil matric potential was at first difficult, but thanks to Paul Hutchinson (CSIRO, Griffith) I was able to successfully log matric potential at hourly intervals using a newly developed and advanced telemetry system. Thank-you also to Neil Hives of Ballarat University who kindly leant me a soil penetrometer.

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<tr>
<td>AFP</td>
<td>air-filled porosity</td>
<td>m$^3$ m$^{-3}$</td>
</tr>
<tr>
<td>ABS</td>
<td>Australian Bureau of Statistics</td>
<td></td>
</tr>
<tr>
<td>AWC</td>
<td>available water capacity</td>
<td></td>
</tr>
<tr>
<td>AWS</td>
<td>automatic weather station</td>
<td></td>
</tr>
<tr>
<td>BD</td>
<td>bulk density</td>
<td>Mg$^1$ m$^{-3}$</td>
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<tr>
<td>BTCs</td>
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<tr>
<td>CC</td>
<td>conventional cultivation</td>
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<tr>
<td>CDE</td>
<td>convection-dispersion equation</td>
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<td>CEC</td>
<td>cation exchange capacity</td>
<td>cmol kg$^{-1}$</td>
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<td>CLT</td>
<td>convection log-normal transfer equation</td>
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</tr>
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<td>CT</td>
<td>controlled traffic</td>
<td></td>
</tr>
<tr>
<td>EC</td>
<td>electrical conductivity</td>
<td>dS m$^{-1}$</td>
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<td>EM</td>
<td>electro-magnetic</td>
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<tr>
<td>ESP</td>
<td>exchangeable sodium percentage</td>
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<tr>
<td>ET$_p$</td>
<td>potential evapotranspiration</td>
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<tr>
<td>FC</td>
<td>field capacity</td>
<td>kPa</td>
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<tr>
<td>GSR</td>
<td>growing season rainfall</td>
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<td>LLWR</td>
<td>least limiting water range</td>
<td>m$^3$ m$^{-3}$</td>
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<tr>
<td>MPIL</td>
<td>mean pore intercept length</td>
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<td>Units</td>
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<tr>
<td>--------</td>
<td>-------------</td>
<td>-------</td>
</tr>
<tr>
<td>Por</td>
<td>porosity</td>
<td>mm$^3$ mm$^{-3}$</td>
</tr>
<tr>
<td>PR</td>
<td>penetrometer resistance</td>
<td>MPa</td>
</tr>
<tr>
<td>PSL</td>
<td>pore star length</td>
<td>mm</td>
</tr>
<tr>
<td>PWP</td>
<td>permanent wilting point</td>
<td>kPa</td>
</tr>
<tr>
<td>RB</td>
<td>raised beds</td>
<td></td>
</tr>
<tr>
<td>SA</td>
<td>surface area</td>
<td>mm$^2$ mm$^{-3}$</td>
</tr>
<tr>
<td>SG</td>
<td>solid genus</td>
<td>x10$^{-2}$ mm$^2$</td>
</tr>
<tr>
<td>SSL</td>
<td>solid star length</td>
<td>mm</td>
</tr>
<tr>
<td>SWD</td>
<td>soil water deficit</td>
<td>mm m$^{-1}$</td>
</tr>
<tr>
<td>TFM</td>
<td>transfer function model</td>
<td></td>
</tr>
</tbody>
</table>

**Symbols**

**Arabic**

- $C_L$: leached solute concentration, g L$^{-1}$
- $C_R$: resident solute concentration, g L$^{-1}$
- $D_e$: depth of soil water, mm
- $H$: height, mm
- $I$: cumulative drainage, mm
- $K$: hydraulic conductivity, m s$^{-1}$
- $K_s$: saturated hydraulic conductivity, m s$^{-1}$
- $K_{us}$: unsaturated hydraulic conductivity, m s$^{-1}$
- $L$: calibration depth, mm
- $M_1$: solute mass leached, g
- $M_o$: solute mass applied, g
- $Q$: volume rate of water flow, m$^3$ s$^{-1}$
- $R^2$: percentage variance accounted for
- $V$: total volume, m$^3$
- $Y_d$: difference in yield (percentage)
- $Y_{dt}$: difference in yield (tonnes), t
- $z$: depth of interest, mm
<table>
<thead>
<tr>
<th>Greek</th>
<th>English Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_a$</td>
<td>air-filled porosity/ volumetric air content</td>
<td>$\text{m}^3 \text{m}^{-3}$</td>
</tr>
<tr>
<td>$\theta$</td>
<td>volumetric water content (also $\theta_v$)</td>
<td>$\text{m}^3 \text{m}^{-3}$</td>
</tr>
<tr>
<td>$\theta(\psi)$</td>
<td>soil water retention characteristic</td>
<td></td>
</tr>
<tr>
<td>$\theta_g$</td>
<td>gravimetric soil water content</td>
<td></td>
</tr>
<tr>
<td>$\theta_m$</td>
<td>mobile water content</td>
<td>$\text{m}^3 \text{m}^{-3}$</td>
</tr>
<tr>
<td>$\theta_{st}$</td>
<td>transport volume</td>
<td>$\text{m}^3 \text{m}^{-3}$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>mean of the log-normal pdf</td>
<td></td>
</tr>
<tr>
<td>$\rho$</td>
<td>bulk density</td>
<td>$\text{Mg}^1 \text{m}^{-3}$</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>standard deviation of the log-normal pdf</td>
<td></td>
</tr>
<tr>
<td>$\sigma^2$</td>
<td>variance of the log-normal pdf</td>
<td></td>
</tr>
<tr>
<td>$\psi$</td>
<td>total water potential</td>
<td>kPa</td>
</tr>
<tr>
<td>$\psi_m$</td>
<td>matric potential</td>
<td>kPa</td>
</tr>
<tr>
<td>$\psi_o$</td>
<td>overburden potential</td>
<td>kPa</td>
</tr>
<tr>
<td>$\psi_s$</td>
<td>osmotic potential</td>
<td>kPa</td>
</tr>
<tr>
<td>$\psi_z$</td>
<td>gravitational potential</td>
<td>kPa</td>
</tr>
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</table>
CHAPTER ONE

1 Introduction

1.1 Problem statement

Crop production in the high rainfall zone (> 500 mm/ annum) of south-western Victoria has failed to develop to its full potential. For many years, the available arable land in this area has produced low yielding crops (Conley and Dennis 1984). The development of a successful system of cropping for this region has been difficult. To understand the reasons for this, research programs were commenced by government departments and research organizations to understand the soils in this area and the factors that influence crop production.

One of the major limiting factors of crop production in south-western Victoria is waterlogged soils (Robinson et al. 2003). Mostly waterlogging occurs during winter and early spring when it often causes poor plant growth and in some cases total crop failure (McDonald and Gardner 1987). As a result, crop production has remained restricted across this region (Knopke et al. 2000). Waterlogging is brought about by the combination of relatively high rainfall during the growing season concomitant with low evaporation rates. The incidence of waterlogging is increased due to the flat topography and the texture contrast soils such as Sodosols (Isbell 2002).

The problems caused by waterlogging have resulted in a number of approaches to develop cropping systems that are suited to the conditions and the environment. For instance, plant breeders have worked at developing varieties more tolerant of waterlogging (Setter and Waters 2003), or varieties that are able to mature earlier (Riffkin et al. 2003) and thus avoid the seasonal effects of waterlogging. Agronomic solutions have been attempted and include changing the time of sowing (Amor et al. 1984) and
increasing seed rates. Subsoil mole drainage, although expensive to install, has also been used to effectively reduce the risk of waterlogging (MacEwan et al. 1992).

Recently the adoption of surface drainage cropping systems with raised beds (RB) has become an increasingly popular method to avoid the effects of waterlogging. The introduction of RB to south-western Victoria has seen some promising crop yield results (Peries et al. 2004). Thus there is potential to increase productivity of cropping using RB rather than conventional cultivation (CC) systems.

To date, no thorough study on the soil physical properties of RB has been reported for the soils of south-western Victoria. For several key soil properties it is not known if RB cropping causes changes; nor the effects of these properties on crop production or the environment. Finally, there is a lack of understanding on the relationship between soil properties and crop yield.

1.2 Aim and objectives

The aim of the thesis was to investigate changes in soil physical properties of RB that are functionally important for cropping. To achieve this aim, a thorough review of the literature was undertaken to identify the key soil physical properties for crop production and collate the current knowledge on RB.

Measurements of soil under RB were undertaken with accompanying measurements on at least one non-RB treatment, namely CC or pasture, to address the following specific objectives:

- quantify the soil water dynamics during the growing season,
- assess changes in the soil water retention characteristic and soil strength,
- quantify the least limiting water range,
- quantify the hydraulic conductivity,
- describe the pore networks in RB and CC as reflected by their solute transport characteristics,
• quantify the soil macropore structure,
• recommend where cropping with RB is suitable.

As RB are a method of cropping, an additional non-soil objective was set to:
• assess and compare plant growth and grain yield of crops grown on RB and CC.

### 1.3 Thesis outline

Chapter two reviews the literature on key soil physical properties that are important for plant growth including soil structure, water content, water potential, hydraulic conductivity, solute transport, aeration, strength and the least limiting water range. The factors that cause waterlogging are evaluated and the effects of waterlogging on crop production are discussed. The drainage of agricultural land is briefly overviewed, and RB are described. Results on soil physical properties and crop production on RB are evaluated with reference to recent research findings from studies in south-western Victoria, across Australia and internationally. Knowledge gaps are identified that aim to be addressed by this thesis.

Chapter three provides background information on south-western Victoria including the climate, geomorphology, soils and agricultural land use. The soils at two experimental sites (Mt Pollock and Briandra) are characterized and the experimental design of each site described. General laboratory methods used to characterise the experimental sites are given here, but the materials and methods specific to each experimental chapter are presented later.

Chapter four considers the soil water dynamics of RB and two non-RB treatments: CC and pasture. Soil water properties are measured using several different methods in the field. These data assisted in the detection of waterlogged conditions and differences between the treatments, including on the soil water deficit and response of surface soil water content to rainfall.
In chapter five measurements of crop growth and grain yield from the RB and CC treatments are presented. In addition, the relationship between plant growth with soil water deficit and air-filled porosity are explored. To complement these data a crop yield survey of RB and CC-type treatments at sites from across south-western Victoria was undertaken.

Two key soil physical properties of RB and CC are measured in chapter six - the soil water retention characteristic (SWRC) and soil strength. Soil strength is measured at a range of soil water content values and comparisons are made between treatments on the soil strength characteristic. The SWRC and soil strength were integrated to a single parameter to determine the limit to plant growth under RB and CC.

In chapter seven the hydraulic conductivity is measured in the field and laboratory and the RB and CC treatments were compared. These data enabled the assessment of soil infiltration and internal drainage for each treatment.

A solute transport experiment was undertaken in chapter eight. The leaching setup in the laboratory and the approach taken are described. Solute transport is modelled using the convective log-normal transfer function and optimised parameters are compared. With these parameters the transport volume was calculated. The work in this chapter imposed conditions that are difficult to measure in the field and used solute transport analysis to compare the soil pore network of RB and CC.

In chapter nine soil structure is measured quantitatively using a resin-impregnated image analysis technique. Image analysis enabled the quantification of porosity (mostly macropores), the size distribution of pore and solid units and several functional parameters of structure. Assessment of these parameters allowed the structural condition of RB and CC systems to be well described.

Finally, chapter ten is the concluding section of the thesis and draws together findings from the previous experimental chapters. The reinforcement of conclusions through the
convergence of results from different methods of measuring soil physical properties are discussed. To conclude recommendations are made on cropping with RB and further areas of research are suggested to advance current understanding on RB.
2 Literature Review

2.1 Important soil physical properties for crop production

This review outlines the importance of soil structure and soil physical properties such as soil water – its storage and movement, soil aeration and soil strength for crop production. The problems caused by and the effects of waterlogging are evaluated. The fundamentals of RB are introduced and recent studies on crop production and soil properties of RB are reviewed.

2.1.1 Soil Structure

Definition of structure

Soil structure is the arrangement of soil particles. However, this simple definition is regularly refined according to the context in which it is used and because of new methods that are developed to measure structure. Some example definitions are: ‘The physical constitution of a soil material as expressed by the size, shape and arrangement of the solid particles and voids, including both the primary particles to form compound particles and the compound particles themselves’ (Brewer 1964). Alternatively there is emphasis on the wide scale over which structure can now be observed, ‘the arrangement of particles and associated pores in soils across the size range from nanometers to centimetres’ (Oades 1993). Kay (1990) reviewed three aspects of soil structure on its form, stability and resilience. Structural form is the total porosity, pore size distribution and continuity of the pore system. Other descriptions have considered an aspect of structure such as the variation of pores or aggregates which are found in the soil. Dexter
(1988) described structure as ‘the spatial heterogeneity of the different components or properties of the soil’.

**Factors that influence structure**

Soil structure is influenced by texture and mineralogy, soil water content, exchangeable cations, organic matter, flora and faunal organisms and non-soil factors. These factors interact to determine structure. No single factor has an overriding influence upon structure. Soil properties are dynamic and structure often changes, especially in agricultural soils.

The percentage and type of clay in the soil strongly influences the structural form of the soil. Rengasamy *et al.* (1984) found that when the amount of clay was less than 30 per cent soil texture had a significant effect on structure. In soils where clay content is greater than this, clay type is more important. For instance clay mineral composition affects the shrink: swell potential of the soil. Soil containing a high proportion of 2:1 layer clay minerals, such as smectite, exhibit more expansive behaviour than 1:1 layer clays (White 2006).

Shrinkage may occur as water is lost (by either drainage or evapotranspiration) from a clay soil, while on wetting clay soil begins to exhibit swelling behaviour. Soil structure develops from such changes in soil water content. Morphological evidence of such behaviour is observed by the presence of slickensides and lenticular peds (Isbell 2002). After a number of wetting and drying cycles distinctive pedality develops. Typical clay soils which possess these properties crack and become friable at the surface are called self-mulching soils. In the Australian Soil Classification system this phenomena is seen in the Vertosol order (Isbell 2002).

Most soils break down upon wetting when particles become suspended in water. Soil that deflocculates is described as being dispersive. Such soils commonly contain a cation exchangeable complex dominated with Na and are structurally unstable. In Australia,
soils with an exchangeable sodium percentage (ESP) >6 per cent are classified as sodic (Northcote and Skene 1972). The simple Emerson test demonstrates the effect of exchangeable cation type on aggregate stability (Emerson 1991). Booltink et al. (1993) reported that detrimental effects on soil strength and hydraulic conductivity (both indicators of structure) were caused by high exchangeable Na. However the extent to which dispersion affects structure depends on other factors such as clay mineralogy.

Soil organic matter stabilizes structure by reducing wetting rates and increasing resistance to disruptive forces (Baldock 2002). Soil organic matter is made up of many components including litter, microbial biomass and humus (White 2006). These components of organic matter use specific mechanisms to influence structure or its stability. Changes in land use can lead to structural degradation brought about by reduced organic matter levels. Carter et al. (2002) measured a decline in soil structural stability in soils under pasture/annual crop systems compared to nearby undisturbed forests. The observed decline was due to significantly lower organic C levels. Cockroft and Olson (2000) found that soils with greater than 40 g C/kg did not coalesce, whereas coalescence was common in soil with less than 30 g C/kg. Mucilage (root exudates) is another component of soil organic matter that has been found to assist in maintaining structure. Morel et al. (1991) showed that mucilage from maize root tips helped to increase stability.

The range of soil biota that influence structure is large, from soil micro-organisms to roots, and earthworms to trees (Oades 1993). The growth and activity of plant roots and fauna bring about the formation of holes or burrows (biopores). Growing roots can have a significant impact as they search for water and nutrients. The density and distribution of roots can alter the macroporosity of the soil as channels are formed. Yunusa et al. (2002) found a greater number of large pores (>2 mm) in the subsoil of a native tree belt compared to the subsoil under annual cropping. This change in porosity developed due to the greater ability of the root of the woody species to penetrate into the hard clay subsoil. Soil faunal organisms such as earthworms make burrows as they move through the soil. Oades (1993) observed earthworms had a stabilizing effect on aggregates, and were significant contributors in the formation of soil structure.
Non-soil factors that influence structure

Non-soil factors such as climate and tillage can influence structure too. Climate causes changes in the water content and temperature of the soil, both of which can alter structure. Kay et al. (1994) showed that changes in functional aspects of structure (greater tensile strength and low hydraulic conductivity) corresponded to seasonal wet periods. Work by McIntosh and Sharratt (2003) indicated that forces from freezing, thawing and wetting and drying caused the collapse of macropores (a decline in structure) over the winter.

The impact of tillage is variable as detrimental effects and improvements to structure are possible. Kooistra et al. (1985) reported a mixture of effects. Tillage initially improved the structure by increasing the rooting depth, but the formation of a plough pan under the tilled area led to soil compaction. Moran and McBratney (1992b) compared conventional and zero tillage treatments and observed that cultivation severed the connection of surface pores to the subsoil. Soil compaction from machinery or animals is another mechanism which can degrade structure. Douglas et al. (1988) showed improvements to structure after the adoption of controlled traffic on a grassland farming system. Sometimes the difference between the effects of tillage and of traffic can be difficult to separate. Bakker and Barker (1998) claim that as a consequence of adopting a controlled traffic system, less tillage rather than less traffic minimized structural decline.

The assessment of soil structure as good or bad is relative to context. Generally, it is the functional effect of structure which determines whether a soil is described as “well structured” or “poorly structured”. For plant growth, a well structured soil will provide adequate space for root exploration, sufficient water storage and rapid drainage. Space in the soil is referred to as porosity and is discussed below. In contrast, a poorly structured soil will inhibit plant root growth, lack aeration, hold low levels of plant available water and readily waterlog.
Porosity

The total volume of any soil is made up of solid, liquid and gas. Porosity is the space that is filled with gas or liquid and is often referred to as the void space. Soil porosity $\phi$ is the volume of the soil that is not solid,

$$\phi = 1 - \left( \frac{V_s}{V} \right)$$  \[2.1\]

where $V$ is the total volume (m$^3$) and $V_s$ is the solid volume (m$^3$). Porosity and pores are frequently referred to in relation to the structure of soil. The measurement of porosity and the quantification of pores are aspects of describing structure. However, a synonymous relationship seems to have developed in the literature, where pores or porosity are measured and reported, followed by a discussion on structure. There is no inherent problem with this, except to acknowledge that an understanding of porosity and pores needs to develop. Otherwise a confused or incorrect interpretation of structure could be formed whereby pores or porosity are structure. Rather pores and porosity are both measures that indicate structure.

Porosity can be measured directly by quantifying structure (see chapter nine) or determined indirectly from the soil bulk density (BD) and particle density. If we assume a particle density of 2.65 (Mg/m$^3$), porosity can be calculated by

$$\phi = 1 - \left( \frac{\rho}{2.65} \right)$$  \[2.2\]

where $\rho$ is BD (Mg/m$^3$). Frequently the pore space is partially filled with liquid and for some studies the water-filled pore space is of interest. A soil with an air-filled porosity greater than 10 per cent is regarded as adequately aerated (White 2006). Total pore space is a crude measure. It provides no indication on individual pores that make up the pore space. For further understanding a pore size distribution must be determined. The pore size distribution is the proportion of pores in a size class over a set measurement range.
The importance of structure and porosity

Structure is of major importance because it affects physical, chemical and biological soil properties. Pores, porosity or the pore size distribution are often measured to represent structure and then related to soil physical properties such as hydraulic conductivity or soil strength. Changes in these properties can alter conditions for plants from optimal to limiting; that is, conditions where plants are able to freely grow, to conditions that induce stress. Soil structural changes are related to changes in soil physical properties. In fact soil physical properties are often measured to indicate structural condition, e.g. Coughlan et al. (1991) reported changes in soil structure (in terms of macropores), but actually measured unsaturated hydraulic conductivity. The strong influence of structure on physical properties and its importance should not be understated.

The study of soil structure was an important part of this thesis and measurements to directly quantify soil structure are described in chapter nine. The following sections review and expand on key soil physical properties that directly effect plant growth and are important for cropping.

2.1.2 The storage of soil water

The storage (or supply) of soil water is considered in two ways. First, the mass or volume of soil water is presented in terms of soil water content ($\theta$). Second, the potential energy of water, $\psi$ is reviewed.

Soil water content, $\theta$

$\theta$ plays a significant role in the soil as it influences many other properties. The total amount of water in the soil can be measured by weight and expressed as the gravimetric water content ($\theta_g$). However it is usually better to express water content as a volume ratio, according to the equation,
\[ \theta_v = \theta_g \rho / \rho_w \]  

[2.3] 

where \( \theta_v \) is the volumetric water content (m\(^3\) water/m\(^3\) total), \( \rho \) is the bulk density of the soil (kg solids/ m\(^3\) total), and \( \rho_w \) is the density of water (kg water/ m\(^3\) water).

Monitoring \( \theta_v \) is useful in agriculture as soil water is essential for plant growth. Both crop and pasture production can be restricted due to a lack of or excess of soil water. By measuring \( \theta_v \), researchers can identify the effects of \( \theta_v \) on a particular land use or the water use efficiency of different practices. O’Connell et al. (2003) monitored \( \theta_v \) on fallow and cropping land to identify the risk posed by long fallows in causing dryland salinity. French and Schultz (1984a) studied the quantitative relationships between wheat yield and water use. They defined the water use efficiency (WUE) as the production per mm of water used (kg of grain or dry matter per mm of extracted \( \theta_v \), plus irrigation applied or rainfall, and evaporation). Water use was calculated as the change in \( \theta_v \) between sowing and maturity.

Soil water can also be expressed with the soil water deficit (SWD). The SWD (usually expressed in mm) is the amount of water required to bring the soil to field capacity (Rowell 1994). SWD per defined depth of soil is used together with information such as potential evapotranspiration and crop factor to decide the required amount of water. Robertson et al. (2004) investigated SWD and initial infiltration depth to improve understanding of the factors that optimize irrigation scheduling. Efficient irrigation scheduling can save water by ensuring that water is not applied too early and that the correct amount is applied. Muchow and Keating (1998) used irrigation scheduling as a key component of the crop production system simulation model APSIM-Sugarcane. It was found that by changing the level of soil water depletion (calculated as SWD) the frequency of irrigation varied, which led to a conflict between yield and irrigation requirement. This illustrated a practical application of using the SWD for irrigated crop management.
A useful way to express the $\theta_v$, is as an equivalent depth of soil water, $D_e$, (mm) for a given thickness of soil, $d$ (mm):

$$D_e = \theta_v d$$ \hfill [2.4]

Expressing $\theta_v$ in this way allows discrete horizons or depth ranges within the profile to be established. In addition, it is compatible (in the same units) with other physical measures of water such as rainfall or irrigation.

The measurement of $\theta_v$ can be used to assess volumetric air content ($\varepsilon_a$) as the difference between $\theta_v$ and total porosity ($\varepsilon$), thus:

$$\varepsilon_a = \varepsilon - \theta_v$$ \hfill [2.5]

Jayawardane and Meyer (1985) used equation 2.5 to determine $\varepsilon_a$ by establishing a relationship between $\varepsilon$ and neutron counts (with a neutron moisture meter). The inferred measurement of $\varepsilon_a$ by Jayawardane and Meyer was used to detect differences between two irrigation treatments. They showed that a non-flooded treatment had a greater $\varepsilon_a$ and therefore an improved aeration profile compared to a flood irrigation treatment.

**Soil water balance**

The calculation of the soil water balance is undertaken to assess the components of water (mm) that are added or lost from the soil, using the equation:

$$P = ET + DD + RO + \Delta D_e$$ \hfill [2.6]

where $P =$ precipitation, $ET =$ evapotranspiration, $DD =$ deep drainage, $RO =$ run-off and $\Delta D_e =$ change in water content. The measurement of $D_e$ is regularly undertaken to track
changes over time. By measuring $\Delta D_e$, ET and P the other components of the soil water balance, RO plus DD can be calculated. Measuring changes in $D_e$ can be used to help solve the soil water balance of a particular land use system. Heng et al. (2001) measured $\theta_v$ on different pastures across south-eastern Australia to calculate differences in SWD and found that perennial pastures extracted more soil water than annual pastures. A similar study by White et al. (2003) measured $\theta_v$ to calculate the SWD and surplus water produced as run-off or drainage. This study showed that the amount of surplus produced was dependent upon the SWD, which varied according to the interaction between and effects of soil type, climate and vegetation. Soil type was particularly sensitive and texture-contrast soils such as Sodosols shed the most water as run-off (50 per cent or more was run-off).

**Soil water potential, $\psi$**

The second method of describing soil water is to consider its potential energy. To understand this concept, soil water potential can be compared to the potential energy of a ‘free’ water surface at the same height. There is no energy difference between a fully saturated soil and a corresponding body of ‘free’ water. The saturated soil and the ‘free’ water are in equilibrium. As the soil drains or dries out the free energy changes and the potential difference is negative relative to the reference point for pure, free water, i.e. 0 kPa, which is saturation. Currently the most commonly used units for soil water potential are kiloPascals (kPa). Total soil water potential ($\psi$) is made up of several components; matric potential ($\psi_m$) is the energy decrease due to the interaction between the water and soil matrix, gravitational potential ($\psi_z$) is from height or gravity and osmotic potential ($\psi_s$) is the effect of soluble salts. An additional component for shrink: swell soils is overburden potential ($\psi_o$). The sum of the components of $\psi$ is shown in the following equation:

$$\psi = \psi_m + \psi_z + \psi_s + \psi_o$$  \[2.7\]
Monitoring $\psi$ is useful for detecting the degree to which the soil is saturated. The relative soil wetness indicates whether conditions for plant growth are restricted or ideal. Gauge-type tensiometers have been a popular instrument for measuring $\psi_m$ under salt-free conditions in the field (Charlesworth 2000). Mullins et al. (1986) cited a number of studies that used tensiometers where the determination of $\psi_m$ was required; e.g. to monitor a drainage system by locating impeded or saturated regions. Oltenfreiter et al. (2003) measured $\psi_m$ with sets of tensiometers to identify the depth of temporary saturated zones and the effect of a compacted ploughed zone on $\psi_m$. The effective range of tensiometers is close to saturation (0 to -85 kPa) so they are useful to establish the $\psi$ value of field capacity (FC).

**Plant available water**

FC is the amount of water in the soil after the macropores have drained. In Australia, 10 kPa suction is the accepted value for FC (White 2006). However the value chosen to represent FC varies and in some situations a suction of 30 kPa is used (Marshall et al. 1996) rather than 10 kPa (McKenzie et al. 2002a). The sensitivity of FC depends upon the antecedent structural condition. For many plants the wilting point occurs at –1500 kPa which is commonly referred to as the permanent wilting point (PWP) (Minasny and McBratney 2003). Plant growth is inhibited outside the FC and PWP as the soil is either too wet or too dry respectively. The amount of water stored which plants can utilise between the FC and PWP is the available water capacity (AWC). The AWC was first suggested by Veihmeyer and Hendrickson (1927) and is calculated using the following equation:

$$AWC = FC - PWP$$  \[2.8\]

The AWC range sets boundaries of water availability. Wetter than FC and the soil becomes saturated and waterlogging conditions develop. Drier than the PWP the soil is very dry and plants lose turgor. The AWC can be used to calculate the total plant available water (PAW) in the root zone by multiplying the AWC (when expressed in mm
per m depth of soil) by the plant’s rooting depth (m) (White 2006). Dalal et al. (1997) measured the PAW at sowing to predict the final yield and grain protein percent. The interaction of PAW with the corresponding amount of soil nitrate N was also investigated. PAW at sowing accounted for nearly 40 per cent of the variation in grain protein, and available water per kg of soil N (plus applied N) accounted for up to 78 per cent variation. The PAW is useful to explain how plants respond in terms of yield or quality parameters such as protein.

**Soil water retention characteristic, \( \theta(\psi) \)**

\( \theta \), and \( \psi \) describe different aspects of soil water and each are useful to aid understanding of soil water behaviour. The significance of these aspects of soil water becomes apparent by understanding their relationship: the soil water retention characteristic (SWRC), \( \theta(\psi) \). Determining the SWRC is useful as it can indicate the soil AWC, aeration status at FC, the pore size distribution in a non-swelling soil and an indirect measure of soil structure. The SWRC can be seen to take different forms depending upon whether it is measured on the wetting or drying curve. This difference is referred to as hysteresis and is due to the way that water is released from and enters pores – desorption and sorption processes. McKenzie et al. (2001d) found a significant effect from hysteresis between two methods of measuring hydraulic conductivity. The differences were found between the sorption and desorption curves.

Barlow and Nash (2002) found significant differences in the SWRC between two soils, despite similarities in these soils (according to wet sieving and Emerson tests). This difference was claimed to indicate a change in structure. Hamblin et al. (1982) used SWRC to assess three different tillage systems. Differences in the slopes of the SWRC data between the tillage systems indicated that there were soil structural differences. To support this finding the pore size distributions were calculated and also found to be different. Vervoort and Cattle (2003) measured SWRC for a number of Vertosol soils in several cotton growing regions to enable the AWC to be compared across sites and between depths. Vervoort and Cattle used a van Genuchten-type equation to fit the
SWRC data. The van Genuchten (1980) equation (or modifications of it) has been very popular to model the relationship between $\theta$ and $\psi_m$, thus:

$$S_e = \left[1 + \left(\alpha \psi_m\right)^n\right]^{-m}$$  \hspace{1cm} [2.9]

where $S_e$ is the effective saturation, $\alpha$ (L$^{-1}$) is a parameter ($\alpha > 0$) to scale the matric potential, $\psi_m$ (cm, positive), and $n$ and $m$ are dimensionless parameters. The $S_e$ term was defined by van Genuchten as:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$  \hspace{1cm} [2.10]

where $r$ is a fitting parameter, $\theta_r$ is called the residual water content, and $\theta_s$ is the volumetric water content at saturation. The van Genuchten equation uses a number of parameters that enable the functional form of the SWRC relationship to be plotted. Fitting the van Genuchten equation often involves a limited number of $\theta$ values with corresponding $\psi$ values. The fitted curve completes the relationship between the input measured values and allows the estimation of $\theta$ from a measured value of $\psi$, or vice versa. In addition, establishing such a relationship allows the diameter of pores ($P_d$) at each $\psi$ value of a SWRC to be determined using:

$$P_d = \frac{300}{\psi_m}$$  \hspace{1cm} [2.11]

where $P_d$ is pore diameter ($\mu$m) and $\psi_m$ is matric potential (kPa). Thus, pore size distribution can be calculated after determining the $\theta(\psi)$ relationship. By separating pores into size classes it is to understand pore function within certain size ranges. For example, large pores (>500 $\mu$m) release water readily and are called aeration or transmission pores (Cass 1999), whilst the smallest pores are residual pores (<0.5 $\mu$m), which hold onto water tightly and water is effectively immobile. Quantifying the size of pores enables the
pore size distribution to be calculated, which can indicate soil structure. Summary details on pore size, type and function are given in Table 2.1.

### Table 2.1 Soil pore size, type and function with corresponding matric suction range

<table>
<thead>
<tr>
<th>Equivalent cylindrical diameter (µm)</th>
<th>Type</th>
<th>Matric suction, Ψ (kPa)</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000–500</td>
<td>Biopores</td>
<td>-0.06 to -0.6</td>
<td>Rapid infiltration of water and inflow of air</td>
</tr>
<tr>
<td>500–75</td>
<td>Macropores</td>
<td>-0.6 to -4</td>
<td>Infiltration of water, exchange of gases and space for root growth</td>
</tr>
<tr>
<td>30–75</td>
<td>Mesopores</td>
<td>-4 to -10</td>
<td>Slower drainage of water and nutrients</td>
</tr>
<tr>
<td>0.5–30</td>
<td>Micropores</td>
<td>-6 x 10^3 to -10</td>
<td>Storage of plant available water</td>
</tr>
<tr>
<td>&lt;0.5</td>
<td>Residual</td>
<td>&lt;-6 x 10^3</td>
<td>Binds particles together</td>
</tr>
</tbody>
</table>

Source: Adapted from Cass (1999) and Hamblin (1985)

Soil water, measured either by θ or ψ, is an important soil property that influences agricultural production. Plant growth and ultimately yield are common responses to soil water status. Our understanding of soil water is shaped by the way in which we measure it. θ_v can provide an assessment on the amount of water that relates well to the soil water balance and water use by plants, while ψ measures the energy with which the soil holds the water. The SWRC relationship provides a useful framework to understand the potential energy (J kg^{-1}) and volume (m^3 m^{-3}) of water. It also provides information on the pores which hold the water and the soil structure.

Soil water properties are considered important for the evaluation of the soil of RB. Measurements of both θ_v and ψ are presented and discussed in chapter four and measurements of the SWRC are given for the field and laboratory in chapter six. As
water is a dynamic and viscous liquid and to more completely understand water in the soil, it is necessary to consider its movement and flow. The strong influence of gravity on soil water and infiltration follows.

### 2.1.3 The movement of soil water

The flow of water through the soil occurs under saturated and unsaturated conditions. The flow of water can occur whenever there is a difference in water potential in the soil. Water moves from high to lower energy until equilibrium is established. The direction of forces governing water flow can be vertical and horizontal, depending upon the antecedent conditions. Early engineering work by Darcy (1803-1858) found saturated flow described by the following equation:

\[ Q = K_s A \Delta P / L \]  

where \( Q \) is the volume rate of water flow (m\(^3\) s\(^{-1}\)), \( K_s \) is the saturated hydraulic conductivity (m s\(^{-1}\)) through columns of length \( L \) and area \( A \) when the hydrostatic pressure difference is \( \Delta P = P_2 - P_1 \). Flow is due to differences in hydraulic head which is made up by hydrostatic and gravitational components. Darcy’s law is valid for one-dimensional flow through a uniform soil only. It is a simple relationship where the hydraulic gradient of the soil determines the flow rate through the soil. During saturated flow the soil matrix is totally filled with water in its non-solid phase. To calculate \( K_s \) using Darcy’s law it is necessary to know the cross-sectional area (A) through which the water is flowing. Previous work by Poiseuille (1799-1869) used a capillary tube model and calculated that \( Q \) was proportional to the fourth power of the radius of a tube (Jury et al. 1991), as shown by:

\[ Q = \frac{\pi R^4 \Delta P}{8Lw} \]
where $R =$ radius and $v =$ viscosity. Therefore, if a pore is compared to a tube, it can be quantified in size. This is based upon the concept that soil pores are like a bundle of capillary tubes. By describing $K_s$ in this way, it is conceivable that, at times, water may not flow through all the “tubes”. Changes in soil properties such as texture, structure or other factors such as root growth and faunal activity may restrict the ability of all pores filling and lower the likelihood of saturated conditions. It is not uncommon for regions of unsaturated flow to be interspersed with small pockets of saturated flow. When the soil is not completely saturated, water flow is described by unsaturated hydraulic conductivity ($K_{us}$).

**Unsaturated hydraulic conductivity, $K_{us}$**

Unsaturated flow is promoted by factors that decrease $\theta$, such as temperature, evaporation rate and plant water uptake (Marshall et al. 1996). These external factors aside, it is the nature of the soil matrix and pore network within it that also determines whether hydraulic conductivity ($K$) is saturated or unsaturated. The pore size distribution and pore connectivity are characteristics which relate to soil structure (see section 2.1.) and strongly influence $K_{us}$. Soils that contain small and irregularly shaped pores or tortuous pore pathways will become wet more slowly and unsaturated flow is more likely to develop. Some differences in $K$ can be understood as changes that occur over time. Jury et al. (1991) defined $K_{us}$ as a nonlinear function of $\theta$ or $\psi$. Richards’ equation (Clothier and Scotter 2002) parameterises $K_{us}$ well by accounting for the effect of gravity and pressure gradients using:

$$\frac{\partial \theta}{\partial t} = \nabla \left[ D(\theta) \nabla \theta \right] + \left[ \frac{dK(\theta)}{d\theta} \right] \left( \frac{\partial \theta}{\partial z} \right)$$

[2.14]

where $t$ is time, $z$ is depth and $D$ is the soil water diffusivity defined as $K(\theta)dh/d\theta$. Richards’ equation provides a generalised explanation of $K_{us}$, but it does not include boundary conditions that restrict its application. Furthermore it cannot be applied in layered soils as varying hydraulic properties will change $\theta(z)$ and it ignores the effects
due to hysteresis, entrapped air and water repellency; nor can it account for preferential flow (Clothier and Scotter 2002).

**Preferential flow**

Predicting and measuring infiltration can be complicated by factors which cause abnormal flow. Some issues that create challenges are preferential flow (or bypass flow), air entrapment and water repellency. Bevan and Germann (1982) defined bypass flow as “the flow of water through a system of large pores that allows fast velocities and bypasses the soil matrix.” Typically it is found in structured clay or well aggregated soils. Its formal acknowledgement was perhaps a development from the mobile-immobile model of soil water presented by van Genuchten and Weirenga (1976). Here water movement between aggregates is mobile and moves much faster than immobile water within aggregates. However, Booltink et al. (1991) claim that as a result of their observation of discontinuous macropores the two region model is oversimplified. Booltink et al. observed bypass flow and identified macropores which were involved in infiltration.

Methylene blue was used as a dye tracer by Bouma and Dekker (1978) to observe the pores through which water infiltrated. Soil with more strongly developed structure had deeper infiltration and indicated a distinct effect of porosity on infiltration. The impact of macroporosity on infiltration is well illustrated by Messing and Jarvis (1993) who measured unsaturated hydraulic conductivity with a tension infiltrometer at supply potentials from –0.5 to –10 cm (Figure 2.1). Such a broad range of K was beneficial in identifying the contribution of pore size ranges to the flow of water; as the supply potential indicates the infiltrating pores (White 1989). A two line regression model suggested that two pore systems seemed to exist. The break point was from -4 to –6 cm of water potential which is equivalent to pore diameters between 0.50 and 0.75 mm. This effectively separates macropores from mesopores. The sharp change of slope at this point was associated with a rapid increase in K. Soil structure determines where preferential flow develops.
Figure 2.1 Unsaturated hydraulic conductivity as a function of water potential for a surface soil. Data points were taken in August (○) and October (■). Source: Messing and Jarvis (1993)

Preferential flow is a significant phenomenon because it increases infiltration rates and the potential volume of water that can move through the soil. Where it occurs there is an increased risk of solute movement that may flow through to groundwater (White 1985a). This should be taken seriously given the suggestion by Radulovich et al. (1992) who claimed that for well-aggregated soils preferential flow may be the rule rather than the exception, even when moisture status is less than saturation.

**Impeded flow**

In contrast to preferential flow, infiltration is sometimes impeded and this creates difficulties for predicting infiltration. Restrictions to infiltration may occur at the soil surface or further down the profile. At the surface, restricted infiltration may be caused
by water repellency or hydrophobicity. McKissock et al. (1998) claimed that water repellency is caused by plant and fungal residues consisting of waxes and is more prevalent with higher organic matter levels. Hammecker et al. (2003) found evidence that infiltration of water was inhibited by entrapped air. Between the extremes of bypass and restricted flow there is matrix flow. Studies on solute transport give information on the nature of the pathways that soil water take as it flows through the soil. Moreover from the modelling of solute transport it is possible to distinguish preferential flow from matrix flow.

**Solute transport**

Because of an increasing interest in the leaching of nutrients from soil, a range of different infiltration experiments are used to follow the movement of water and solutes. Most methods use dyes or chemical tracers, such as a chemical dissolved in water. Solute transport studies measure both the outflow eluted from the soil and characterise the flow within it. Several experimental approaches have been used to measure solute transport, from field studies with lysimeters (Edis 1998) to undisturbed cores in the laboratory (Heng et al. 1999). A variety of solutes has been used when following the movement of water through the soil. Most studies have used a solute containing a chemical anion of interest, such as Cl\(^-\) (Jarvis et al. 1991b), Br\(^-\) (Edis 1998), SO\(_4^{2-}\) (Heng et al. 1994), or a pesticide such as phosmet (Suter 1997). In these studies the behaviour of the solute and its interaction with the soil matrix were monitored.

**Transport volume, \(\theta_{st}\)**

Solutions flow through a given region within the soil which Jury et al. (1986) called the transport volume (\(\theta_{st}\)). This is defined as the wetted pore space that participates in the movement of solute during the time of the experiment (White et al. 1986a). It excludes dead end pores that are not connected to the outflow boundary. The size of \(\theta_{st}\) can vary widely according to the length of time for solute transport. The difference between \(\theta_{st}\) and \(\theta\), can indicate the effect of soil structure on solute transport and the extent of preferential
flow through the soil’s pore space. Parameters derived from modelled data and measured experimental data can be used to calculate $\theta_{st}$ according to:

$$\theta_{st} = \frac{q}{\bar{v}} = \frac{q}{L}$$  \[2.15\]

where $q$ is the soil water flux density, $\bar{v}$ is the average pore water velocity, $L$ is the calibration depth, and $\bar{t}$ is the average travel time (Jury and Roth 1990).

**The modelling of solute transport**

Several models have been developed for solute transport to allow measured data to be fitted against existing theory. The best known are non-equilibrium models, stochastic-convective models and the convection-dispersion model. A good review on solute transport models and relevant software programs was given by Dane and Topp (2002). A frequently used model is stochastic in nature and is exemplified by the convective lognormal transfer function (CLT) (Jury 1982). The development of this model was influenced by field measurements where solute drainage concentrations were found to be distributed log-normally (Biggar and Nielsen 1976). The parametric form of the CLT uses a log-normal distribution $f_L(I, z)$, described as a function of the soil column depth ($L$) and cumulative drainage ($I$),

$$f_L(I, z) = \frac{\exp\left[-\left(\frac{\ln(I/L) - \mu}{\sigma}\right)^2/2\sigma^2\right]}{\sqrt{2\pi}\sigma I}\quad \text{[2.16]}$$

where $\mu = \text{mean;} \quad \sigma^2 = \text{variance;} \quad L = \text{calibration depth and } z = \text{depth of interest.}$ As there was only one point of measurement at the base of the soil column, the calibration depth is also the depth of interest, so $L = z$. Using the best-fit values of $\mu$ and $\sigma^2$ from equation [2.16] and substituting in equation [2.15], the transport volume $\theta_{st\, I}$ derived from the median travel time is given by [2.17], while $\theta_{st\, II}$ which was derived from the mean travel time is given by [2.18],

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Another popular model uses the convection dispersion equation (CDE). It is a deterministic model that assumes solute transport occurs through a homogeneous medium and solutes completely mix (by diffusion or dispersion) in a radial direction before they reach the outflow end of a column in an axial direction (Jury et al. 1991). The CDE is a Fickian distribution $f_L(I, z)$ which can be expressed as a function of the soil column depth ($L$ which is equal to $z$) and cumulative drainage ($I$),

$$f_L(I, z) = \frac{z \exp\left(-\frac{(z - vI)^2}{4DI}\right)}{2\sqrt{\pi DI}^3}$$  \hspace{1cm} [2.19]$$

where $D =$ effective dispersion coefficient and $v =$ mean pore water velocity.

The application and utility of solute transport theory (including modelling and model parameters) is presented in chapter eight with an experiment that describes the movement of solute through the soil in RB and CC.

**Spatial and temporal variability**

Whether measuring K or solute transport, difficulties are sometimes encountered because of spatial and temporal variability. A leaching experiment conducted by Biggar and Nielsen (1976) examined the spatial variation of an applied solute in a field experiment. A lognormal distribution of the pore water velocity was detected, thus indicating a high spatial variability of these soil properties. The implication of this work was that a large number of samples are sometimes required to accurately estimate K. Coutadeur et al. (2002) observed that tillage increased the spatial variability of $K_{us}$ which was six times
greater in the seed bed than in a ploughed layer, but only twice as much as an untilled layer. Loch and Orange (1997) measured K over a period of time on a rehabilitated mine site. From this work Loch and Orange suggest that is necessary to wait at least four seasons of plant growth before measuring K.

Existing theory based upon Darcy’s law and Richards’ equation underpins our understanding of K, albeit with certain assumptions and some limitations. This knowledge is crucial when determining soil infiltration, although sometimes it is difficult to measure K. Infiltration is largely a function of K and greatly influences components of the soil water balance, in particular, the pathways of water loss in the form of deep drainage or run-off. As a result of the importance of K it was measured on RB and other treatments in chapter seven.

The interaction of infiltration with other soil physical properties determines the conditions which develop. Slow infiltration rates can lead to the formation of saturated layers in the soil that inhibit plant growth. This can potentially lead to problems with soil aeration.

2.1.4 Soil aeration

Soil aeration is the movement of gases through the air space in the soil and between the soil and the atmosphere. For plant growth, the composition of and changes in two gases, CO₂ and O₂, are of principal interest. The composition of these gases depends upon the biological respiration rate, solubility of gases in water and the gaseous exchange with the atmosphere (Jury et al. 1991). High moisture contents and conditions that restrict the escape of gases from the soil increase the concentration of CO₂. Changes in gas composition occur as a result of gas transport processes. Gas transport through the soil can be described by convection and diffusion. Environmental factors such as soil temperature, barometric pressure, wind and rainfall (or resultant θv) affect the extent of gas movement by convection (Marshall et al. 1996). Diffusion is the movement of gases as a result of a concentration gradient. It is best explained by Fick’s law:
where $q_s$ is the flux per unit area of cross section of soil, $D_o$ is the diffusion coefficient in bulk air, $b$ is an impedance factor, $\varepsilon_a$ is the air-filled porosity, $C$ is concentration and $x$ is the space co-ordinate normal to the section. The impedance factor accounts for the tortuosity of the pore network and is related to the $\varepsilon_a$. Increasing water content reduces the effective $\varepsilon_a$ which is a factor that controls gas diffusion. Diffusion, according to Currie (1983), is related to the fourth power of $\varepsilon_a$:

$$\frac{D}{D_o} = \alpha \varepsilon_a^4$$

where $D$ is the gas diffusion coefficient in the soil, assuming a unimodal pore size distribution. Xu et al. (1992) determined the gas diffusion coefficient on soils of four different BD values and texture, but no differences were detected. However, at 10 per cent $\varepsilon_a$ the diffusion coefficient was close to zero reflecting a discontinuity in pathways at air-filled pore space <10 per cent. This highlights the importance of $\varepsilon_a$ on gas diffusion.

**Aerobic conditions**

Aerobic conditions exist when the soil is well aerated and diffusion is not restricted; $O_2$ is present and plants can freely respire. Typically there will be increasing $CO_2$ and decreasing $O_2$ levels, but exchange with the atmosphere will ensure that the $O_2$ concentration is maintained. To monitor $O_2$, researchers have used the oxygen diffusion rate as a key measure of soil aeration and as an indicator of conditions critical for plant growth. McIntyre (1970) reviewed a popular method used by researchers which involves the reduction of dissolved oxygen on a platinum electrode to determine $O_2$ flux. Meyer et al. (1985) used the platinum electrode method to indicate the concentration of soil $O_2$, whilst monitoring root and shoot growth. They observed that root growth was slowed at low soil $O_2$ concentrations and actually stopped below 10 mg /L of soil by volume. There
were no negative effects seen in shoot growth, but the final yield results showed that the soil with poorest O\textsubscript{2} status had the lowest yield, which was 44 per cent less than a well aerated soil. Nisbet \textit{et al.} (1989) used the same method to characterise O\textsubscript{2} status and variation in soil water of a waterlogged soil. Regions of zero diffusion current (no O\textsubscript{2}) were associated with saturated zones, whilst regions with a positive O\textsubscript{2} flux were well aerated. As a result Nisbet \textit{et al.} recommended that if such a relationship is found for similar soils, then O\textsubscript{2} status can be predicted from the location of saturated regions within the profile.

\textbf{Anaerobic conditions}

Poor exchange of gases, whereby O\textsubscript{2} consumption exceeds supply, leads to under-aerated soil and the development of anaerobic conditions. Anaerobic conditions develop as water replaces the soil air. Oxygen diffuses through water more than 10,000 times slower than through air (White 2006). As the soil becomes increasingly saturated and approaches waterlogged status the oxygen concentration falls. This has several negative effects on plant growth: the roots are stressed by low O\textsubscript{2}, e.g. Brisson \textit{et al.} (2002) found the critical value of oxygen concentration to be 0.12 mol m\textsuperscript{-3} for root growth. Low levels of oxygen retard root growth by causing the death of root cells. Other negative effects include: the potential loss of N by denitrification as well as the production of organic acids, H\textsubscript{2}S or the growth of pathogens (Tiedje \textit{et al.} 1984). Ethylene is another by-product of anaerobic conditions which can potentially reduce root growth (Smith and Restall 1971). Increased soil water content will contribute to the development of anaerobic conditions by reducing gas diffusion. Experimental studies have explored anaerobic conditions in the soil and their effects on plants.

\textbf{Air-filled porosity}

Early work by Wesseling and van Wijk (1957) suggested that air-filled porosity (AFP) should be kept above 10 per cent for adequate diffusion to be maintained for plant growth. Grable and Siemer (1968) then established that the critical lower range of AFP
was between 12 to 15 per cent and that it was influenced by soil texture and aggregation. Wright (1985a) reported several significant findings in a study on the period of inundation (hours of water ponding) of water applied by irrigation in a sorghum crop. Increasing the period of inundation reduced dry matter production and grain yield and reduced soil AFP. AFP was recorded after three, six hours and 24 hours over four depth ranges. Increasing the time of inundation reduced the AFP (Table 2.2). Moreover, the longest periods of inundation resulted in the increased recovery time in AFP afterwards. The recovery period was specified as the time taken for the AFP to exceed $0.10 \, m^3/m^3$.

In the second part of this study Wright (1985b) showed that longer periods of inundation were associated with lower plant N uptake. It was speculated that this could have contributed to the reduced yield. The conditions which reduced soil aeration probably resulted in losses of N by denitrification and leaching. Tiedje et al. (1984) showed the inhibiting effect that O$_2$ has upon denitrification. In fact there was increased denitrification when the O$_2$ concentration was reduced by <2 per cent.

### Table 2.2 The effect of ponding time (h) on air-filled porosity (m$^3$/m$^3$) in the centre of the ridge immediately after furrow irrigation of a Vertisol at Kununurra, Western Australia.

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>Ponding time</th>
<th>3 h</th>
<th>6 h</th>
<th>24 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-50</td>
<td></td>
<td>0.16</td>
<td>0.11</td>
<td>0.06</td>
</tr>
<tr>
<td>50-100</td>
<td></td>
<td>0.09</td>
<td>0.06</td>
<td>0.04</td>
</tr>
<tr>
<td>100-200</td>
<td></td>
<td>0.03</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>200-300</td>
<td></td>
<td>0.12</td>
<td>0.11</td>
<td>0.08</td>
</tr>
</tbody>
</table>

*Source: Wright (1985a)*

Aeration in the soil is an important process for plant growth. An unrestricted diffusion of gases will allow the soil to be well aerated with adequate O$_2$ levels. In contrast, poor aeration can result in the development of anaerobic conditions that restrict growth and lead to denitrification. Aeration is a property of the non-solid component of the soil and is strongly influenced by soil water. In chapter five the AFP was calculated using the same
method as Wright (1985a). This enabled a comparison of AFP between the RB and CC during the growing season.

The solid component of the soil also influences soil physical condition e.g. in soil strength, and this is the next soil physical property reviewed.

### 2.1.5 Soil strength

The strength of a soil is the stress or force that it can withstand. It can be expressed by the load bearing capacity of a soil when used as a foundation for a road or buildings. For tillage, it is understood in terms of soil friability or the degree to which the soil is compacted. Alternatively, the way that a plant experiences soil strength is useful. In this context soil strength can be related to the ease with which a root grows or the force that is required for a seedling to emerge. In relation to plants, soil strength is important because it affects growth and crop yield.

The forces imposed on soil can be classified as compressive, tensile or shear strength. The former two involve forces that are applied perpendicular to a given surface. A compressive force pushes in, whereas a tensile force pulls away in a lengthening direction. Richards (1953) introduced the modulus of rupture as an index to measure the strength of soil crusts. This method determines strength that is related to tensile stress and thereby measures the load that can be applied to the soil. It has often been used in engineering work to measure the breaking strength of materials. For soil, this measurement was devised to assess the force required by bean seedlings to emerge. Soil properties, such as the nature of the exchangeable cations present, especially the amount of sodium, have been found to influence the strength of soil crusts. Soils with these characteristics are typically referred to as hard-setting (Aylmore and Sills 1982).

Shear strength is a triaxial compressive force which involves forces that are applied parallel to a surface. To improve the visualisation of a shearing plane an illustration is
The expression of shear strength in terms of cohesion $c$, is given in the Mohr-Coulomb equation,

$$\tau = c + \sigma_s \tan \phi_f$$  \[2.22\]

where $\tau$ is the shear stress at failure, $\sigma_s$ is the stress normal to the shear plane and $\tan \phi_f$ is the coefficient of internal friction. The angle $\phi$ is the friction angle of a given soil. The line of rupture is the failure point of a soil at a range of BD values. Cohesion values vary according to soil texture, from zero for cohesionless sand to 30 kPa for some clays (Marshall et al. 1996). The shear strength, $\tau$ increases with greater BD and is sensitive to $\theta$. The interactions between forces that are applied to soil and the effects of different soil properties are well illustrated by the Coulomb model of shear strength.

Figure 2.2 The line of rupture with a friction angle, $\phi$ of shear strength. Source: Rose (2004)
The effect of soil water

All measures of soil strength are a function of a number of different soil properties, including soil texture, mineralogy, organic matter content, BD, antecedent $\theta$ and soil structure. The relationship between $\theta$ and soil strength is referred to as the soil strength characteristic. $\theta$ has the most significant effect in varying the magnitude of soil strength. Applying a force upon a saturated soil will determine the ability of the soil to resist the applied force or to drain thereby partially relieving the stress. As water is extracted from soil its space is replaced by air. A change in state to increasingly unsaturated soil occurs which affects the response to an applied force. Foundational work by Towner and Childs (1972) explored the variation in soil strength according to the degree of soil saturation. It was observed that the greater the proportion of air that entered the soil, the lower was the corresponding pore-water suction and the greater the measured effective stress. Experimental results on the influence of pore-water suction (in cm of water) on effective stress (kg m$^{-2}$) were obtained on a wetting curve to saturation using beach sand (Figure 2.3). Effective stress was measured using a standard unconfined compression test. This work measured effective stress as an indicator of soil strength. It showed that increased soil strength correlated with decreased $\psi$ (measured as suction).
Weaich et al. (1992) accounted for changes in soil strength according to differences in $\theta$. Soil strength was found to develop more quickly at high drying rates, but drying rate did not alter the soil strength characteristic relationship. McQueen and Shepherd (2002) recorded penetration resistance less than 3 MPa (established as a critical value), but they predicted (from laboratory work) that under drier ($\psi <100$ kPa) conditions the soil strength could become a limiting factor for plant growth. These studies further emphasize the value of measuring soil water (either as $\theta$ or $\psi$) with soil strength.

The effect of bulk density

An increase in the load applied to the soil will result in compaction and higher BD. Compaction from animals or wheel traffic will compress the soil and thus pack soil particles together. Bridge and Bell (1994) noted increases in soil strength as BD increased. This relationship was also associated with lower $\theta$ and led to a decline in the
physical fertility of the soil for cropping potential. Grant et al. (2001) measured strength and density changes in two soils over a period of wetting and draining cycles. Differences in the amount and composition of organic matter were shown to significantly affect the soil strength development (described as age-hardening) in each case. Soils with higher organic matter content had a lower water uptake rate and were not as dense or strong. For soils with similar texture, soil strength has been found to increase with aggregation. From poorly to well aggregated, e.g. coherent < prismatic < blocky < crumbly, platy < sub-angular blocky; thus Horn and Baumgartl (2002) proposed that an increase in the number of contact points between individual particles causes greater effective stress (an indicator of strength).

**Penetrometer resistance**

Probably the most popular instrument for measuring soil strength in agricultural experiments has been the penetrometer. A penetrometer contains a metal shaft that is inserted into the soil with a sensor that records force. As the shaft is pushed through the soil it experiences resistance due to mechanical deformation. This resistance is a combination of shear strength, metal: soil friction and compression below the shaft. Soil strength measured with a penetrometer is referred to as penetrometer resistance (Warrick 2002). It is a convenient and effective way to assess soil strength in the field, whereby a profile of soil strength with increasing depth can be determined. Penetrometer resistance does not equate to the absolute resistance experienced in the soil by a growing root, but it is the best indicator available (Bengough and Mullins 1990).

However, there are drawbacks with penetrometers. McKenzie and McBratney (2001) commented that penetrometers performed poorly in a wet clay soil. In this situation the stickiness of the soil was problematic and they recommended the use of a shear vane. The design of penetrometers with a rigid shaft does not exactly reflect the behaviour and growth of a root. A comparison by Whiteley et al. (1981) of the pressure exerted by penetrometers with the resistance felt by growing roots identified some substantial differences. It was found that a penetrometer had to exert over five times the pressure.
compared to a root tip. Roots can preferentially find planes of weakness and pathways of least resistance that require less pressure to be exerted. High soil strength values, as recorded by Ehlers et al. (1983) can ignore the presence of a small (<1 per cent) yet important number of biopores or channels which provide potential paths for root growth. Bengough and Mullins (1990) claim that resistance as measured by penetrometers overestimate the resistance required by plant roots by between two and eight times.

Root elongation rates of peas (Pisum sativum) are slowed with increasing penetration resistance (Figure 2.4). Thus, Cass (1999) recommends that the critical range of soil strength (penetration resistance) for root growth is between 1 to 3 MPa. This is lower than 5.1 MPa which was recorded by Ehlers et al. (1983), but agrees with the limit recommended by Dexter (1986). The effect of soil strength on plants varies according to the pressure exerted by the roots. The diversity that exists was clearly demonstrated in a survey of 22 species, where plants with a larger root diameter (dicotyledons) penetrated further than smaller diameter plants (monocotyledons) (Materechera et al. 1991).

Figure 2.4 Relation between root elongation rate and penetration resistance of a sandy loam (▲) and clay loam (●) soil. Source: Kirby and Bengough (2002)
The effect of soil strength on plant growth

High soil strength restricts plant growth. Kirby and Bengough (2002) undertook experimental and predictive work to explore the constraints to root growth in strong soils. In particular they studied the interaction between root growth characteristics (such as radial expansion and axial advance) with imposed stresses. The role of friction at the interface between the root and the soil was found to be important. Two soils were tested: a clay loam (assumed to be frictionless) and a sandy loam (with greater friction). Larger diameter roots were found to develop in the sandy loam. While there was less friction in the clay loam, there was a greater build up of axial stresses, particularly at the tip. Thus, the distribution of stresses which develop on a growing root are dependant upon the impedance response at the tip and along the root /soil boundary. Consequently Kirby and Bengough (2002) postulated that thicker roots experience less axial and shear stresses than thinner roots.

Plants respond to soil strength firstly through their roots. However, the effect goes beyond the roots and sometimes can reduce crop yield. Hamza and Anderson (2002) showed that lower soil strength gained from deep ripping and applying gypsum partially resulted in crop yield improvements. Likewise, Belford et al. (1992) observed a positive plant response (higher root densities at depth) with lower soil strength after deep ripping. A review by Unger and Kaspar (1994) cited several studies where soil compaction was treated which reduced the soil strength and led to increased crop yields, but in each case the yield response was due to improved water extraction.

Soil strength is a dynamic property that can be measured in several ways. Stresses and forces that make up soil strength are a function of other soil properties such as texture, organic matter and $\theta_v$. It is a property that varies both spatially and temporally. It affects plant growth and potential crop yield, although identifying causal relationships is difficult because of other interacting factors. There is evidence to suggest that plants respond to the combined effect of soil strength and $\theta_v$ (Hamza and Anderson 2002) and soil strength...
and aeration (Hulme et al. 1991; Meyer et al. 1985). Due to its importance, measurements of penetration resistance are presented and discussed in chapter six. The following section explores relationships between the soil physical properties that were previously discussed.

2.1.6 An integration of soil physical properties

Agricultural studies often measure various soil physical properties and their effects on crop yield. Some workers have only considered the direct effect of single and not explored relationships between measured properties. Kooistra et al. (1985) measured physical properties such as hydraulic conductivity, penetration resistance and other properties, but did not draw their findings together to develop an understanding of their combined effect. Relationships between properties are identified with correlation matrices (Cotching et al. 2002b) or by using linear regression (Whitbread et al. 1998). However, such statistical methods do not incorporate a functional integration of physical properties by providing a new parameter nor do they normally compare more than two parameters. Furthermore, the interpretation of statistically derived relationships is often difficult. Sometimes this is due to scatter in the data or the lack of a strong definitive relationship.

Non-limiting water range

An alternative approach is to integrate several soil physical properties into a single parameter. The first formal parameterisation of soil physical properties was introduced by Letey (1985) with the concept of the non-limiting water range (NLWR) (Figure 2.5). The NLWR incorporates mechanical resistance and aeration into the established range of available water capacity. Thus, the effects of soil strength and soil aeration were introduced at opposite ends of the soil water range. In example A (Figure 2.5), the $\theta_v$ associated with inhibitory mechanical resistance does not overlap with the alternative lower boundary of the NLWR - the permanent wilting point (PWP). Similarly, with higher water content at the wet end the influence of poor aeration does not extend to
below the FC, which is the upper boundary of the NLWR. In example B both the values for mechanical resistance and poor aeration have changed. The mechanical resistance is greater than the PWP and critical aeration occurs at $\theta$ less than the FC. Thus example B the NLWR is less than in example A. The difference between example A and B can be explained by changes in BD and structure. The model proposed by Letey (1985) simplifies relationships between soil water, strength and aeration by applying set values that limit plant growth.

![Diagram of soil water characteristics](image)

Figure 2.5 Non-limiting water range for two soils, A and B of different density and structure. Source: Letey (1985) with modification.

**Least limiting water range**

The NLWR was developed upon by da Silva *et al.* (1994) to give the least limiting water range (LLWR). da Silva *et al.* described the LLWR as an improvement to the
determination of AWC as it was more responsive to the effect of soil structure. da Silva and Kay (1996) showed that the LLWR could be correlated with the shoot growth of corn, which declined when θ was outside the LLWR. However, da Silva et al. (1994) noted difficulties in establishing values to define the LLWR; the values used had set cut-off values for AFP (at 10 per cent) and penetrometer resistance (at 2 MPa). The step-function approach by da Silva et al. (1994) and previously Letey (1985) has drawbacks because the selected value that limits soil water availability may be questionable, also it assumes that plants switch on and off at a specified value.

McKenzie and McBratney (2001) criticised the limits used by da Silva et al. (1994) for the LLWR as “dubious”. The values used were >2000 kPa (Taylor et al. 1966) for penetration resistance and <0.10 m³/m³ (Grable and Siemer 1968) for AFP. The use of these values has drawbacks. For instance, the work by Taylor et al. (1966) was on cotton, but it has been shown that plant species vary in their response to soil strength (Materechera et al. 1991). In addition, if oxygen diffusion rate is accounted for, AFP can be above and below the value used by Grable and Siemer (1968). McKenzie and McBratney (2001) measured AFP from 0.08 to 0.17 m³/m³ by following the method of Hodgson and MacLeod (1989) to determine the aeration limit and this method requires oxygen diffusion data. Despite these drawbacks other studies (Betz et al. 1998; Leao et al. 2005) have also used the same limits as da Silva et al. (1994). Alternatively selecting a specific value can be avoided by calculating a partially limiting water range. McKenzie and McBratney (2001) specified a partially limited θ, where the θ was restricted between 10 and 90 per cent for resistance or aeration.

**Integral water capacity**

A more advanced method of overcoming the drawbacks of a step-function was developed by Groenevelt et al. (2001). The new approach was defined as the integral water capacity (IWC):
where $C(h) = -(d\theta/dh)$, the differential water capacity, $\omega$ is a weighting function accounting for various limiting physical properties from $i$ to $n$, $\Pi$ indicates that the applicable weighting functions must be multiplied, and $h$ is the matric potential expressed in cm. The key to this concept is that weighting functions allow a graduated change at either end of the range of available water. Weighting functions need to be chosen at the dry and wet limits of available water. At the dry end, account needs to be taken of the low hydraulic conductivity and low root penetrability; while at the wet end, the restrictions are rapid drainage by gravity and lack of aeration. A further benefit of the IWC is that the overburden effect in swelling soils can be included. The IWC was intended to be a more realistic determination of available water because it used continuous functions that incorporate the physical and physiological constraints of plants. Further development of the IWC was given by Groenevelt et al. (2004) where the effect of soluble salts on soil water availability was taken into account. Here Groenevelt et al. showed that the effect of salt over a range of electrical conductivity (EC) values can be quite dramatic, although the restrictions of aeration and soil resistance were ignored (Groenevelt et al. 2001). This contribution by Groenevelt et al. includes weighting functions that may seem arbitrary, but it does provide an alternative concept that accounts for the variation in conditions in swelling and saline soils that plants experience, as well as addressing the dynamics of actual water availability. The integration of soil physical properties was considered useful for the evaluation of raised beds in this study. Therefore the method of da Silva et al. (1994) was modified and results are given in chapter six.

### 2.2 Evaluation of the problem

#### 2.2.1 Waterlogging

The risk of waterlogging depends upon the interactions between the soil, slope of the land, climate and land use. The internal drainage (infiltration) and external drainage (run-
off) of a soil both affect whether a soil becomes waterlogged. The texture and structure of soil both strongly influence drainage. Soils that are well structured have more space to hold water and are less likely to become waterlogged. The depth of soil determines the total space where water can be stored. A shallow soil with poor structure will waterlog more readily as it has reduced storage capacity. Waterlogged soil has restricted soil aeration and leads to the development of anaerobic conditions (section 2.1.4). Furthermore, the access to the land is restricted when the soil is wet and there is an increased risk of damage from machinery or animals.

2.2.2 The effect of waterlogging on plants

The rhizosphere is a dynamic area of the soil profile in a cropping system. An increase in $\theta$ can rapidly change this zone from conducive to hostile for plant growth. The effect of anaerobic conditions upon plant growth for crop production is considered amongst the most serious of the problems caused by waterlogging. Waterlogged soil can rapidly reduce plant growth, as measured by root and shoot development. Moreover, there is evidence that waterlogging has both above and below ground effects on plants which potentially can cause significant reductions in final yield. Symptoms of waterlogging include: wilting, chlorosis (yellowing of the plant), inhibited overall root growth, lower nutrient uptake and the stimulation of ethylene production (Skaggs and van Schilfgaarde 1999). Plant species vary in their tolerance to waterlogging and some plants have adapted to grow in flooded soils. Wetland plants, such as rice, contain a tissue of gas-filled spaces called aerenchyma (Taiz and Zeiger 2002). This provides a gaseous pathway to saturated roots so that the stress of waterlogging is avoided. However, most plants used for crop production do not contain a well-developed aerenchyma and are at risk of being damaged when waterlogged. The duration and timing of waterlogging influences the amount of resultant damage. Young plants are the most sensitive to waterlogging.

Anaerobic conditions slow down root growth. But shoots are typically much slower to reflect the effects of waterlogging than roots. Trought and Drew (1980) detected a response from roots after just two days of waterlogging. After a 14 day period of
waterlogging Malik et al. (2002) found that there was very little growth from the seminal root system, whereas the adventitious roots increased their growth. Compensatory growth from the adventitious roots could not make up for the inhibited seminal roots when compared with roots in a drained environment. The initiation of stress induced by waterlogging alters both the rate and type (seminal/adventitious balance) of root development. Any slowing of root growth has the potential of reducing the final plant biomass. Even short-term (3 day) exposure to waterlogging can severely reduce longer-term growth of wheat (Malik et al. 2002). Repartitioning of nutrients occurs within plants so that the effect of waterlogging may be hidden within other parts of the plants.

Experimental work by Meyer et al. (1985) recorded no damage to leaf and stem growth after three flooding events. In contrast, Malik et al. (2002) showed significant differences in the shoot growth of wheat under drained and waterlogged conditions up to 28 days. Trought and Drew (1980) concluded that shoot growth was an unreliable indicator to detect short-term waterlogging. However, prolonged waterlogging can lead to smaller tillers and lower tiller survival which leads to smaller grain size and reduced final yield (Condon and Giunta 2003).

During the early vegetative stages, plants are more sensitive to waterlogging damage than plants in the late vegetative or reproductive stages (Watson et al. 1976). The contrasting response to shoot growth between the experiments by Malik et al. (2002) and Meyer et al. (1985) highlight the importance that timing has on the effects of waterlogging. Furthermore Malik et al. (2002) commenced waterlogging with three week old wheat plants, whereas Meyer et al (1985) started at 83 days after sowing. Regardless of plant age, increasing the duration of waterlogging leads to greater reductions in growth and yield. McDonald and Gardner (1987) claimed that waterlogging during the 30 days prior to anthesis is critical. They found that every one per cent fall in mean air-filled porosity corresponded to a yield penalty of 0.3 tonne per hectare.

Relationships between waterlogging and yield are often highly variable and determining the expression of the waterlogged conditions is not always clear. Meyer et al (1985)
recorded a 44 per cent reduction in wheat yield for waterlogged compared to drained conditions. Belford (1981) found that yield loss was additive according to the time exposed to waterlogging, which was calculated by Melhuish et al. (1991) at 69 kg /day that water was ponded on the soil surface. Crops vary in their response to and recovery from waterlogging. Zhang et al. (2004) reported that canola outperformed (greater by 17 per cent) wheat and reached its estimated yield potential after recovering from waterlogged conditions. Zhang et al. attributed the difference between the crops due to the indeterminate growth of canola and its ability to photosynthesise for longer. Variable effects from waterlogging have been found to exist between genotypes of the same plant. McFarlane et al. (2003) observed a perennial ryegrass genotype that exhibited improved growth and prolonged photosynthesis during waterlogging. The root mass and shoot growth was not reduced in a tolerant cultivar, whereas waterlogging significantly affected three other cultivars.

2.2.3 Agronomic solutions to waterlogging

The potential impact of waterlogging on yield can be damaging, but the effects are often highly variable. Crop yields typically vary widely according to the severity and duration of waterlogging within a field. Condon and Giunta (2003) measured yields ranging from 0.5 to 4.7 t /ha, with waterlogging thought to be the biggest cause of this variation. The development of agronomic solutions to address this problem are challenging as there are often many interacting variables such as climate, soil, crop type or variety and nutrient level. Predicting the onset or frequency of waterlogging events is difficult and usually very approximate. The use of past climatic records provides a general indication.

Change in sowing date

Bringing forward or delaying sowing dates is one strategy that has been used to avoid waterlogging. Amor et al. (1984) advocated an early sowing date (April) for south-western Victoria to allow plants to get well established before the development of wet conditions. Likewise, McDonald and Gardner (1987) recommended an earlier sowing
date combined with choosing a long season variety as the best way to minimise the impact of waterlogging. The advantage of early sowing is to avoid wet conditions for seedlings. Long season varieties are slower to mature and consequently better able to handle the stress of waterlogging events. Varieties with conventional maturity were significantly (P <0.05) out-yielded by longer season varieties of wheat in undrained conditions at Hamilton, Victoria (Gardner et al. 1992). This contrasts with more recent findings by Riffkin et al. (2003) who report that early maturing spring wheat yielded more than late-maturing winter wheat. However, the latter data were from two low rainfall years during which time waterlogging was not a problem.

**Optimising tiller number**

Higher seeding rates at sowing may be able to help compensate for lost tillers from waterlogging. This could enable the optimum tiller numbers to be maintained after a waterlogging event. Choosing the optimum seeding rate to produce tillers which exactly match the environmental conditions is difficult. Condon and Giunta (2003) compared two seeding rates and found that there was no significant benefit from higher seed rates. In addition this study evaluated the benefit of restricted tillering varieties of wheat compared with a normal commercial variety. No yield advantage from the restricted tillering trait was found under waterlogged conditions.

**The application of fertiliser**

Belford (1981) demonstrated that tiller survival after waterlogging was improved by the application of N fertiliser. The response from N fertiliser was variable as it depended upon the condition of the crop and soil (i.e. the mineral N content and antecedent water content). Work by Stone (1991) in south-western Victoria concluded that when crops were waterlogged for extended periods they were too damaged and did not respond to N. A response was sometimes detected with the deep placement of N fertiliser, but when there was spring drought (i.e. low soil water content) the crop struggled to access this
supply of N. Direct physiological effects caused by waterlogging are not the only factors that constrain crop yield. Other problems can develop indirectly from weeds and disease.

**The use of tillage**

Minimizing waterlogging by modifying the soil profile is an alternative option. Deep ripping or subsoiling reduces the effects caused by hard pans or dense subsoils. This breaks up the subsoil and increases its permeability. Mechanical deep ripping has been shown to reduce waterlogging (Brouwer and van de Graaff 1988). However, the longevity of this modification can be short-lived, especially with a sodic clay subsoil. Gardner *et al.* (1991) reported improved soil condition with deep ripping and added gypsum. The structural stability of the subsoil was improved with gypsum and this allowed the soil to drain. In contrast, Gardner and McDonald (1988) found no significant benefit from deep ripping in reducing waterlogging or improving yield. Reducing the impact of waterlogging with tillage by deep ripping has provided mixed results, and at best only short-term remediation is gained.

The risks of waterlogging can be reduced by adopting agronomic management practices that overcome or avoid the development of these conditions. Changing the sowing date, crop type, seeding rate or adding extra N fertiliser can at times reduce the most damaging effects of waterlogging. These solutions have limited success due to the complexity of the factors involved when anaerobic conditions develop. Furthermore, it is difficult to get the right agronomic balance given the unpredictable and transient nature of waterlogging. Taking measures to avoid waterlogging may not be compatible with managing other limitations such as weeds, disease, frost or nutrition. Thus, it is proposed that the most effective way to reduce waterlogging is to artificially drain the land. There is a wealth of evidence of the benefits to crop production from drainage (Cox and McFarlane 1995; Gardner *et al.* 1991; MacEwan *et al.* 1992).
2.3 Drainage

Drainage is the removal of excess water from the land. Effective drainage provides the soil with adequate aeration for crop growth. Improved trafficability of the land is achieved for operations such as sowing, harvesting and applying fertiliser. This ensures better timeliness and crop management that lead to higher yields. A range of field drainage systems exist which are suitable for crop production depending upon the climate, soils, hydrology, hydrogeology and agricultural practices (Madramootoo 1999). Site specific information on the rainfall, soil hydraulic conductivity, depth to water table and many other factors is required to determine the most suitable method of drainage. All field drainage systems are installed to change the soil hydrology to promote optimum plant growth. In general, most field drainage systems are developed to either remove water from the surface or the subsoil (van Schilfgaarde 1974).

Despite the identification of large areas of land that are susceptible to waterlogging in Victoria (Robinson et al. 2003), there are very few farms that have installed drainage systems. In addition there has been a lack of research into agricultural drainage in the region. This is surprising given the observed effects of waterlogging on agricultural production. MacEwan et al. (1992) claimed that difficult installation conditions are the cause for the limited adoption of subsurface drainage across Victoria. First, sodic subsoils mean that mole draining will not be stable; and second, rapid drying in spring restricts the time during which moling can take place.

Methods of surface drainage vary according to the topography, soil characteristics, the crops grown and the availability of suitable outlets (Schwab et al. 1992). Surface drains cost less and require simpler engineering compared to subsurface drainage. The field is set up to allow excess water to quickly flow away from where a crop is being grown. The installation of surface drainage will alleviate surface waterlogging, but is not likely to prevent waterlogging from developing in the subsoil. Sometimes this does not matter and for certain soils in Western Australia it has been concluded that surface drainage was the only effective means of preventing waterlogging for cropping (Hamilton et al. 1998). MacEwan et al. (1992) predicted that using surface drainage systems on texture-contrast
soils would require a change in the style of land management. Furthermore, the installation of surface drainage results in the loss of productive land and the risk of erosion. Despite the drawbacks associated with surface drainage, raised beds (RB) have been increasingly used for cropping over the past decade in the high rainfall zones of southern Australia, principally in southern Western Australia (Hamilton et al. 2005) and south-western Victoria (Peries et al. 2004).

2.4 Raised beds

2.4.1 Introduction

RB are a cultivation system with a deepened seedbed where crops are grown. Tisdall and Hodgson (1990) described RB as an example of ridge tillage of which there are many variations, from one to several rows per ridge. For example, in south-western Victoria RB have seedbeds which are generally between 1.7 to 2.2 m wide and typically have at least 10 plant rows. This is bordered by furrows that are up to 0.3 m in depth. Below a cross-sectional diagram (Figure 2.6) of a RB and a photograph (Figure 2.7) of a RB field are given.

![Cross sectional representation of the raised beds used in south-western Victoria](image)

RB are a form of surface drainage that are designed to create an improved soil conditions for crop production. RB allow improved water movement away from the bed area, across the bed and then along the furrow. The furrow in particular allows a direct pathway for excess water to flow away (Figure 2.8).
Raised bed cropping across the world

RB of various configurations have been used for centuries across the world. There is evidence that RB were used in South America over 1000 years ago (Barrow 1999). Chinampas - a form of wet or drained field agriculture was used by the Maya between
AD 100 and 700, whilst the Aztecs adopted similar methods to crop the swamplands of central Mexico (Barrow 1999). Sometimes these systems were agropiscicultural and incorporated fish production between broad beds of crops. More recently, there is evidence of quite favourable results from the use of RB for growing irrigated wheat in China. Fahong et al. (2004) compared wheat production on RB with a conventional system of flood irrigation on the flat. Significant benefits were found, including a 30 per cent saving in applied irrigation water with improved water use efficiency, overcoming a soil surface crust problem, increased N use efficiency, reduced crop lodging and incidence of disease, better grain quality and an increase in >10 per cent grain yield. RB experiments in eastern Indonesia were undertaken to develop a suitable new cropping system for soils in that region. Whilst Borrell et al. (1998) found no significant difference in grain yield between RB and the conventional flooded bay system, it was speculated that there were water savings. In addition the drainage was improved and there was greater flexibility for growing other crops. It was claimed that the furrows between the RB provided drainage during heavy rainfall and water storage during the dry season. Subsequently, van Cooten and Borrell (1999) concluded that RB reduced the risk of erosion by providing ground cover all year (with the proposed intercropping), improved timeliness at sowing and harvest and better compatibility in matching water supply to crop production. Further benefits from RB have led to adoption of improved management techniques. Work by Limon-Ortega et al. (2000) investigated different techniques of managing RB in Mexico. In RB where the crop residue was left there was improved N use efficiency and total N uptake compared with sites where residue was not incorporated. Thus, various techniques of crop management will affect the productivity of RB.

Raised bed cropping in Australia

In Australia RB were first used in irrigation systems (Tisdall and Hodgson 1990). The popularity of using RB in irrigated agriculture is probably due to the intensive nature of this type of production system and the recognition of the need to effectively drain the soil containing the growing roots. RB have been used in Australia for at least 25 years, with
Adem and Tisdall (1984) undertaking an experiment in the early 1980’s to investigate the suitability of RB in irrigated double cropping. This system has been found to be well suited to intensive vegetable production such as tomatoes (Nguyen et al. 1988). Irrigated horticultural production in northern Victoria and irrigated cotton production (with >200,000 hectares in NSW and Queensland) are two other examples where RB type systems have successfully been adopted (Tisdall and Hodgson 1990). Borrell et al. (1997) reported up to 32 per cent water saving for saturated soil culture (a variant of RB) compared to a flooded system for rice production in northern Australia. The suitability of RB in irrigated systems is still being tested. Recently, Beecher et al. (2005) investigated a number of perceived advantages of RB such as better water use efficiency in rice production. RB have been used for nearly 20 years in the Riverina, southern NSW (Beecher et al. 1994).

The adoption of RB in non-irrigated agriculture has occurred relatively recently. The initial investigation of RB began in 1996 with a drainage demonstration site at Gnarwarre, south-western Victoria (Wightman and Kealy 1997). Early observations indicated that RB provided improved drainage, with better vegetative and root growth (Wightman and Kealy 2000). The maximum slope suggested from this work was 1.5 per cent and the installation of collector waterways at the headland was recommended. Since this experimental work was done there has been strong interest from farmers in RB and a rapid adoption of cropping using RB. There has been a significant increase in the area of RB during the last decade in south-western Victoria and other parts of Australia (Table 2.3). The performance of RB and the benefits derived from RB in terms of crop production are discussed in the following sections.
Table 2.3 Estimated area of raised beds in Australia (x 1,000 ha)

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<tbody>
<tr>
<td>Vic (south-west)</td>
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<td>0.3</td>
<td>7</td>
<td>15</td>
<td>18</td>
<td>20</td>
<td>24</td>
</tr>
<tr>
<td>Vic (north-east &amp; north central)</td>
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<td>0.3</td>
<td>0.3</td>
<td>0.5</td>
<td>1.5</td>
<td>1.8</td>
<td>2</td>
</tr>
<tr>
<td>WA (south-west)</td>
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<td>0.3</td>
<td>2</td>
<td>6</td>
<td>7</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>Tas (northern)</td>
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<td>0</td>
<td>0.4</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>SA (south-east)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.3</td>
<td>0.6</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>NSW (southern)</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
<td>1</td>
<td>2</td>
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2.4.2 Crop production using raised beds

Crop yield is an important indicator which relates to the production capacity of an agricultural system. One of the earliest experiments comparing RB of varying widths (1.5 and 20 m beds) with a control (flat) treatment produced some significant results. Canola was grown with 20 m RB yielding 3.3 t/ha and the standard RB (1.5 m width) 3.55 t/ha, compared to the control with 2.2 t/ha (Wightman and Kealy 1997). Peries et al. (2001) measured the crop yields over two years of RB and non-RB treatments, i.e. conventional cultivation (CC), (referred to as ‘flat’ cropping) and found no significant difference in yield. However, these results were recorded during years of below average rainfall when the risk of waterlogging was reduced. The furrow between RB leads to a loss in the productive area of land estimated at 25 to 30 per cent (Riffkin and Evans 2003). In comparing the yield of RB with a CC-type treatment Riffkin et al. (2003) found that during a wetter than average year, the RB produced greater yield on an areal basis (per m²) i.e. raised beds only. But the result was approximately the same or not significantly different (P <0.05) when calculated per hectare i.e. over the total area – raised beds and furrows. When the rainfall was less, than average the CC produced greater yields and there was no benefit from the RB. A summary of three seasons of experimental work from several locations in southern Western Australia by Bakker et al. (2001a) reported that RB usually produced higher yields than the control treatment. In some cases, there
was a significant difference (P <0.05) in yield with increases up to 47 per cent reported. The overall mean yield of RB was 2.2 compared to 1.7 t/ha for CC (an increase of 26 per cent). Thus it was concluded that dry matter production and yield were increased on RB for a variety of crops across a range of climatic conditions and soil types. However, more recent results by Bakker (2005) showed that in drier years (for example, 2001) there was little difference in yield benefit from RB. Peries et al. (2004) claimed that on average, RB produced 20 per cent higher yields compared to cropping with CC over a five year period. However, as the data were not presented the veracity of this statement could not be checked.

Much attention given to RB has focused upon production aspects. This ignores concerns that the introduction of RB often involves a change in land use, usually the conversion of pasture to cropping. There is a suspicion that RB cropping represents a potential threat to existing remnant vegetation. Indeed, MacEwan (2002) warned that the introduction of RB cropping could in some areas of south-western Victoria affect vegetation biodiversity, particularly rare or threatened flora species. However, there is currently a lack of information currently to predict the broader environmental effects of RB.

**An economic evaluation of raised beds**

The relative value of yield as a parameter for evaluating RB is put into context if the economics are considered. A worthwhile technique to assess the financial position of a farm business is enterprise costing analysis (Barnard and Nix 1979); that is, determining whether a profit or loss is realised. O’Brien (1999) used a partial budgeting approach to evaluate the profitability of RB cropping. The financial costs and returns to farmers of replacing an area of pasture with cropping was calculated for four different management scenarios. It was established that given the prices and costs at the time, cropping with RB was profitable. In the best case scenario investment on RB was up to $270 /ha more profitable than livestock production. However, the return on investment was reduced if there were high initial costs for new machinery and extra labour. O’Brien’s report does not account for a very wide range of grain prices (only +/- 10 per cent), nor can it be
applied to farms of all sizes. Nevertheless, it is a useful guide on the potential profitability and risk of RB cropping. Howell (2005) cited a farmer from south-western Victoria who introduced RB to deal with the risk of crop failure. “Raised beds dramatically reduced production risk and we can comfortably take positions in the market.” Dean (Pers. com) commented that he saw RB as a risk-minimisation tool that was most appropriate for high-value crops such as poppies, which are grown in waterlog-prone areas of Tasmania.

2.4.3 Hydrology of raised beds

Properly constructed and maintained raised beds increase the lateral drainage of the soil (Hamilton et al. 2005). This reduces the likelihood of saturated conditions and improves soil aeration. Consequently RB have the potential to increase the productivity of land which would otherwise be waterlogged. Hamilton et al. (1998) suggested that the depth of the A horizon was an important factor influencing the extent of waterlogging. They suggested that RB cropping was essentially a method of deepening the A horizon. Bakker et al. (2001a) found that over three growing seasons RB were efficient at reducing the risk of waterlogging crops on the duplex soils of southern WA. For instance, soil moisture data showed that the RB never exceeded a saturation index (i.e. where \( \theta_v \) is expressed as a ratio of the maximum \( \theta_v \) ) of 0.43, whereas the CC-type treatment was often saturated and averaged around 0.80 on the same scale. Further modelling work on these data by Hamilton et al. (2003) found that waterlogging was never predicted on RB, but it was frequently predicted on the CC land. Hamilton et al. claimed that a major factor controlling waterlogging was seasonal rainfall, followed by the depth of A horizon and then soil texture.

Therefore, it is thought that RB have a unique effect on the local pathways of water movement compared to other land uses. Thus, locally and at the catchment scale, RB may behave differently. Johnston (2003) has monitored the hydrology of RB, in particular the quantity and quality of run-off water from RB, CC and pasture. The length and intensity of rainfall events were identified as major contributors to the run-off volume produced. Significantly greater run-off was collected from RB after a large storm event (147 mm),
whereas negligible differences were measured from the lower intensity rainfall events (<5 mm hr\(^{-1}\)) that are more typical of winter rainfall in this region. Run-off water quality varied according to the amount of the rainfall. High total phosphorus (TP) and total nitrogen (TN) concentrations were measured from run-off samples collected after sowing because of the fertiliser that had been applied. Lower measured TP and TN concentrations were produced after the large storm event which was probably due to a dilution effect. The work by Johnston (2003) shows that whilst there is potential for RB to significantly alter the run-off component of the soil water balance, this is largely contingent on the type of rainfall event.

### 2.4.4 Soil physical properties of raised beds

The measured differences in run-off (Johnston 2003) and reduced risk of waterlogging (Hamilton et al. 2003) were probably caused by differences in the soil physical properties. In fact, this has been confirmed by consistently lower soil BD on RB compared to a CC type treatment (Bakker et al. 2001b), e.g. Peries (Peries et al.) measured the BD of RB decreased from 1.6 to 1.2 Mg/ m\(^3\). The unsaturated hydraulic conductivity of RB were between 3 and 15 times greater under RB (Bakker et al. 2002). The largest differences were detected at low tensions (i.e. 10 and 20 mm) which indicated the proportion of large soil pores that cause the higher infiltration rates. Cotching and Dean (2001) found that significantly (P <0.05) better physical properties developed under RB. They found greater infiltration, reduced BD, less shear strength and less penetration resistance. These changes were accompanied by smaller dry soil aggregates which indicated that the changes were due to the increased tillage intensity required on RB. The formation of RB requires additional cultivation passes compared to ‘flat’ cropping systems such as CC. Bakker et al. (1999) postulated that tillage influenced the difference measured between RB and CC cropping treatments. Peries et al. (2001) postulated that this was due to reduced traffic on the RB. Studies by Bakker et al., Peries et al. and Cotching and Dean all show that the soil physical properties of RB are improved, particularly shortly after RB are first formed, e.g. Cotching and Dean’s data were taken just one year after the RB were formed. However the longevity and cause of these
differences in physical properties are yet to be understood. Furthermore there are some physical properties that have not yet been measured.

### 2.4.5 Controlled traffic

Tulberg (2001) claimed that the effect of traffic on soil properties (such as aggregate size) and crop yield is greater than tillage, but both effects are additive. Wightman and Kealy (2000) advocated that RB cropping should become a controlled traffic (CT) system. Under optimal management RB cropping can be designed as a CT system. This is achieved by restricting machinery travel on certain furrows, rather than using every furrow available. CT avoids re-compaction of the soil near the root zone (Olsson et al. 1995). Furthermore, CT can provide improved trafficability during wet periods and allow the crop’s sowing window to be extended (Bolton and Arnott 2004). A review on CT by Tulberg (2001) claimed the following benefits: reduced energy requirements, improved soil structure and easier crop management. For example, McHugh et al. (2003) detected a distinct improvement in soil physical properties three years after adopting controlled traffic. Hydraulic conductivity was increased by 65 per cent and the plant available water capacity rose markedly from 10 to 15 mm per 100 mm of root zone. The benefits of CT are not restricted to physical properties and there is evidence of increased biological soil activity. Pangnakorn et al. (2003) measured a greater incidence of earthworms under CT compared to a wheeled traffic treatment. Determining the effect solely from CT can be difficult as changes in some soil properties may be a function of the intensive tillage to form the RB rather than the CT afterwards.

### 2.5 Conclusion and knowledge gaps

#### 2.5.1 Conclusion

Soil structure is an important indicator of soil physical condition. Soil pores form a network of pathways within the soil and constitute the structure which influences soil aeration and soil water movement. Two different methods of measuring soil water were
considered. The $\theta_v$ is best for determining the soil water balance or the amount of water used by plants, whilst $\psi$ is preferred when assessing relative soil wetness, especially close to saturation. The hydraulic conductivity of a soil can affect its suitability for crop production. Similarly, adequate soil aeration is important for maintaining healthy plant growth. Plant response, including yield is sensitive to soil strength. However, there is evidence of a combined effect between at least two physical properties. Thus, as a way of avoiding confusion between the effects of different soil physical properties, they can be integrated; either with the NLWR (Letey 1985), the LLWR (da Silva et al. 1994) or the IWC (Groenevelt et al. 2001). These conceptual models have shown that either the potential or the limit of a soil for crop production requires consideration of more than one soil physical property.

It was found that a greater frequency and duration of waterlogging results in increased plant damage. Plant age and the timing of waterlogging during the growing season are important, with the youngest plants being the most vulnerable. Minimising damage from waterlogging has been achieved by a range of agronomic or management solutions, such as changing the crop variety. However, some techniques provide limited alleviation e.g. deep ripping. Drainage is the most certain method to control waterlogging and to improve the productivity of the land.

RB have proven successful for a range of crop production systems across the world. In Australia, RB are well established in irrigated agriculture, but are relatively new to rain-fed farming systems. Since their introduction to south-western Victoria, RB have been rapidly adopted. Evidence to date suggests that RB provide an increased potential for crop production. In particular, greater yields are predicted in years with above average rainfall. As a result, farmers use RB to reduce their risk from waterlogging, although the broader environmental effects of RB are yet to be determined. It is suspected that under certain conditions rainfall on RB produce significantly greater run-off volume than comparable land uses. Therefore it is probable that the pathways of water loss from under RB will be different from other land uses. Some soil physical properties of RB have been
found to be significantly better than under CC. Hence the soil under RB may have improved structure.

2.5.2 Knowledge gaps

To date, there has been very little reported on the soil water dynamics of RB in south-western Victoria. In Victoria, only one study (Clark 2004) has comprehensively monitored the soil water content of RB but this study was conducted during years with below average rainfall and it was focused on RB and did not make any comparisons with other land agricultural uses. Consequently, little is known on the soil water behaviour of RB compared with cropping on CC or uncropped land under pasture. In particular, there is a need to focus on periods just prior to and during waterlogging (a small soil water deficit or surplus soil water) as well as dry periods (maximum deficit).

Whilst it is clear that sometimes there are increases in yield from RB (Bakker et al. 2001a; Wightman and Kealy 1997), it is less obvious when there are not (Peries et al. 2001; Riffkin and Evans 2003). Previous workers may have overstated the benefits of RB (Hamilton et al. 2005; Peries et al. 2004). Nevertheless there are indications that wet years favour crop production with RB. The critical rainfall during the growing season that favours crop production on RB in south-western Victoria is not known. Most RB studies to date have only reported yield results and so there is a lack of information on plant growth on RB, which is important in developing an understanding of RB agronomy. A thorough comparison of the yield of RB and CC systems is also required.

Measurements of soil physical properties of RB and a comparable treatment has been undertaken for soils in Western Australia (Bakker et al. 2005) and Tasmania (Cotching and Dean 2001). However in south-western Victoria there is a lack of data on a comprehensive range of soil physical measurements of RB and as such changes over time of these properties are yet to be determined. Important properties that require investigation include the soil water retention characteristic and soil strength. Further as RB are often installed on waterlog-prone soils, the movement of water through the soil is
often a problem. However no data has been reported on the infiltration for soils under RB in Victoria. Field measurement of hydraulic conductivity and knowledge of the porous pathways that contribute to drainage in these soils are valuable pieces of missing information.

Albeit some measurements of bulk density (and from that porosity) e.g. Peries et al. (2001) there have been few direct measurements of soil structure on RB. Thus the quantification of soil structure is needed on RB. This will allow the pore size distribution and the nature of the porous network to be determined. In addition the measurements described above will enable temporal and spatial variation of soil physical properties to be assessed.
CHAPTER THREE

3 The study area and experimental sites

3.1 Background of the study area

3.1.1 Location

The study area for this thesis was the volcanic plains of the Western District of Victoria. The plains lie in a narrow belt west of Melbourne almost to the South Australian border. They are elevated between 180 to 220 m above sea level and bounded by the Otway Ranges in the south and the Grampians to the north. Soil samples were collected and experiments were undertaken from two experimental sites for the study. Mt Pollock was the main experimental site, located approximately 30 km west of Geelong (38° 10’ S, 144° 05’ E). It lies between Inverleigh and Winchelsea and was a small area of commercial cropping and pastoral property. The second (minor) experimental site Briandra was also on a farm further west of Mt Pollock and 20 km north of Lismore (38° 50’ S, 143° 20’ E) (Figure 3.1.).

The following background information describes the climate, geology, geomorphology, soils and historical land use of the area. The study area includes land that is currently used or is targeted for raised bed (RB) cropping. This contextual information outlines the physical environment in which the experimental work took place. An assessment of the regional climate follows.
3.1.2 Climate

Prevailing winds blow across south-western Victoria from the south-west in a north-easterly direction. The region is not protected and sometimes experiences high winds, especially in winter. Temperatures during the summer are warm to hot, mostly averaging over 25 °C. Winters are cool with daily maximum average temperatures often less than 15 °C. The region regularly receives frosts from as early as April through until October. Frosts are most common further inland, particularly in low lying sheltered spots. During the winter low temperatures and reduced net radiation result in considerably less potential evapotranspiration (ETp) than in summer. Daily ETp in winter are often only between one to two mm, whereas in summer the average is 10 mm. This increases the supply of soil moisture during the winter as less is lost from transpiring plants and to evaporation. As evaporatranspiration increases during the summer there is often a soil moisture deficit. Annual average rainfall in the region ranges from 500 to 800 mm and decreases in a gradient from west to east. For instance, Hamilton’s annual average rainfall is around 690 mm, compared to Lismore which is 630 mm and Geelong 525 mm (Bureau of
Meteorology 2005b). In Geelong the rainfall is distributed relatively evenly throughout the year, whereas further west in Hamilton there is greater rainfall during the winter and early spring compared to the summer (Figure 3.2). South-western Victoria lies within the high rainfall zone of southern Australia. The high rainfall zone is an area which receives greater than 500 mm per annum (Singh et al. 2003) and is high compared to areas further inland.

Figure 3.2 Long-term monthly rainfall for Hamilton, Lismore and Geelong. Source: Bureau of Meteorology (2005b)

### 3.1.3 Geology and geomorphology

South-western Victoria is home to some of the youngest volcanoes on the Australian continent. The most recent eruptions occurred during the last 15,000 years – the Quaternary period (Young and Young 2002). Thus, the geology of south-western Victoria is unique and the volcanic activity had a major recent effect on the regional geomorphology. The area is divided into two geomorphic units – undulating plains and stony undulating plains in western Victoria (Figure 3.3.). These plains have been described as one of the largest basaltic plains in the world (Conley and Dennis 1984). Most of the landscape is composed of older and recent phases of the Newer Volcanics province. The volcanoes were active from the late Tertiary (<20 million years) to recent
times (estimated at 7,000 years ago at Mount Napier). During these periods the volcanoes extruded lava flows of basalt across the landscape and now remain scattered over the landscape as small hills (Cochrane et al. 1991). Eruption points are notable landscape features e.g. scoria cones such as Mount Elephant and maars such as Lake Purrumbete (Robinson et al. 2003). Interestingly, the summit of Mt Pollock is very close to the main experimental site (hence the same name). It is a moderately inclined low cone and is one of the most easterly eruption points on the Western volcanic plains.

Figure 3.3 Map of geomorphic units across Victoria. Source: DPI (2005)

The youngest flows contain rocky outcrops with the original relief preserved, whereas the older flows have weathered to flat and undulating plains. Lava from the volcanic eruptions often flowed to the lowest point in the landscape and blocked the drainage system (Dahlhaus et al. 2003). As a result the landscape has poorly developed lines of drainage. The drainage is shallow and not continuous, so that low lying areas often
contain swamps or ephemeral lakes. Low relief across most of the landform has corresponded with minor erosion. Joyce (1988) claimed that erosion is restricted to water erosion of scoria cones and wind erosion of ploughed paddocks.

Jenny’s (1941) notion of soil as a function of physical and environmental variables (climate, organisms, relief and parent material) helps to explain the soil types that are found on the volcanic plains of the south-western Victoria. The majority of soils on the plains are derived from weathered volcanic basalt (parent material), which has influenced the grain size and mineralogy of the soil. Despite the common parent material, the soils vary considerably according to the thickness, and age of the lava flows and the extent of influence from sedimentary or aeolian deposition. Soils that have developed on lava flows are dark (black or grey) clay soils that often crack deeply and contain CaCO₃ in the subsoil. On younger flows the soil is thinner, while soil formed on volcanic ash is lighter in colour and more friable (Joyce 1988). Duplex soils are commonly found on the plains in the landscape. Several theories have been put forward to explain the formation of duplex soils such as the weathering, illuviation of clay and bioturbation. But, Chittleborough (1992) concluded that the theories for determining the genesis of duplex soils are complex and the evidence for causes and effects are often incomplete. Other unique soils that have formed are lunette soils and stony rise soils. Soils found on lunettes vary, but generally they are sandy and unconsolidated. These soils are often bleached and held together by organic matter at the surface (Robinson et al. 2003). On stony rises, shallow, black gradational soils with a loam texture have developed (Leeper et al. 1936). Between the stony rises deeper soils have formed such as black cracking clays.

### 3.1.4 Soils

Maher and Martin (1987) probably undertook the most comprehensive soil survey of south-western Victoria. They mapped soil and landforms across the region (a 1:100 000 scale) using a system based upon Northcote’s Factual Key (Northcote 1979), and physical observations e.g. the presence /absence of waterlogging. This technique was undertaken to develop soil-landform map units that could be easily used and interpreted for land use
management or planning. Maher and Martin (1987) claimed that the survey was done because changes in land use were anticipated, namely the expansion of cropping. Probably the most useful piece of information from the survey is a map that shows the distribution of the most dominant soil units. This showed that large areas (>42 per cent) are made up of mottled-yellow duplex soils. Probably because of such a large area of one soil type spatial patterns in the soils of south-western Victoria have been found. For instance Dahlhaus et al. (2003) reported a climatic gradient influencing changes in some soil properties, e.g. an increase in sodicity and carbonate content was found across south-western Victoria in an easterly direction.

Duplex soils (now referred to as texture contrast (Isbell 2002)) are defined as soil profiles with a texture contrast of one and a half texture groups or greater between the A and B horizons. In south-western Victoria many texture contrast soils are classified in the Sodosol order of the Australian Soil Classification (ASC) (Isbell 2002). Interspersed across the region are smaller soil-landform units, such as red and black loam soils (Chromosol according to the ASC) found on stony rises. Due to the changes in the soil profile of texture contrast soils deep root growth has been found to be restricted (Tennant et al. 1992). Despite difficulties of texture contrast soils, Anderson et al. (1992) found they were not inherently less productive than other soils, but suggested these soils may require different management practices for successful crop production.

**Typical soil characteristics**

A typical soil profile found extensively across the Western volcanic plains is described as follows. The organic surface A horizon (0 to 10-15 cm) overlies a weakly pedal to massive subsurface (A2) horizon (to 20-60 cm) with some ferruginous gravel, which abruptly overlies a dark coarse structured hard-setting mottled heavy clay (B2 horizon). This may overlie a calcareous clay horizon (at 90 cm or more), which is above the parent material (B3 horizon). Characteristic features of this soil type are: texture contrast, coarse structure (columnar), very hard when dry, strong sodicity in the subsoil, free carbonate (calcareous) at depth and deep profiles (Robinson et al. 2003). Notable variations
include: the presence and amount of ferro-magniferous gravel (buckshot), the depth and horizontal characteristics of the A1 and A2 horizons, the extent of bleaching/mottling within the profile and the sharpness of the texture contrast between horizons. Mottling is often present, particularly in the heavy clay subsoils and is usually caused by water percolating to depth and remaining there. Thus, the development of oxidizing and reducing conditions results in a visible contrast in soil colour. Brouwer and Fitzpatrick (2002b) recently detected a strong correlation between the duration of saturation and soil colour along a soil catena on the Dundas Tableland in south-western Victoria. The colour of mottles, cutans and the soil matrix were recorded according to the hue, value and chroma (Munsell Soil Color Charts 1994) and compared with piezometric observations. The presence of mottling does not imply current oxidized or reduced conditions, as sometimes such conditions only developed in the past (Isbell 2002).

Clay mineralogy

Briner and Jackson (1970) found that black clay soils in southern Victoria contained montmorillonite (up to 39 per cent), vermiculite (up to 16 per cent) and amorphous material identified as allophane. Norrish and Pickering (1983) stated that basalt-derived soil in the Melbourne area contained clay dominated with smectite. Martin (unpublished data) also found that smectite was the most dominant mineral at several locations across south-western Victoria. Illite and kaolinite were present only in minor amounts (5 to 20 per cent) and quartz was detected in trace amounts (<5 per cent). Martin’s survey was of most interest as some samples were taken close to the experimental sites in this study. Despite these studies there remains a limited understanding on the distribution of clay minerals in the soils of south-western Victoria.

Hydraulic properties

A better understanding has developed on the permeability of these soils. Texture contrast soils typically have restricted movement of soil water. For instance, Tennant et al. (1992) reported that the low hydraulic conductivity of the B horizon led to the development of a
perched watertable. Tennant et al. found large differences (often at least one order of magnitude) in the saturated hydraulic conductivity between the A and B horizons. Subsurface flow can be an important contributor to perched water tables and their longevity depends upon landscape position. Hammermeister et al. (1982) found that a perched watertable lasts longer in lower slope positions than upslope regions of a hillside. Nevertheless Ward et al. (1998) measured deep drainage from texture contrast soils, which occurred during periods of waterlogging. Consequently the pathways of water movement through and within these soils are complex. Eastham et al. (2000) found there was more vertical than lateral water movement in texture contrast soils, because the lateral movement was strongly dependent upon the local topography.

3.1.5 Agricultural land use

Historical background

Before European settlement the Western volcanic plains were a sparsely populated, open grassland with some small areas of woodland (Conley and Dennis 1984). In 1836 Major Sir Thomas Mitchell was one of the first explorers to visit the area. He was most impressed with the pastoral potential of the area and he called it “Australia Felix”. Thus, from the middle of the nineteenth century pioneering settlers moved into the Western District. As the area was previously native grassland, it did not take long for a pastoral industry to establish and become a dominant part of the local economy. However, difficulties with the soil and climatic conditions were soon experienced. An early account from 1857 records that “farmers could do little upon the plains and that the soil was not good for agriculture” (Bonwick 1858). The poor natural drainage restricted agricultural development. Consequently for many years cropping has been limited and was only undertaken opportunistically.

Waterlogging

Victoria has large areas that are prone to waterlogging. A survey by Myers (1963) estimated that 50-60 per cent of southern Victoria was affected by waterlogging. The
Maher and Martin (1987) survey of south-western Victoria described the dominant soils as poorly drained or showing signs of intermittent waterlogging. More recently, a land assessment of the Corangamite region found high to very high susceptibility of these soils to waterlogging (Robinson et al. 2003). However, the waterlogging is transient in nature and only occurs seasonally. It is most common during the winter and early spring when rainfall (which exceeds evapotranspiration) supplies considerable water to the land. Typically a saturated region forms on the top of the B horizon, which is often clay with low permeability. The duration of waterlogging depends upon the depth of the topsoil (A horizon) (Gardner et al. 1983). Another concern is the evidence that salinity can be spread by waterlogging in south-western Victoria (Dahlhaus et al. 2000).

Changes in regional land use

Currently most of the Western volcanic plains are managed as improved pastures or arable land (State of Victoria 1982). Consequently, native vegetation in the area has almost become extinct and only remnant patches still exist. This has been due to the introduced grasses strongly competing with the native species such as kangaroo grass and spear grass (Conley and Dennis 1984). As the region had commenced strongly with pastoral farming, particularly wool production, so it continued. Therefore land use in south western Victoria probably did not change much during the 100 years prior to 1970.

By 1983, only seven per cent of land was engaged in cropping compared to over 80 per cent under pasture (Gardner et al. 1983). Pastoral land use is still important and Beattie and Hamilton (2001) reported that wool sheep receipts on average accounted for 42 per cent of gross farm income, while hay and grain only provided 17 per cent. The cropping area in south-western Victoria has fluctuated considerably over the past 30 years. The variation has been caused by economic (production quotas and commodity prices) and climatic (annual rainfall) factors. Low prices for animal products led to more cropping, whilst in wet years the area of cropping decreased (Gardner et al. 1983). For instance during the 1970’s Gardner et al. (1983) reported an increase from 110,000 ha to 260,000 ha due to the favourability of conditions. The previous two decades before 1999 the
productivity growth in the grain sector in south-western Victoria was low (Knopke et al. 2000). This is shown in the wheat production and area grown in south-western Victoria during the 1980’s and 1990’s (Figure 3.4). There were drier years in 1984, 1985, 1986 and 2003 so presumably waterlogging was as widespread and there was greater wheat production. In 2003 south-western Victoria produced 16 per cent of the total Victorian wheat crop. This was the most for the previous 20 years and substantially more than the previous surveyed year in 1997. The other years (with lower wheat production) were of average or above average rainfall when waterlogging may have been a problem.

![Figure 3.4 Wheat production (tonnes) and area (hectares) for the combined regions of the Barwon and South Western/ Western District, Victoria and their percentage contribution to Victorian wheat production.](image-url)

**Figure 3.4** Wheat production (tonnes) and area (hectares) for the combined regions of the Barwon and South Western/ Western District, Victoria and their percentage contribution to Victorian wheat production.


Since 1997 few ABS survey data on crop area or production are available, but local observers have noticed changes. Wightman (Pers. com) has seen a significant increase in the area of cereals and other crops such as canola. Wightman believes partly due to the adoption of RB cropping and estimates that at least 40, 000 hectares of RB have been installed within the last ten years (prior to 2005). The most recent data available (ABS 2003) agrees with Wightman’s observations and indicates recent changes to land use in southwest Victoria, in particular with increased crop production. Other contributing factors include the new improved cultivars (Riffkin et al. 2003). Furthermore since 1995
Southern Farming Systems Ltd. (a farming research and development organisation) has increased regional confidence in crop production by conducting trials and field demonstrations. There have been other changes in agricultural land use and more land has been dedicated to forestry, in particular blue gum plantations (Dahlhaus et al. 2003).

**Crop production in south-western Victoria**

South-western Victoria produces <0.6 per cent of the Australian grain crop (Knopke et al. 2000). During most of the 1980’s and 1990’s the region accounted for less than five per cent of wheat production in Victoria (Figure 3.4). By comparison, the Wimmera region regularly produced up to 10 times the amount of grain from the Barwon and Western District regions as shown in Australian Bureau of Statistics (ABS) surveys over several years (ABS 1984; ABS 1985; ABS 1986; ABS 1987; ABS 1988; ABS 1989; ABS 1992; ABS 1994).

Crop yields in south-western Victoria have been consistently limited by waterlogging (Gardner et al. 1983; McDonald and Gardner 1987; Stephens and Lyons 1998). Stephens and Lyons (1998) emphasized a rainfall: month effect in high rainfall regions where yield was negatively correlated with periods of waterlogging. French and Schultz (1984a) investigated the relationship between grain yield and growing season rainfall (i.e. from April to October) and found several factors were responsible for crops failing to reach their full yield potential. Yields were reduced when crops were sown late, affected by weeds or waterlogged. Thus, the yield: rainfall relationship (Figure 3.5) of French and Schultz (1984b) can be applied to crop production in south-western Victoria, although the relationship was developed from data under conditions in South Australia. The sloping line indicates the calculated potential yield. Data within the square box (on lower right side of Figure 3.5) represent sites where yield was affected by waterlogging. Here the rainfall was high (>400 mm) but the yield was low. Above this the oval selection represents the gap in potential yield with data closest to the sloping line the least affected by waterlogging. This yield gap identifies an opportunity to improve crop production, if
constraints to waterlogging can be overcome. Therefore drainage is recommended on soils in this environment (Gardner et al. 1992; MacEwan et al. 1992).

![Figure 3.5 The relationship between grain yield and rainfall (from April to October). Source: French and Schultz (1984b)](image)

### 3.1.6 Conclusion

The dominant characteristic of the climate in south-western Victoria is its comparatively high annual rainfall and low ET\(_p\) during winter. There is a strong association between parent material and soil type that has developed on it. A gently, undulating landform with sodic texture contrast soils are common across the region. The climate, topography and soils have combined to create a landscape that is highly susceptible to waterlogging. Waterlogging has been a major limiting factor of crops and has restricted their full yield potential. As a result pastoral farming became the dominant form of agricultural land use. However, recently there has been a significant increase in cropping, which seems to be
partly due to the use of RB. Indeed it is thought that the gap in yield potential identified by French and Schultz (1984b) could be reduced by cropping with RB.

3.2 Laboratory methods for characterisation

The methods outlined below are either general in nature or were only used to characterise the soil of the experimental sites.

3.2.1 Soil pH and electrical conductivity

Soil pH and electrical conductivity (EC) were measured according to standard methods (Rayment and Higginson 1992). Before any measurements were taken the pH meter was calibrated at pH 4.0 and 7.0 with a buffer solution. EC was calibrated according to temperature. Measurement was done on a soil/water ratio of 1:5 at 25°C. Duplicate samples of 20 g air dried soil were shaken end-over-end for 1 hour with 25 mL of deionised water. The sample was allowed to settle for 30 minutes. An electrode was placed into the suspension to measure the pH and EC. In addition, pH was measured in the same way using a solution of 0.01 M CaCl₂.

3.2.2 Cation exchange capacity

The cation exchange capacity (CEC) of the soil was calculated from the sum of major exchangeable cations (Ca²⁺, Mg²⁺, K⁺, Na⁺) and as well the exchangeable sodium percentage (ESP) was calculated. The method used atomic absorption spectrometry (AAS) to measure the cation concentrations (Rayment and Higginson 1992). Soil samples collected for analysis were air dried and sieved (<2 mm). Sub-samples of 5 g soil were mechanically shaken with 100 mL 1M NH₄Cl for 1 hour, filtered and extracts were added to diluting solutions. Samples that were >0.3 dS/m were extracted with deionised water. The filtered extracts were diluted with a Sr solution (1667 ppm) to determine the Ca²⁺ and Mg²⁺ cations, whilst for K⁺ and Na⁺ cations a Cs solution (1250ppm) was used. The diluted solutions were measured using the standard flame absorption technique with a
Varian Spectra AA 200 (Varian Australia Pty Ltd Mulgrave, Australia). The concentration of each exchangeable cation was calculated from established calibration curves. A set of reagent blanks was measured to check that the AAS was operating correctly.

3.2.3 Particle size analysis

The particle size analysis of the soil was done according to the hydrometer method (Gee and Bauder 1986). A soil water suspension was made up containing 50 g of air-dried soil and 100 mL of distilled water. \( \text{H}_2\text{O}_2 \) was added to oxidise organic matter and dispersion was promoted with sodium hexametaphosphate. The samples were heated to encourage the oxidation and dispersion reactions. Extra water was added to increase the sample volume to 400 mL and an electric blender was used to mix the suspension thoroughly. The suspension was then poured through a 212 \( \mu \text{m} \) sieve (to retain the coarse sand fraction) into a measuring cylinder. After mixing the suspension a hydrometer was placed into the suspension and readings were taken. In addition, a blank solution containing only distilled water was measured. The hydrometer recorded the density of the soil water suspension which changed as it settled. This method is based upon Stokes’ Law and uses a sedimentation technique to determine the proportion of different particle sizes within the soil. This analysis of sedimentation is based upon established relationship between settling velocity and particle diameter (Gee and Bauder 1986). The particle size classification system used was according to the International Union of Soil Sciences (IUSS) system (White 2006); where clay is \(<2 \mu \text{m}\), silt is 2-20 \( \mu \text{m} \), fine sand is 20-200 \( \mu \text{m} \), coarse sand is 200-2000 \( \mu \text{m} \) and gravel is >2000 \( \mu \text{m} \).

3.2.4 Total C

The soil samples taken for previous analyses were sieved (<2 mm), oven-dried (70\(^\circ\) C) for 48 hours and finely ground into a powder using a rock grinder. Between 30 and 40 mg of soil was weighed into a tin capsule. The tin capsules were folded over, placed into sample trays and passed into the combustion tube for analysis. Two standards of a known
total C per cent were included and also measured. Total C was then measured by the dry combustion method (Dumas type combustion) (Nelson and Sommers 1996) using a Carlo Erba, NA1500 Series II, CNS elemental analyzer.

### 3.2.5 Bulk density

Soil bulk density was measured using undisturbed soil cores. The coring device (internal diameter 73 mm, height 63 mm) was pushed into the soil by hand and dried at 105 °C or constant weight was reached. Drying drove off any moisture from within the soil when it was sampled and allowed the dry bulk density to be calculated using the following equation:

\[
\rho = \frac{M}{V}\]  

[3.1]

where \(M\) is the mass of dry, solid soil (Mg) per unit volume \(V\) (m\(^3\)). When sampling at depth a hammer-driven core sampler was used. Usually the cores were pre-lubricated so that could easily be removed afterwards. Extra care was required when sampling friable topsoils. The samples were wrapped in plastic and transported gently to maintain the soil integrity.

### 3.2.6 Electromagnetic mapping

In May 2003 the Mt Pollock site was surveyed using a non-intrusive electromagnetic (EM) induction technique (Kachanoski et al. 2002). Firstly the area was surveyed by Farmworks Ltd. (Meredith, Victoria) using a MagnaScan EM38 dual dipole ground conductivity meter. At selected locations across the experimental area soil samples were taken at three depths (0-10, 10-30 and 50-70 cm). Software modelling of the measured data was undertaken to establish relationships between the EM readings and the soil properties. Values of different soil properties were derived to produce maps of predicted soil properties for the Mt Pollock site.
3.2.7 Clay mineralogy

Soil samples from the A and B horizons at Mt Pollock and Briandra were taken at both sites for analysis of clay mineralogy. A sub-sample was collected of the <2 µm material using the sedimentation method based upon Stokes law that was used to measure particle size analysis (Gee and Bauder 1986). The separated material was then ground in a swing mill agate to a fine powder. The powder was mounted for analysis as a random oriented sample. The samples were analysed by x-ray diffraction using a powder x-ray diffractometer (Siemens D5000) at the Department of Earth Sciences, La Trobe University.

3.3 Experimental site descriptions

3.3.1 Experimental site design of Mt Pollock

Most work in this thesis has focused upon two treatments at Mt Pollock, namely RB and CC. CC was colloquially known as the ‘flat treatment’ because it contrasted with the furrows every two metres in the RB. The Mt Pollock site was a randomized block design containing 0.2 hectare plots (20 m width, 100 m length) with three tillage treatments, which are replicated three times (Figure 3.6). A third tillage treatment (deep cultivation) was imposed in plots 3, 5 and 9, but was not measured in this study. An additional third treatment – pasture, was investigated in chapter four. The pasture treatment was located in a separate paddock on a same soil order (Sodosol) about 1.5 km west of the main experimental site and was not divided into individual plots. Measurements and soil samples taken in experimental chapters 4, 5, 6, 7, 8 and 9 will refer to the CC (plots 1, 6 and 8) and the RB treatments (plots 2, 4 and 7).
The top of the plots were approximately aligned in a northerly direction and the area was
gently sloping with a slope <2 per cent. Surrounding the plots on all sides were RB that
were commercially managed (by the local farmer) with the same crop as within the plots.
The crops in each plot were sown and managed in the same way which was similar to
local conventional commercial practices (i.e. with regard to the application of fertiliser
and pesticides). Details on the instrumentation that was located and the sampling from
each plot are given later with each experimental chapter.

**Experimental site history and cultivation**

Prior to April 1999 the experimental site at Mt Pollock was permanent pasture and part of
a commercial mixed farming operation. In April 1999 the experimental plots designated
for RB were deep-cultivated (to 25 cm depth) and beds 1.7 m in width were formed using
a commercial bed former. One year later the RB plots were re-cultivated and the bed
width was widened to 2 m. This was undertaken to ensure the RB were the same width as
elsewhere on the farm. In March 2002 the conventional cultivation (CC) plots were
cultivated to a shallow depth (to 4 cm depth) and the RB were deep-cultivated again. On
the RB plots traffic was controlled as machinery only travelled along the furrows,
whereas traffic was not controlled on the CC. Throughout the study it was assumed that
the depth in each treatment was calculated relative to the soil surface in each plot.
Therefore, it is possible that due to small differences in micro-relief the depths were not
exactly equivalent across the whole experiment. Indeed the formation of the RB may well have slightly increased the height of the soil surface relative to the CC; although any differences in the soil surface between the RB and CC would be minor. During the first three years of the experimental site the RB plots were deep-cultivated three times while the CC was cultivated less often and only to a shallow depth. Subsequently and during the period of this experiment a minimum tillage policy was adopted for both treatments. There was no cultivation for the seedbed preparation and the only mechanical disturbance was at sowing. Finally, all cropping inputs (e.g. fertiliser and sprays) were applied at the same rate and time for the RB and CC treatments.

3.3.2 Soil characterisation at Mt Pollock

The experimental area lies on the western side of Mt Pollock. This area was probably an alluvial fan below the eruption point (MacEwan and Imhof 2000). The soil and landscape form is similar to the surrounding district that is cropped or targeted for RB cropping in the future. However at this site, rocky outcrops and most large stones were removed to facilitate cultivation. The soil at Mt Pollock was surveyed in 2000 as part of the Southern Farming Systems (SFS) soil reference site descriptions (MacEwan and Imhof 2000). It was described according to McDonald et al. (1990) and classified using the Australian Soil Classification (Isbell 2002). Soil profile morphological descriptions are given for three profile pits at Mt Pollock (Table 3.1). The profile at SFS 3 was closest to the experimental plots and was classified as a vertic, subnatric, Grey Sodosol (Figure 3.7). The profile at SFS 13 was classified as a sodic, Black Vertosol, while SFS 14 was within a nearby pasture plot and classified as a Brown Sodosol.
Table 3.1 Soil profile morphology description at Mt Pollock

<table>
<thead>
<tr>
<th>Site</th>
<th>Depth (cm)</th>
<th>Horizon</th>
<th>Texture*</th>
<th>Munsell Colour</th>
<th>Structure/ pedality</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFS 3</td>
<td>0-15</td>
<td>Ap</td>
<td>SCL</td>
<td>10YR 4/2</td>
<td>Weakly pedal</td>
<td>20-30 % gravel</td>
</tr>
<tr>
<td></td>
<td>16-75</td>
<td>B21cg</td>
<td>gC</td>
<td>10YR 4/2</td>
<td>Fine polyhedral</td>
<td>50 % gravel</td>
</tr>
<tr>
<td></td>
<td>76-100</td>
<td>B22</td>
<td>SC</td>
<td>10YR 6/6</td>
<td></td>
<td>Quartz, little gravel</td>
</tr>
<tr>
<td></td>
<td>&gt;100</td>
<td>B23ss</td>
<td>gC</td>
<td>2.5YR 5/2</td>
<td>slickensides</td>
<td>50 % gravel</td>
</tr>
<tr>
<td>SFS 13</td>
<td>0-15</td>
<td>Ap</td>
<td>MC</td>
<td>10YR 5/1</td>
<td>Coarse peds</td>
<td>30 % mottles</td>
</tr>
<tr>
<td></td>
<td>20-40</td>
<td>B21g</td>
<td>MHC</td>
<td>10YR 3/1</td>
<td>Prismatic, blocky</td>
<td></td>
</tr>
<tr>
<td></td>
<td>60-80</td>
<td>B22</td>
<td>MHC</td>
<td>10YR 3/1</td>
<td>Slickensides, lenticular peds</td>
<td></td>
</tr>
<tr>
<td>SFS 14</td>
<td>0-15</td>
<td>A1</td>
<td>SCL</td>
<td>10YR 4/2</td>
<td>Weakly pedal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>16-55</td>
<td>B21</td>
<td>gMC</td>
<td>10YR 5/2</td>
<td>Prismatic, polyhedral</td>
<td>20 % gravel, mottles</td>
</tr>
<tr>
<td></td>
<td>&gt;55</td>
<td>B22k</td>
<td>MC</td>
<td>10YR 5/3</td>
<td>Soft calcareous segregations</td>
<td></td>
</tr>
</tbody>
</table>

* SCL = sandy clay loam, L = loam, C = clay, HC = heavy clay, MHC = medium heavy clay, MC = medium clay, LC = light clay, gC = gravelly clay, SC = sandy clay. Source: MacEwan and Imhof (2000)

Aggregate stability was determined using the standard Emerson Dispersion Test (Emerson 1967) on dry and re-moulded aggregates. The air-dry aggregates from the Ap horizon (i.e. the upper ploughed layer) did not disperse although slight dispersion was detected at 20 to 40 cm at the SFS 13 site but not at SFS 3. However, strong dispersion was detected at >80 cm. Overall the subsoil samples were more dispersive than the dry aggregates from the A horizon. However, the re-moulded aggregates from the SFS 13 site
were slightly dispersive in the Ap horizon. Therefore under cultivation the soil may possess stability problems. Selected soil properties including pH (1:5 water), EC (1:5 water), total exchangeable cations (Ca$^{2+}$, Mg$^{2+}$, K$^+$, Na$^+$), exchangeable sodium percentage (ESP) and the per cent clay of the particle size analysis are summarized in Table 3.2.

![Figure 3.7 Soil profile of Grey Sodosol at Mt Pollock. Source: MacEwan and Imhof (2000)](image)

The soil organic C was measured in the Ap horizon and was relatively low, at only 2.3 per cent. This is similar to the organic C measured in a nearby pasture topsoil - at 2.6 per cent. From 2000 to 2004 organic C was measured annually at Mt Pollock. Organic C was consistently low and was only between two and three per cent.
The soil at Mt Pollock contains large amounts of gravel (ferro-magniferous nodules) which is thought to be derived from the volcano. The gravel (known colloquially as buckshot) was found to be a spatially variable and distinctive characteristic of the site. Its presence caused concern when calibrating the neutron moisture meter (see section 4.2.3). Difficulties from gravel were also experienced by Johnston (Pers. com) with the use of Time Domain Reflectrometry to measure soil moisture. Furthermore the high soil bulk density and high clay content were also thought to cause problems. The depth of soil was probably not greater than 1.1 m over most of the experimental area. Indeed, it was only possible to install neutron access tubes to 1 m depth and sometimes even this depth was not possible. Below this depth was the parent material, although sometimes it may have been large basalt rocks called “floaters”.

<table>
<thead>
<tr>
<th>Site</th>
<th>Depth (cm)</th>
<th>pH (water)</th>
<th>EC (dS/m)</th>
<th>Total CEC (cmolc/kg)</th>
<th>ESP (%)</th>
<th>Clay (&lt;0.002 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFS 3</td>
<td>0-10</td>
<td>6.2</td>
<td>0.21</td>
<td>16.1</td>
<td>5.04</td>
<td>28.5</td>
</tr>
<tr>
<td></td>
<td>16-75</td>
<td>7.4</td>
<td>0.15</td>
<td>22.6</td>
<td>12.4</td>
<td>48.5</td>
</tr>
<tr>
<td></td>
<td>76-100</td>
<td>9.1</td>
<td>0.23</td>
<td>18.2</td>
<td>23.6</td>
<td>32.5</td>
</tr>
<tr>
<td></td>
<td>&gt;110</td>
<td>9</td>
<td>0.35</td>
<td>25.7</td>
<td>25.3</td>
<td>43</td>
</tr>
<tr>
<td>SFS 13</td>
<td>0-15</td>
<td>6.1</td>
<td>0.22</td>
<td>14.5</td>
<td>4.9</td>
<td>23.5</td>
</tr>
<tr>
<td></td>
<td>20-40</td>
<td>6.3</td>
<td>0.12</td>
<td>19.0</td>
<td>8.4</td>
<td>41.5</td>
</tr>
<tr>
<td></td>
<td>60-80</td>
<td>8.2</td>
<td>0.25</td>
<td>24.1</td>
<td>15.3</td>
<td>43.0</td>
</tr>
<tr>
<td>SFS 14</td>
<td>0-15</td>
<td>5.2</td>
<td>0.18</td>
<td>10.0</td>
<td>7.3</td>
<td>20.5</td>
</tr>
<tr>
<td></td>
<td>16-55</td>
<td>7.7</td>
<td>0.29</td>
<td>19.1</td>
<td>18.8</td>
<td>42.0</td>
</tr>
<tr>
<td></td>
<td>&gt;55</td>
<td>9.1</td>
<td>0.61</td>
<td>25.0</td>
<td>21.6</td>
<td>44.0</td>
</tr>
</tbody>
</table>

Source: MacEwan and Imhof (2000)

Electromagnetic mapping of Mt Pollock

As the Mt Pollock site was the main experimental site it was mapped using an EM technique to spatially characterise the soil texture. This was undertaken because a well
The output information from the EM survey was presented in maps of several soil variables, including EC, percentage sand, silt and clay, the depth to the A horizon and the percentage soil moisture. Soil texture maps were produced for three depth intervals 0-10, 10-30 and 50-70 cm. The strongest relationship between EM readings and soil properties was for the percentage clay at 0-10 cm ($R^2 = 0.70$) (Figure 3.8). This map provided useful information in spatially characterizing the experimental site. No relationship was found between treatment and soil texture, but there was a trend of increasing clay content across the site from east to west. The measured clay content ranged from a minimum of 19 per cent to a maximum of 34 per cent. At 50-70 cm depth (not shown) showed less variation and the majority of the experimental area was between 37 to 43 per cent clay.

Figure 3.8 Map of predicted clay percentage at 0-10 cm, Mt Pollock. Labels 1A, 1B, 2A etc. refer to the neutron access tubes in each plot.
Clay mineralogy at Mt Pollock

A detailed survey of Vertosol soils by Vervoort and Cattle (2003) found that clay containing the largest proportions of smectite tended to have the greatest hydraulic conductivity values. This provides evidence of a relationship between clay mineral type and an important soil physical property - hydraulic conductivity. Such a finding has implications for other work done with clay soils. Thus clay mineral type and composition could assist in explaining soil behaviour at Mt Pollock. The clay minerals measured at Mt Pollock are shown in Table 3.3.

Table 3.3 Percentage of clay minerals in the A and B horizon at Mt Pollock

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Quartz</th>
<th>Kaolinite</th>
<th>Illite</th>
<th>Halite (NaCl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>49</td>
<td>13</td>
<td>30</td>
<td>8.0</td>
</tr>
<tr>
<td>B</td>
<td>32</td>
<td>21</td>
<td>46</td>
<td>&lt;1.0</td>
</tr>
</tbody>
</table>

The large percentage of quartz was not expected nor the amount of halite. Indeed the survey by Martin (2004) detected only trace amounts (<5 per cent) of quartz. Whilst the presence of quartz often is indicative of aeolian deposition, the quartz could be residual from the parent material. Thus the origin of the quartz during the soil formation process is uncertain. Illite was in greater abundance and is likely to influence clay behaviour most strongly. Perhaps most significantly this analysis shows that smectite was not found, although the clay mineral detection of this method is only accurate to +/- five per cent.

3.3.3 Experimental site design of Briandra

Measurements were taken from two established treatments at the Briandra site - pasture (Burns 1) and two RB sites - Burns 2 and Burns 3. The treatments units were at the paddock scale and the farmer had only recently established the RB. Burns 2 was formed into RB in 1999 and Burns 3 was in 2001. Measurements were repeated three times at the same distance apart as at Mt Pollock. This increased the precision of the measurements and provided a degree of within-field replication. Likewise soil samples, such as the cores taken for the soil water retention characteristic were taken three times.
3.3.4 Soil characterisation at Briandra

The experimental site lies on a flat to very gently undulating plain. Two soil pits were dug and the soil was described according to the methods of McDonald et al. (1990) and classified using the Australian Soil Classification (Isbell 2002). The soil was classified as a sodic, Brown Vertosol. Soil profile morphological descriptions are given in Table 3.4.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Horizon</th>
<th>Texture*</th>
<th>Munsell Colour</th>
<th>Structure/pedality</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-18</td>
<td>A1</td>
<td>LC</td>
<td>10YR 4/2</td>
<td>Apedal, massive</td>
<td>Some gravel, faunal activity</td>
</tr>
<tr>
<td>19-25</td>
<td>A2</td>
<td>SCL</td>
<td></td>
<td>Prismatic, polyhedral</td>
<td>Variable presence</td>
</tr>
<tr>
<td>26-50</td>
<td>B21</td>
<td>MHC</td>
<td>10YR 4/1</td>
<td>Polyhedral</td>
<td>Quartz, little gravel</td>
</tr>
<tr>
<td>51-90</td>
<td>B22</td>
<td>HC</td>
<td>2.5Y 4/2</td>
<td>Slickensides, polyhedral</td>
<td></td>
</tr>
<tr>
<td>91-120</td>
<td>B23</td>
<td>HC</td>
<td>2.5Y 5/3</td>
<td>Slickensides, lenticular peds</td>
<td></td>
</tr>
<tr>
<td>&gt;120</td>
<td>C</td>
<td>-</td>
<td>-</td>
<td>Weathered basalt</td>
<td></td>
</tr>
</tbody>
</table>

* SCL = sandy clay loam, C = clay, HC = heavy clay, MHC = medium heavy clay, MC = medium clay, LC = light clay.

Additional selected soil properties including pH (1:5 water), EC (1:5 water), total exchangeable cations (Ca$^{2+}$, Mg$^{2+}$, K$^+$, Na$^+$), exchangeable sodium percentage (ESP) and per cent clay are given for two soil profile pits (Burns 1 and Burns 3) in Table 3.5.
Table 3.5 Selected soil properties at Burns 1 and Burns 3, Briandra

<table>
<thead>
<tr>
<th>Site</th>
<th>Depth (cm)</th>
<th>pH (water)</th>
<th>EC (dS/m)</th>
<th>Total CEC (cmolc/kg)</th>
<th>ESP (%)</th>
<th>Clay (% &lt;2 µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burns 1</td>
<td>0-10</td>
<td>5.3</td>
<td>0.15</td>
<td>4.5</td>
<td>4.0</td>
<td>21.0</td>
</tr>
<tr>
<td></td>
<td>10-30</td>
<td>5.6</td>
<td>0.09</td>
<td>5.2</td>
<td>6.7</td>
<td>31.3</td>
</tr>
<tr>
<td></td>
<td>30-60</td>
<td>7.5</td>
<td>0.40</td>
<td>7.7</td>
<td>10.8</td>
<td>42.2</td>
</tr>
<tr>
<td></td>
<td>60-90</td>
<td>8.4</td>
<td>1.12</td>
<td>10.4</td>
<td>18.9</td>
<td>55.8</td>
</tr>
<tr>
<td>Burns 3</td>
<td>0-10</td>
<td>5.6</td>
<td>0.25</td>
<td>5.0</td>
<td>3.9</td>
<td>22.5</td>
</tr>
<tr>
<td></td>
<td>10-30</td>
<td>5.9</td>
<td>0.11</td>
<td>5.4</td>
<td>5.7</td>
<td>31.8</td>
</tr>
<tr>
<td></td>
<td>30-60</td>
<td>7.4</td>
<td>0.27</td>
<td>7.3</td>
<td>9.8</td>
<td>40.3</td>
</tr>
<tr>
<td></td>
<td>60-90</td>
<td>8.3</td>
<td>0.98</td>
<td>10.0</td>
<td>16.4</td>
<td>49.4</td>
</tr>
</tbody>
</table>

The soil surface was hard-sealed with some slight micro-relief or gilgai evident. At the sampling time, the A horizon was very dry, but soil moisture did increase with depth. When the profile was described (March, 2003) there was a lot of surface cracking, with some cracks greater than 2 cm in width and up to 30 cm in depth. Generally there was 60 to 80 cm between the cracks. This observation was strongly related to the time of year. No cracking was visible at the site with increased supply of soil water during the winter and early spring. A surface drain (up to 20 cm in depth) had recently been excavated near to the soil pits. It was several hundred metres in length and exposed some local soil heterogeneity. The A2 horizon varied in its presence as did the abundance of gravel. There were intermittent pockets of bleached A2 material (estimated <10 per cent of the exposed area) in the A1 horizons of more uniform depth. These observations in addition to the others made from the soil pits indicated that the area contained a complex of vertic Sodosol and a sodic Vertosol. In some places these two soils appeared to be evenly distributed, whilst elsewhere there was only 10 per cent Sodosol.
Clay mineralogy at Briandra

An interest developed in the clay minerals due to the extensive cracking of the soil that was seen during the summer at Briandra. The clay minerals measured at Briandra are given in Table 3.6.

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Quartz</th>
<th>Kaolinite</th>
<th>Illite</th>
<th>Halite (NaCl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>55.5</td>
<td>9.8</td>
<td>18.6</td>
<td>16.1</td>
</tr>
<tr>
<td>B</td>
<td>43.2</td>
<td>15.0</td>
<td>39.2</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Similarly to Mt Pollock a large percentage of quartz and halite was measured, although this was also unexpected. Indeed this was different to other studies (Briner and Jackson 1970; Martin 2004) in the area. In general the composition of clay minerals at Briandra was not significantly different from at Mt Pollock. The expected behaviour of soil with this suite of clay minerals would not be expected to be expansive. However the illite could have some potassium removed to form an interstratified mica-smectite and thereby exhibit swelling behaviour (Norrish and Pickering 1983). In addition the presence of sodium as one of the exchangeable cations could also explain further swelling on hydration.
CHAPTER FOUR

4 Soil water properties under raised beds, conventional cultivation and pasture

4.1 Introduction

RB have been growing in popularity as a method of cropping in south-western Victoria over the past decade, but there remains a dearth of knowledge exists on soil water properties under RB cropping. Several benefits have been attributed to RB. Peries et al. (2004) reported that RB provided better drainage, while Bluett and Wightman (1999) claimed that RB did not appear to become as waterlogged. However these benefits were poorly supported by evidence and currently there are only anecdotal reports (i.e. based upon unpublished or non-replicated work) on soil water behaviour of RB.

Understanding the soil water dynamics is important on soils of south-western Victoria, because waterlogging has been identified as a major constraint to crop production (McDonald and Gardner 1987). In fact Robinson et al. (2003) classified the area as prone to seasonal waterlogging, which mostly occurs during the winter months. For many years waterlogging restricted the development of cropping in south-western Victoria (Conley and Dennis 1984). Furthermore waterlogging still causes problems today.

Therefore further work is required on soil water under RB during periods close to saturation, as well as the soil water deficit during drier periods. The rate of change in soil water under RB needs to be quantified temporally, from small time steps to seasonally. The spatial distribution (within the soil profile) and variation (across a field) of soil water (in terms of both $\psi$ and $\theta_v$) have not yet been determined. This information is required to
establish whether soil water on RB is a constraint or if it reduces the development of waterlogged conditions.

4.1.1. Aim

The aim of this chapter was to test the hypothesis that RB exhibit improved soil water properties compared to non-RB land uses, namely CC and pasture. Improved soil water properties for cropping are those that minimise the development of waterlogged or excessively dry conditions. To achieve this several different field measurements were taken and objectives are set out in the following three areas.

First, the volumetric water content ($\theta_v$) was measured and the soil water deficit (SWD) was calculated. Thus information was gathered to answer the following questions (a) what are the differences between RB, CC and pasture with regard to soil water extraction from the whole profile? and (b) do RB provide benefits in terms of creating a larger SWD sink at the end of summer?

Second, to observe periods closest to saturation the $\theta_v$ was measured at hourly intervals in the soil surface (0-10 cm) of the RB and CC. Attention was focused on the rate of change in $\theta_v$ after selected large rainfall events. Therefore (a) how does the $\theta_v$ of RB respond to rainfall? and (b) do RB provide improved drainage?

Third, soil matric potential ($\psi_m$) was measured in the RB and CC at depths of 20, 40 and 60 cm. This provided an alternative measure of soil water. The zone near to saturation was of particular interest and also the wetting and drying patterns. Thus (a) do the $\psi_m$ readings corroborate the other observations of soil water? and (b) which treatment showed the most distinct wetting and drying fronts?
4.2 Materials and methods

The experimental work presented in this chapter used several different methods to monitor soil water in the field over three growing seasons – 2002, 2003 and 2004 at Mt Pollock and Briandra. Long-term (seasonal) and short-term (from hourly to weekly) soil water measurements of RB and non-RB treatments (CC and pasture) were taken during the growing season of grain crops.

4.2.1 Rainfall and Climate

Climate especially rainfall has a strong influence on the amount and changes in $\theta_v$. Thus, to compliment the soil water measurements climatic data was regularly recorded at each experimental site. An automatic weather station (AWS) was installed at the Mt Pollock (Handar with Vaisala sensors) and Briandra (Measurement Engineering Australia Pty Ltd.). Each AWS was equipped with several sensors to log climatic variables. Humidity, temperature, wind speed, solar radiation and rainfall were recorded hourly. Rainfall was measured with a tipping bucket rain gauge that logged every 0.2 mm of rainfall.

The long-term average rainfall for Mt Pollock was estimated using the SILO Data Drill data set (SILO 1998). The data were calculated for the latitude and longitude of Mt Pollock by employing a spatial interpolation technique (Jeffrey et al. 2001). Consequently the long-term average rainfall is synthetic but it was derived from actual point data at nearby Bureau of Meteorology (BOM) stations. The simulated rainfall values were similar to the nearest BOM station at the Winchelsea Post Office (10.5 km to the west). Rainfall records at Winchelsea began in 1889. The long-term average rainfall (1965 to 2004) for Briandra was calculated on data provided by the farmer (Wilson, Pers. com). At each site deciles were calculated for each month from long-term data. The designation of deciles separates the long-term rainfall data into ten groups of equal frequency. Deciles are a useful method to rank historical rainfall data and assist in evaluating whether the rainfall is above average, average or below average over a period of interest (Bureau of Meteorology 2005a), e.g. decile 1 is very dry while decile 9 is very wet.
Potential evapotranspiration ($ET_p$) was calculated using the Penman-Monteith equation (Allen et al. 1998). This was calculated relative to a reference surface which has been specified as a uniform cover of actively growing green grass with adequate water. The climatic variables measured were solar radiation, air temperature, humidity and wind speed. The Priestly-Taylor equation (Priestly and Taylor 1972) was considered, but not used as both sites were quite windy.

### 4.2.2 Soil profile water content

The $\theta_v$ over the whole profile was measured using two different pieces of equipment. A ThetaProbe was used for soil surface (0 to 0.1 m) measurements (further details in 4.2.4) and a neutron moisture meter (NMM) (Boart Longyear CPN 503 DR Hydroprobe Moisture Gauge) was used to measure $\theta_v$ below 0.1 m down to a depth of 0.9 m. The NMM was not used to measure $\theta_v$ at the soil surface (0-10 cm) because of the potential escape of neutrons to the atmosphere and the subsequent under-estimation of $\theta_v$ (Greacen et al. 1981). Two aluminium access tubes were installed at Mt Pollock in the RB and CC plots, and the pasture in August 2002. The tubes were located approximately mid-way across each plot, one 30 m from the northern edge and the other 30 m from the southern edge (Figure 4.1). As a further comparison, a non-cropping treatment was included by installing six access tubes in a nearby pasture field. At Briandra six access tubes were installed in two treatments in pasture (field name - Burns 1) and RB (Burns 3). At both sites bentonite was placed around the top of each tube to prevent water from flowing down the side. The tubes were regularly checked in case any cracks developed beside the tubes that would have caused an air gap. A rubber bung was put in the top of each access tube and covered with a tin can to prevent water filling the tubes from rainfall.

Each day before an NMM reading was taken, a neutron count rate was determined in a large drum of water. Greacen et al. (1981) recommended regularly taking a standard count in this way. A standard count was only accepted if it had a $\chi^2$ value between 0.75 and 1.25. This avoided measurement bias that could result from instrumental drift.
Duplicate neutron count readings were taken after a 16 second time interval. Measurements were taken at four depths: 20, 40, 60 and 80 cm. Due to the presence of saprolite or consolidated rock (C horizon), it was not possible to install the access tubes that allowed measurement below 80 cm. Indeed, in some places it was difficult to reach 80 cm and required several auger holes to be dug to achieve this depth e.g. access tubes were installed to 60 cm in plot 1 (CC treatment) at Mt Pollock.

Figure 4.1 Layout of installed soil water sensors and related equipment in plots at Mt Pollock.

NB. Distances are not to scale and equipment location is only approximate; spot readings with handheld ThetaProbe were taken in the shaded area (approx. 3 x 3 m)

**Soil water deficit**

The soil water deficit (SWD) was calculated as the difference between the mean profile field capacity (FC) and the mean profile water content at the time of measurement (White *et al.* 2003). The wettest observed times of the year were chosen to determine the mean
profile FC. A time-averaged mean was taken using dates which were selected over the duration of the experiment when the soil profile was near to or at its wettest point (Table 4.1). Both SWD and FC were determined from the water content in mm for the 0-90 cm depth of soil profile.

Table 4.1 Mean FC (± SE) and FC estimation dates for each treatment at Mt Pollock and Briandra

<table>
<thead>
<tr>
<th>Site</th>
<th>Treatment</th>
<th>FC (mm to 0.9 m depth)</th>
<th>FC Estimation Dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mt Pollock</td>
<td>RB</td>
<td>296 ± 1.6</td>
<td>28/7/2003, 12 and 19/08/2004, 13 and 17/09/2004</td>
</tr>
</tbody>
</table>

Surface $\theta_v$ readings were excluded when calculating the SWD at Briandra, but were included at Mt Pollock for 2003 and 2004 only. Thus, the SWD values at Briandra and in 2002 at Mt Pollock were from 10-90 cm. The profile water content in mm was calculated from the $\theta_v$ at each depth over a 20 cm interval. For instance the 20 cm depth was from 10-30 cm, at 40 cm from 30-50 cm, at 60 cm from 50-70 cm and at 80 cm from 70-90 cm. Where surface $\theta_v$ was measured the water content (in mm) was included from 0-10
cm. The SWD was plotted against time as negative values with respect to the FC. This follows the convention used by Heng et al. (2001) and White et al. (2003). From these data wet periods were defined as values when the SWD was close to the FC. This included SWD values between -10 mm and FC and small positive values above the estimated FC.

4.2.3 Neutron moisture meter calibration

To calibrate the NMM at Mt Pollock four aluminium access tubes were installed close to the experimental plots. The calibration method outlined by Greacen et al. (1981) was used. The measured neutron count ratio and corresponding $\theta_v$ were recorded to establish a site specific calibration. Further details are given in the Appendix. NMM calibration at Briandra was similarly performed on specified access tubes.

4.2.4 Soil surface water content

The $\theta_v$ at the surface (0-10 cm) was measured mostly with a ThetaProbe® (Delta-T Devices, Cambridge U.K.). Measurements were taken with permanently installed ThetaProbes and a hand-held ThetaProbe.

The permanently installed ThetaProbes were inserted into the soil surface of each plot (Figure 4.1) and connected to a data logger (DL), (Micropower, Tain Electronics Pty Ltd). The prongs of each sensor are six cm long, but the measurement depth of $\theta_v$ was considered to represent the 0-10 cm. The output signal from each ThetaProbe was a dielectric constant value which was converted to $\theta_v$ at an accuracy of $\pm 0.01$ m$^3$/m$^3$ (Delta-T Devices Ltd. 1999). The cable from the DL was limited to less than five metres to prevent the dielectric constant value from dropping. Thus the logged ThetaProbes were too far away from the neutron access tubes to be used to calculate the profile $\theta_v$. The sampling frequency selected was hourly and data was routinely extracted from the DL to a notebook computer.
In addition, to the above measurements, spot readings of surface $\theta_v$ were taken with a hand-held ThetaProbe connected to a moisture meter (HH2, Delta-T Devices). At Mt Pollock four readings were regularly taken close (<3 m) to each neutron access tube (Figure 4.1). Spot readings were sometimes taken at Briandra and as a result the data were incomplete over the whole experimental period. Readings on the soil surface were taken at the same time as subsoil $\theta_v$ was measured with the NMM. This ensured that $\theta_v$ was calculated for the whole profile at Mt Pollock. Sometimes such as when the soil was dry and hard it was not possible to take measurements by hand. In these situations soil samples were taken to measure the gravimetric water content ($\theta_g$) from which $\theta_v$ was calculated using equation 2.3.

4.2.5 Soil matric potential

Soil matric potential ($\psi_m$) was measured at Mt Pollock in the 2004 growing season using a loggable wireless monitoring system. Data were transmitted via a mobile phone link into a spreadsheet on a CSIRO computer server. An identical method of data transmission was described by Bond (2005). The moisture sensors selected were granular matrix resistance sensors (Watermark, Irrometer Co. USA), which operate in the same way as gypsum blocks. Each sensor used was 70 mm in length and 20 mm diameter with a two-banded wire cable attached. The sensors contained electrodes covered by quartz material and the outer layer was a protective steel mesh over a synthetic membrane (Charlesworth 2000). Watermark sensors are only suitable for an approximate estimation of soil matric potential ($\psi_m$). The effective operating range of these sensors was 0 to -200 kPa, but they are not very reliable between saturation and -10 kPa (Spaans and Baker 1992). Consequently they are not sufficiently accurate to calculate water fluxes through the soil (Scanlon et al. 2002). The sensors measure soil water potential ($\psi$) and as such account was not taken of gravitational potential ($\psi_g$). $\psi_g$ was greater with increasing depth and was removed to give $\psi_m$. At 20 cm depth $\psi_g$ was -2 kPa, at 40 cm it was -4 and at 60 cm it was -6 kPa. It was assumed that salts in the soil solution diffused into the sensor and that the difference in osmotic potential ($\psi_s$) between the sensor and the surrounding soil was zero. Any effects of overburden potential ($\psi_o$) were ignored. In any case, $\psi_s$ and $\psi_o$
would unlikely to be significantly different between the treatments. The effect of temperature on measured sensor resistance was noted (Spaans and Baker 1992), but the temperature values that were measured were not considered meaningful and calibration for temperature was not undertaken. At times this may have slightly reduced the accuracy in measuring $\psi_m$, although this was considered to be minor and would not have affected comparison of $\psi_m$ between the RB and CC.

**Sensor installation**

Duplicate sensors were installed at two depths (20 and 40 cm) in three replicate plots of each treatment (RB and CC). Sensors at 60 cm depth were only installed in two plots (Plot 7 and 8) of each treatment. The Watermark sensors were installed near (approx. 5 m) from the most northerly positioned neutron access tube in each plot and their location is given in Figure 4.1. Each sensor was soaked overnight in a bucket of tap water before installation. An auger hole (outside diameter 22.2 mm) was dug to install each sensor. The sensors were tightly fitted to ensure good contact with the surrounding soil matrix and then back-filled with a slurry mixture (using soil extracted from the hole). Above this bentonite filled the hole further, to prevent water from flowing down the hole.

**4.2.6 Statistical analysis**

All statistical analyses were performed using GenStat software (Lawes Agricultural Trust 2005). Initially summary statistics – including the mean, median, minimum, maximum, number of missing values, standard deviation (SD), standard error (SE) and coefficient of variation (CV) – were calculated, but not all of these statistics are presented. Analysis of variance (ANOVA) was used to calculate the least significant difference (LSD) between treatments for $\theta_v$ at each depth (20, 40, 60 and 80 cm) and the SWD. Statistical significant difference was determined at the five per cent level ($P <0.05$). At Briandra there were a high number of missing values so it was not possible to undertake any statistical significance tests. Missing values were due to some access tubes becoming flooded while others were driven over. At Mt Pollock the LSD was calculated for three
treatments (RB, CC and pasture) on most measurements. However, as the pasture treatment was not measured as frequently there were a number of missing values. At these times, the LSD was calculated between RB and CC only. In addition, a temporal analysis of the soil water data ($\theta_v$ at all depths and SWD) was undertaken. A repeated measures ANOVA (with treatment as the main factor and time as an interaction factor) was used to calculate the LSD between pairs (in time) of the response variable. Mead et al. (2003) expressed concern with the use of a split-plot ANOVA for temporal analysis, because “time cannot be randomised”. However, as only two times were used for each comparison, a repeated measures ANOVA remains valid and the effect of time on $\theta_v$ or SWD at each depth can be adequately assessed.

As $\theta_v$ in the soil surface (0-10 cm) was recorded hourly, a quantitative method of time-series analysis was undertaken on these data. Correspondingly, rainfall was recorded and then summed to derive cumulative rainfall as a comparative response variable. The method of time-series analysis followed the approach taken by Nash et al. (1991). Nash et al. (1991) studied the relationship between $\theta_v$ and rainfall along a transect in the arid rangeland of New Mexico, USA. For this study, time was analysed in lags, where one lag was equal to one hour. The autocorrelation coefficient ($r_k$) for the time series of each variable ($\theta_v$ of RB and CC, and cumulative rainfall) was calculated and viewed as a correlogram. Autocorrelation is the correlation between values in a time series lagged by particular time intervals. The significant autocorrelation coefficient ($r_k$) was calculated at the five per cent level ($P < 0.05$). The cross-correlation between one time series and another at various lags was calculated, e.g. between RB and CC with cumulative rainfall. Definitions for lag, autocorrelation, and cross-correlation were taken from the GenStat help menu (Lawes Agricultural Trust 2005).
4.3 Results

4.3.1 Rainfall and evapotranspiration

Mt Pollock

Over the duration of the study period annual rainfall was less than the calculated long-term average (556 mm). The annual rainfall in 2002 was 376 mm (decile 1), 440 mm (decile 2) in 2003 and 488 mm (decile 3) in 2004. In comparison, in 2001, the year prior to the start of the experiment, there was 576 mm (decile 5). Thus, each year of the study was characterised by lower than average rainfall during the autumn and fluctuating amounts (mostly below, but also above average) rainfall in the winter and spring months. Spring rainfall was the most reliable during 2003 and 2004. Rainfall and potential evapotranspiration ($ET_p$) for each month are given in Figure 4.2. Rainfall intensity (mm hr$^{-1}$) was also recorded (but is not shown here). $ET_p$ generally followed a seasonal trend that is typical of south-western Victoria with low daily winter $ET_p$ (1 to 2 mm) rising up to 10 mm in summer.

![Figure 4.2 Monthly rainfall (bars) and potential evapotranspiration ($ET_p$) (line with squares) from January 2002 to December 2004 at Mt Pollock. NB. Missing $ET_p$ data for March, April and May 2002.](image-url)
A crop’s growing season rainfall (GSR) is most important when considering plant growth or yield and is therefore more relevant to this study than the annual rainfall, which may not all contribute to crop production. In the Mallee region of northern Victoria the growing season for winter crops is from April until October (Wightman, Pers. com). Initially the same growth period was used, but Wightman observed that the growing season began and ended later in south-western Victoria. Consequently, Wightman has recommended that the period from May to November be adopted as the designated growing season for south-western Victoria. The same period was used as the growing season by Riffkin (2003). Monthly GSR and deciles during the study period are shown in Table 4.2.

<table>
<thead>
<tr>
<th>Month</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>Long-term average</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>33.6 (4)</td>
<td>12.8 (1)</td>
<td>19.4 (2)</td>
<td>50.4</td>
</tr>
<tr>
<td>June</td>
<td>40.0 (4)</td>
<td>27.6 (2)</td>
<td>59.4 (8)</td>
<td>50.4</td>
</tr>
<tr>
<td>July</td>
<td>52.4 (6)</td>
<td>66.8 (9)</td>
<td>50.4 (6)</td>
<td>50.2</td>
</tr>
<tr>
<td>August</td>
<td>32.4 (2)</td>
<td>63.8 (7)</td>
<td>46.6 (4)</td>
<td>57.2</td>
</tr>
<tr>
<td>September</td>
<td>39.6 (3)</td>
<td>33.4 (2)</td>
<td>49.0 (5)</td>
<td>56.9</td>
</tr>
<tr>
<td>October</td>
<td>28.2 (2)</td>
<td>98.2 (10)</td>
<td>31.2 (2)</td>
<td>56.8</td>
</tr>
<tr>
<td>November</td>
<td>36.8 (4)</td>
<td>12.4 (1)</td>
<td>67.2 (7)</td>
<td>47.3</td>
</tr>
<tr>
<td>Total</td>
<td>263.0 (3)</td>
<td>315.0 (4)</td>
<td>323.2 (4)</td>
<td>369.2</td>
</tr>
</tbody>
</table>

NB. Deciles are given in brackets.

**Briandra**

As Briandra is located further west than Mt Pollock it was expected to have a higher annual rainfall. This was the case and the long-term average at Briandra was 656 mm. The annual rainfall in 2002 was 600 mm (decile 3), 519 mm (decile 1) in 2003 and 643 mm (decile 4) in 2004. The ETₚ at Briandra was consistently higher than Mt Pollock,
especially during the summer months. Monthly rainfall and ET<sub>p</sub> for Briandra are given in Figure 4.3.

![Figure 4.3 Monthly rainfall (bars) and potential evapotranspiration (ET<sub>p</sub>) (line with squares) from September 2002 to December 2004 at Briandra. NB. Missing ET<sub>p</sub> data for March and April 2003.](image)

4.3.2 Soil water content by depth through the profile

The θ<sub>v</sub> for each depth interval (20, 40, 60 and 80 cm) measured from August 2002 until December 2004 are displayed in Figure 4.4. Dates when there was a significant difference between the treatments are given in Table 4.3.

Generally at all depths the changes in θ<sub>v</sub> followed a seasonal pattern that can be broadly divided into three periodic trends. Firstly, θ<sub>v</sub> increased through autumn and the beginning of winter, secondly it generally stayed uniform through winter and finally it decreased in late spring and early summer. The amplitude of variation decreased with depth and the least seasonal fluctuation (the range between the minimum and maximum) was seen at 80 cm. Details on the changes and where significant differences were detected at each depth follow.
\(\theta_v\) at 20 and 40 cm

The largest range between maximum and minimum was found at 20 cm, but it was at this depth that the least number of significant differences were detected. Each treatment increased and decreased to a similar extent. The only times when there was a significant difference at 20 cm was in November 2002 and May/June 2003. During this period the RB and particularly the pasture were much drier than the CC. Over the whole experiment the CC stood out consistently as the wettest at the 20 cm depth interval.

At 40 cm either the pasture or RB were significantly drier than the CC on a few occasions more than at 20 cm. In June 2004 growing season the CC were significantly wetter than the RB. This was one of only three periods when there was a significant difference solely between RB and CC (i.e. no pasture readings were taken at this time). For the majority of occasions when there was a significant difference, it was associated with the pasture being much drier or wetter than RB and CC values. At the end of 2004 (21 December), the RB were significantly drier than the CC and pasture which had similar values. In summary the smallest differences between the treatments (in \(\theta_v\)) occurred at 40 cm.
Table 4.3 Dates of a significant difference in $\theta_v$ between treatments by depth and year at Mt Pollock

<table>
<thead>
<tr>
<th>Year</th>
<th>Depth</th>
<th>20 cm</th>
<th>40 cm</th>
<th>60 cm</th>
<th>80 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>18 Nov</td>
<td>25 Oct</td>
<td>18 Nov</td>
<td>18 Nov</td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td>15 May</td>
<td>18 Sept</td>
<td>21 Nov</td>
<td>15 May</td>
<td>5, 26 June</td>
</tr>
<tr>
<td></td>
<td>5, 26 June</td>
<td>04 Oct</td>
<td>13, 24 Dec</td>
<td>04 Oct</td>
<td>18 Sept</td>
</tr>
<tr>
<td></td>
<td>24 Dec</td>
<td></td>
<td></td>
<td>04, 11, 21 Nov</td>
<td>4, 9 Nov</td>
</tr>
<tr>
<td>2004</td>
<td>5, 11 June</td>
<td>29 Jan</td>
<td>13 May</td>
<td>22 June</td>
<td>6, 30 July</td>
</tr>
<tr>
<td></td>
<td>21 Dec</td>
<td>13 May</td>
<td>19, 25 Aug</td>
<td>25 Aug</td>
<td>2, 10, 17, 24 Sept</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5, 11 June</td>
<td>6 July</td>
<td>10, 24 Sept</td>
<td>10, 26, 29 Oct</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 July</td>
<td>10, 18, 26 Oct</td>
<td>10, 18, 26 Oct</td>
<td>9 Nov</td>
</tr>
</tbody>
</table>

$\theta_v$ at 60 and 80 cm

In contrast to the 20 and 40 cm depth intervals, there were numerous times when a significant difference was found between the treatments at 60 and 80 cm, especially through the 2003 winter. At this point the $\theta_v$ of pasture had slowly wet up and by the spring was significantly wetter than the RB and CC treatments which were drying out. During the spring and summer of 2003 there were seven times when the pasture was significantly the wettest. This change in $\theta_v$ in the pasture continued from late 2003 through into 2004 when the pasture continued to be significantly wetter. The greater $\theta_v$ of the pasture was probably a function of shallower root development and less plant water use in comparison to the RB and CC. Over the whole period the RB remained always the driest treatment at 60 cm and often the driest (although sometimes CC was drier) at 80 cm.
Temporal differences in $\theta_v$

From the commencement of the growing season the period between measurements of $\theta_v$ was often a week to 10 days, but towards the end of the year the interval was up to three weeks. The significant difference between pairs of measured $\theta_v$ was determined and for most pairs of $\theta_v$ either a significant (P<0.05) or very highly significant (P<0.001) difference was found (dates from the split-plot ANOVA are not shown). These treatment differences were significant throughout the year at all depths. This finding was expected close to the soil surface, but was not expected at depth. This indicates there was frequent to constant change in $\theta_v$ with time.
Figure 4.4 Volumetric soil water content (m$^3$/m$^3$) for RB (◊), CC (●) and pasture (■) at 20 cm, 40 cm and 60 cm from August 2002 to December 2004. LSD bars are shown at the top of each chart.
4.3.3 Profile soil water deficit

Mt Pollock

The SWD for Mt Pollock was calculated from August 2002 until December 2004 (Figure 4.5). The dates when a significant difference between the treatments (CC, RB and pasture) and the number of wet periods was determined over the measurement period (Table 4.4). Prior to the first measurements in 2002 it was very wet and run-off occurred on three occasions. As a result, the SWD commenced just below the estimated FC. Thereafter there was a fall and rise in the SWD as is seasonal for the high rainfall zone in southern Australia. Typically the soil profile was filled to capacity during the late winter/early spring and emptied in the summer. A wide range of SWD values were observed, with up to nearly -150 mm in summer. In contrast during the winter and early spring there were some wet periods when slightly positive values (i.e. >FC) were measured. Over three years there were 14 wet periods observed for the CC compared to six for RB and
only five for pasture which indicates that CC was consistently the wettest of all the treatments.

Table 4.4 Number of wet periods for each treatment and the dates of significant difference in soil water deficit between treatments by year at Mt Pollock

<table>
<thead>
<tr>
<th></th>
<th>2002</th>
<th></th>
<th>2003</th>
<th></th>
<th>2004</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RB</td>
<td>CC</td>
<td>Past</td>
<td>RB</td>
<td>CC</td>
<td>Past</td>
</tr>
<tr>
<td>Wet periods</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>7</td>
<td>0</td>
</tr>
</tbody>
</table>

Dates of significant difference (P <0.05)

12-Oct 15-May, 5/26 June 5/11 June
28-Jul, 16/22/27 Aug 21-Dec
04/12/18 Sept, 04/10 Oct
15-Nov

NB. Wet periods are values between a soil water deficit of -10 and 10 mm

During the whole experiment the SWD of the RB was frequently greater (i.e. drier) than the CC treatment. For instance this was clearly seen during three periods from August 2002 to July 2003, from November 2003 to May 2004 and lastly from November 2004 until the end. During the same period SWD changes in the pasture were more erratic.
Briandra

The SWD for pasture and RB at Briandra is given in Figure 4.6. Both treatments followed a similar seasonal pattern of change in soil moisture as at Mt Pollock, which is typical for this region. The RB fluctuated (between wet and dry) much more than the pasture. In early summer 2002 the RB profile dried out to a greater extent than the pasture. Early in 2003 the RB wet up more rapidly than the pasture and on four occasions (during the winter /spring) the RB was close to FC. Later the pasture was unexpectedly drier than the RB and developed a greater SWD. This is quite different to Mt Pollock where the RB used more soil water and was the driest treatment. A less intensive sampling regime was undertaken than at Mt Pollock. This meant that the soil water dynamics were not followed as closely. Nevertheless the RB were often found to be wetter (i.e. less SWD) than the pasture at Briandra.
4.3.4 Logged surface soil water content

From the analysis of $\theta_v$ by depth (4.3.2) the most frequent changes and largest number of fluctuations were found closest to the soil surface. Using hourly logged data an intensive temporal analysis of surface $\theta_v$ (0-10 cm) was undertaken on RB and CC at Mt Pollock. Preliminary observation of the data identified that sharp increases in $\theta_v$ occurred after significant rainfall events (i.e. $>10$ mm). Each event was a delineated series of data (including surface $\theta_v$ and cumulative rainfall). The data included readings 12 hours before rainfall commenced and continued for 12 hours after it had stopped. Specifying the event length was undertaken to maintain a degree of standardisation (or uniformity) between events. This was necessary in order to make valid comparisons on the response to rainfall in each event. Setting the length of the rainfall events was arbitrary, but the selected length captured the majority of the changes in $\theta_v$ and as the greatest change in $\theta_v$ was during the first 24 hours.

Seven rainfall events during the growing seasons of 2003 and 2004 were selected for further investigation. Summary statistics - the amount of rainfall, rainfall intensity,
minimum and maximum $\theta_v$ and the percentage increase in $\theta_v$ - characterise each event (Table 4.5). The rainfall intensity reported was the average over the whole rainfall event.

Table 4.5 Summary details of rainfall and surface $\theta_v$ for seven selected rainfall events for RB and CC in 2003 and 2004 at Mt Pollock

<table>
<thead>
<tr>
<th>Event no.</th>
<th>Date</th>
<th>Total rainfall (mm)</th>
<th>Mean rainfall intensity (mm/hr)</th>
<th>Treatment</th>
<th>Min $\theta_v$ (m$^3$/m$^3$)</th>
<th>Max $\theta_v$ (m$^3$/m$^3$)</th>
<th>Percentage increase in $\theta_v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>01/10/03</td>
<td>30</td>
<td>1.2</td>
<td>CC</td>
<td>0.19</td>
<td>0.37</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RB</td>
<td>0.23</td>
<td>0.36</td>
<td>36</td>
</tr>
<tr>
<td>2</td>
<td>30/10/03</td>
<td>21</td>
<td>1.2</td>
<td>CC</td>
<td>0.28</td>
<td>0.36</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RB</td>
<td>0.28</td>
<td>0.36</td>
<td>22</td>
</tr>
<tr>
<td>3</td>
<td>25/07/04</td>
<td>21</td>
<td>1.3</td>
<td>CC</td>
<td>0.34</td>
<td>0.41</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RB</td>
<td>0.28</td>
<td>0.34</td>
<td>18</td>
</tr>
<tr>
<td>4</td>
<td>12/08/04</td>
<td>15</td>
<td>0.4</td>
<td>CC</td>
<td>0.36</td>
<td>0.41</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>5</td>
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<td>18</td>
<td>0.6</td>
<td>CC</td>
<td>0.35</td>
<td>0.39</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RB</td>
<td>0.32</td>
<td>0.35</td>
<td>9</td>
</tr>
<tr>
<td>6</td>
<td>26/10/04</td>
<td>20</td>
<td>1.6</td>
<td>CC</td>
<td>0.16</td>
<td>0.33</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RB</td>
<td>0.12</td>
<td>0.30</td>
<td>61</td>
</tr>
<tr>
<td>7</td>
<td>10/11/04</td>
<td>25</td>
<td>1.1</td>
<td>CC</td>
<td>0.30</td>
<td>0.38</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RB</td>
<td>0.28</td>
<td>0.37</td>
<td>24</td>
</tr>
</tbody>
</table>

NB. Min $\theta_v$ is effectively the starting $\theta_v$, while Max $\theta_v$ is the highest measured $\theta_v$.

Qualitative observations of seven selected rainfall events

The cumulative rainfall and $\theta_v$ for RB and CC of seven rainfall events are plotted hourly in Figure 4.7. The change-in-rate pattern of $\theta_v$ was similar, with both treatments increasing in response to the rainfall. Likewise after rainfall stopped, the $\theta_v$ of each treatment slowly decreased. To avoid confusion between rainfall and the $\theta_v$, the
cumulative rainfall was plotted upside down and the scale is given on the secondary y axis.

In the first event (1 October 2003), the $\theta_v$ of RB was initially greater than the CC, but by the end the RB was less. In this case the $\theta_v$ of the CC increased by nearly 50 per cent compared to 36 per cent for RB. The second event (30 October 2003) had a similar $\theta_v$ before rainfall started. Thus with the antecedent $\theta_v$ quite close together the behaviour of each treatment was the same.

The five events selected from the winter and spring 2004 varied widely in initial $\theta_v$. The CC was always greater (higher minimum) than the RB, including on 12 August when the CC was higher by 0.09 m$^3$/m$^3$. Again each treatment increased in response to rainfall at a similar rate. This is confirmed by referring to the percentage increase in $\theta_v$ over each event (Table 4.5). However, as the $\theta_v$ of the CC had started above the RB, the CC remained higher than the RB during and after the rainfall had stopped.

The magnitude of change for each rainfall event was related to mean rainfall intensity, rainfall amount and antecedent $\theta_v$. The mean rainfall intensity of all events was 1.0 mm hr$^{-1}$ (S.E. ± 0.14) and average values ranged from 0.4 to 1.6 mm hour$^{-1}$ (Table 4.5). However, the maximum rainfall intensity in one hour was 8.6 mm during the event on 25 July 2004, although rainfall intensity was predominantly much lower than this. Famiglietti et al. (1998) found that heavier rains and higher mean $\theta_v$ were often associated with higher variability of $\theta_v$. Thus, rainfall intensity was probably of lesser importance than rainfall amount and antecedent $\theta_v$. In this study the amount of rainfall that fell during an event strongly influenced the subsequent changes in $\theta_v$. Large increases were found in events 1 and 6, although both these events had low antecedent $\theta_v$. Events 2 and 7, which each had moderate and similar antecedent $\theta_v$ values, recorded similar responses which was probably due to the amount of rainfall. So while the amount of rainfall was important, it did not produce a clear or consistent response. Antecedent $\theta_v$ was the most influential factor in causing change for both treatments e.g. event 6 had the
lowest $\theta$, but also the largest percentage increase in $\theta$. Therefore no overwhelming effect from any of the previous factors was identified; rather a combination of these factors influenced change.
Figure 4.7 Hourly surface $\theta_v$ of CC (●) and RB (○) and cumulative rainfall (solid line) for (a) 1 October 2003, (b) 30 October 2003, (c) 25 July 2004. One lag equals one hour.
Figure 4.7 (continued) Hourly surface $\theta_v$ of CC (•) and RB (○) and cumulative rainfall (solid line) for (d) 12 August 2004, (e) 10 September 2004, (f) 26 October 2004 and (g) 10 November 2004
Quantitative analysis of seven selected rainfall events

Time series analysis of surface $\theta_v$ and rainfall during each event enabled the relationship between the $\theta_v$ of RB and CC to be quantified. This was done by calculating the autocorrelation coefficient ($r_k$) of the $\theta_v$ of RB and CC with cumulative rainfall and the cross-correlation between the $\theta_v$ of RB and CC and each treatment with cumulative rainfall. Comparisons were made between each time series by calculating the differences in terms of lags. Each lag was equal to one hour which was the shortest time period between measurements. This is in agreement with Webster and Oliver (2000) who recommend that the interval between nearest neighbours of data sets the lag.

Significant autocorrelation coefficients ($r_k$) for the $\theta_v$ of RB, CC and cumulative rainfall for each event are given in Table 4.6. In addition the associated lag is given, as well as the number of lags for which the $r_k$ is positive and the total number of lags per event. For most events the $r_k$ of RB, CC and cumulative rainfall were similar. This indicates the temporal change of these variables was similar. While the $r_k$ for rainfall were sometimes the same, often they were slightly higher. The number of lags that $r_k$ was positive was greater than the number of lags with significant $r_k$. In addition there was similarity between the treatments in the number of lags that were positive which confirms that the rate of temporal change was the same for the RB and CC.
Table 4.6 Significant autocorrelation coefficients for RB, CC and cumulative rainfall (CR) with the corresponding lag (±SE), the number of lags (r_k) that were positive and the total number of lags for each event

<table>
<thead>
<tr>
<th>Event no.</th>
<th>Significant coefficients</th>
<th>Significant autocorrelations</th>
<th>No. “positive” lags of CC</th>
<th>Total no. of lags</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CC</td>
<td>RB</td>
<td>CR</td>
<td>SE</td>
</tr>
<tr>
<td>1</td>
<td>0.35 (10)</td>
<td>0.28 (12)</td>
<td>0.28 (13)</td>
<td>0.14</td>
</tr>
<tr>
<td>2</td>
<td>0.30 (7)</td>
<td>0.41 (6)</td>
<td>0.38 (9)</td>
<td>0.15</td>
</tr>
<tr>
<td>3</td>
<td>0.34 (7)</td>
<td>0.42 (5)</td>
<td>0.33 (9)</td>
<td>0.16</td>
</tr>
<tr>
<td>4</td>
<td>0.25 (17)</td>
<td>0.27 (16)</td>
<td>0.27 (17)</td>
<td>0.12</td>
</tr>
<tr>
<td>5</td>
<td>0.27 (11)</td>
<td>0.27 (11)</td>
<td>0.30 (14)</td>
<td>0.13</td>
</tr>
<tr>
<td>6</td>
<td>0.38 (9)</td>
<td>0.36 (9)</td>
<td>0.39 (9)</td>
<td>0.16</td>
</tr>
<tr>
<td>7</td>
<td>0.37 (7)</td>
<td>0.35 (7)</td>
<td>0.41 (7)</td>
<td>0.17</td>
</tr>
</tbody>
</table>

NB. The lag corresponding to each autocorrelation coefficient is in brackets

Comparisons in temporal changes of different treatments or variables are seen well with a correlogram. Figure 4.8 shows changes in surface $\theta_v$ over time between each series for the first event on 1 October 2003. The correlogram given was typical of most events analysed. The number of lags that were significant and positive was mostly similar between the treatments. This indicates that these observations were correlated (i.e. over time they changed in a similar manner), while those outside this range are independent observations.
The number of lags over which positive cross-correlations occurred (between each treatment and rainfall) were calculated (Table 4.7). These data were presented with the associated starting and ending lag, and the maximum significant cross-correlation with its corresponding lag. The cross-correlation for the fifth event shows the pattern of change in cross-correlation that was typical in most events (Figure 4.9). For some events (2, 6 and 7) there was no difference in the ending lag of either treatment with rainfall. In the other events the difference in ending lag was only minor. However, where there was a different ending lag - the RB was always higher than the CC. This suggests the RB were slower to respond, and changes in $\theta_v$ were slightly delayed as a result of rainfall. Events 3 and 5 are the most notable examples and the RB were greater by 6 and 3 lags respectively. The maximum significant (i.e. positive) cross-correlation was similar for both treatments and was mostly found close to the beginning - either at lag 1 or 2. This is further evidence that the RB and CC response to rainfall was not very different. However, event 5 was an exception where the maximum cross-correlation for RB was 0.77 at lag 8, whilst for CC it remained at lag 1.
Table 4.7 The starting (S.) and ending (E.) lag of the positive cross-correlations between cumulative rainfall and the surface $\theta_v$ of RB and CC and the maximum significant cross-correlation (Max-cor)

<table>
<thead>
<tr>
<th>Event no.</th>
<th>CC $\theta_v$: Rainfall</th>
<th>RB $\theta_v$: Rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S.</td>
<td>E.</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>13</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>24</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>19</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>12</td>
</tr>
</tbody>
</table>

NB. The lag corresponding to the Max-cor is given in brackets.

Figure 4.9 The cross-correlation between cumulative rainfall and the surface $\theta_v$ of RB ($\Delta$), cumulative rainfall and the surface $\theta_v$ of CC ($\blacksquare$) and between RB and CC ($\Diamond$) on 25 July 2004. The solid horizontal lines represent the SE of the cross-correlation function.

4.3.5 Soil matric potential

Soil matric potential ($\psi_m$) was measured every two hours from mid-July until the end of December 2004 at three depths: 20, 40 and 60 cm (Figure 4.10). Technical malfunctions
at certain times led to a high number of repeat readings (>20 on some days). On other occasions there were a large number of missing values. Consequently an uneven set of data was collected, but fortunately with sufficient sensors installed readings were taken every day for both treatments at all depths. It was therefore decided to assess only the mean $\psi_m$ for each day of the second half of 2004. For clarity an initial description of the data has divided the measurements into two periods in terms of the amount of change in $\psi_m$. The first period was from mid-July until 19 September during which time there was little change. The second period was from 20 September until the end of 2004. Over this period all depths of both treatments exhibited fluctuations on wetting and drying according to the rainfall and crop water use (Figure 4.10).
Figure 4.10 Mean daily soil matric potential ($\psi_m$) for RB and CC from July to December 2004 at three depths: (a) 20 cm RB (o) CC (●), (b) 40 cm RB (Δ) CC (▼) and (c) 60 cm RB (□) CC (■)
Changes in matric potential

Observations made from the plot of mean daily $\psi_m$ (Figure 4.10) follow. The first period was typical winter-type conditions and was characterised by regular rainfall and low daily $ET_p$; concomitant with cool temperatures and slow plant growth. During this time there was little difference between the treatments particularly at 20 and 40 cm. Both treatments mostly remained above -10 kPa and were close to saturation. The early increase and decrease in $\psi_m$ in the RB at 60 cm is strange and could be due to sensors approaching equilibrium with the soil. Indeed care should be taken in the interpretation of the first two weeks of data as the sensors often take time to settle in to the surrounding soil (Bond 2005). While the first period showed the least daily variation, from 20 September onwards there was a notable changes in $\psi_m$ for both treatments and at all depths.

During the second period, spring and summer conditions meant less rainfall that was erratic and much higher $ET_p$ (section 4.3.1). In this period the conditions were drier than the preceding period. At the start of the second period both treatments began a drying phase, before the first of three significant rainfall events: on 26 October, 10 November and 8 December (the first two were discussed in 4.3.4). First, rainfall (20 mm) on 26 October caused the CC (at 20 and 40 cm) to sharply decrease in $\psi_m$ (i.e. soil became wetter) and the wetting front from this rainfall caused little change at 60 cm. At the same time the RB only responded at 20 cm depth while at 40 and 60 cm the RB maintained a drying trend. The following changes were caused by a series of showers in early November, culminating in a second major rainfall event (>25 mm) on 10 November. The response was similar to 26 October. The third rainfall event on 8 December also wet up the CC and RB at all depths with the CC moving very close to just below saturation. The first two rainfall events produced a quite different effect on $\psi_m$ for RB and CC, especially at 40 and 60 cm. Overall the measured $\psi_m$ values showed that the CC was closer to saturation and the RB was drier and less sensitive to change in $\psi_m$. 

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4.4 Discussion

4.4.1 Rainfall

This study took place during an historically low rainfall period. Each year – 2002, 2003 and 2004 – was below the annual average rainfall and average GSR. Nevertheless within this period there were some individual months of above average rainfall (Figure 4.2 and 4.3). Despite the drier than average weather there were some transient periods of waterlogging observed. Most soil water measurements were taken in the second half of the year, i.e. from May onwards, which coincided with the growing season, but omitted much of the summer and autumn period. This probably did not matter as the period of effective rainfall was covered i.e. when rainfall was used directly and indirectly for crop production (Dastane 1978).

4.4.2 Differences in volumetric water content by depth

In agreement with previous studies (Dolling et al. 2005; Kirby et al. 2003), this study showed that the magnitude of the variation in \( \theta_v \) decreased with soil depth for all treatments. The deepest measured depth (80 cm from the surface) was the slowest to respond to rainfall. Closer to the surface the seasonal range between the minimum and maximum in \( \theta_v \) was greatest (Figure 4.4). The extent to which \( \theta_v \) in each treatment changed was different according to depth. CC was the least variable treatment at 20 and 40 cm while the pasture was least variable at 60 and 80 cm depth. The extent of variation in \( \theta_v \) for RB was mostly between that of CC and pasture.

There were relatively few significant differences in \( \theta_v \) between the treatments at 20 and 40 cm (Table 4.3). It is possible that the lack of significant differences was due to the below average rainfall, but this is unlikely as higher rainfall would have increased \( \theta_v \) for all treatments. Furthermore during the wettest periods measured, no significant differences were found. In fact, the year (2004) with the highest rainfall resulted in the \( \theta_v \) of the pasture coming closer to the CC and RB.
In comparison at 60 and 80 cm, there were a larger number of significant differences. These depths were well below the depth of cultivation and effectively more similar in terms of mechanical disturbance. These depths are still within the root extraction zone of crop plants, but are not as accessible for plant species in a pasture. The amount of soil water extracted varies according to the crop (Dardanelli et al. 1997). Robertson et al. (1993) showed that the relative abundance of roots affects the amount of soil water that is extracted from the soil. Therefore differences in $\theta_v$ can be explained by differences in the density and spatial distribution of roots, e.g. clear differences in rooting depth between pasture species were shown by White et al. (2003). However, differences in root density do not always relate to a significant change in soil water use, e.g. Clark (2004) found no correlation between root growth and $\theta_v$. As no root measurements were taken in this study, the effect of root density on soil water extraction is unknown. Furthermore, at 60 and 80 cm depth it is very difficult to determine how long it takes for water to arrive. The drainage of water through medium to heavy clay soil will be slow which makes explaining specific changes in $\theta_v$ complicated. The effect of cultivation is unlikely and plant water use/ root density is uncertain, thus differences in $\theta_v$ could be due to soil structure or infiltration. Attention on these properties is covered in subsequent chapters.

Differences in $\theta_v$ at any depth could be caused by the micro-relief of the land. Likewise topography and a site’s location within the landscape can strongly influence $\theta_v$. At both sites all treatments were located in a similar topographic position so no differences were likely to arise from this. At a local scale the micro-relief of RB is distinctly different from CC and pasture. For RB a furrow (like a narrow trench) is located every two metres. This provides a regular, local depression which would probably affect the flow and distribution of soil water within the upper part of the soil profile. In this study the furrow edges were avoided and measurements on RB were always done in the middle of the bed. Newton (2003) specifically measured $\theta_v$ at several points across a RB and found significant differences. The edge effect on RB was emphasized in Newton’s finding. Thus some of the differences detected in this study (between RB and CC) may have been due to micro-relief, regardless of other factors such as soil properties.
4.4.3 Soil water deficit dynamics

The changes in SWD at Mt Pollock (Figure 4.5) and Briandra (Figure 4.6) followed the generalised trend described by Fu et al. (2003). The same trend has also been reported by White et al. (2003) and Heng et al. (2001). The drying trend was particularly prominent for all treatments, as were the fluctuations close to the estimated FC during the middle of winter. The increasing phase at the start of the cropping season is less well defined, partly due to few readings being taken in the autumn. Consequently there exists a degree of uncertainty in the interpretation of these results due to the method of estimating FC. Important issues that added to the difficulty in estimating FC were the amount of time for soil water redistribution and differences in soil profile due to the presence of impeding layers (Sumner 1999).

While all treatments followed a similar seasonal trend, there were times when differences were measured. In particular 2003 stands out from 2002 and 2004, because in this year there were 13 times when a significant difference was measured between the treatments (Table 4.4). Thus it would appear as though 2003 was a transition year, going from low to higher rainfall (albeit still below the long-term average). After the dry year in 2002 the cropping treatments (CC and RB) were able to wet up much more rapidly than the pasture. This was probably due to less soil water extraction from an undeveloped crop root system at the start of the 2003 growing season compared to a denser root system in the pasture.

Similarly at Briandra the RB was much quicker to wet up than the pasture in 2003 and 2004, although fewer observations at Briandra provide a less comprehensive assessment of SWD than at Mt Pollock. However the consistently higher rainfall at Briandra may partly explain why the RB were close to saturation on more occasions than the pasture. In comparison the RB was always drier than the CC, but not always as dry as the pasture at Mt Pollock. Some of the difference between the experimental sites could be partly due to the exclusion of the surface $\theta_v$ in calculating SWD at Briandra. Focusing on Mt Pollock there was evidence of improved drainage in the RB, as seen by the greater number of times that the CC was close to FC (Figure 4.5).
Differences in SWD during winter can sometimes be explained by the maximum SWD in the preceding summer. White et al. (2003) refer to the maximum SWD as ‘the size of the bucket,’ whilst Dolling et al. (2005) described the maximum SWD (measured in summer or autumn) as a drainage buffer: i.e. ‘the amount of rainfall the profile could store before drainage.’ Put simply, the greater the SWD the lower the likelihood of deep drainage in winter. Each year the CC had the smallest maximum SWD. In 2002 and 2003 the RB had the largest maximum SWD but in 2004 the pasture and RB were the same (although the 2004 measurements were not taken at the end of summer). This suggests that the CC extracts the least soil water, while the RB and pasture each extract more. There are several explanations for the wetter status of the CC, for instance it is predicted that the RB has a deeper effective Ap horizon than the CC and the reduced tillage on the CC treatment may also be a factor.

A relationship between years can develop whereby the SWD in one season influences the SWD subsequently; also the annual and monthly rainfall can help explain changes in SWD. For instance, the RB had a larger SWD in the summer of 2002/03 than CC and pasture. This took place during the lowest annual rainfall and driest period during the experiment (Figure 4.2). Following on, the RB was slower to wet up in the winter of 2003 than the CC and the CC was measured five times more close to the estimated FC than the RB (Figure 4.4). This coincided with above average monthly rainfall in July, August and October 2003 (Table 4.2). Likewise the pasture was considerably wetter at 60 and 80 cm in the later half of 2003 and throughout 2004. The increased rainfall during this period could have percolated additional water deep into the profile and beyond the region of root extraction. Earlier (2002 and much of 2003) the pasture extracted more of the available soil water and it did not wet up as much. Further discussion on the effect of SWD on plant growth and yield (of RB and CC) is discussed in Chapter Five.

Much experimental work has focused on the difference between RB and non-RB cropping systems, even though the management of RB varies. Clark (2004) explored different cultivation techniques that farmers use in RB cropping. The effect of direct
drilling and deep ripping was evaluated by monitoring soil water use. Deep ripping increased infiltration and resulted in higher yields during a year with above average rainfall. However, during a year with below average rainfall, deep ripping led to greater soil water use and lower water use efficiency. In comparison, conservation of soil water was favoured by direct drilling. Clark’s work shows that the variables of yield and soil water use interacted significantly on RB. Therefore, the cultivation technique on RB influences soil water use according to the amount of rainfall.

**Run-off**

While the soil water balance was not specifically investigated in this study, comment will be made on the effect of the SWD on run-off and their relationship. From 2002 to 2004 RB was about >30 per cent CC in total run-off recorded (Table 4.8). Over the same period the pasture seldom produced run-off, with only 6 mm collected. The differences in run-off volumes and rainfall of individual events for each treatment are given in Table 4.8. The effect of rainfall is clearly shown, e.g. on 8 February 2002 a large rainfall event produced a large volume of run-off, although most rainfall events were smaller than this. In temperate environments typically most rainfall events are of low intensity and are likely to produce saturation excess run-off (Nash and Murdoch 1997). Hydrological studies by White *et al.* (2003) and Melland (2003) each found that most run-off in southern Australia was saturation excess run-off. Run-off from high intensity rainfall that exceeds the soil’s infiltration capacity produces run-off via an infiltration excess mechanism (Haygarth *et al.* 2000). Melland (2003) reported there was only a small proportion of infiltration excess run-off produced, mostly after very intense storms.

Each year run-off was measured a similar number of times, four times in 2002 and 2003 and three in 2004. There appeared to be minimal difference in the timing of run-off discharge between CC and RB. Only twice – 24 July and 31 October 2003 – was run-off measured from RB, but not CC. This was unexpected as the CC was the wetter treatment. Evidently becoming or staying wet does not correlate directly to run-off being produced. The pasture was quite different which suggests that permanent vegetation cover and lack
of cultivation may reduce run-off (Don Scott 2000). In 2002 and early in 2003 the SWD of pasture was greater than the CC and RB, consequently the pasture produced no run-off. This indicates that pasture was absorbing water, while run-off was coming from the RB and CC. Therefore even though the SWD is important in determining the likelihood of run-off, other factors such as vegetation cover also influence hydrological partitioning and whether run-off is produced. However in general the drier the soil profile as measured by the SWD, the less the volume of run-off.

Table 4.8 Mean surface run-off (mm) from CC, RB and pasture with corresponding rainfall (mm) at Mt Pollock from 2002-2004

<table>
<thead>
<tr>
<th>Date</th>
<th>CC</th>
<th>RB</th>
<th>Pasture</th>
<th>Rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/02/2002</td>
<td>6.6</td>
<td>11.6</td>
<td>0</td>
<td>50.4</td>
</tr>
<tr>
<td>28/06/2002</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>12</td>
</tr>
<tr>
<td>23/07/2002</td>
<td>2.3</td>
<td>4.2</td>
<td>0</td>
<td>21</td>
</tr>
<tr>
<td>3/08/2002</td>
<td>0.3</td>
<td>0.9</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>sub-total : 2002</td>
<td>9.2</td>
<td>16.7</td>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>24/07/2003</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
<td>24</td>
</tr>
<tr>
<td>22/08/2003</td>
<td>0.1</td>
<td>0.8</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>1/10/2003</td>
<td>0.1</td>
<td>0.2</td>
<td>0</td>
<td>25.6</td>
</tr>
<tr>
<td>31/10/2003</td>
<td>0</td>
<td>0.1</td>
<td>0.2</td>
<td>20.2</td>
</tr>
<tr>
<td>sub-total : 2003</td>
<td>0.2</td>
<td>1.1</td>
<td>0.2</td>
<td>65.8</td>
</tr>
<tr>
<td>26/07/2004</td>
<td>5.5</td>
<td>6.4</td>
<td>0</td>
<td>21</td>
</tr>
<tr>
<td>14/08/2004</td>
<td>1.9</td>
<td>0.4</td>
<td>0</td>
<td>13.4</td>
</tr>
<tr>
<td>11/09/2004</td>
<td>6.3</td>
<td>2.2</td>
<td>5.8</td>
<td>18.6</td>
</tr>
<tr>
<td>sub-total : 2004</td>
<td>13.7</td>
<td>9</td>
<td>5.8</td>
<td>53</td>
</tr>
<tr>
<td>Grand Total</td>
<td>23.1</td>
<td>26.8</td>
<td>6.2</td>
<td>339</td>
</tr>
</tbody>
</table>

ND = no data because of datalogger and flow equipment failure

* Data from Johnston (2003), Johnston (2004), Johnston (2005)

Run-off volumes (Table 4.8) were measured following some of the same rainfall events as given in Table 4.5. For those rainfall events it was shown that the rainfall (both amount
and intensity) and antecedent $\theta_v$ influenced change in surface $\theta_v$. These factors also can explain the run-off volumes that were produced. For instance, all run-off came after at least 15 mm rainfall and mostly it came from events with the highest $\theta_v$ values. It is predicted that most run-off was due to saturation excess.

Another important hydrologic pathway on texture-contrast soils (which was not measured) is sub-surface lateral flow (Smettem et al. 1991). Together with deep drainage these are additional components of the soil water balance that would assist in explaining changes in SWD as well as treatment differences.

4.4.4 Response of surface volumetric water content to rainfall

The time series analysis of surface $\theta_v$ and cumulative rainfall was in general agreement with the findings from the visual observations. There was little difference in the wetting response from rainfall between the surface $\theta_v$ of RB and CC (Figure 4.7). Using time-series analysis provided quantitative confirmation that the rate of increase in surface $\theta_v$ was the same between the treatments.

When the crop was small in winter, plant water extraction was assumed to be negligible and changes in the surface $\theta_v$ could not be explained by crop extraction. The spring rainfall events took place with larger and more mature plants could potentially be different. At this time, crop water extraction could contribute to differences in the antecedent $\theta_v$ (before a rainfall event). The most pronounced example of this was on 26 October 2004 (Table 4.5) which had the lowest starting $\theta_v$ of all the events, which in turn led to a large percentage increase in $\theta_v$ over the duration of the rainfall. The lower starting $\theta_v$ of the RB could have been due to greater crop water extraction or improved drainage. However, the short duration (one to two days) that the rainfall events were assessed puts emphasis on the wetting-up phase, not drainage. Nevertheless as the RB started most rainfall events with lower $\theta_v$ and also ended lower. This suggests that the RB surface soil was better drained.
A similar study in Western Australia showed that over two years RB remained consistently drier (at several depths to 30 cm) than the control treatment (similar to the CC) (Bakker et al. 2001b; Bakker et al. 2002). In addition, greater increases in $\theta_v$ of the control treatment than RB were shown after rainfall, followed by gradual drainage. Thus the findings of Bakker et al. were in agreement to those observed in this study.

4.4.5 Changes in matric potential by depth

Effect of rainfall /ET

The bifurcation of the measured $\psi_m$ values (Figure 4.10) correlates well with changes in the rainfall and ET$_p$ (Figure 4.2). During the first period there would have been little water taken up by the crop, but with the warmer temperatures in the second period there would have been higher transpiration and increased crop water use (Salisbury and Ross 1992). Furthermore the rainfall was higher before mid September. In July, August and September 2004 the rainfall was close to the median (respectively decile 6, 4, 5), whereas October was much drier at decile 2 (Table 4.2). Also the ET$_p$ sharply increased from the first to the second period, e.g. the average daily ET$_p$ in September was 1.9 mm compared to 3.4 mm in October. Thus the combined factors rainfall and ET$_p$ had a marked effect on the $\psi_m$ of RB and CC, although the response was stronger for the RB treatment than the CC.

Comparison of matric potential with surface volumetric water content

Simultaneous with monitoring $\psi_m$ at 20, 40 and 60 cm, the surface (0 to 6 cm) $\theta_v$ was measured every hour. Seven selected rainfall events were analysed in 4.3.4, five of which took place in the latter half of 2004. Thus the relationship between $\psi_m$ and surface $\theta_v$ over short periods can be explored. Despite dynamic changes in surface $\theta_v$ on 25 July, 12 August and 10 September these corresponded to minimal differences in $\psi_m$ (Figure 4.10). On these dates $\psi_m$ remained constant and was $<$20 kPa for both treatments and all depths.
Thus the lower part of the soil profile (beneath 10 cm) was kept wet over this period and changes were restricted to the surface soil.

As previously mentioned, after 20 September there were dramatic changes in $\psi_m$. For instance the wetting up after the rainfall on 26 October and 10 November 2004 was followed immediately by sharp drying down. However this was not the case after rainfall in early December because by then the crop had senesced. Nevertheless some agreement between the measurements was found as the RB were always lower than the CC, both in $\theta_v$ and $\psi_m$. The much lower $\psi_m$ at depth (Figure 4.10) in the RB could have provided increased storage for soil water and lowered the wetting up (i.e. percentage increase) at the surface, but this did not occur. Therefore it is evident that while RB have superior drainage to CC at the surface, it appears that at depth the drainage of RB remains impeded.

Comparison of $\psi_m$ with $\theta_v$ measured with the NMM (Figure 4.4) showed that the resistance blocks were slightly more responsive to the drying front in spring 2004. The decrease in $\psi_m$ began at the end of September, but a detectable change did not appear in $\theta_v$ until 10 October 2004 which was two weeks later. Admittedly the measurement of $\theta_v$ (with the NMM) was not as frequent as the measurement of $\psi_m$ with the resistance blocks, but notwithstanding this, $\psi_m$ appeared more sensitive to change in soil water status.

### 4.5 Conclusion

Throughout the measurement period rainfall was below average, but the rainfall increased progressively from 2002 to 2004. For almost the entire measurement period at Mt Pollock the RB were much drier than the CC, although at times (early in the measurement period) the pasture was the driest. RB produced the greatest soil water deficit and this was mostly beneficial in reducing the risk of waterlogging on RB compared to soil than under CC or pasture. The short-term response to rainfall of surface $\theta_v$ was found to be similar between
the RB and CC. The increase in surface $\theta_v$ after rainfall was strongly influenced by the antecedent $\theta_v$ and as the RB soil often began drier it usually did not become as wet as the CC soil. The better drainage of the RB was probably a function of the furrows which acted as effective drainage pathways and the greater cultivation that was undertaken on the RB soil. Further evidence of the improved drainage of RB was shown with the measurement of $\psi_m$ which showed that RB were much drier than the CC. The $\psi_m$ was particularly sensitive in detecting drying fronts, which were strongest in the RB.
5 Plant growth and crop yield on raised beds and conventional cultivation

5.1 Introduction

RB are widely adopted in south-west Victoria as a form of surface drainage for cropping on waterlog-prone soils. The area of RB has steadily increased over the past decade and now RB are a regionally important cropping system. However a close examination of studies on RB with non-RB treatments in Victoria shows some mixed results. There have been studies that have reported increases in grain yield (Wightman and Kealy 2000). However, work by Riffkin and Evans (2003) and Bufton et al. (2000) showed that RB reduced yields in some years, while Peries et al. (2001) found no significant differences in yield. This introduces some uncertainty as to whether RB increases crop yields. Articles in newspapers such as “The Weekly Times” have often lauded the benefits of RB (in terms of yield), but they are usually poorly supported by evidence; for example, articles by Dalton (2004) and Hacking (2005) provided no data for their claims. Similarly some conference papers have reported yield improvements from RB which were also unsubstantiated (Bluett and Wightman 1999; Peries et al. 2004). Thus collectively these studies reveal no clear difference in yield between RB and non-RB treatments. There is also a lack of understanding of the effect of rainfall and soil physical properties on RB.

5.1.1 Aim

The hypothesis tested was that crop yields on RB are greater than on CC. Therefore, the objectives of this chapter are to:

- determine whether plant growth or crop yield on RB are significantly different compared to conventional cultivation (CC),
- evaluate changes in the soil water deficit with plant growth,
• assess changes in air-filled porosity (AFP) with plant growth,
• undertake a regional yield survey of RB and CC type treatments, and
• determine the effect of rainfall on yield.

5.2 Materials and methods

5.2.1 Plant sampling

Plant growth variables were measured on crops in three years at Mt Pollock; they were canola in 2002, wheat in 2003 and barley in 2004. A representative number of observations were taken from RB and CC plots which were replicated three times. Germination counts (twenty per plot) were taken when seedling growth was well developed, usually between three and four weeks after sowing. Dry matter samples (five per plot) were cut twice during the growing season to establish plant growth development at different times. The Zadoks Decimal Code (ZDC) system was used to determine the growth stage of the cereal crops (Zadoks et al. 1974). The first dry matter sample was taken whilst the crop was at the tillering stage or early stem elongation. The second was taken during ear emergence or at anthesis. Only above-ground plant material was sampled. The samples were taken on each plot along a line following a zigzag pattern (like a W) in a north: south direction. Due to crop size 0.25 x 1m quadrants were sampled for canola, and 0.5 x 1m quadrants taken for wheat and barley. The RB plots included furrows as part of the treatment area and this was often bare of plants. Thus, to ensure that a comparable area was sampled from each treatment, the RB samples were cut from five drill rows, whereas six rows were taken for the CC samples (Figure 5.1). In addition, the total plant dry matter was sampled at harvest. Plant dry matter material was oven-dried until reaching a constant weight (usually after 48 hours).
5.2.2 Grain yield and harvest index

Grain yield was measured on hand-cut samples and machine-harvested samples. The dry matter samples taken at harvest were air-dried and the grain was separated then threshed to determine the grain yield (t/ha). The harvest index was calculated from the ratio of grain yield to total dry matter. In addition, the numbers of ears were counted and individual grain weight was recorded. Five sub-samples (of 500 grains) from each plot were dried at 30°C for 48 hours and weighed to measure individual grain weight.

Machine-reaped samples were harvested with a specialised small-plot harvester. Three harvester runs (1.6 m width and 30 m length) harvested an area of 0.14 ha. The grain collected from this area was used to estimate the yield (t/ha) for the whole plot (2 ha). Differences in yield between hand-cut and machine-harvested samples were found and probably due to grain losses during mechanical harvesting; also it could have been a reflection of the spatial variability in growth.

5.2.3 Soil water deficit and soil aeration

Soil water deficit (SWD) was calculated using the same method described previously in chapter four (see section 4.2.2). Here it is presented for the upper part of the soil profile only (to a depth of 30 cm) – although, in 2002 measurements of the SWD were from 10-30 cm, while in 2003 and 2004 it was 0-30 cm. This depth range was considered the
most relevant for relating to crop growth. For instance, measurements of root length density on RB by Clark (2004) showed that a large percentage of roots (under cereals) were within the top 30 cm.

Soil aeration was calculated as the percentage of air-filled porosity (AFP) \( (m^3/m^3) \) in the soil surface (0-10 cm) and at 20 cm depth. The AFP was calculated from the difference between the saturated volumetric water content \( (\theta_s) \) and the field-measured volumetric water content \( (\theta_v) \). The \( \theta_s \) was determined from intact cores that were sampled to measure the soil water retention characteristic (presented in chapter six). The critical value for soil AFP was determined as \( 0.1 \, m^3 \, air/ \, m^3 \, soil \) (Marshall et al. 1996).

### 5.2.4 Crop dry matter production and crop value

The difference between RB and CC in total crop dry matter production (at harvest) and crop value (from grain yield) was determined by accruing the results from each year. This enabled an overall comparison without the effects of crop type (the same crops were grown on RB and CC) or rainfall in an individual year. It does not make sense to sum the grain yield of different crops together. Thus a measure was sought to determine the economic component of crop production from the yield. Mead et al. (2003) recommended using grain price to assess the combined yield of intercropping systems containing different crops. Thus this approach permits a meaningful evaluation of grain produced in different years on RB and CC. The machine-harvested grain yield \( (t/ha) \) of each crop was multiplied by the unit commodity price \( ($AUD) \). The prices (per tonne) to calculate crop value were provided by the farmer and were $400 for canola, $230 for wheat and $195 for barley (Peel, Pers. com). The overall average for total crop dry matter and crop value for each treatment was calculated too.

### 5.2.5 Crop yield survey of south-western Victoria

Over the last decade there have been a number of studies on the crop yield of RB and CC cropping systems. This allowed a survey to be undertaken to determine the difference in grain yield between RB and CC cropping systems at a regional scale. Eight experimental and demonstration sites from across south-western Victoria provided 31 observations from several years of grain yield that compared these two treatments. Data
from Mt Pollock was included, with the remaining seven sites from the following studies: Wightman and Kealy (2000), Southern Farming Systems (2000), Southern Farming Systems (2001), Southern Farming Systems (2002), Holden (unpublished data) and Newton (unpublished data). The percentage difference in grain yield ($\pm Y_d$) between the RB and CC was expressed using the equation,

$$Y_d = \left( \frac{Y_{RB} - Y_{CC}}{Y_{RB}} \right) \times 100$$  \[5.1\]

where $Y_{RB} = RB$ yield and $Y_{CC} = CC$ yield. Assessing the $Y_d$ enabled a treatment effect to be determined without the confusion of different crop types. To compliment the calculation of $Y_d$ the tonnage difference in grain yield ($\pm Y_{dt}$) was calculated using the following equation.

$$Y_{dt} = Y_{RB} - Y_{CC}$$  \[5.2\]

The $Y_{dt}$ was expressed in standard units (t/ha) and was more sensitive to crop type. The data was collected from 1996 until 2004 and included the following crops: barley, canola, wheat and triticale. The selected years varied in rainfall from dry years with below average to wetter years with above-average rainfall. Annual rainfall was plotted according to a decile scale from 0 to 10 (section 4.2.1). Both $Y_d$ and $Y_{dt}$ were plotted with rainfall decile on the independent axis. This allowed a relationship between yield and rainfall to be investigated as well. Account was not taken of specific initial or site conditions for each experimental site.

5.2.6 Statistical analysis

Comparison of the means of the plant growth and yield data was made using an analysis of variance (ANOVA). Statistical significant difference was determined at the five percent level ($P <0.05$) with the least significant difference (LSD). Treatment means are subscripted with the same letter if no significant difference was detected, but different subscripts were used when there was a significant difference. Statistical analysis was performed using GenStat software (Lawes Agricultural Trust 2005).
5.3 Results and discussion

5.3.1 Crop growth and yield at Mt Pollock in 2002

The crop at Mt Pollock germinated well with a significantly greater count for CC compared to RB. The greater plant density did not result in any difference in the dry matter yields which were sampled at the early podding /late anthesis stage (25/09/2002) (Table 5.1). Furthermore visual observations did not suggest any difference in crop maturity between the two treatments. The total dry matter at maturity was significantly greater on the RB than the CC. Likewise the grain yield (by hand) was proportionally greater by a similar amount. Thus the harvest index was similar for each treatment. As the crop was windrowed on 29/11/2002 and remained on the ground for six weeks there were high losses when it was machine harvested on 14/01/2003. The machine harvested grain yield was 2 t/ha for each treatment and no significant difference was detected. Because of these losses the hand yield results are considered more reliable. The comparatively greater losses on the RB were probably due to difficulties (e.g. pod shattering) at harvest because of such a large canopy.

Table 5.1 Mean crop growth and harvest variables for canola at Mt Pollock, 2002

<table>
<thead>
<tr>
<th>Crop variable</th>
<th>Date</th>
<th>RB</th>
<th>CC</th>
<th>LSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germination count (no. /m²)</td>
<td>31/07/2002</td>
<td>74.8a</td>
<td>87.8b</td>
<td>9.6</td>
</tr>
<tr>
<td>Dry matter - late anthesis (t/ha)</td>
<td>25/09/2002</td>
<td>4.7a</td>
<td>4.7a</td>
<td>0.9</td>
</tr>
<tr>
<td>Total dry matter at maturity (t/ha)</td>
<td>14/01/2003</td>
<td>10.7a</td>
<td>8.9a</td>
<td>1.5</td>
</tr>
<tr>
<td>Grain yield – hand (t/ha)</td>
<td>14/01/2003</td>
<td>3.5a</td>
<td>3.0a</td>
<td>0.4</td>
</tr>
<tr>
<td>Grain yield – machine (t/ha)</td>
<td>14/01/2003</td>
<td>2.0a</td>
<td>2.0a</td>
<td>0.2</td>
</tr>
<tr>
<td>Harvest Index</td>
<td>-</td>
<td>0.33</td>
<td>0.34</td>
<td></td>
</tr>
</tbody>
</table>

NB. Mean variables with the same letter are not significantly different (P <0.05) between treatments

The higher germination count of the canola on the CC treatment was probably due to increased soil moisture (less SWD). But this can only be predicted as the first measurements of \( \theta_v \) were not until the 21/08/2002, although subsequently the CC was always wetter than the RB (Figure 5.2). This difference suggests that the CC had improved conservation of soil moisture or slower drainage. Annual rainfall was low (decile 3) in 2002 and there were no periods of waterlogging observed. Towards the end
of 2002 a stronger drying front (i.e. greater SWD) was detected in the RB treatment. After anthesis the canola on the RB extracted more soil water than the CC, which resulted in greater dry matter at maturity. Thus despite the low rainfall which probably reduced the grain yield potential, the RB produced higher yields than the CC. This is an unexpected result and suggests that the RB were not stressed by the greater SWD, in fact under these conditions the RB probably extracted the soil water more effectively than the CC.

![Figure 5.2 Rainfall (mm) and soil water deficit (mm) from 10-30 cm for RB (◊) and CC (●) under canola in 2002](image)

**5.3.2 Crop growth and yield at Mt Pollock in 2003**

In 2003 wheat was sown on the 5 June and plant growth and harvest variables are reported in Table 5.2. The conditions at sowing were very dry as there was little rainfall during the autumn period. The number of emerged seedlings was significantly greater for CC than RB which may have been due to slightly more soil moisture in the CC i.e. a smaller SWD (Figure 5.3). This good start led to strong plant growth in the CC and
there was significantly more dry matter than the RB at the late tillering /early stem elongation growth (ZDC 31 on 28/08/2003). This trend continued until early anthesis (ZDC 60 on 22/10/2003) when a second dry matter cut was taken. No periods of waterlogging were experienced and visual observations of the crop did not indicate any serious stress. However, there was an infection of rust during October which equally affected both treatments and was not thought to have reduced plant growth. At harvest the improved growth of the CC resulted in a significantly greater grain yield (by machine) than the RB and the harvest index for CC also was slightly greater. Associated with the greater grain yield the CC also had significantly greater individual grain weight than the RB. This indicates that the CC was more efficient and better suited to the environmental conditions of 2003. The measured harvest indices fall within the higher end of the range (0.19 to 0.46) of those reported by Riffkin et al. (2003) at Hamilton, south-west Victoria. But they were less than the values (0.42 to 0.46) which Clark (2004) measured at Cressy (which is closer to Mt Pollock than Hamilton) in 2002.

Table 5.2 Mean crop growth and harvest variables for wheat at Mt Pollock, 2003

<table>
<thead>
<tr>
<th>Crop variable</th>
<th>Date</th>
<th>RB</th>
<th>CC</th>
<th>LSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germination count (no. /m²)</td>
<td>26/06/2003</td>
<td>157_a</td>
<td>211_b</td>
<td>38</td>
</tr>
<tr>
<td>Dry matter – late tillering (t /ha)</td>
<td>28/08/2003</td>
<td>1.2_a</td>
<td>1.9_b</td>
<td>0.4</td>
</tr>
<tr>
<td>Dry matter – post-anthesis (t /ha)</td>
<td>22/10/2003</td>
<td>10.6_a</td>
<td>13.0_b</td>
<td>1.8</td>
</tr>
<tr>
<td>Total dry matter at maturity (t /ha)</td>
<td>24/12/2003</td>
<td>17.2_a</td>
<td>18.6_a</td>
<td>1.8</td>
</tr>
<tr>
<td>Grain yield – hand (t /ha)</td>
<td>24/12/2003</td>
<td>6.7_a</td>
<td>7.7_a</td>
<td>1.5</td>
</tr>
<tr>
<td>Grain yield – machine (t /ha)</td>
<td>05/02/2004</td>
<td>6.3_a</td>
<td>6.9_b</td>
<td>0.4</td>
</tr>
<tr>
<td>Ear count</td>
<td>-</td>
<td>485_a</td>
<td>508_a</td>
<td>26</td>
</tr>
<tr>
<td>Grain weight (mg)</td>
<td>-</td>
<td>31.6_a</td>
<td>33.2_b</td>
<td>1.3</td>
</tr>
<tr>
<td>Harvest Index</td>
<td>-</td>
<td>0.39_a</td>
<td>0.41_b</td>
<td>1.3</td>
</tr>
</tbody>
</table>

NB. Mean variables with the same letter are not significantly different (P <0.05) between treatments

The rainfall in 2003 (decile 4) was greater than 2002 but it was still below average and under these conditions the crop growth on the CC performed better than the RB. However while there was a significant difference in the machine harvested grain yield, there was not for hand yield. This difference was probably due in part to a delay in the crop being machine harvested.
Good growing conditions prevailed for the wheat crop in 2003 as waterlogging was rarely observed. It is speculated that increased $\theta$ at sowing led to improved growth in the CC. Clark (2004) also found that soil moisture (especially at sowing) was important in determining the final grain yield of different RB treatments. For instance, at early stem elongation and during anthesis the RB developed a greater SWD than the CC (Figure 5.3). During this period there was greater plant growth on the CC than the RB which ultimately may have been the difference which led to significantly greater grain yield and grain size for the CC.

![Figure 5.3 Rainfall (mm) and soil water deficit (mm) from 0-30 cm for RB (○) and CC (●) under wheat in 2003](image)

Alternatively the lower yield on RB could have been due to a smaller effective cropping area compared to CC. The installation of RB results in a loss in productive area (up to 25 per cent) compared to flat types of cropping such as CC. Sometimes plants are sown along the furrow and the area lost is smaller. Riffkin and Evans (2003) also cited ‘loss of productive area’ as resulting in lower yields. However as the difference in productive area always applies it can only partially explain the differences found in 2003.
Consequently RB must always produce more grain per m$^2$ to yield greater than the CC treatment which effectively covers a larger area.

5.3.3 Crop growth and yield at Mt Pollock in 2004

Barley was grown in the third year of the experiment (2004) and plant growth and harvest variables are reported in Table 5.3. Early in the season there were mixed results with no significant differences between the treatments for the number of plants germinated or the dry matter sampled at mid-tillering (ZDC 25 on 07/09/2004). Visual observations indicated that waterlogging was minimised on the RB in comparison to the CC. The number of tillers per plant was significantly more for RB than the CC at mid-tillering (07/09/2004). This indicates more vigorous growth on the RB despite the occurrence of waterlogging. It is not known whether the CC compensated for the lower number of tillers per plant as measurements of tiller density were not taken. By post-anthesis (during milk development; ZDC 75 on 26/10/2004) the RB continued to increase in plant growth compared to the CC and significantly greater dry matter was measured. Despite this difference by the end of the growing season the treatments were much closer and at harvest there was no significant difference in total dry matter, grain yield (as measured by both hand and machine), ear count or grain weight. Likewise harvest index was the same for each treatment, but it was greater than in the previous two years.
Table 5.3 Crop growth and harvest data for barley at Mt Pollock, 2004

<table>
<thead>
<tr>
<th>Crop variable</th>
<th>Date</th>
<th>RB</th>
<th>CC</th>
<th>LSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germination count (no. /m²)</td>
<td>30/06/2004</td>
<td>146a</td>
<td>141a</td>
<td>25</td>
</tr>
<tr>
<td>Dry matter – mid tillering (t /ha)</td>
<td>07/09/2004</td>
<td>2.0a</td>
<td>1.9a</td>
<td>0.3</td>
</tr>
<tr>
<td>Tillers – mid tillering (no. /plant)</td>
<td>07/09/2004</td>
<td>6.7a</td>
<td>4.5b</td>
<td>0.7</td>
</tr>
<tr>
<td>Dry matter – post-anthesis (t /ha)</td>
<td>26/10/2004</td>
<td>10.3a</td>
<td>7.8b</td>
<td>2.3</td>
</tr>
<tr>
<td>Total dry matter at maturity (t /ha)</td>
<td>20/12/2004</td>
<td>13.2a</td>
<td>12.5a</td>
<td>2.9</td>
</tr>
<tr>
<td>Grain yield – hand (t /ha)</td>
<td>20/12/2004</td>
<td>5.9a</td>
<td>5.6a</td>
<td>0.9</td>
</tr>
<tr>
<td>Grain yield – machine (t /ha)</td>
<td>20/12/2004</td>
<td>4.6a</td>
<td>3.9a</td>
<td>1.2</td>
</tr>
<tr>
<td>Ear count</td>
<td>-</td>
<td>436a</td>
<td>406a</td>
<td>57</td>
</tr>
<tr>
<td>Grain weight (mg)</td>
<td>-</td>
<td>45.4a</td>
<td>46.3a</td>
<td>2.9</td>
</tr>
<tr>
<td>Harvest Index</td>
<td>-</td>
<td>0.45</td>
<td>0.45</td>
<td></td>
</tr>
</tbody>
</table>

NB. Mean variables with the same letter are not significantly different (P <0.05) between treatments.

2004 was the year with the most rainfall during the experiment, but it was still below the long-term average. There were several periods when waterlogging was observed which presumably led to an excess (SWD values close to or >0 mm) of soil water (Figure 5.4). Such wetness affected plant growth on the CC with visible signs of plant stress, e.g. yellowing on several occasions (7, 11 and 13 September). At the same time the RB plots were seemingly less affected and remained much greener. Although this improved plant growth on the RB did not continue until maturity. One reason for this may have been the low rainfall in October (decile 2). It is speculated that during October excess water drained from the CC and led to some compensatory growth in that treatment. Thus by harvest the CC grain yield was not significantly different from the RB. Alternatively the waterlogged conditions were too late to cause substantial crop damage as young plants are most sensitive to waterlogging. For instance, Meyer (1988) showed that in wheat a single short-term waterlogging event after stem elongation did not affect yield.
Each year plant growth on CC and RB was sensitive to soil moisture and 2004 was no different. However increased plant growth did not automatically result in higher grain yields. Over the three cropping seasons only once did the RB yield significantly more grain (hand yield measurement in 2002) than the CC. There was no significant yield difference in 2004 and in 2003 the CC was significantly greater (only machine-harvested grain yield). These mixed yield results could be related to the low rainfall, which was always below the long-term average. Riffkin and Evans (2003) reported that RB can only produce greater yields than CC under waterlogged conditions. In this experiment 2004 was the only year when waterlogging was observed with corresponding plant stress. But the waterlogging was for a limited period only and did not ultimately affect the final yield.

5.3.4 Crop growth and soil physical properties

Soil water deficit (SWD) was a derived soil physical property that was previously compared with plant growth. Differences in plant growth and ultimately crop yield could have been directly affected by soil physical properties, such as high soil strength.
or low aeration, which have been found to limit crop production (Letey 1985). The percentage AFP at 0-10 cm and 20 cm depth was calculated and is plotted against time for the most important part of the growing season in 2003 (Figure 5.5) and 2004 (Figure 5.6).

In 2003 there were only a few occasions when the AFP of the CC was less than the critical AFP value of 10 per cent. This is to be expected given that no waterlogging was observed. The RB soil was better aerated in the surface (0-10 cm) and at 20 cm depth. The higher AFP of the RB was seen most strongly in 2004 where the CC was <10 per cent AFP on several occasions.

![Figure 5.5](image_url) Changes in soil air-filled porosity (%) at (a) 0-10 cm and at (b) 20 cm depth for RB (◊) and CC (●) under wheat in 2003
Higher rainfall and greater \( \theta_v \) in 2004 resulted in lower AFP values than in 2003. In the soil surface (0-10 cm) the CC was <10 per cent AFP from sowing on 5 June until stem elongation on 2 September. In comparison during this period the RB had greater AFP and was mostly >10 per cent. The poor aeration status of the CC soil (in particular the length of time that the AFP was <10 per cent) corresponds with the waterlogging that was observed on several occasions in 2004. Thus the improved plant growth found on the RB (Table 5.3) was probably in part because of the greater AFP in the 0-10 and 10-20 cm depth intervals.

![Figure 5.6 Changes in soil air-filled porosity (%) at (a) 0-10 cm and (b) 20 cm depth for RB (\( \Diamond \)) and CC (\( \bullet \)) under barley in 2004](image-url)
Other studies have reported the effect of soil aeration on several different crops and production systems. Studies on irrigated wheat (Melhuish et al. 1991) and irrigated sorghum (Wright 1985a) have shown a significant effect of soil aeration on grain yield. Farming systems more similar to south-western Victoria have also found that wet periods during winter reduced AFP which caused slower plant growth and reduced yield in peas (McDonald 1995) and wheat (McDonald and Gardner 1987). In fact, McDonald and Gardner (1987) reported that a one per cent decrease in AFP during the 30 days prior to anthesis reduced grain yields by 0.3 t/ha. McDonald (1995) noted that other factors such as disease and nutritional problems were associated with poor aeration and may have also adversely affected crop performance. While no disease was observed in either treatment of the 2004 crop, detrimental effects of poor nutrition were possible. More frequent sampling of the crop and additional observations would have assisted in better monitoring plant growth on the RB and CC.

### 5.3.5 Total dry matter production and crop value

Total dry matter (t/ha) and crop value ($/ha) were calculated to evaluate accrued differences (i.e. the overall effect) of different crop types in different years between treatments. The mean annual and overall total crop dry matter (t/ha) at harvest and crop value ($/ha) from the grain yield of RB and CC are given in Table 5.4. The highest total dry matter was found to produce the highest crop value. The relationship between dry matter and crop value varied each year according to the harvest index. The RB produced significantly greater total dry matter in 2002, but crop value was no different between treatments. Conversely in 2004 the crop value was significantly different, but the dry matter was not. While in 2003, the CC produced significantly more total dry matter and crop value. Thus, significant differences were detected in individual years for dry matter production and crop value, but there was no significant difference for the three year average between the treatments. Overall, the RB produced slightly greater dry matter, but less crop value. Thus no production benefit can be attributed to either treatment.
Table 5.4 Mean annual and overall total dry matter and crop value

<table>
<thead>
<tr>
<th>Production variable</th>
<th>RB</th>
<th>CC</th>
<th>LSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002 Total dry matter (t/ha)</td>
<td>10.7a</td>
<td>8.9b</td>
<td>0.8</td>
</tr>
<tr>
<td>2003 Total dry matter (t/ha)</td>
<td>17.2a</td>
<td>18.6b</td>
<td></td>
</tr>
<tr>
<td>2004 Total dry matter (t/ha)</td>
<td>13.2a</td>
<td>12.5a</td>
<td></td>
</tr>
<tr>
<td>Mean total dry matter (t/ha)</td>
<td>13.7a</td>
<td>13.3a</td>
<td>1.6</td>
</tr>
<tr>
<td>2002 Crop value ($/ha)</td>
<td>799a</td>
<td>814a</td>
<td>55</td>
</tr>
<tr>
<td>2003 Crop value ($/ha)</td>
<td>1455a</td>
<td>1596b</td>
<td></td>
</tr>
<tr>
<td>2004 Crop value ($/ha)</td>
<td>906a</td>
<td>766b</td>
<td></td>
</tr>
<tr>
<td>Mean Crop value ($/ha)</td>
<td>1053a</td>
<td>1059a</td>
<td>75</td>
</tr>
</tbody>
</table>

NB. Mean variables with the same letter are not significantly different (P < 0.05) between treatments.

5.3.6 RB and CC grain yields across south-western Victoria

The following crop yield survey (Figure 5.7 and 5.8) provides an overview of $Y_d$ between RB and CC from 31 experiments across south-western Victoria. This survey expands on the findings on crop yield of RB and CC at Mt Pollock between 2002 and 2004 which were discussed previously.

The calculated $Y_d$ between RB and CC are given in Figure 5.7. In approximately half of the experiments there was a positive $Y_d$ (i.e. greater yield) for RB compared to the CC. This included both wetter-than-average years (decile 7) and drier years (< decile 5). The range of $Y_d$ was wide and no consistent relationship between rainfall and yield was found. This presentation of RB and CC yield data indicated a variable relationship and no consistent treatment effect.
Figure 5.7 Percentage difference in yield ($Y_d$) between RB and CC from sites across south-western Victoria, 1996-2004

The data from Figure 5.7 were re-calculated and are presented in Figure 5.8 and expressed in tonne per hectare (equation 5.2). This shows that the absolute difference was more often greater in favour of RB. There were several times when almost no difference in yield was detected and when CC was greater (i.e. the negative values) than the RB. The positive $Y_{dt}$ shows that RB were able to more frequently out-yield the CC, particularly under wet conditions (Decile 7) (Figure 5.8). The comparatively greater yields by the RB were achieved by overcoming the effects of waterlogging (Riffkin and Evans 2003; Wightman and Kealy 2000). The negative $Y_{dt}$ found at decile 7 was due to the crop (canola) lodging which was probably caused by disease (Riffkin, Pers. com). In another case the RB yield suffered due to poor plant establishment after difficulties at sowing (Holden, unpublished data). Thus some values do not represent best growing conditions. Nevertheless this applies equally to both treatments. No consistent relationship was found between crop type and $Y_{dt}$ and both positive and negative $Y_{dt}$ were found from the same crop, e.g. all the data at decile 7 was from canola.
Rainfall Deciles
difference in yield (tonnes)

Figure 5.8 Tonnage difference in yield ($Y_{dt}$) between RB and CC from sites across south-western Victoria, 1996-2004

From the relationship between grain yield and rainfall (French and Schultz 1984a), it was predicted that the high rainfall years would favour the RB and correlate with increased yields. Stephens and Lyons (1998) study of the relation between wheat yield and rainfall emphasized the importance of rainfall distribution, particularly in the month after crop sowing. Waterlogging in this period can cause serious crop damage and low final grain yields. This yield survey (expressed as $Y_{dt}$; Figure 5.8) showed that the higher rainfall years strongly favoured the RB.

The findings of this survey conflict with other survey-type studies. For example in Western Australia, Bakker et al. (2005) reported an average of 18 per cent increase in yield for RB compared to a CC type treatment. However the results reported by Bakker et al. are questionable as they adjusted their 2001 yield data by increasing the RB yield because of difficulties at sowing. Such an adjustment is unacceptable as it distorts the actual yields from the RB that were measured. While in south-western Victoria Peries et al. (2004) found that on average RB produced 20 per cent greater yields from a sample of 18 demonstrations and farmer surveys. However, by reporting only the average percentage increase in RB yields, Peries et al. did not reveal the absolute difference by weight.
As the yield survey pairs RB and CC together, it assumes that all sites were suitable for both treatments. However this ignores a key advantage of RB. RB allow cropping on areas where it is not possible using CC. Thus the broader benefits of RB are not taken into account in this survey due to the data which were collected. Indeed more data about each experimental site would be useful in understanding the causes for the differences in yield. For instance, the data collected for the yield survey mostly came from small plot experiments. This reduces the potential variability compared to that at a field scale. The farmer of Mt Pollock Peel (Pers. com) claims: “that RB have increased yields” and it was “probably due to improved uniformity of crop growth across whole fields” and previously it was observed that in some areas crops were “wiped out”. Thus installing RB alleviated the problem of low-lying areas which otherwise would become waterlogged.

Unfortunately the yield survey was not able to fully capture the extent of spatial variability and this may have led to an underestimation of the yield from RB. Thus, given the brevity of the data included, it is admitted that the survey has limitations. The survey included a number of experiments where differences such as rotation or crop management were not taken into consideration. Therefore the findings of this study must be viewed cautiously.

5.4 Conclusion

During the drier than average years of the experiment, the crop yield at Mt Pollock varied, with the same or significantly lower yields on RB compared to the CC soil. At the same time there were some significant differences found in plant growth and total dry matter between the treatments. For instance, poorer plant growth in 2003 on the RB was probably caused by less available soil water (greater SWD). While in 2004 the RB had greater AFP and increased plant growth compared to the CC which was <10 per cent AFP for long periods. The regional survey of crop yields from RB and CC showed there was no absolute advantage for either treatment. However, these data showed that the amount of annual rainfall was important and RB performed better in years with higher than average rainfall (i.e. >decile 5). Therefore as the benefits of improved AFP are not found every year, it is predicted that the effects may be cumulative over consecutive wet seasons.
6 The soil water retention characteristic, soil strength and the least limiting water range under raised beds and conventional cultivation

6.1 Introduction

Many of the soils commonly found in south-western Victoria present difficulties for crop production. Robinson et al. (2003) reported that across the Corangamite catchment (which partly includes south-western Victoria) there was a large area (nearly 800,000 ha) highly susceptible to soil structure decline. Such soils have poor physical properties for plant growth, because they restrict root exploration and soil aeration. At times cultivation has been found to provide temporary improvement in soil physical properties (Gardner et al. 1994). As RB and CC are two cropping systems that involve different methods of cultivation it is timely to study their physical properties.

Previous workers have reported changes to some soil physical properties of RB. A study in Tasmania by Cotching and Dean (2001) found that lower bulk density (BD) of RB was associated with lower shear strength and lower penetration resistance than a CC treatment. Peries et al. (2001) also reported on reduced BD of RB. These studies are an example of the limited work that has been done on soil physical condition. Therefore there is a need to establish values for RB and CC soil. This chapter considers soil physical properties in three aspects: the soil water retention characteristic (SWRC), soil strength and an integrated soil physical parameter.
6.1.1 Aim

The aim of the experimental work in this chapter was to determine whether there were any significant differences in key physical properties between RB and other land uses (either CC or pasture). To achieve this, measurements were made at two experimental sites over several sampling times to:

- calculate the SWRC in the laboratory and the field of RB, CC and pasture,
- measure the penetrometer resistance profiles for RB and CC,
- explore the relationship between soil strength and soil water content for RB and CC, and
- compare the least limiting water range (LLWR) for RB and CC.

6.2 Materials and methods

6.2.1 Laboratory-derived soil water retention characteristic

Soil samples were collected from the field in May, 2002 and November, 2003 at the Mt Pollock and Briandra experimental sites. At Mt Pollock samples were taken from RB and CC treatments. While at Briandra samples were taken from two different RB treatments and one pasture treatment. The RB samples were from fields that had been established at different times. Burns 2 (field name) was formed into RB in 1999 and Burns 3 in 2001. The pasture (Burns 1) was selected as an undisturbed control to the RB.

Sampling was the same at both sites. Soil cores (height 6.3 cm, internal diameter 7.3 cm) and loose soil were sampled at three depths; 0-10 cm, 10-20 cm and 30-40 cm. Care was taken to ensure that the cores were excavated with minimal disturbance. A coring device with a slide hammer was used to extract the samples at the lower depths, whereas cores were pushed in by hand on the surface. Sometimes it was necessary to take repeat cores because of the high gravel content. Once sampled the cores were enclosed in plastic zip-lock bags to prevent moisture loss and transported to the cool room until laboratory measurement commenced.
In the laboratory the cores were prepared by trimming off excess soil from the top and bottom. Nylon mesh was attached to the bottom of each core for protection. The cores were slowly wet up to saturation with de-aerated water. Once saturated, the cores were drained and weighed. A hanging water column was used to apply matric potential values ($\psi_m$) with a column of water of 20, 50 and 100 cm height which corresponded to $\psi_m$ of 2, 5 and 10 kPa (field capacity). The weight of each core was monitored to establish when equilibrium was reached at each applied suction. The samples were weighed and converted to volumetric water content, $\theta_v$ (m$^3$/m$^3$) using equation 2.3. The bulk density was measured using the core method which was given in Chapter Three, section 3.2.5.

Greater suction at -200 and -1500 kPa (permanent wilting point) was applied using porous ceramic plates in pressure chambers (Klute 1986). Good soil: plate contact was achieved by using small repacked cores. These cores were filled with moistened loose soil. The water level in an up-turned burette was monitored to determine when equilibrium was established. Only samples taken in 2002 were measured at these greater suctions.

The available water capacity (AWC) was determined as the difference in $\theta_v$ between the field capacity and the permanent wilting point (McKenzie et al. 2002a). The soil BD was used to calculate the total porosity (m$^3$/m$^3$) using equation 2.2. The van Genuchten (1980) model was fitted to measured data but was found to fit poorly and so it was decided to focus solely upon the measured data.

6.2.2 Field-derived soil water retention characteristic

During the second half of 2004 the SWRC was measured in the field at Mt Pollock. The SWRC was determined by measuring $\theta_v$ with the neutron moisture meter (NMM) and $\psi_m$ with soil resistance blocks (for further details see Chapter Four). Measurements were taken at three depths: 20, 40 and 60 cm. Discrepancies between $\theta_v$ and $\psi_m$ due to spatial variation were minimised by measuring $\psi_m$ close (<5 m) to the access tubes of the NMM.
The field SWRC was derived from daily-averages of $\theta_v$ and $\psi_m$ on the days that measurements of both were taken.

### 6.2.3 Soil strength

Penetrometer resistance (PR) was selected as an indicator of the soil strength in the field. A Bush recording cone penetrometer measured PR every 3.5 cm intervals down to a maximum depth of 52 cm. The cone at the end of the shaft was 1.29 cm diameter. This provided a series of 15 readings from a single stroke through the soil profile. The readings were initially recorded in kilograms of force, which was converted to pressure (MPa) by multiplying by 0.0762. Measurements on RB and CC treatments were taken on ten different occasions in 2002, 2003 and 2004 at Mt Pollock and once in 2002 at Briandra. In 2002 and 2003 twenty readings were taken randomly in a V pattern from north to south across each plot, but only ten readings were taken per plot in 2004. Measurements in each plot were replicated three times. On the same day crop growth stage was noted and $\theta_v$ was measured. Hignett (2002) recommended that all soil strength readings are taken in conjunction with field infiltration readings and this would have been ideal, but this was not possible due to a lack of time. Some plots (especially 1 and 2) were stony which caused a greater number of missing values. In addition, when measurements were taken under dry conditions, it was difficult to push the penetrometer to its full depth.

### 6.2.4 Least limiting water range

The non-limiting water range (NLWR) proposed by Letey (1985) provided conceptual stimulus to integrating soil physical properties into a single parameter. The approach used in this study (least limiting water range - LLWR) was a modification of the approach by da Silva et al. (1994). This brought together measurements of soil strength and the available range of soil water.

The LLWR was defined by the difference in $\theta_v$ between an upper and lower point of available $\theta_v$. The wet end (upper point) was either the $\theta_v$ at field capacity (FC) or the $\theta_v$ at
an air-filled porosity (AFP) of 0.10 m³/m³, depending whichever was the lowest θv. The dry end (lower point) was the θv at a critical soil strength value or the permanent wilting point (PWP) was used, whichever was the highest θv. For this study the critical soil strength for root growth was set at a PR of 3 MPa (Bridge and Bell 1994; Cass 1999; Dexter 1986; Ehlers et al. 1983), whereas da Silva et al. (1994) used 2 MPa.

6.2.5 Statistical analysis

Due to the small number of samples taken for determining the SWRC it was not possible to undertake formal statistical significance tests for the difference between treatments. But there were enough measurements for tests to be performed on ancillary data of total porosity. For this variable the least significant difference (LSD) was calculated at the five percent probability level (P <0.05).

Several issues were encountered when using the penetrometer which created difficulties when analysing the data. For instance, sporadic and occasional instrument error meant that zero values were sometimes recorded. Zero values were ignored and considered as missing values. In addition there were missing values due to rocks or soil dryness. Consequently an irregular number of measurements were collected. Descriptive summary statistics were calculated (not shown) and checks performed to ensure that the values followed a normal distribution. Analysis of variance (ANOVA) was used to calculate the LSD for PR at each depth for data from Mt Pollock and Briandra in 2002.

Subsequently PR data was used to develop the soil strength characteristic. Greenwood et al. (1997) used an exponential function to describe the relationship between soil strength and soil water content, while Zou et al. (2000) found that a logarithmic function best fitted their data. Regression functions such as exponential and power functions were tested, but generally the best fit was found using a linear regression. Mean values were plotted for penetration resistance (the response variable) and θv (the explanatory variable). Data for both variables were measured over a wide range of values which were obtained on nine occasions in 2003 and 2004. A comparison of the regression lines was
undertaken to test for the equality of the slope and intercept coefficients between the fitted straight line for RB and CC. Differences in the coefficients were assessed at a significance level of five percent (P <0.05). Statistical analysis was performed using GenStat software (Lawes Agricultural Trust 2005) and graphs were prepared using Sigma Plot (Systat Software Inc. 2004).

The linear regression analysis method described above was also performed on the field-derived SWRC data, also for the comparison of RB and CC treatments. However as a power function was used to describe the $\theta_v$ and $\psi$ relationship a $\log_{10}$ transformation was first performed to back transform the data before undertaking linear regression analysis.

6.3 Results

6.3.1 Laboratory-derived soil water retention characteristic

Mt Pollock

The SWRC at three depth intervals (0-10, 10-20 and 30-40 cm) for RB and CC in 2002 is given in Figure 6.1.
Figure 6.1 Soil water retention characteristic at (a) 0-10 cm, (b) 10-20 cm and (c) 30-40 cm at Mt Pollock in 2002. n = 3.
There was little difference found between the treatments in the SWRC at 0-10 cm or 10-20 cm. The most notable difference was from 30 - 40 cm where the RB was much drier than the CC. At this depth the CC had a consistently greater $\theta_v$ than the RB for the same $\psi$ value. For instance, at field capacity the $\theta_v$ of CC was 0.45, which was much greater than the RB at 0.35. Likewise at the permanent wilting point of the CC was 0.22 compared to 0.17 for the RB. In 2003 (data not shown) there was even greater similarity between the treatments at all depths. Indeed the variation between the two sampling times was greater than the difference between the treatments.

The AWC and total porosity was calculated which provided ancillary data from the SWRC (Table 6.1). The largest difference between the treatments was found closest to the surface (from 0-10 cm), especially in 2002. In particular, the total porosity for the RB was significantly greater than CC, but there were only minor differences between the RB and CC in the AWC. Missing values for the 10-20 cm depth range meant that it was not possible to make a statistical comparison in 2002. At 30-40 cm there was greater AWC for CC, but the total porosity were quite similar. At all depths more difference between the treatments was found in 2002 than 2003. Many of the differences and changes can be related to the soil BD.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Treatment</th>
<th>Total porosity (m$^3$/m$^3$)</th>
<th>AWC (m$^3$/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2002</td>
<td>2003</td>
</tr>
<tr>
<td>0-10</td>
<td>RB</td>
<td>0.55 (0.02)$^a$</td>
<td>0.48 (0.04)</td>
</tr>
<tr>
<td>0-10</td>
<td>CC</td>
<td>0.44 (&lt;0.01)$^b$</td>
<td>0.45 (0.04)</td>
</tr>
<tr>
<td>10-20</td>
<td>RB</td>
<td>0.44</td>
<td>0.37 (0.06)</td>
</tr>
<tr>
<td>10-20</td>
<td>CC</td>
<td>0.46 (0.02)</td>
<td>0.36 (0.06)</td>
</tr>
<tr>
<td>30-40</td>
<td>RB</td>
<td>0.47 (0.04)</td>
<td>0.42 (0.07)</td>
</tr>
<tr>
<td>30-40</td>
<td>CC</td>
<td>0.49 (0.04)</td>
<td>0.43 (0.02)</td>
</tr>
</tbody>
</table>

NB. SE are shown in brackets. Means followed with a different letter differ at P <0.05 using the LSD multiple comparison test. No significant difference between means without letters.
The soil BD of RB was often lower than the CC, especially between 0-10 cm depth. To illustrate this several BD measurements taken in the soil surface (0-10 cm) over the last five years are shown in Figure 6.2. On four occasions the RB was considerably lower in BD than the CC, while twice the treatments quite similar. However, sometimes the variability was large (as indicated by the SE). This suggests that the number of samples taken should have been increased. Below 10 cm there was only a small difference detected between treatments at the different sampling times; but the BD for both treatments increased (data not shown).

![Figure 6.2](image)

**Figure 6.2** Mean surface (0 to 10 cm) bulk density for RB and CC at Mt Pollock. Bars represent ± SE; n = 9.

**Briandra**

The SWRC was determined over three depth intervals (0-10, 10-20 and 30-40 cm) at Briandra in 2002 and 2003 and is given in Figure 6.3.
Figure 6.3 Soil water retention characteristic for Burns 1 (Δ), Burns 2 (●) and Burns 3 (■) at (a) 0-10 cm, (b) 10-20 cm and (c) 30-40 cm at Briandra in 2002
The SWRC at Briandra indicated similar relationship between the treatments at 0-10 and 10-20 cm depth in 2002. At 30-40 cm depth Burns 3 (the most recently formed RB) was distinctly different from Burns 1 and 2 which were similar. In 2003 (data not shown) the SWRC of all treatments measured greater $\theta_v$ than in 2002 and the differences between the treatments were the same. However at 30-40 cm depth Burns 3 was more similar to the other two treatments.

The total porosity and AWC at Briandra are given in Table 6.2. At the surface (0 – 10 cm) in 2002 Burns 2 – the 1999 established RB - had significantly greater total porosity than Burns 3 (2001 established RB) and the pasture (Burns 1). At the 10-20 cm depth interval the difference in total porosity was smaller, but both RB treatments were larger than the pasture. At 30-40 cm the total porosity of the RB treatments had continued to decline and the pasture had stayed the same as the depth above. Generally, there was a decrease in porosity with depth and the total porosity was greater in 2002 than 2003. There was very little difference in porosity between treatments in 2003. The most AWC was from 10-20 cm, where the RB treatments (Burns 2 and 3) were comparable and greater than the pasture.
Table 6.2 Total porosity and available water capacity (AWC) for Burns 1, Burns 2, Burns 3 at three depths at Briandra in 2002 and 2003

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Treatment</th>
<th>Total porosity (m³/m³)</th>
<th>AWC (m³/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2002</td>
<td>2003</td>
</tr>
<tr>
<td>0 – 10</td>
<td>Burns 1 (pasture)</td>
<td>0.50 (0.01) a</td>
<td>0.49 (0.03)</td>
</tr>
<tr>
<td>0 – 10</td>
<td>Burns 2 (RB)</td>
<td>0.60 (0.02) b</td>
<td>0.51 (0.01)</td>
</tr>
<tr>
<td>0 – 10</td>
<td>Burns 3 (RB)</td>
<td>0.50 (0.05) a</td>
<td>0.50 (&lt;0.01)</td>
</tr>
<tr>
<td>10 – 20</td>
<td>Burns 1 (pasture)</td>
<td>0.45 (0.03)</td>
<td>0.41 (0.03)</td>
</tr>
<tr>
<td>10 – 20</td>
<td>Burns 2 (RB)</td>
<td>0.49 (0.03)</td>
<td>0.40 (0.01)</td>
</tr>
<tr>
<td>10 – 20</td>
<td>Burns 3 (RB)</td>
<td>0.51 (0.04)</td>
<td>0.44 (&lt;0.01)</td>
</tr>
<tr>
<td>30 – 40</td>
<td>Burns 1 (pasture)</td>
<td>0.44 (0.01)</td>
<td>0.41 (0.03)</td>
</tr>
<tr>
<td>30 – 40</td>
<td>Burns 2 (RB)</td>
<td>0.41 (0.02)</td>
<td>0.37 (0.02)</td>
</tr>
<tr>
<td>30 – 40</td>
<td>Burns 3 (RB)</td>
<td>0.41 (0.04)</td>
<td>0.45 (&lt;0.01)</td>
</tr>
</tbody>
</table>

NB. SE are given in brackets. Means (for the same depth interval) followed with a different letter were significantly different at P <0.05 using the LSD multiple comparison test. No significant difference between means without letters.

Total porosity is affected by changes in BD. Measurements of BD taken when calculating the SWRC are given in Figure 6.4. The BD of all treatments increased with depth and most increased with time, but due to the large SE little difference could be found between the treatments, except in 2002 at 0-10 cm when Burns 2 was much lower than the other two treatments.
6.3.2 Field-derived soil water retention characteristic

The field-derived SWRC was only measured over a short period of time (second half of 2004). Fortunately a wide range of soil water values were captured during this period. The SWRC is given at three depth intervals (20, 40 and 60 cm) and is fitted with power function (Figure 6.5). The power function was found to best describe the relationship between $\theta_v$ and $\psi_m$. The largest difference between the RB and CC was away from saturation (<20 kPa). At the 20 and 40 cm depths the SWRC for RB was less than the CC which indicates that the relationship between $\theta_v$ and $\psi_m$ was drier for RB, but at 60 cm depth the fitted relationship for CC was drier.
Figure 6.5 Field-derived soil water retention characteristic with a power function fitted for RB (○, dashed line) and CC (●, solid line) at three depths: (a) 20 cm, (b) 40 cm and (c) 60 cm at Mt Pollock

At 20 cm the RB exhibited more variation in $\psi_m$ and the fitted relationship was much drier than for the CC. Furthermore regression analysis at 20 cm showed that the slope and intercept were significantly different between the treatments. At 40 cm the RB also covered a wider range of values than the CC which likewise suggested a drier relationship. This was confirmed by the lower fitted regression line, but the difference
between the treatments was not as great as at 20 cm and only the slopes were significantly different. At 60 cm the CC measured some positive $\psi_m$ values which indicates a saturated zone, whereas the RB measured negative values from close to 0 kPa to the measurement limit at -200 kPa. Due to the unequal range of measured values at 60 cm it was considered unrealistic to compare the fitted relationship for the SWRC between RB and CC. Nevertheless over the whole profile the positive $\psi_m$ values at 60 cm is a key finding that differentiates the field SWRC between the treatments.

### 6.3.3 Soil strength

**Differences in penetrometer resistance through the profile**

First, a profile of the PR was measured on CC and RB treatments at Mt Pollock in July, 2002 (Figure 6.6). Both treatments increased in resistance with depth, although the trends were quite different. Significant differences were found at four depth intervals between 10.5 and 21 cm. Over this range the RB values were less than the CC at each point. At 24 cm depth and below there was no significant difference between the treatments and the variability of the measurements was much greater at these depths.

![Penetrometer resistance (MPa)](image)

**Figure 6.6 Profile of mean penetrometer resistance of CC (■) and RB (□) at Mt Pollock in July, 2002. LSD bars (P = 0.05)**
Second, a profile of the mean PR was measured on two RB treatments: Burns 2 and Burns 3 at Briandra in October, 2002 (Figure 6.7). However, despite the different age of the two RB treatments no significant difference detected at any measured depth. The profile of PR for both treatments was greater than the RB at Mt Pollock and more similar to the CC (Figure 6.6). This demonstrates the variability that can exist in PR profiles of RB in different soils.

These results (Figure 6.6 and 6.7) show the depth intervals where the largest differences between treatments were found. They also show the general pattern of PR profile which was similar to the other times when penetrometer readings were taken. The difference in PR may have been due to differences in $\theta_v$, but in 2002 the $\theta_v$ was not measured. Nevertheless it was noted that the soil was moderately moist conditions in July, 2002 at Mt Pollock. In comparison the soil was slightly drier at Briandra in October. Therefore, to avoid the further complicating factor of crop or soil type, all subsequent measurements were taken at Mt Pollock and $\theta_v$ was always measured with PR.

Figure 6.7 Profile of mean penetrometer resistance of Burns 2 (♦) and Burns 3 (◊) at Briandra in October, 2002; LSD bars (P = 0.05)
Differences in penetrometer resistance profiles over time

Measurements of PR were taken on RB and CC on nine occasions at Mt Pollock. Seasonal changes in $\theta_v$ were found to strongly influence the measured PR values. The lowest PR was measured during the winter when the soil was moist. Correspondingly the highest PR was recorded at low $\theta_v$ which was in the late spring when the soil was drier. The relationship between PR and $\theta_v$ was consistent for both treatments. A wide range of mean PR values was measured. To illustrate this, the mean minimum and mean maximum values at each depth for RB and CC are given in Table 6.3. The most striking difference was found for the minimum values and to a depth of 21 cm the RB minimum was much less than the CC. At some depths the PR of the RB was less than half the CC value. At the same point this corresponded with lower $\theta_v$ of the RB (further details on the $\theta_v$ were given in Chapter Four). Below 21 cm there was often only a small difference in the minimum and maximum of each treatment.
Table 6.3 Mean minimum and maximum penetrometer resistance (MPa) of all measurements for RB and CC by depth at Mt Pollock

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>RB</th>
<th>CC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>3.5</td>
<td>0.18</td>
<td>1.31</td>
</tr>
<tr>
<td>7.5</td>
<td>0.39</td>
<td>1.94</td>
</tr>
<tr>
<td>10.5</td>
<td>0.43</td>
<td>2.15</td>
</tr>
<tr>
<td>14</td>
<td>0.44</td>
<td>2.24</td>
</tr>
<tr>
<td>17.5</td>
<td>0.61</td>
<td>2.44</td>
</tr>
<tr>
<td>21</td>
<td>0.99</td>
<td>2.75</td>
</tr>
<tr>
<td>24.5</td>
<td>1.42</td>
<td>3.06</td>
</tr>
<tr>
<td>28</td>
<td>1.78</td>
<td>3.65</td>
</tr>
<tr>
<td>31.5</td>
<td>1.90</td>
<td>3.66</td>
</tr>
<tr>
<td>35</td>
<td>1.83</td>
<td>3.35</td>
</tr>
<tr>
<td>38.5</td>
<td>1.69</td>
<td>3.20</td>
</tr>
<tr>
<td>42</td>
<td>1.61</td>
<td>3.12</td>
</tr>
<tr>
<td>45.5</td>
<td>1.58</td>
<td>4.34</td>
</tr>
<tr>
<td>49</td>
<td>1.60</td>
<td>2.95</td>
</tr>
<tr>
<td>52.5</td>
<td>1.61</td>
<td>4.27</td>
</tr>
</tbody>
</table>

Relationship between penetrometer resistance and $\theta_v$ of RB and CC

The relationship between PR and $\theta_v$ was assessed according to a linear regression analysis. Comparison between RB and CC was undertaken every 3.5 cm (at 15 depth intervals) through the profile. In most cases there was a slight (but not significant) negative correlation between PR and $\theta_v$. To show the relationship between these variables an illustration is given of the average PR and $\theta_v$ data at 7 cm and at 28 cm depth (Figure 6.8).
Comparison of regression lines was undertaken to test the equality of the slopes and intercepts for RB and CC. At the first depth interval (3.5 cm) there was no significant difference in slope or intercept. The slopes of the remaining depths were not significantly different from one another except at the lowest recorded depth - 52.5 cm. The difference in slope (at 52.5 cm) can be partly explained by the increased variability and the high
number of missing values. The most important difference was found in the intercept and in the upper depth intervals (from 7 to 24.5 cm) there was a significant difference between the RB and CC. However at the lower depth intervals (from 28 to 52.5 cm) there was no significant difference in the intercept. In most cases the $R^2$ values of the regression lines for the RB was greater than the CC. For each treatment they were lowest with increasing depth which was probably due to greater number of missing values.

6.4 Discussion

6.4.1 Soil water retention characteristic

At Mt Pollock and Briandra the largest difference in the SWRC between RB and the non-RB treatment was found in 2002 in the 30-40 cm depth range (Figure 6.1 and 6.3). Further there was little difference for all depths between samples taken in 2002 and 2003. The data collected at Briandra suggested that the magnitude of difference was as great between RB of different age as it was with the pasture treatment. Because of these differences and the small amount of data available, it was not possible to detect a length-of-establishment effect for Burns 2 or Burns 3. This was unexpected as the SWRC has been found to be a sensitive soil hydraulic property in other studies. Valzano et al. (2001) used the SWRC to differentiate between tillage treatments in determining the field capacity and permanent wilting point. Likewise Williams et al. (1983) reported a strong association between structure and the SWRC on several soils from across Australia, but often significant differences between treatments were difficult to find. Indeed Barlow and Nash (2002) found that the soil heterogeneity was masking differences in soil water of intact soil cores. In this study no treatment effect for RB was determined partly due to the inherent variability of the soil, but also due to an insufficient number of samples collected. However from the available data on the laboratory-derived SWRC the pore size distribution and physical condition would be unlikely to be different between the RB and the other treatments.
The RB often had much lower BD which was associated with greater porosity (Figure 6.2). Thus a significant difference was found in total porosity from 0-10 cm depth at both sites (Table 6.1 and 6.2). This difference corresponds with the depth that was most disturbed by cultivation and also the part of the profile with the least clay content at both experimental sites. Differences in total porosity at 10-20 cm and 30-40 cm between the treatments were minor. As the largest difference in the SWRC and total porosity were at different depths there is evidence of a unique soil structural network for each treatment.

The field-derived SWRC data (Figure 6.5) was collected to 60 cm depth only with data <200 kPa. Over the three measured depth intervals the RB was found to have a drier relationship between $\theta_v$ and $\psi$ than the CC. The most distinct difference was found at 60 cm. However given the lack of accuracy when measuring $\psi_m$ with a Watermark sensor, the data should be used to indicate relative indications of soil wetness only (Spaans and Baker 1992). Hysteresis is another factor that may have lead to the variation in field data collected. Therefore, it is acknowledged that measurements were probably taken on both the drying and wetting-phase of the SWRC for each treatment.

It was considered inappropriate to make a direct comparison between the laboratory-derived SWRC and the field-derived SWRC at Mt Pollock because the measurements were taken at separate times, under different conditions, and there was considerable variation in the field collected data. In addition, for the laboratory-derived measurements it was predicted that the measured changes in time were probably as great as the changes in space. This was unfortunate as there was some overlap in the depth intervals of the two methods used to measure the SWRC. Consequently any comparison between methods is restricted to the results presented, where the field-derived SWRC was more sensitive and showed larger treatment differences than the laboratory-derived SWRC.

### 6.4.2 Soil strength

Initial measurement of PR (Figure 6.6 and 6.7) identified significant differences within the surface 20 cm. Comparison of data from Mt Pollock and Briandra demonstrated the
strong effect of $\theta_v$ on penetration resistance. The lower PR measured at Mt Pollock was associated with wetter soil in July, 2002 (Figure 6.6). By the time measurements were taken at Briandra in October of the same year, the soil had dried out. Consequently the PR measurements at Briandra were greater. The different crops on the RB treatments at Briandra did not seem to have affected the penetrometer resistance. The lack of difference between Burns 2 and Burns 3 indicates a degree of homogeneity in PR between RB of different age.

The soil strength characteristic at Mt Pollock showed that both treatments ranged from low soil strength ($<1$ MPa) when the soil was moist to high soil strength ($>3$ MPa) during dry conditions. The upper depth range (7.5 to 24.5 cm) the intercept of the RB was significantly lower than the CC. Thus within this depth range, at a given water content the soil strength for CC was greater than the RB and closer to critical values which inhibit root growth. Therefore the lower PR of the RB should allow easier penetration for root growth.

Over four consecutive years Hamblin et al. (1982) measured PR and $\theta_v$ to detect changes in physical properties of different tillage treatments. Hamblin et al. declared that as values from different years were plotted on the same line this represented a lack of change for each treatment. In addition, the PR varied little in $\theta_v$, in comparison to this study. It is proposed that the lower annual rainfall during Hamblin’s study led to smaller changes in $\theta_v$ and resulted in a smaller range PR values. The greater fluctuations at Mt Pollock were associated with higher rainfall and a resultant greater range in $\theta_v$. Hignett (2002) stated that measurement variability of PR increases as $\theta_v$ decreases and in fact this was the case with the measurements taken at Mt Pollock.

A drawback of the method used to determine the soil strength characteristic relates to the different volume of soil that are sampled in measurements of $\theta_v$ and PR. The NMM measures over a much larger volume than the penetrometer. This problem was highlighted by Jayawardane and Blackwell (1990). Measurements of PR are more sensitive to variation between single points. Consequently, a large number of
measurements were taken (up to 60 per depth interval) to improve the precision with which this variable was measured. Recently, advanced instruments have been developed which measure PR and $\theta_v$ together (Lapen et al. 2004a). Regardless of the different scales of measurement for each variable, information on one soil property can provide an indication about the other. Indeed, Fawcett (1977) claimed that recorded changes in penetration force could be used to estimate the amount (i.e. depth) of available soil water. Therefore, it is suggested that the greater depth of low PR values in the RB would be associated with more available soil water than the CC.

Differences in PR between RB and CC could have been due to factors apart from $\theta_v$, namely BD, texture, structure or cultivation. The BD of the RB was mostly less than the CC, particularly close to the soil surface (Figure 6.2). Fawcett (1977) reported a weak correlation between soil strength and $\theta$. The low coefficient of determination ($R^2$) between the variables was caused by soil texture variability. Soil texture, in particular clay content varied by over 10 per cent in the soil surface across the Mt Pollock site (see EM map - Figure 3.8). The lower PR of the RB may have been due to improved soil structure. Belbin and Cotching (2004) found significant differences in the relationship between PR and soil wetness (measured as gravimetric water content, $\theta_g$) of poorly and well structured soil. Small $\theta_g$ in the poorly structured soil corresponded with higher PR than in well structured soil. Zhang et al. (2001) showed that cultivation reduces soil strength compared to undisturbed land. Both CC and RB are cultivated, but greater cultivation is required to form RB. Cotching and Dean (2001) found smaller mean aggregate size in RB and claimed this was brought by additional cultivation in RB.

### 6.4.3 Identification of the least limited water range for plant growth

The results in this chapter have focused on two aspects of Letey’s (1985) model, namely the range of plant available water (with the SWRC) and soil strength (with PR). Until this point the data presented have been considered separately. This section integrates the SWRC and PR measurements. Consequently the LLWR was calculated at three depths: 0-10, 10-20 and 30-40 cm for each treatment (Figure 6.9).
At the 0-10 cm depth range (Figure 6.9a) the LLWR was slightly greater for the RB than the CC. There was no restriction due to soil strength or aeration for either treatment. As the FC was the same for each treatment (0.31 m$^3$/m$^3$) the difference was found at the lower end of the range. The RB had a lower PWP which led to an increased LLWR. The largest and most striking difference in the LLWR was found at 10-20 cm (Figure 6.9b). Here the LLWR of the RB was almost twice that of the CC. At the wet end the CC was restricted by an aeration limit and consequently was similar to the limit for the RB. In contrast, the largest difference was at the dry end where the CC was restricted by soil strength, but the RB was not. Consequently the LLWR for CC was 0.12 m$^3$/m$^3$ compared to 0.22 for the RB. At the third depth range, 30-40 cm (Figure 6.9c) - the LLWR was similar between treatments. The difference in LLWR was comparable to the 0-10 cm depth, except that the CC was slightly greater than the RB. Soil strength had a major impact on the LLWR of both treatments and cut in before the PWP was reached.
Determining the LLWR at each depth has identified some large differences between the RB and CC and trends with depth were found. Soil strength caused no problems in the soil surface, but became increasingly important with depth. This was first found in the CC at 10-20 cm and for both treatments at 30-40 cm. This agrees with the PR data which showed that the RB were significantly lower in strength to 24.5 cm depth. The PWP was the most restricting factor in the surface. Changes at the upper end of the LLWR were small, but aeration became more restricted with increasing depth. At 0-10 cm the FC set the upper limit for the LLWR, but at 10-20 and 30-40 cm the $\theta_v$ of the AFP was less than
the FC and so the AFP set the upper limit. da Silva et al. (1994) questioned whether it was appropriate to include the FC in the LLWR because $\theta_v$ greater than FC does not strictly result in a limit to plant growth. This probably does not matter as the water contents at FC and AFP were mostly similar.

The LLWR has been sensitive in detecting differences in traffic and tillage experiments (Betz et al. 1998; Lapen et al. 2004b). Thus the greater LLWR of the RB may be partly a reflection of the controlled traffic on the RB which would lead to less soil compaction. Zou et al. (2000) calculated the LLWR on several different soils. Differences in LLWR were found to be caused by changes in texture and BD, but BD caused the most significant effect. Increasing BD equated with reducing the LLWR. Likewise in this study the higher BD of the CC (Figure 6.2) was associated with a smaller LLWR than the RB. Betz et al. (1998) claimed that the LLWR reflected the soil structural condition and was affected by compaction and drainage.

**Outside the LLWR**

In exploring the relationship of the LLWR with plant response, da Silva and Kay (1996) determined the proportion of $\theta_v$ measurements outside ($p_{out}$) the LLWR. This was calculated as a proportion of the total number of $\theta_v$ measurements that were taken. da Silva and Kay found that the shoot growth rate of corn correlated better with $p_{out}$ than LLWR. The measurements of $\theta_v$ (at the relevant depths) presented in Chapter Four were examined in order to determine the $p_{out}$ over the entire experimental period (Table 6.4).

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>RB</th>
<th>CC</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 10</td>
<td>0.06</td>
<td>0.19</td>
</tr>
<tr>
<td>10 – 20</td>
<td>0.12</td>
<td>0.16</td>
</tr>
<tr>
<td>30 – 40</td>
<td>0.34</td>
<td>0.12</td>
</tr>
</tbody>
</table>
Closest to the soil surface (0-10 cm) the \( p_{out} \) for the RB was much less than the CC. At the 10-20 cm depth interval the \( p_{out} \) was only slightly lower for RB. Thus in the top 20 cm the RB had the best conditions for plant growth and \( \theta_v \) was more often measured within the LLWR. This is not surprising as the RB had a larger LLWR at these depth intervals (Figure 6.9). At the 30-40 cm depth the RB exceeded the FC several times and it had a much greater \( p_{out} \) than the CC. This suggests that at 30-40 cm there were much better physical conditions in the CC than the RB. Therefore the calculation of the \( p_{out} \) should be used carefully to compliment the LLWR. There are problems with calculating the \( p_{out} \). For instance, \( p_{out} \) is affected by the total number and the timing of \( \theta_v \) measurements taken as well as the values chosen as limits for the LLWR. Nevertheless the calculation of \( p_{out} \) provides an alternative perspective upon which to scrutinize the LLWR and how it was determined.

### 6.5 Conclusion

Over the period of measurement only small differences were detected in the laboratory-derived SWRC between RB and non-RB treatments. In comparison, the field-derived SWRC showed that the RB was mostly drier and at 60 cm depth the CC had a saturated zone that was not found in the RB. The soil strength characteristic of the RB was significantly lower than the CC from seven to 24 cm depth which indicates improved soil condition for roots to grow in the RB. While at 10-20 cm the LLWR of the RB was nearly twice that of the CC. This shows that the surface 20 cm of soil had much better physical properties for cropping under RB than the CC. The accrued benefits in the RB are probably due to increased cultivation compared to the CC soil.
CHAPTER SEVEN

7 Hydraulic conductivity in raised beds and conventional cultivation

7.1 Introduction

As highlighted previously RB have become a popular method of cropping in south-west Victoria, but the reasons for the adoption of RB are yet to be established. Wightman and Kealy (2000) claim that RB were introduced to overcome problems caused by waterlogging. Typically many soils in south-west Victoria have restrictive hydraulic properties. One of the most important is infiltration, especially the transmission of water through the subsoil. Poor permeability in this part of the soil profile leads to slow drainage and can result in waterlogging. The main cause of this is a hydraulic “throttle” to water movement through the profile. This often develops due to the texture contrast between the A and B horizons (Belford et al. 1992). The A horizon (topsoil) is often coarse textured and well structured, whereas the B horizon (subsoil) of many soils has a high clay content which is typically sodic and impermeable.

Previous workers have found that RB have different hydraulic conductivity (K) compared to control treatments. In fact studies in both Western Australia (Bakker et al. 2005) and Tasmania (Cotching and Dean 2001) reported higher infiltration for RB. However the work previously done in south-western Victoria has been limited. Therefore there is a need to measure the K so that values on infiltration are quantified for soils in this region, particularly those under RB.

It was hypothesized that the K of RB is greater than CC soil. Consequently the aim of the experimental work in this chapter was to determine whether there were any significant
differences in K between RB and other land uses (such as CC or pasture). Several objectives were developed before measurements were taken. They were to:

- measure the saturated ($K_s$) and unsaturated ($K_{us}$) hydraulic conductivity of RB and CC,
- establish the factors that influence the K of RB, and
- determine the effect of K on the risk of waterlogging.

### 7.2 Materials and methods

#### 7.2.1 Disc permeameter

A disc permeameter was selected to measure unsaturated hydraulic conductivity ($K_{us}$). The disc permeameter used was very similar to the CSIRO version described by (White et al. 1992). The base of the disc permeameter was 200 mm in diameter and covered underneath with Nytal mesh. The base was connected to a bubble tower (which controlled the tension applied) and a reservoir column (which supplied the infiltrating water). Before use the disc permeameter was calibrated according to the method of Reynolds (1993). This ensured that the height of water in the bubble tower corresponded with the intended measured tension. Calibration was done at 20 mm tension and adjustments were made accordingly.

Care was taken in site preparation to maintain the structural integrity of the soil. A level area was selected and all plant material including stubble was removed. The uneven and cloddy nature of the soil surface meant that it was often difficult to find a suitable site. A minimal (very thin) covering of sand was used to act as a contact material between the soil and the disc permeameter. A metal ring was used to prepare the sand pad as recommended by McKenzie et al. (2002b). In preparation for measurements, the reservoir column was filled with water, the tension set in the bubble tower and all air bubbles removed. A large syringe with 5 mm silicon tubing was used to accurately fill the bubble tower to the correct height (tension). The disc permeameter was then placed on the sand pad to commence infiltration measurements.
Measurements were taken at two times (September, 2003 and March 2004) on two treatments - RB and CC - at Mt Pollock. Three infiltration runs were taken randomly on each treatment plot which were replicated three times at the soil surface only. $K_{us}$ was measured at four tensions - 40, 30, 20 and 10 mm. These tensions were chosen because they are close to saturation and $K_{us}$ is most important closest to saturation. The order of tensions to measure $K_{us}$ was selected to ensure that an increasing wetting front was imposed. Furthermore problems with hysteresis are minimized (Reynolds and Elrick 1991). Measurements were taken at frequent intervals during the early part of infiltration until steady-state infiltration was reached. Steady-state was defined as a constant infiltration rate i.e. when the change in water level was the same for five consecutive time intervals. Using the steady state infiltration data the method of Ankeny et al. (1991) was selected to measure $K_{us}$.

### 7.2.2 Constant head well permeameter

The well permeameter method (Talsma and Hallam 1980) was selected to measure subsoil saturated hydraulic conductivity ($K_s$). An auger hole with a diameter of 6 cm was dug to a depth of 50 cm and was then filled with 30 cm water. The hole was then left for at least an hour to allow the soil to wet up. The well permeameter was filled with water and a clamp was attached before upturning it and placing it in the hole. The clamp was set on the well permeameter to maintain a constant depth of water. Once in place, the well permeameter was left to allow further wetting up. After at least one hour infiltration measurements began at regular intervals varying from every five minutes to once an hour according to the infiltration rate. Measurements continued until at least five consecutive readings were taken at steady-state infiltration.

$K_s$ was calculated from an average of the volume rate of water infiltrated $q$ (mm$^3$/min), using equation 7.1 (McKenzie et al. 2002b),

$$K_s = \frac{1.6q}{\pi H^2} \quad [7.1]$$
where $H$ is the depth of water in the auger hole (500 mm) and a scaling factor (1.6) recommended by McKenzie et al. (2002b). The scaling factor was recommended by Talsma (1987) who found that values measured with this method were less than the more reliable auger-hole method. Subsequently these measurements of $K_s$ were multiplied by 1440 (i.e. to convert from minutes/hour and hours/day, x 60 and x 24) to present the data in mm$^3$/day.

$K_s$ was measured 16 times in each treatment (RB and CC) at Mt Pollock in spring 2003. Sometimes there was no detectable infiltration, i.e. no change in water level within the well permeameter after at least 4 hours. In these cases the minimum measurement unit (1 mm drop for the well permeameter = 0.02 mm$^3$/day) was taken as the recorded measurement. Measurements were also taken at Briandra of RB and pasture, but are not presented due to the large number of observations with no detectable change in infiltration.

### 7.2.3 Laboratory core constant head method

A constant head method (Rowell 1994) was used to measure $K_s$ in the laboratory. This measurement was done opportunistically on small intact cores that were sampled from the surface soil for the determination of the soil water retention characteristic (presented in chapter six). Measurement was done after the cores were removed from the pressure plates.

The cores were 7.3 cm diameter and 6.5 cm height. Each core was wet up to saturation, and an extension ring was attached above with PVC tape. A volumetric flask (upturned over the soil core) was used to apply a constant head of 3 cm. Below this the core was placed over a funnel and collecting beaker. Once set up, measurements of the volume eluted were taken every 10 minutes for two hours. Two labelled beakers were weighed alternately.

$K_s$ was calculated from an average of the volume rate of water infiltrated $Q$, (cm$^3$/hour) using equation 7.2 (Marshall et al. 1996),

$$K_s = \frac{Ql}{\pi r^2 \Delta \phi} \quad [7.2]$$
where \( l \) is the length of the soil core, \( \Delta \phi \) is the hydraulic head difference between the entry and exit of the sample and \( r \) is the core radius.

### 7.2.4 Statistical analysis

The collected data was assessed for each plot and then by treatment. Descriptive summary statistics were calculated and checks made to ensure that the data were normally distributed. The significant difference between treatments was determined using ANOVA at the 5 per cent level (\( P < 0.05 \)). Where there were an insufficient number of samples a t-test was performed. Statistical analysis was performed using GenStat software (Lawes Agricultural Trust 2005).

### 7.3 Results

#### 7.3.1 Surface unsaturated hydraulic conductivity

Unsaturated hydraulic conductivity (\( K_{us} \)) measurements of RB and CC taken in September 2003 are shown in Figure 7.1. No significant differences were found between the treatments at any of the four tensions applied. The means of each treatment were close with low variation (small SE bars). The highest \( K_{us} \) was at the lowest tension (10 mm) and for both treatments \( K_{us} \) decreased as the applied tension increased. Considerable spatial variability was found with the coefficient of variation (CV) for some means of the CC > 100 per cent, but the CV for RB was much lower.
Figure 7.1 Unsaturated hydraulic conductivity of RB (□) and CC (■) at Mt Pollock in September, 2003. Bars indicate SE.

$K_{us}$ was measured again at Mt Pollock in March 2004 (Figure 7.2). As found previously there was no significant difference between the treatments. However there was more variation (larger SE and again the CV > 100 per cent) than was measured in September.

Figure 7.2 Unsaturated hydraulic conductivity of RB (□) and CC (■) at Mt Pollock in March, 2004. Bars indicate SE.
Additional observations of $K_{us}$ at Mt Pollock were taken by Johnston and Newton (unpublished data) in 2001 and 2005 (Table 7.1). These measurements were taken at different tensions (-20 and –10 mm), but regardless of this no significant difference was detected at either time.

### Table 7.1 Unsaturated hydraulic conductivity ($K_{us}$) of RB and CC at Mt Pollock in 2001 and 2005

<table>
<thead>
<tr>
<th>Time</th>
<th>Treatment</th>
<th>Tension (mm)</th>
<th>$K_{us}$ (mm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>July 2001</td>
<td>RB</td>
<td>-20</td>
<td>2.2 (0.7)</td>
</tr>
<tr>
<td></td>
<td>CC</td>
<td>-20</td>
<td>2.3 (0.2)</td>
</tr>
<tr>
<td>July 2005</td>
<td>RB</td>
<td>-10</td>
<td>7.6 (0.8)</td>
</tr>
<tr>
<td></td>
<td>CC</td>
<td>-10</td>
<td>6.7 (0.6)</td>
</tr>
</tbody>
</table>

NB. SE is given in brackets

### 7.3.2 Subsoil saturated hydraulic conductivity

Values of saturated hydraulic conductivity ($K_s$) of the subsoil at Mt Pollock in the spring 2003 are given in Table 7.2. The mean $K_s$ of the RB were significantly greater than the CC. The CC was particularly low and demonstrates the poor permeability of the B horizon. In particular, there were a number of times when the infiltration was very slow and there was no observed change in infiltration. Over a period of at least 4 hours and in other cases overnight (>12 hours) there was no difference in the level of the well permeameter. For CC, there was no observed change in the reservoir volume for three-quarters of the measurements taken, but for RB it was only a quarter of the measurements. In addition, the spatial variability was high and the CV was >100 per cent for both treatments.

Measurements of subsoil $K_s$ on pasture and RB treatments at Briandra produced similar results (data not shown). This supports the previously reported low infiltration of the subsoil which has been well-documented in studies in south-west Victoria, e.g. Gardner et al. (1994) reported a $K_s$ of 3 mm/day for a similar soil in south-western Victoria while MacEwan (1992) reported a much wider range of $K_s$ values from 3 to 660 mm/day.
Table 7.2 Saturated hydraulic conductivity ($K_s$) and percentage of measurements with no observed change (No$\Delta$) for RB and CC at Mt Pollock

<table>
<thead>
<tr>
<th>Treatment</th>
<th>$K_s$ (mm$^3$/day)</th>
<th>SE</th>
<th>No$\Delta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>1.0</td>
<td>0.6</td>
<td>75</td>
</tr>
<tr>
<td>RB</td>
<td>9.9</td>
<td>4.1</td>
<td>25</td>
</tr>
</tbody>
</table>

7.3.3 Laboratory saturated core measurement

$K_s$ was measured on intact cores taken from three depths: 0 – 10, 10 – 20 and 30 – 40 cm and the results are shown in Table 7.3. Unfortunately there were an insufficient number of samples for a statistical significance test to be undertaken. As with the previous measurements there was high variability in both treatments, but in general $K_s$ for RB was greater than $K_s$ for CC at all depths.

Table 7.3 Saturated hydraulic conductivity ($K_s$) by depth for RB and CC at Mt Pollock

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Depth (cm)</th>
<th>$K_s$ (mm/day)</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>0-10</td>
<td>375</td>
<td>133</td>
</tr>
<tr>
<td>RB</td>
<td>0-10</td>
<td>689</td>
<td>-</td>
</tr>
<tr>
<td>CC</td>
<td>10-20</td>
<td>46</td>
<td>13</td>
</tr>
<tr>
<td>RB</td>
<td>10-20</td>
<td>484</td>
<td>209</td>
</tr>
<tr>
<td>CC</td>
<td>30-40</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>RB</td>
<td>30-40</td>
<td>45</td>
<td>36</td>
</tr>
</tbody>
</table>

7.4 Discussion

Results from this study showed that the $K_{us}$ of RB and CC were similar at all tensions from -10 to -40 mm. In fact the $K_{us}$ of RB and CC were not significantly different at four sampling times in the soil surface (0-10 cm) (Figure 7.1, 7.2 and Table 7.1). Indeed this shows that different tillage methods do not necessarily result in differences in surface $K_{us}$. The $K_s$ of the RB was greater than the CC for the subsoil measurements in the field and on surface soil samples in the laboratory. The field-measured $K_s$ values (Table 7.2) were low and were measured in the spring when the soil may have remained wet or swollen from winter rainfall. Thus, it is predicted that $K_s$ would be greater (for both treatments) after a
period of cropping in the summer. The measurements of $K_s$ taken in the laboratory on the cores (Table 7.3) were considerably greater than in the field (Table 7.2). This includes soil of a similar nature from the same depth, i.e. when comparing the 30-40 cm depth. The reason for this difference could be due to edge flow along the side of the core (Rowell 1994) or the small size of the cores (Reynolds et al. 2000), both of which can lead to errors. Reynolds et al. (2000) found that the measurement of $K_s$ with soil cores was highly variable and much more variable than other measurement methods. In addition the field values could be low due to smearing in the auger hole (Nash et al. 1986). The greater $K_s$ of the RB compared to the CC equates with an increased functional depth of the A horizon in the RB. This could be caused by the greater cultivation depth on the RB compared to the CC. The RB were cultivated up to 25 cm depth while the CC only received shallow cultivation to 4 cm (section 3.1.1). Therefore from the data given it is predicted that RB reduce the risk of waterlogging. However as a significant difference was not found in the soil surface these results should be viewed cautiously. In addition the significant difference between the RB and CC was detected at only one measurement of subsoil $K_s$ in the field.

By way of comparison other RB studies have found differences in $K$. In Western Australia, Bakker et al. (2005) measured the $K$ of RB and a control (similar to the CC treatment in this study). At some sites $K$ for RB was much higher than the control at saturation, but at tensions of 20 or 40 mm the control was higher. However as no statistical tests were performed the significance of the difference between the treatments is not known. Furthermore, geometric mean values were presented which averaged data taken over four years. This adds to the uncertainty of the actual treatment difference and also hides any temporal variation. A Tasmanian study by Cotching and Dean (2001) reported significantly ($P < 0.05$) greater infiltration for RB compared to a control treatment. This finding was based on a single observation taken < 2 years after the RB were formed. Therefore, at times RB have greater $K$, although the difference may not always be significant; in particular the results from Bakker et al. (2005) were unclear.

Whether differences are found or not, depends upon external factors which are yet to be understood. Differences in $K$ have been caused by many factors, including the effect of plant roots (Yunusa et al. 2002) and sodicity (Naidu et al. 1995). Differences in these
factors are unlikely given that at 10 mm tension both treatments were measured between 60-80 mm/hr. K is also affected by compaction and Ankeny et al. (1990) found a significant difference between areas with and without traffic. Any effects induced by these factors were assumed to be the same (or minimal) on the RB and CC soil. The lack of difference in K_us suggests there are no unique factors that control K in the soil surface of RB. Possibly the measurement of soil structure will yield a better understanding of K. Indeed the relationship between K and structure is becoming increasingly well understood (Collis-George 1991; Crawford 1994; Durner 1994; Vervoort and Cattle 2003).

The length of time since a tillage treatment has been imposed is important because it affects the extent of change in K. Measurements at Mt Pollock were made on treatments that had been established in 1999. Previous studies have shown that it takes time for K to change. For example, two years after clearing Whitbread et al. (1998) detected no significant difference in K between a cropping treatment compared to an undisturbed site, but a site that had been cultivated for > 15 years significantly lower K was measured. While in a mine rehabilitation study Loch and Orange (1997) noted that it took four years for the maximum change in K to occur, after which time there was minimal change. Therefore, it is possible that an insufficient length of time has elapsed for changes between RB and CC to have completely developed in surface K_us.

The times when the surface K_us was measured are important. Seasonal variation can add a degree of complexity and cause difficulties when detecting differences between treatments. Murphy et al. (1993) reported considerable temporal changes in K during a growing season. Murphy et al. claimed that changes were partly explained by the formation of new pores from growing roots and the drying of the soil. Thus it is possible that seasonal changes are masking differences between the treatments. Indeed Murphy et al showed that several measurements of K are required during a growing season to adequately cover the range of temporal variation. Consequently, from the measurements taken, it is not possible to detect whether there was any seasonal effect in this study.

Regardless of temporal or other physical factors that may complicate the measurement of K, this study clearly shows that there was a large difference in the infiltration of water
between the A and B horizons. For instance in the RB, the field measured $K_{us}$ in the surface was $> 60$ mm/ hour compared to 10 mm/ day for the subsoil $K_s$. This throttle to soil infiltration at the B horizon was found in both treatments. Thus over the whole profile it was shown that the internal drainage was similar between the treatments. Therefore $K$ appears to have little effect on the development of saturated conditions for either RB or CC. In contrast the external drainage of RB was found to be much greater, e.g. $>30$ per cent more run-off was produced from RB between 2002 and 2004 (Table 4.8). A discussion on external drainage measured as run-off was given previously in section 4.4.3. The greater run-off from the RB equates to improved drainage and is probably due to the different surface morphology of the soil, i.e. with furrows (that act as conduits) compared to flat. Consequently, it is proposed that RB reduce waterlogging risk by providing better external drainage pathways for excess water to be shed.

### 7.5 Conclusion

The $K_{us}$ of the soil surface on RB was not significantly different from the CC. However in the B horizon the $K_s$ of the RB was significantly greater. A large difference was found in $K$ between the A and B horizons. $K$ may have been influenced by the time of measurement and almost certainly by the length of time since the treatments were established. Therefore it is possible that insufficient time has elapsed for a significant difference to develop between the treatments. This suggests that internal drainage was similar between the treatments, although it was found to be slightly better for the RB. The most important difference between the treatments is probably the greater external drainage which reduces the risk of waterlogging.
CHAPTER EIGHT

8 Pore pathways of raised bed and conventional cultivated soil from the analysis of solute flow

8.1 Introduction

Solute transport studies have become increasingly popular in monitoring the flow of water and chemicals that are dissolved in it. The simplest way to understand solute transport data are by plotting breakthrough curves (BTCs). A BTC is a plot of the effluent concentration as a function of time or volume of solution eluted from a column of soil (Skaggs and Leij 2002). Such a plot can be described as a probability density function (pdf) of travel times or drainage pathways. The patterns of BTCs are affected by several factors, namely the nature of the pore network, the method and period of solute application and the type of solute.

This experiment will focus only on the physical processes that occur during solute transport that can yield information on the porous network through which solution flows. For example, Jury et al. (1991) found that solute was eluted most quickly from a better structured, undisturbed soil column compared to repacked soil. The breakthrough in the repacked column occurred later which indicated it contained less macropores than the undisturbed column. Andreini and Steenhuis (1990) measured concentrations of Br\(^-\) from two tillage treatments (no-till and conventional) to calculate BTCs and differentiate areas where bypass flow occurred in contrast to flow through the soil matrix. Almost all the soil matrix was bypassed in the no-till treatment, whereas in the conventional tillage soil the Br\(^-\) passed through the matrix. This showed that the no-till treatment contained a more connected pore network. Therefore, observations made from BTCs that describe solute transport can provide indications on soil structure.
8.1.1 Experimental objectives

This chapter aims to measure solute movement through RB and CC soil to describe the network of pores through which solution flows in each treatment. In particular, preferential flow is thought to be a significant flow process. It is predicted that an improved understanding of soil structure will be gained by exploring the extent to which solution from each treatment is absorbed, transmitted and released. To achieve this, a number of objectives were set, such as to:

- measure the soil bulk density and calculate the total porosity and pore volume;
- measure the drainage flux density of the solute for each applied pulse;
- model the solute movement through the soil using a transfer function approach with the CDE model and the CLT model;
- compare the breakthrough curves and key parameters from the best fitted model;
- monitor the soil water content ($\theta_v$) during each drainage event;
- calculate the transport volume ($\theta_s$) and compare it to $\theta_v$; and
- determine the relative proportion of preferential to matrix flow.

8.2 Material and methods

8.2.1 Sampling of intact cores

Undisturbed soil samples were collected with PVC cores (internal diameter 23.6 cm, length 20 cm) from six experimental plots (one from three replicates of each treatment - RB and CC) at Mt Pollock in July 2004. The excavation method chosen was the same as that described by McKenzie and Cresswell (2002) (Figure 8.1.). Using this method ensured that the samples retained an intact status which closely represented their condition in the field.

In each plot a representative uniform area was selected and a circular trench was dug (25 cm deep) to form a pedestal of approximately 35 cm diameter. A core guide was placed...
over the middle of the pedestal and made level (using a spirit level). A PVC core with a bevelled leading edge was placed inside the core guide and above the core a spacer and steel plate was placed. The bottom side of a backhoe bucket was pushed downwards onto the plate, thus forcing the PVC sample core into the soil (Figure 8.1.) After the sample core was completely pushed in, the core guide was removed. Petroleum jelly (Shell Snow White Petrolatum™) was heated until melting point and injected into a gap between the soil and the inside edge of the core. The petroleum jelly was injected to prevent the occurrence of edge-flow down the wall of the core (Cameron et al. 1990). The diameter of soil within the core was 22.5 cm due to the thickness of petroleum jelly around the edge of each core. After the petroleum jelly had solidified the core sample was removed by digging underneath it, thus to yield a complete structural unit. The core sample was then transported to a cool room for storage until commencement of the leaching experiments.

Figure 8.1 Excavating large intact cores using a core guide. Photograph: A. Ringrose-Voase
Visual observation of the soil (within the intact cores) when samples were collected (after solute leaching was finished) to measure BD indicated there was a distinct change in texture towards the base of each core. This was characterised by an increase in clay content, approximately within the bottom 5 cm. This clay layer was most likely the upper part of the B horizon. Further details on the profile pedology were given in the characterisation of the experimental site in chapter three.

### 8.2.2 Preliminary experiment

When the six cores were sampled for the experiment an additional core was taken and used as a “practice” core before commencing on the experimental cores. A preliminary test run was performed to check that the correct apparatus was selected so that the experiment would operate smoothly. For instance different tensions were selected as initially the mean pore water velocity was unknown. The drainage was tested at -100 mm, but it was found to be extremely slow at this tension. Subsequently the two tensions chosen were close to saturation (-5 mm) and slightly unsaturated (-30 mm). At the same time an effective method was found to collect the eluted solution. The solute chosen was potassium chloride (KCl) - a conservative, non-reactive solute. It was assumed there was little indigenous K or Cl in the soil before the experiment. In addition, minimal ion exchange should occur between the salt solution and the soil matrix.

### 8.2.3 Leaching experiment methodology

The apparatus used for the drainage experiment was similar to that described by Magesan et al. (1995) and Heng et al. (1999). One modification to the apparatus was the insertion of ThetaProbes (Delta – T, Cambridge, U.K.) into the side of the cores at two depths: 5 and 15 cm from the soil surface. The ThetaProbes measured the $\theta_v$ every 20 minutes and were connected to a data logger (TAIN Electronics, Melbourne, Australia). The edge of each ThetaProbe was sealed with a silicon sealant where it was inserted into the PVC core. This prevented solute from leaking out during the experiment (Figure 8.2). $\theta_v$ data were downloaded after the last solution had finished draining.
A KCl solution was used and its velocity was determined by measuring the EC (dS m⁻¹) of the eluted solution with a digital EC meter (Model WP-81 Conductivity-Salinity-pH-Temp. Meter TPS Pty Ltd Brisbane, Australia). A linear relationship was found between EC and the concentration of KCl in solution (g L⁻¹), established using values from Weast and Astle (1981). Two concentration strengths of solution were used: a resident solution (0.02 M KCl) and a pulse solution (2 M KCl). The pulse solution is most important, because it supplies a known solute concentration at a set starting point. This allows the determination of BTCs and the characterization of solution flow behaviour. The amount of pulse solution supplied was approximately 10 % of one half pore volume (PV). PV is the volume of total pore space within a column of soil.

A disc permeameter supplied solution (under tension) at the soil surface (Figure 8.2). Three pulse solutions were run on each core, first a pulse at –30 mm tension (slightly unsaturated), followed by a pulse at -5 mm (close to saturation) and finally a repeat (of the first pulse) pulse at – 30 mm tension. The repeat pulse was performed to test the stability of the soil to further wetting and as a comparison with the first pulse applied. A small negative pressure (equal to the applied tension at the surface) was maintained at the base of each core. A vacuum was regulated by passing suction through a bubbling tower (Heng et al. 1999).
The base of each core was carefully levelled off to maintain natural structure without any smeared macropores. As this was the exit surface, it was covered in nylon mesh to prevent any collapsed soil particles from coming into solution. The core was then placed into a large perspex funnel and sealed with multi-purpose silicon sealant along the edge between the core and the funnel. Underneath the funnel a 2 L Erlenmeyer flask was connected for the collection of leached solution (Figure 8.3). The effluent collected was measured by weight on a digital balance, assuming a density of 1 g/cm³. The frequency of changing the flask was adjusted according to the outflow rate, which varied with each soil core and according to the tension applied.
At the start of the experiment each core was wet up (at –30 mm tension) with resident solution to ensure that uniform antecedent $\theta_v$ was attained before the addition of a pulse solution. This avoids the potential variability of $\theta_v$ in affecting solute outflow as highlighted by Vogeler et al. (1997). In order to be consistent between cores, an estimated two PV was applied in each case. The solute eluted from each core was measured to establish a baseline concentration value before the pulse solution was applied. After the pulse was applied the resident solution was immediately supplied until the eluting solution had dropped to the solute concentration of the resident solution (i.e. “free” of the pulse solution).

During the application of the second pulse of the third replicate (cores 7 and 8) insufficient data were collected to adequately represent BTCs. This was caused by the malfunction (crash) of the computer that was recording the collected solute data and also
there was a leakage of solution from the side of the cores. Both these mishaps occurred approximately simultaneously. Consequently cores 7 and 8 received an additional pulse of solute which was nine extra hours leaching time. This equates to at least 7 L for core 7 and over 3 L for core 8. However to avoid confusion the third and fourth pulses (for cores 7 and 8) will be referred to as the second and third measured pulses, thus using the same notation as the other cores.

After the soil water and drainage measurements were completed the soil bulk density (BD) was determined using the core method (given previously in section 3.2.5). Four cores were taken at two depths: 0-7 cm and 10-15 cm. The total soil porosity was calculated from the BD using equation 2.2 and the PV was then calculated from the total porosity.

8.2.4 Parameterisation of transfer function models

Transfer function models (TFMs) were chosen to characterise the solute transport from the measurement of solute concentration and drainage volume. TFMs were selected, because of the quasi-functional meaning of their coefficients which describe aspects of measured drainage data. Two TFMs were used, the convective log-normal transfer function model (CLT) (equation 2.15) and the convective-dispersion transfer function model (CDE) (equation 2.18). However the CDE was found to fit poorly compared to CLT. Thus only parameter coefficients from the CLT were used to make numerical comparisons between each treatment. The concentration of KCl was normalised to account for the mass of solute leached ($M_1$). The solute mass applied ($M_o$) was found to be close (<15 per cent different) to $M_1$. No attempt was made to distinguish the resident solute concentration ($C_R$) from the leached solute concentration ($C_L$). The $C_L$ was modelled as a proportion of the $M_1$.

$$f = \frac{C_L}{M_1} \quad [8.1]$$
The TFMs are presented as a pdf. The pdf describes the probability that an individual solute molecule, applied at the surface at time \( t_1 \), will have exited from the core at depth \( L \) in time \( t_1 + t_2 \). The CLT was solved using a least squares optimisation regression method using Sigma Plot software (Systat Software Inc. 2004). The independent variable was cumulative drainage \( I \) (mm) and the pdf was expressed in units of mm\(^{-1}\).

### 8.2.5 Statistical analysis

Analysis of variance (ANOVA) was used to calculate the least significant difference (LSD) between the treatments for BD, total porosity; in the same way at each pulse the treatments were compared for \( \mu, \sigma^2, \theta_{st} \) and the \( \theta_{st} : \theta_c \) ratio. The ANOVA was performed with treatment as the main factor and the pulse as an interaction term. Due to the irregular number of measurements taken for the drainage flux density the student’s T-test was used to calculate the significant difference between the treatments for each pulse. The T-test was on paired samples and variance was calculated separately. Statistical significant difference was determined at the five per cent level (\( P < 0.05 \)) using GenStat software (Lawes Agricultural Trust 2005).

### 8.3 Results and discussion

#### 8.3.1 Bulk density and total porosity

The BD and total porosity of each core sample are shown in Table 8.1. There was no significant difference between the RB and CC over the two measured depth ranges in total porosity or BD. There was a slight increase in BD from the surface soil (0-7 cm) compared to samples from the 10-15 cm depth range. As a corollary for both treatments there was a decrease in total porosity. The total PV for each core was estimated from the total porosity between 0-7 and 10-15 cm. A comparison of the estimated PVs identifies some variation, with the range of values greater for the CC cores.
Similarity in BD was unexpected and differs from previously where the RB had lower BD (e.g. Figure 6.2). This demonstrates that at times there is little difference in the physical properties between the RB and CC. The lack of difference in total porosity ensures that the pore architecture would be tested without the amount of porosity as an additional complicating factor. For instance, differences in porosity would have also affected the solution flow characteristics. Determining differences in structure has been made easier with additional measurements such as the pore size distribution. This was done in the solute transport studies by Bejat et al. (2000) and Suter (1997). The measurement of pore size distribution was not considered for this experiment because the data presented in chapter six showed only small differences between the RB and CC.
## Table 8.1 Bulk density and total porosity by depth for both treatments of each core, and the total pore volume for each core

<table>
<thead>
<tr>
<th>Plot</th>
<th>Treatment</th>
<th>Depth (cm)</th>
<th>Bulk density (Mg/m³)</th>
<th>Total porosity (m³/m³)</th>
<th>Total pore volume (cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CC</td>
<td>0 – 7</td>
<td>1.31</td>
<td>0.50</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>CC</td>
<td>0 – 7</td>
<td>1.27</td>
<td>0.52</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>CC</td>
<td>0 - 7</td>
<td>1.38</td>
<td>0.48</td>
<td>-</td>
</tr>
<tr>
<td>mean</td>
<td>CC</td>
<td>0 - 7</td>
<td>1.32 (0.02)</td>
<td>0.50 (0.01)</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>RB</td>
<td>0 - 7</td>
<td>1.24</td>
<td>0.53</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>RB</td>
<td>0 - 7</td>
<td>1.37</td>
<td>0.48</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>RB</td>
<td>0 – 7</td>
<td>1.34</td>
<td>0.49</td>
<td>-</td>
</tr>
<tr>
<td>mean</td>
<td>RB</td>
<td>0 – 7</td>
<td>1.32 (0.03)</td>
<td>0.50 (0.01)</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>CC</td>
<td>10 – 15</td>
<td>1.22</td>
<td>0.54</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>CC</td>
<td>10 – 15</td>
<td>1.55</td>
<td>0.42</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>CC</td>
<td>10 – 15</td>
<td>1.59</td>
<td>0.40</td>
<td>-</td>
</tr>
<tr>
<td>mean</td>
<td>CC</td>
<td>10 – 15</td>
<td>1.45 (0.05)</td>
<td>0.45 (0.02)</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>RB</td>
<td>10 – 15</td>
<td>1.33</td>
<td>0.50</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>RB</td>
<td>10 – 15</td>
<td>1.49</td>
<td>0.44</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>RB</td>
<td>10 – 15</td>
<td>1.48</td>
<td>0.44</td>
<td>-</td>
</tr>
<tr>
<td>mean</td>
<td>RB</td>
<td>10 – 15</td>
<td>1.44 (0.03)</td>
<td>0.46 (0.01)</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>CC</td>
<td>0 – 20</td>
<td>-</td>
<td>-</td>
<td>4152</td>
</tr>
<tr>
<td>6</td>
<td>CC</td>
<td>0 – 20</td>
<td>-</td>
<td>-</td>
<td>3717</td>
</tr>
<tr>
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<td>CC</td>
<td>0 – 20</td>
<td>-</td>
<td>-</td>
<td>3501</td>
</tr>
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<td>0 – 20</td>
<td>-</td>
<td>-</td>
<td>4082</td>
</tr>
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<td>RB</td>
<td>0 – 20</td>
<td>-</td>
<td>-</td>
<td>3660</td>
</tr>
<tr>
<td>7</td>
<td>RB</td>
<td>0 – 20</td>
<td>-</td>
<td>-</td>
<td>3720</td>
</tr>
</tbody>
</table>

**LSD**  
0.30 0.04

NB. At each depth four BD samples were taken from each core; the number of samples for each treatment was 12. SE is shown in brackets.
8.3.2 Drainage flow rates

The drainage flux density (mm/hr) was calculated on the solution collected and is given for all cores at the first, second and third pulses in Table 8.2.
Table 8.2 Drainage flux density (mm/hr) for each core at pulse 1, 2 and 3 by treatment

<table>
<thead>
<tr>
<th>Plot</th>
<th>Treatment</th>
<th>Pulse</th>
<th>Flux density (mm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CC</td>
<td>1</td>
<td>8.8 (0.59)</td>
</tr>
<tr>
<td>6</td>
<td>CC</td>
<td>1</td>
<td>6.6 (0.21)</td>
</tr>
<tr>
<td>8</td>
<td>CC</td>
<td>1</td>
<td>7.3 (0.6)</td>
</tr>
<tr>
<td>mean</td>
<td>CC</td>
<td></td>
<td>7.6 <em>a</em></td>
</tr>
<tr>
<td>2</td>
<td>RB</td>
<td>1</td>
<td>9.31 (0.38)</td>
</tr>
<tr>
<td>4</td>
<td>RB</td>
<td>1</td>
<td>6.33 (0.19)</td>
</tr>
<tr>
<td>7</td>
<td>RB</td>
<td>1</td>
<td>4.72 (0.59)</td>
</tr>
<tr>
<td>mean</td>
<td>RB</td>
<td></td>
<td>6.8 <em>a</em></td>
</tr>
<tr>
<td>1</td>
<td>CC</td>
<td>2</td>
<td>46.1 (2.5)</td>
</tr>
<tr>
<td>6</td>
<td>CC</td>
<td>2</td>
<td>5.6 (0.17)</td>
</tr>
<tr>
<td>8</td>
<td>CC</td>
<td>2</td>
<td>8.5 (0.11)</td>
</tr>
<tr>
<td>mean</td>
<td>CC</td>
<td></td>
<td>20.1 <em>a</em></td>
</tr>
<tr>
<td>2</td>
<td>RB</td>
<td>2</td>
<td>112.1 (12.0)</td>
</tr>
<tr>
<td>4</td>
<td>RB</td>
<td>2</td>
<td>24.2 (1.5)</td>
</tr>
<tr>
<td>7</td>
<td>RB</td>
<td>2</td>
<td>35.3 (2.0)</td>
</tr>
<tr>
<td>mean</td>
<td>RB</td>
<td></td>
<td>57.2 <em>b</em></td>
</tr>
<tr>
<td>1</td>
<td>CC</td>
<td>3</td>
<td>11.9 (0.19)</td>
</tr>
<tr>
<td>6</td>
<td>CC</td>
<td>3</td>
<td>1.5 (0.08)</td>
</tr>
<tr>
<td>8</td>
<td>CC</td>
<td>3</td>
<td>6.1 (0.15)</td>
</tr>
<tr>
<td>mean</td>
<td>CC</td>
<td></td>
<td>6.5 <em>a</em></td>
</tr>
<tr>
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<td>RB</td>
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<td>11.8 (0.25)</td>
</tr>
<tr>
<td>4</td>
<td>RB</td>
<td>3</td>
<td>6.1 (0.34)</td>
</tr>
<tr>
<td>7</td>
<td>RB</td>
<td>3</td>
<td>8.3 (0.34)</td>
</tr>
<tr>
<td>mean</td>
<td>RB</td>
<td></td>
<td>8.7 <em>a</em></td>
</tr>
</tbody>
</table>

NB. Treatment means for the same pulse are not significantly different (P < 0.05) with the same letter. SE is shown in brackets.

The drainage flux density for the first pulse was mostly around 7 mm/hr for both treatments. The core samples varied within a range from 4 to 9 mm/hr. Greater
variability was found for the RB compared to the CC, but there was no significant difference between the treatment means.

As the second pulse was operating at nearly saturated conditions (-5 mm tension) it drained much more quickly than the first pulse. The faster drainage flux density meant that the whole experiment took less than two hours compared to more than eight hours at -30 mm tension. It was so fast that maintaining continual steady state flow was not easy, especially at the change-over point when the disc permeameter required re-filling. The mean for the RB was 57 mm/hr which was significantly faster than the CC mean at 20 mm/hr. Each treatment showed considerable variability both within and between cores.

The third pulse was the same tension as the first pulse (-30 mm) and the drainage flux density was the most uniform of the three pulses. The mean of the RB cores was 8.7 mm/hr which very similar to the flux density for the first pulse. In comparison the CC cores varied more, but the CC mean (6.5 mm/hr) was also similar to the value measured for the first pulse.

One difficulty in carrying out these experiments was the long period required to reach completion (up to 12 hours for one pulse). Usually it was necessary to re-fill the reservoir column in the disc permeameter at least two or three times. Thus discontinuity of leaching during the experiment caused the drainage flux density to fluctuate.

Several explanations for the variability in the flux density are suggested. First, it is possible that during the first two pulses, there was a lack of control in applying a constant supply of solute because the disc permeameter emptied of solute before sufficient volume had been eluted. At the same time there could have been some instability in the network of pore pathways which had slowed by the third pulse. Despite the pre-wetting of all cores before the first concentration pulse, it is possible that the soil had not completely wet to homogenous $\theta_v$. Consequently there were two components to the variability that was measured. There was within core variability which resulted in fluctuations in flux density and there was between core variability which was due to field spatial variability.
or actual treatment differences. Heng et al. (1999) also reported considerable fluctuations in drainage flux density and suggested this was due to ongoing biological activity in the soil during the experiment. Nevertheless despite the variability the largest difference between the RB and CC was found during the fastest period of drainage which was closest to saturation.

Differences in soil structure may explain the drainage flux density values of the RB and CC cores. Suter (1997) noticed that one core was flowing faster than another in a solute transport experiment. To investigate this difference Suter measured the SWRC, which enabled the calculation of a pore size distribution. This showed that at each soil water potential value, the faster core was associated with a distinctly different arrangement of pores. Bejat et al. (2000) claimed that under unsaturated conditions it was not possible to determine a direct relationship between drainage and structure because differences in $\theta$, at a given flow rate would be related to pore size distribution differences. Thus it is interesting that the largest difference between RB and CC found in this study was closest to saturated conditions. Such conditions are considered to be of most relevance when the soil is approaching the risk of waterlogging. On these soils the RB were found to have a significantly greater flux density than the CC (Table 8.2).

Persson and Berndtsson (1999) and Vanderborght et al. (2000) showed that flow rate strongly influenced which parametric model best fitted the measured data. In each study the slow flow rate was well described by the CDE whereas the CLT better described the faster flow rate. Thus flow rate (which is a function of the applied tension, the pore size distribution and pore continuity) affects which TFM best fits the data.

### 8.3.3 Solute breakthrough curves

Before fitting the measured data to a TFM, the data were plotted as BTCs to check their shape and form. Plotting the distribution of solute concentration as a function of cumulative drainage ($I$) was undertaken to provide a preliminary overview of solute transport through each soil core. Most BTCs were log-normal in shape and often
characterised by a front that sharply rose to a peak. This was followed by a gentle falling slope that tailed off to the initial value of the resident solute concentration. Differences in the shape of the BTCs indicate differences in the solute travel pathlength and amount of solute mixing in the soil of each treatment. An example of typical BTCs are given in Figure 8.4 for each treatment. Here core 1 (CC) was a distinctly different shape to core 2 (RB) as it rose sharply to a peak and fell away much earlier. In contrast, core 2 was slower to increase and rose to a broad peak before decreasing to the same resident concentration as core 1.

![Figure 8.4 Concentration of leached solute (C_L) from the second pulse at -5 mm tension for core 1 - CC (●) and core 2 - RB (▲)](image)

### 8.3.4 Convective lognormal transfer model parameters

The parameterised CLT was used to fit the measured data and to derive values for the key parameters - $\mu$ and $\sigma$. The parameters for the first, second and third pulse are given in Table 8.3.
Table 8.3 Optimised parameters ($\mu$ and $\sigma$) from the CLT model for the pulse 1, 2 and 3 by treatment

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Replicate</th>
<th>Plot</th>
<th>Pulse</th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4.20</td>
<td>0.64</td>
<td>0.88</td>
</tr>
<tr>
<td>CC</td>
<td>2</td>
<td>6</td>
<td>1</td>
<td>3.97</td>
<td>0.77</td>
<td>0.91</td>
</tr>
<tr>
<td>CC</td>
<td>3</td>
<td>8</td>
<td>1</td>
<td>3.87</td>
<td>0.57</td>
<td>0.91</td>
</tr>
<tr>
<td>CC mean</td>
<td></td>
<td></td>
<td>1</td>
<td>4.02</td>
<td>0.66</td>
<td></td>
</tr>
<tr>
<td>RB</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>4.12</td>
<td>0.69</td>
<td>0.86</td>
</tr>
<tr>
<td>RB</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td>3.93</td>
<td>0.60</td>
<td>0.94</td>
</tr>
<tr>
<td>RB</td>
<td>3</td>
<td>7</td>
<td>1</td>
<td>4.08</td>
<td>0.46</td>
<td>0.90</td>
</tr>
<tr>
<td>RB mean</td>
<td></td>
<td></td>
<td>1</td>
<td>4.04</td>
<td>0.58</td>
<td></td>
</tr>
<tr>
<td>CC</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3.96</td>
<td>1.08</td>
<td>0.88</td>
</tr>
<tr>
<td>CC</td>
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<td>6</td>
<td>2</td>
<td>3.76</td>
<td>1.24</td>
<td>0.93</td>
</tr>
<tr>
<td>CC</td>
<td>3</td>
<td>8</td>
<td>2</td>
<td>3.52</td>
<td>1.11</td>
<td>0.85</td>
</tr>
<tr>
<td>CC mean</td>
<td></td>
<td></td>
<td>2</td>
<td>3.74</td>
<td>1.14</td>
<td></td>
</tr>
<tr>
<td>RB</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>4.32</td>
<td>0.80</td>
<td>0.95</td>
</tr>
<tr>
<td>RB</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>3.78</td>
<td>0.94</td>
<td>0.95</td>
</tr>
<tr>
<td>RB</td>
<td>3</td>
<td>7</td>
<td>2</td>
<td>4.11</td>
<td>0.80</td>
<td>0.81</td>
</tr>
<tr>
<td>RB mean</td>
<td></td>
<td></td>
<td>2</td>
<td>4.07</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td>CC</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3.97</td>
<td>0.70</td>
<td>0.87</td>
</tr>
<tr>
<td>CC</td>
<td>2</td>
<td>6</td>
<td>3</td>
<td>3.49</td>
<td>0.73</td>
<td>0.91</td>
</tr>
<tr>
<td>CC</td>
<td>3</td>
<td>8</td>
<td>3</td>
<td>3.76</td>
<td>0.76</td>
<td>0.96</td>
</tr>
<tr>
<td>CC Mean</td>
<td></td>
<td></td>
<td>3</td>
<td>3.74</td>
<td>0.74</td>
<td></td>
</tr>
<tr>
<td>RB</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3.94</td>
<td>0.54</td>
<td>0.85</td>
</tr>
<tr>
<td>RB</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>4.10</td>
<td>0.65</td>
<td>0.81</td>
</tr>
<tr>
<td>RB</td>
<td>3</td>
<td>7</td>
<td>3</td>
<td>4.11</td>
<td>0.49</td>
<td>0.92</td>
</tr>
<tr>
<td>RB Mean</td>
<td></td>
<td></td>
<td>3</td>
<td>4.05</td>
<td>0.56</td>
<td></td>
</tr>
<tr>
<td>LSD</td>
<td></td>
<td></td>
<td></td>
<td>0.32</td>
<td>0.12</td>
<td></td>
</tr>
</tbody>
</table>

The $\mu$ for the first pulse varied over a similar range and the mean for both treatments was similar. The $\sigma$ was slightly less for RB (0.58) than for CC (0.66), but there was no significant difference between the treatments for either parameter. The largest differences were found at the second pulse. The $\mu$ of the CC (3.74) was significantly less than the RB (4.07), while $\sigma$ for CC (1.14) was significantly greater in comparison to the RB (0.85), in fact the $\sigma$ of CC was nearly twice $\sigma$ at the first pulse. $\mu$ is the mean value for the distribution of $I$ and thus the mean travel pathlength. The smaller $\mu$ of the CC at the
second and third pulse indicates that the CC has a shorter travel pathlength than the RB. \( \sigma \) is the standard deviation of the distribution of \( I \) and relates to the amount of solute dispersion. The larger \( \sigma \) of the CC indicates significantly greater solute spreading in the CC than the RB at the second and third pulses. At the third (i.e. the repeat –30 mm tension) pulse there was no significant difference between the treatments for \( \mu \). The \( \mu \) did not change much compared to the values optimised at the second pulse, but \( \sigma \) returned to values nearer to the first -30 mm pulse. Although \( \sigma \) was still significantly less for the RB than the CC.

From the optimised parameters of the CLT model some distinct and significant differences were detected. Four key findings were made from the derived parameters:

1) There were only minor differences (not significant) between the parameters for each treatment at the first pulse. This was most likely due to the antecedent unsaturated conditions.

2) At the second pulse the CC had a significantly smaller travel pathlength (less \( \mu \)) than the RB. This shows that solute flowed through in a shorter time in the CC than the RB.

3) However at the second pulse and third pulse there was significantly greater solute spreading (according to \( \sigma \)) in CC compared to RB. This indicates that over the course of the experiment there was more variation in flow paths of the CC than the RB.

4) Both the RB parameter values were more uniform than the CC over the course of the experiment. This suggests that the pore structure through which the solute travelled was more stable.

After reviewing several solute transport studies Edis and White (2003) reported there was no relationship between \( \sigma \) and soil texture. It would also seem that \( \sigma \) has no relationship with structure. Published values of \( \sigma \) from previous solute transport experiments using intact cores that contained structured clay include: 0.38 to 0.58 (Suter 1997) and 0.8 (Heng and White 1996). Where the structure was not specified \( \sigma \) varied over a similar range 0.43 to 0.70 (Persson and Berndtsson 1998) and 0.40 to 0.81 (Vanderborgh et al. 1997). In this experiment the RB (ranged between 0.56-0.85) were mostly less than the
CC (ranged between 0.66-1.14), but there was some overlap. With such a large variation in \( \sigma \) there does not appear to be a direct relationship to soil structure.

### 8.3.5 Transport volume and volumetric water content

The transport volume \((\theta_{st})\) was calculated with the optimised parameters (\(\mu\) and \(\sigma\)) using the mean travel time pathlength (given previously in equation 2.17). The \(\theta_{st}\) is the proportion of the soil volume that participates in solute transport. It enables a functional relationship to be developed between parameters of the CLT and solute transport within the whole soil volume. In fact the magnitude of the \(\theta_{st}\) can explain the type of solute flow that is occurring. Dyson and White (1987) reported that the effects of macropore flow could be detected when the \(\theta_{st}\) was less than the volumetric water content \((\theta_v)\). On this basis, the \(\theta_{st}\) was calculated and are compared with the measured \(\theta_v\). The \(\theta_{st}\) and \(\theta_v\) for each treatment at the first, second and third pulse are given in Table 8.4.
Table 8.4 Calculated transport volume ($\theta_{st}$) and measured volumetric water content ($\theta_v$) for all leaching events

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Replicate</th>
<th>Plot</th>
<th>Pulse</th>
<th>Applied tension (mm)</th>
<th>Transport volume, $\theta_{st}$</th>
<th>Volumetric water content, $\theta_v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-30</td>
<td>0.05</td>
<td>0.38</td>
</tr>
<tr>
<td>CC</td>
<td>2</td>
<td>6</td>
<td>1</td>
<td>-30</td>
<td>0.06</td>
<td>0.38</td>
</tr>
<tr>
<td>CC</td>
<td>3</td>
<td>8</td>
<td>1</td>
<td>-30</td>
<td>0.05</td>
<td>0.34</td>
</tr>
<tr>
<td>CC</td>
<td>mean</td>
<td></td>
<td></td>
<td></td>
<td>0.05 (&lt;0.01)</td>
<td>0.37 (0.01)</td>
</tr>
<tr>
<td>RB</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>-30</td>
<td>0.05</td>
<td>0.36</td>
</tr>
<tr>
<td>RB</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td>-30</td>
<td>0.06</td>
<td>0.39</td>
</tr>
<tr>
<td>RB</td>
<td>3</td>
<td>7</td>
<td>1</td>
<td>-30</td>
<td>0.04</td>
<td>0.36</td>
</tr>
<tr>
<td>RB</td>
<td>mean</td>
<td></td>
<td></td>
<td></td>
<td>0.05 (&lt;0.01)</td>
<td>0.37 (&lt;0.01)</td>
</tr>
<tr>
<td>CC</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>-5</td>
<td>0.05</td>
<td>0.39</td>
</tr>
<tr>
<td>CC</td>
<td>2</td>
<td>6</td>
<td>2</td>
<td>-5</td>
<td>0.07</td>
<td>0.38</td>
</tr>
<tr>
<td>CC</td>
<td>3</td>
<td>8</td>
<td>2</td>
<td>-5</td>
<td>0.04</td>
<td>0.35</td>
</tr>
<tr>
<td>CC</td>
<td>mean</td>
<td></td>
<td></td>
<td></td>
<td>0.06 (0.02)</td>
<td>0.37 (0.12)</td>
</tr>
<tr>
<td>RB</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>-5</td>
<td>0.04</td>
<td>0.37</td>
</tr>
<tr>
<td>RB</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>-5</td>
<td>0.05</td>
<td>0.39</td>
</tr>
<tr>
<td>RB</td>
<td>3</td>
<td>7</td>
<td>2</td>
<td>-5</td>
<td>0.05</td>
<td>0.37</td>
</tr>
<tr>
<td>RB</td>
<td>mean</td>
<td></td>
<td></td>
<td></td>
<td>0.05 (&lt;0.01)</td>
<td>0.38 (&lt;0.01)</td>
</tr>
<tr>
<td>CC</td>
<td>3</td>
<td>8</td>
<td>3</td>
<td>-30</td>
<td>0.04</td>
<td>0.39</td>
</tr>
<tr>
<td>CC</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>-30</td>
<td>0.05</td>
<td>0.38</td>
</tr>
<tr>
<td>CC</td>
<td>2</td>
<td>6</td>
<td>3</td>
<td>-30</td>
<td>0.04</td>
<td>0.35</td>
</tr>
<tr>
<td>CC</td>
<td>mean</td>
<td></td>
<td></td>
<td></td>
<td>0.04 (&lt;0.01)</td>
<td>0.37 (&lt;0.01)</td>
</tr>
<tr>
<td>RB</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>-30</td>
<td>0.04</td>
<td>0.38</td>
</tr>
<tr>
<td>RB</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>-30</td>
<td>0.05</td>
<td>0.39</td>
</tr>
<tr>
<td>RB</td>
<td>3</td>
<td>7</td>
<td>3</td>
<td>-30</td>
<td>0.04</td>
<td>0.39</td>
</tr>
<tr>
<td>RB</td>
<td>mean</td>
<td></td>
<td></td>
<td></td>
<td>0.05 (&lt;0.01)</td>
<td>0.38 (&lt;0.01)</td>
</tr>
<tr>
<td>LSD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.01</td>
<td>0.05</td>
</tr>
</tbody>
</table>

NB. SE is shown in brackets.

The calculated transport volume ($\theta_{st}$)

There was no significant difference between the $\theta_{st}$ of RB or CC at any pulse. The small SE of each treatment showed that there was little associated variability in $\theta_{st}$. This indicates that at both times the –30 mm tension was applied a similar volume of solute
was transported as defined by $\theta_{st}$. Under these slightly unsaturated conditions the effect of pores $>1$ mm diameter was excluded (Coughlan et al. 1991). In any case the $\theta_{st}$ at $-5$ mm was similar to that calculated at $-30$ mm. This was unexpected and a greater $\theta_{st}$ value was expected as the solute transport took place closer to saturation. This shows that the soil volume participating in solute transport did not change according to the tension at which it was applied. White et al. (1986b) stated that changes in $\theta_{st}$ should reflect the influence of soil structure, provided input conditions are constant. Thus the lack of differences in calculated $\theta_{st}$ (Table 8.4) may suggest little structural difference between the RB and CC.

The measured volumetric water content ($\theta_v$)

For most of the drainage period $\theta_v$ remained fairly constant. In most cases the differences in $\theta_v$ were not large enough to cause concern. The biggest change was always at the beginning when there was an increase in $\theta_v$ as the soil wetted up. This was most pronounced in the upper part of the soil column (indicated from the ThetaProbe at 5 cm) and showed that the soil was initially drier near the surface. This could have been due to greater solute flow heterogeneity at this level when compared to lower in the soil column. A solute transport experiment by Persson and Berndtsson (1999) found that variability in $\theta_v$ was inversely related to the frequency of solution applied. This was also found in this study and the periods of continually applied solution coincided with relatively uniform $\theta_v$, while fluctuations were associated with breaks in solute application. Periods of fluctuating $\theta_v$ were usually quite short and mostly at the start or around the change-over period between applying concentration pulses.

An example of the difference in $\theta_v$ between the top and the bottom of the soil cores is shown in Figure 8.5. Here core 2 (RB) was consistently lower in $\theta_v$ than core 1 (CC) throughout the experiment. However no consistent trend according to treatment was found for the other cores (cores 4, 6, 7 and 8). Nevertheless in both treatments the bottom of the soil core was often wetter than the top, especially during the pre-wetting period. Over the course of the experiment, typically there was a convergence in $\theta_v$ between the top and the bottom. An example of this convergence is shown in Figure 8.5 where both
readings for core 2 come together by the second pulse. Thus, from this point the $\theta_v$ had become uniform through the whole core.

![Figure 8.5 Mean volumetric water content ($\theta_v$) measured at 5 cm (top) and 15 cm (bottom) from the surface of each core. Core 1 (solid line – CC) top (◊), bottom (♦) and Core 2 (dashed line - RB) top (□), bottom (■)](image)

**Comparison between $\theta_{st}$ and $\theta_v$**

It is understood that the mobile water content ($\theta_m$) is analogous to the $\theta_{st}$. In fact White *et al.* (1984) referred to the $\theta_m$ as the fraction of the soil water that participated in solute transport. Thus, Clothier *et al.* (1995) measured the mobile fraction of the soil water content ($\theta_m$; $\theta_v$) to determine the proportion of preferential flow at different hydraulic conductivities. An increased ratio of $\theta_m$; $\theta_v$ was associated with decreasing preferential flow. This agrees with Vervoort *et al.* (1999) who also calculated the $\theta_m$; $\theta_v$ and found more developed structure was associated with smaller $\theta_m$; $\theta_v$ values. In contrast soil with a massive structure had a greater $\theta_m$; $\theta_v$ ratio. Consequently in this study the $\theta_{st}$; $\theta_v$ will be used (instead of the $\theta_m$; $\theta_v$) to infer soil structure.

The mean $\theta_{st}$; $\theta_v$ ratio was determined for each pulse by treatment (Table 8.5). At -30 mm tension (i.e. pulse 1 and 3) the calculated $\theta_{st}$; $\theta_v$ ratio was similar between the treatments.
At closer to saturation (-5 mm tension) the $\theta_s:\theta_v$ ratio of the RB was significantly smaller than the CC. This suggests greater preferential flow in the RB than the CC. At the same time the solution was flowing faster in the RB than the CC. These findings each suggest that the network of pores in the RB were better connected than in the CC soil. All the values in Table 8.5 were much lower than field-measured values (0.41-0.64) of the $\theta_s:\theta_v$ ratio calculated by Clothier et al. (1995). Okom et al. (2000) also measured a $\theta_s:\theta_v$ ratio of 0.50 on a similar texture-contrast soil to this study, although this was also measured in the field. In contrast this study found that solute was flowing through only a small proportion of the wetted pore volume. The difference in $\theta_s:\theta_v$ between this study and the field measured values above could be due to the time scale over which the experiment ran. Another difference with this study was that the $\theta_s:\theta_v$ ratio was calculated close to saturation (at pulse 2) while the studies by Clothier et al. and Okom et al. measured the mobile fraction >20 mm tension. The low values in this study were surprising as solute flowing at closer to saturated conditions would be expected to fill a greater proportion of pore space.

Table 8.5 Mean transport volume to volumetric water content ($\theta_s:\theta_v$) ratio for pulse 1, 2 and 3 by treatment

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Pulse 1</th>
<th>Pulse 2</th>
<th>Pulse 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>0.13</td>
<td>0.17</td>
<td>0.11</td>
</tr>
<tr>
<td>RB</td>
<td>0.12</td>
<td>0.14</td>
<td>0.12</td>
</tr>
<tr>
<td>LSD</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

8.4 Conclusion

There was little difference in the BD between the CC and RB and hence the total porosity was not significantly different either. Under slightly unsaturated conditions (-30 mm tension) the flux density of the RB and CC was similar, but close to saturation (-5 mm tension) the RB had significantly greater drainage flux density than the CC. The CLT was found to be the best fitting TFM for the measured BTC data. The optimised CLT parameters indicated no significant differences in solute transport at the first unsaturated
pulse, but at the second saturated pulse the CC had a significantly smaller travel pathlength which indicates the solute would flow through in a shorter length of time. However at the same time the CC had more solute spreading than the RB. This is a sign that the solute flowed through a more tortuous and less well connected network of pores in the CC. At the third unsaturated pulse the CC continued to have more solute spreading which suggests more variation in the flow paths of the CC. Over the whole experiment the optimised parameters of the RB were more uniform and this indicates the pore pathways were more stable through the RB soil. The $\theta_v$ was fairly constant, but there were small differences between the top and bottom of the core samples. The $\theta_{st}$ was similar between the treatments under saturated and unsaturated flow conditions. However close to saturation the $\theta_{st}$:$\theta_v$ ratio was significantly smaller in the RB than the CC. This suggests there was significantly greater preferential flow in the RB than the CC. Therefore analysis of solute flow shows that the pore pathways of the RB are better connected than the CC.
CHAPTER NINE

9 Macropore structure of soil under raised beds and conventional cultivation

9.1 Introduction

The previous experimental chapters have explored a range of soil physical properties of RB and other treatments. Physical properties such as the SWRC, soil strength and K are strongly controlled by the amount of soil pore space and related to bulk density (BD). Most recent RB studies have focused on agronomy with only brief attention on soil physical properties.

However work over five years by Bakker et al. (2005) found that the BD was consistently lower in the top 25 cm of RB in comparison to a control. The same finding was detected to 15 cm depth in Tasmania (Cotching and Dean 2001) and reduced BD in RB has also been reported in south-western Victoria (Peries et al. 2001). Thus there is limited understanding on the soil structure of RB as the only reported changes have been for BD. This can be related to total porosity only; it does not describe pore size, pore connectivity or any solid components.

There are numerous methods used to measure or observe structure which vary in the scale and resources required. Some methods involve a great deal of complexity and require specialist equipment; also the expense and time required of some methods are considerable. The suitability of each method for a particular soil depends on soil type, colour and condition. The most appropriate method will be influenced by the questions that need to be answered and the type of problems which are encountered. Sometimes it is necessary to modify the chosen method accordingly. The commonly used methods can be broadly divided into three groups: qualitative, semi-quantitative and quantitative methods.
Methods of structural analysis

Qualitative methods are based upon visual analysis and are descriptively vivid, but lack numerical classification to allow statistical comparison. They are popular for use in soil survey and landscape evaluation. The recommended field method in Australia describes structure by referring to the size of aggregates and the shape or grade of pedality (McDonald et al. 1990). A study by Brouwer and Fitzpatrick (2002b) provides a good example of this approach. They visually assessed soil profiles and reported structure in qualitative terms of pedality, as platy, prismatic or angular blocky. This was an appropriate method for describing the morphological features of a soil toposequence at the landscape scale.

McKenzie (2001a) developed a semi-quantitative scoring system (named SOILpak) to assess soil structural form for the Australian cotton industry. The assessment of soil compaction in the field was the major objective in developing SOILpak. The scoring procedure was based upon the method detailed in the Australian Soil and Land Survey Field Handbook (McDonald et al. 1990) and involved a description of aggregates, fabric and void spaces. McKenzie’s approach provided a framework that ensured pedological descriptions were related to functional soil properties. It provided more rigour than a standard soil survey because it assigned numerical classes to different conditions of soil structure.

In the past 30 years there has been continual development and use of quantitative methods of measuring soil structure. Unlike the qualitative and semi-quantitative methods, quantitative methods precisely determine structure by measuring the solid and void (pore space) components of the soil. Such methods are able to analyse structure at greater resolutions and can be tested statistically. In addition, there is no reliance put upon an individual describing structure as they observe it. Description with the human eye to differentiate between aggregates and the pores within them is replaced by utilising equipment such as digital cameras or scanners. Several methods have been developed to assess soil structure quantitatively and each method varies in complexity and the output data it provides. Table 9.1 summarizes some common methods that have recently been used to quantify structure.
Table 9.1 Methods of quantifying structure

<table>
<thead>
<tr>
<th>Method</th>
<th>Pore diameter measured</th>
<th>Advantage</th>
<th>Observation method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scanning Electron Microscope</td>
<td>&lt;10 µm</td>
<td>Very high resolution</td>
<td>Backscattered electrons</td>
<td>(Lebron et al. 2002)</td>
</tr>
<tr>
<td>Computed tomography</td>
<td>0.46 mm³</td>
<td>3D reproduction of pores; potential to quantify soil macroporosity and water movement patterns</td>
<td>Recorded on magnetic tape, image analysis</td>
<td>(Mooney 2002)</td>
</tr>
<tr>
<td>Mercury porosimetry</td>
<td>0.003 – 360 µm</td>
<td>Detection of very fine pores; estimation of pore tortuosity</td>
<td>Pressure change of intruded mercury</td>
<td>(Flint and Flint 2002)</td>
</tr>
<tr>
<td>Polyester resin (laboratory)</td>
<td>&gt;176 µm</td>
<td>Large samples with fine resolution</td>
<td>Photograph, image analysis</td>
<td>(Moran et al. 1988)</td>
</tr>
<tr>
<td>Epoxy resin (field)</td>
<td>&lt;100 µm</td>
<td>Pores connected to the soil surface</td>
<td>Photograph, image analysis</td>
<td>(Moran et al. 1989a)</td>
</tr>
<tr>
<td>Epoxy resin (laboratory)</td>
<td>&lt;0.4 mm</td>
<td>Good for macropore assessment</td>
<td>Photograph, image analysis</td>
<td>(Bakker and Barker 1998)</td>
</tr>
<tr>
<td>Methylene blue dye staining</td>
<td>&lt;1mm</td>
<td>Integrates the infiltration of water through the soil with soil structure</td>
<td>Photograph, digitization</td>
<td>(Minh et al. 1997)</td>
</tr>
</tbody>
</table>
The first three methods of Table 9.1 require access to specialist equipment and are very expensive to operate. Computed tomography with x-rays is a non-destructive imaging method that allows 3D visualizations of air and water-filled pore space and differentiation of solid components in the soil matrix (Mooney 2002). Lebron et al. (2002) used an SEM to reflect electrons from soil solid and pore components and relate to their elemental atomic weight. The mercury porosimetry method calculates the pore size distribution by incrementally intruding the soil with mercury. This method can measure very fine pores and enables the estimation of pore tortuosity and the size of pore necks (Flint and Flint 2002). The last method given in Table 9.1 is much simpler and has developed from the work by Bouma and Dekker (1978) who used dye stain coverage to observe structure as observed in pore infiltration pathways. Minh et al. (1997) used this method to quantify the number and distribution of water-conducting pores on RB of different age.

The other methods in Table 9.1 involved the impregnation of soil with resin. These methods have been successfully undertaken to produce images that indicate structure by directly showing soil pores and solid space (Moran and McBratney 1992a). Several studies have employed resin-impregnated image analysis to assess the structure of soil under different tillage systems. Shipitalo and Protz (1987) found significantly greater macroporosity in a tilled treatment compared to a no-till plot. Associated with this the mean pore diameter was smaller and pore shape was significantly different. Another study with similar treatments by Moran and McBratney (1992b) showed that cultivation severed the connection of surface pores to the subsoil below and greater pore connectivity was found in the zero tillage treatment. Differences were found with depth and effects between the treatments and from stubble retention were detected. Moran and McBratney (1992b) claimed that a benefit of resin-impregnated image analysis was that it effectively maintains the pore structure in its initial field condition. Structural parameters can be calculated which describe both solid and porous components (McBratney and Moran 1990), and pore type can be differentiated (Ringrose-Voase and Bullock 1984). Using stereology (Ringrose-Voase 1996) and serial sectioning (Vogel 1997) techniques the calculation of porosity by image analysis can provide the basis for predicting pore connectivity and tortuosity. Given the advantages and potential of resin-impregnated image analysis, it was the quantitative method chosen for this experiment.
9.1.1 Aim

The aim of this chapter was to quantify the macropore structure of the soil under RB and CC. Thus, it was hypothesized that the structure of RB was better than the CC soil.

9.2 Material and Method

9.2.1 Sampling of soil cores

Undisturbed soil samples were collected using aluminium soil cores (100 mm outside diameter, 75 mm height). Where possible, the cores were pushed slowly into the soil by hand to ensure that minimal disturbance was caused during excavation. The location of excavation on the RB was mid-way between the furrows to avoid compacted areas. Two samples were taken at one point; one from the surface (0-75 mm) and another from 75-150 mm depth (which was immediately below the upper core). Sampling was done at the beginning of the winter cereal crop growing season in June 2003 (T1) and post-harvest in February 2004 (T2). Twelve cores were sampled at T1 and 24 sampled at T2. These were taken only from plot 4 for the RB and plot 6 for CC. The lower core was pushed in with the aid of a hydraulic cylinder at T1 because of the hard nature of the soil in the CC treatment (Figure 9.1). At T2 a trickle irrigation system (McKenzie and Cresswell 2002), was set up to slowly wet the soil and soften it. After excavation, the cores were wrapped in black plastic bags to preserve their structural condition. At T1 the \( \theta_v \) of RB samples were 0.21 m\(^3\)/m\(^3\) and the CC were 0.18 m\(^3\)/m\(^3\). In contrast, at T2 the samples were much wetter; the RB samples were 0.27 m\(^3\)/m\(^3\) and the CC were 0.33 m\(^3\)/m\(^3\). In addition, samples for BD were taken at T2.
9.2.2 Dehydration

In the laboratory, cores were dried in an oven at 40°C for at least 24 hours as water-filled pores are not displaced by resin (McKenzie 2001b). This gentle drying was undertaken to drive off any freely held water without introducing shrinkage. This method was chosen because it was quick and simple. More complex methods use solvent replacement techniques, e.g. Moran et al. (1989b) described the use of acetone and 1, 4 dioxane to dehydrate samples of high clay content and no cracking was caused. However these methods are slow (up to 12 weeks), require specialist apparatus (especially if a continuous flow system is attempted) and there are health risks associated with 1, 4 dioxane. Samples that are dried are more easily impregnated. Water in the soil can cause resin to become cloudy or inhibit the resin curing process (Salins and Ringrose-Voase 1994). While Mooney et al. (1998a) found that when conditions were wet, impregnation occurred with varying success on milled peat samples.

9.2.3 Resin impregnation

Several attempts were initially made using epoxy resins, but difficulties were encountered and acceptable impregnation could not be achieved. The fast curing properties and low viscosity of the epoxy resin mixture were the likely cause of these problems. In addition the samples were probably too large. Consequently a polyester
resin was selected instead. Polyester resin is sufficiently viscous so as to easily penetrate most pore space in soils. It is slower curing than epoxy resin which ensures that structural integrity is maintained and the samples do not shrink (Murphy 1986). The samples were impregnated according to the method described by Salins and Ringrose-Voase (1994). In brief summary, the samples were submerged in a tub of polyester resin (CR64 polyester embedding resin, methyl methacrylate monomer and a hydroperoxide catalyst). A fluorescent dye (UVtex OB fluorescent dye – Ciba-Geigy Pty Ltd) was added so that the pore space could be illuminated under ultraviolet (UV) light. A vacuum chamber was employed to remove entrapped air and improve the penetration of resin into the soil. The cores were then left for six weeks to cure and harden. Once hardened the aluminium cores were cut away from each sample. The majority of samples were sectioned horizontally, but four samples taken at T2 were sectioned vertically. Cutting each section was slow (10 min per cut), but it produced high quality sections with well-defined, smooth faces. Cutting was done at 10 mm intervals with a circular diamond saw bathed in kerosene (Figure 9.2). Seven sections were prepared from each core sample starting from the surface at 10 mm depth, 20 mm, 30 mm and so on through the lower core down to 140 mm.

![Figure 9.2 Cutting sections of resin-impregnated soil with a circular diamond saw](image-url)
9.2.4 Digital image generation and processing

The sections were photographed under UV light using a digital camera (Olympus C-4040). A specially prepared light box was used to keep out visible light. Constant conditions (camera settings and distance) when the sections were photographed prevented differences in lighting or focus from causing variations in pixel brightness. A UV filter was fitted to the camera to ensure that only light fluorescing from the subject reached the camera lens. The photographs were stored in a TIF format to preserve maximum detail and avoid image compression. The photographs were then processed with image analysis techniques, which required each photograph to be converted into a binary (black and white) image that accurately represented the soil solid and pore space. The bifurcation process is known as image segmentation.

Image segmentation

Care was taken during the segmentation process to ensure that the binary image accurately reflected the actual photograph. Each image was treated uniformly so that no subjective judgement was allowed to bias individual images. A poorly segmented image will either over or under estimate actual porosity. Ringrose-Voase (1996) warns that small differences in threshold value can cause considerable changes in the number of pixels that are designated as either pore or solid space.

Initial observation of the photographs revealed a brightly illuminated pore space which represented a network of pores and fine cracks. The soil matrix was clearly identified, often in two shades of colour with the darker areas containing higher clay content. It was also interspersed with numerous stones which appeared black. The wide range of colours and shades of colours produced a histogram that was distributed with several peaks of intensity (Figure 9.3). Such variation as illustrated in Figure 9.3 introduced some challenges in determining the point (threshold value) at which to segment the image. Typically most images had irregular distributions of pixel intensity with the pores separated from the solid in arbitrary units of brightness between 130 and 160. Alternative methods of viewing the images were sought to reduce the variation within this range of brightness. It was found that a histogram with less peaked pixel intensity was produced by using the green band of the colour spectrum only (Figure 9.4). It was
thought that the blue band was over ranging and the red did not contribute to the range of interest.

Figure 9.3 Pixel frequency histogram of a typical image showing the full spectrum of light (including the red, green and blue channels)

NB. The lower brightness values (dark) correspond to pixels that represent solid areas and higher values (bright) to pixels in pore spaces.

Figure 9.4 Pixel frequency histogram of a typical image showing the green channel only

NB. The same image was photographed in Figure 9.3 and 9.4
With the pixels in each image well identified according to brightness, attempts were made to segment the image accordingly. Ringrose-Voase (1996) used a Laplacian filter to sharpen edges between pixels of a grey level image. Analysis with the OPTIMAS software (Media-Cybernetics 1999) enabled several filters (including Roberts, Sobel and Laplacian) to be applied in order to demarcate the edges. But these filters were not successful in improving the delineation between the pore and solid pixels and either over or under estimated the actual pore space. This was clearly seen by comparing an image before and after it had been segmented using a filter. In fact the filters created a lot of noise (fuzziness) which did not help separate the pore from the solid areas. Reith and Mayhew (1988) claimed that the complexity of different biological and natural systems can be so great that image segmentation requires finding a customized method which applies to each image under given conditions.

As a result of the problems that were encountered with using filters, an alternative method was sought. A simple method of image segmentation based upon the watershed extraction method using the OPTIMAS program was adopted. Reith and Mayhew (1988) defined the watershed extraction method as “detecting the set of all points on the surface of a gray tone function that represent minima”. Firstly images were viewed at close magnification to easily detect individual pixels. The brightness value (intensity) of pore pixels adjacent to solid pixels from across seven images was recorded. The five lowest pore pixel intensity values were averaged to determine the most representative segmentation value. Thresholding was performed using this value to convert every gray level image into a binary format. A range of brightness values (on a scale from 0 to 255, where 1 is dark and 255 is very bright) was used to assess the images for thresholding. For T1 the threshold value was 135 and for T2 samples it was 142. It was noted that small areas (e.g. narrow pore necks) of some images were excluded, but overall most images were segmented well. Lastly, the images were inverted so that pore space represented black and solid space white. The binary images were saved in an 8-bit grey level format and loaded into SOLICON software (Cattle et al. 2000) for batch processing. Each image was then ready for soil structural image analysis.
Image analysis

SOLICON was selected because it is specialist software for the analysis of binary images. It calculates a number of parameters of soil structure using a pixel counting approach. All objects (i.e. pore or solid) that intersected the edge of the image were excluded to remove the effect of edges on image analysis. This was undertaken to avoid exaggerating the porosity or the other structural parameters that were measured. All parameters were estimated according to stereological principles (e.g. isotropic sampling) that are briefly outlined by Ringrose-Voase (1996).

The soil pore and solid parameters calculated were: porosity, surface area (SA), mean pore intercept length (MPIL), mean solid intercept length (MSIL), pore star length (PSL), solid star length (SSL), pore genus (PG), solid genus (SG), mean pore star area (MPSA) and mean pore star shape (MPSS). Porosity is the proportion of pixels representing pore space of the whole image in mm$^3$/mm$^3$. SA is a measure of the pore/solid interface and is calculated from the interface boundary length of pixels representing pore space and pixels representing solid; it is expressed in mm$^2$/mm$^3$. The MPIL measures the continuity of pores and is the average (in four directions – 0, 45, 90 and 135°) pore length (mm) across the whole the image (Vervoort and Cattle 2003). The MSIL is calculated in the same fashion as MPIL, but for solid pixels. The star length parameters (PSL and SSL) are the expected continuous length (mm) of a pore or solid calculated from a random point (Vervoort and Cattle 2003). The measurement of PSL and SSL are skewed to longer intercepts compared to MPIL and MSIL. Nevertheless pore size can effectively be described using either PSL or MPIL. The PG and SG are a measure of independent loops per mm$^2$ (Vogel and Roth 1998) and are calculated using the Euler-Poincare number (Cattle et al. 2000) to estimate either pore or solid connectivity. MPSA is the pore area averaged over the whole image. MPSS indicates pore shape, circles have a value of 1 and long thin objects are close to 0. Further explanation on these structural parameters are found in the SOLICON user manual (Cattle et al. 2000) and are also given in McBratney and Moran (1990) and McBratney et al. (1992).

The size distribution of solid and pore components were determined using custom selected classes. The solid size classes were 0-0.5, 0.5-1, 1-2 and 2-5 mm diameter. The pore size classes were 0 – 0.075, 0.075 – 0.15, 0.15- 3, 0.3 – 1, 1 – 2, 2 – 5 and >5 mm
diameter. These pore sizes are classified as mesopores, macropores and biopores (given previously in Table 2.1). Micropores, those pores with diameter <30 µm, were not detected. Image selections were circular and varied between 1200 and 1300 pixels in diameter. The diameter of each image selection was 90 to 93 mm (+/- 0.1 mm); therefore, each pixel was approximately 70 to 75 µm width. This was considered sufficient resolution to quantify the pores of interest for this study.

### 9.2.5 Statistical analysis

Due to difficulties with impregnating and sectioning the soil, and also when photographing the images, there were a number of missing values at some depths. In addition there was no replication of samples taken. Consequently there were too few samples at each depth at T1 to undertake significance testing of the structural parameters between the treatments. Consequently the significant difference (P<0.05) was calculated with the student’s T-test for samples taken over all depths at T1 and T2. The mean was calculated and was presented with the SE. Correlation matrices were calculated on samples taken at T1 and T2 to determine the extent to which each structural parameter was linearly related to the other structural parameters. The strength of the relationship was expressed as a correlation coefficient (r). The critical r value was calculated (according to the number of pairs sampled) to determine the r value that was significant at the five per cent level (Clewer and Scarisbrick 2001). A linear regression model was used to determine the proportion of variation between porosity (as response variable) with all the other structural parameters (as explanatory variables) A pair-wise comparison of slopes was conducted which allowed significant differences to be tested. Slopes were compared for four treatment by time combinations; i.e. RB T1, CC T1, RB T2 and CC T2. The data was analysed in this way as the sampling times were distinctly separated in time. The full model (all combinations together) tested the significance of the interaction between the variables and the time by treatment combination. Statistical analysis was performed using GenStat software (Lawes Agricultural Trust 2005).
9.3 Results

9.3.1 Pore and solid size distribution

The pore size distribution was calculated according to seven different classes of pore diameter. There was very little difference in pore size distribution between the treatments as illustrated at T1 in Figure 9.5. Likewise there was little change with time and the pore size distribution was similar at T2 to T1. Therefore the pore size classes are not shown for T2.

![Figure 9.5 Pore size classes by treatment at the first sampling time](image)

NB. Pore sizes are greater than the diameter shown, but less than the consecutive pore class; bars indicate the SE.

There was slightly greater difference between the two treatments for the distribution of solid components. The calculated solid class size units at T1 are given in Figure 9.6. In particular RB had a greater proportion (not significant) of the smallest class size units (0-0.5 mm) than CC. In contrast, CC was greater for the class sizes from 0.5-1 mm and 1-2 mm. There was little difference between the treatments in largest solid class size (2-5 mm). A similar trend was found at T2.
Figure 9.6 Solid class size units by treatment at the first sampling time; bars indicate the SE

NB. Different size class units are given compared to Figure 9.5.

### 9.3.2 Parameters of soil structure

**Depth dependency of structural parameters**

The measured depth range (0-150 mm) was within the cultivated zone for the RB, but it was deeper than the cultivation depth for the CC. As a result it was anticipated that strong depth dependency would be found for structural parameters such as porosity. Consequently trends with depth were investigated for each parameter at separate sampling times. The response to depth was varied, but overall the parameters values were apparently random and insensitive to depth which suggested no consistent depth trend. But there were some that did correlate with depth, such as the weak positive trend found for porosity. The mean porosity of RB and CC at each depth interval for T2 is given in Figure 9.7. The greater porosity at 80 mm was thought to be an artifact of the sampling division between cores. It is at this depth that the first section of the second (lower) core was taken. Better impregnation in the surface (also at 10 mm) of the sample probably caused this increase in porosity rather than an actual increase in porosity. Both treatments had very similar depth trends for porosity, but no significant differences were found between the treatments with depth.
While there was a lack of clear depth trend in the horizontal images that were analysed (Figure 9.7), a vertical image (Figure 9.8) provided a contrasting finding. Here the porosity (black) was greatest in the surface 25 mm (the top of Figure 9.8 is the soil surface) and clearly decreased with depth. Other cultivation studies that have measured the same structural parameters have shown depth dependency e.g. Bakker and Baker (1998) and Moran et al. (1988). The discrepancy in depth dependency between the horizontal and vertical images in this study cannot be explained.
Average of structural parameters

As no depth dependency was found, the structural parameters (calculated using SOLICON) are summarized by averaging over all depths for each treatment at both sampling times (Table 9.2). At T1 the RB had significantly greater porosity than CC samples. This combined with significantly larger PG indicates a better connected and larger network of pore space. SA was also significantly greater for the RB which is to be expected as SA relates to the extent of porosity. The SA relates to a greater area of solid soil where resin has flowed into the soil matrix. Functionally, this suggests a larger pore network where water might flow through when the soil drains. In contrast the CC had larger pores and solid components (greater MPIL and MSIL) which were not as well connected (smaller PG). PSL and MPIL (each descriptors of pore size) were both larger (although not significantly) in CC than in RB. The equivalent solid components - SSL and MSIL - were significantly greater in the CC treatment. Thus the CC contained larger pore and solid components than the RB. MPSA was significantly larger in the CC which was probably associated with the larger measured pore components. Pore shape (MPSS) was calculated as significantly different between the treatments across both times.
At T2 no significant differences were measured between the treatments and the values of many parameters were close to those of the CC samples at T1. Parameters which can be used to indicate that the soil was well structured - porosity, SA and PG - all decreased from T1 to T2 for the RB samples. While over the same period the CC did not change as much. The small SE shows that the variability was consistently low for each treatment at both sampling times.

Table 9.2 Image analysis parameters of soil pore and solid space by treatment and sampling time

<table>
<thead>
<tr>
<th>Image analysis parameter</th>
<th>Raised bed, T1 (n = 38)</th>
<th>Conventional cultivation, T1 (n = 35)</th>
<th>Raised bed, T2 (n = 70)</th>
<th>Conventional cultivation, T2 (n = 69)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity (mm³ /mm³)</td>
<td>0.35 a (&lt;0.01)</td>
<td>0.32 b (&lt;0.01)</td>
<td>0.31 a (&lt;0.01)</td>
<td>0.31 a (&lt;0.01)</td>
</tr>
<tr>
<td>SA (mm² /mm³)</td>
<td>1.78 a (0.04)</td>
<td>1.28 b (0.03)</td>
<td>1.40 a (0.02)</td>
<td>1.31 a (0.02)</td>
</tr>
<tr>
<td>PSL (mm)</td>
<td>0.80 a (0.02)</td>
<td>1.00 a (0.04)</td>
<td>0.75 a (0.03)</td>
<td>0.90 a (0.05)</td>
</tr>
<tr>
<td>SSL (mm)</td>
<td>6.23 a (0.40)</td>
<td>6.77 b (0.18)</td>
<td>7.20 a (0.18)</td>
<td>7.45 a (0.31)</td>
</tr>
<tr>
<td>MPIL (mm)</td>
<td>0.31 a (&lt;0.01)</td>
<td>0.35 a (&lt;0.01)</td>
<td>0.29 a (&lt;0.01)</td>
<td>0.31 a (&lt;0.01)</td>
</tr>
<tr>
<td>MSIL (mm)</td>
<td>1.90 a (0.16)</td>
<td>2.31 b (0.06)</td>
<td>2.38 a (0.05)</td>
<td>2.43 a (0.06)</td>
</tr>
<tr>
<td>PG (x 10⁻² mm²)</td>
<td>0.12 a (&lt;0.01)</td>
<td>0.06 b (&lt;0.01)</td>
<td>0.05 a (&lt;0.01)</td>
<td>0.05 a (&lt;0.01)</td>
</tr>
<tr>
<td>SG (x 10⁻² mm²)</td>
<td>0.86 b (0.02)</td>
<td>0.67 b (0.02)</td>
<td>0.87 a (0.02)</td>
<td>0.79 a (0.01)</td>
</tr>
<tr>
<td>MPSA</td>
<td>228 a (2.8)</td>
<td>242 b (2.0)</td>
<td>212 a (1.3)</td>
<td>218 a (1.2)</td>
</tr>
<tr>
<td>MPSS</td>
<td>0.49 a (&lt;0.01)</td>
<td>0.50 b (&lt;0.01)</td>
<td>0.50 a (&lt;0.01)</td>
<td>0.50 a (&lt;0.01)</td>
</tr>
</tbody>
</table>

NB. Means at with the same letter are not significantly different (P<0.05) for treatments at T1 and T2; SE is shown in brackets.

**Relationship between structural parameters**

The relationship between structural parameters was explored by calculating the correlation coefficient (r). Correlation matrices were constructed at T1 (Table 9.3) and T2 (Table 9.4) to determine the extent to which each structural parameter was linearly related to other structural parameters.

At T1 there was a much stronger correlation in the RB between porosity and PG (0.90) compared to the CC (0.60). This indicates that as RB increased in porosity they became more connected. PG also had much stronger correlations with SA, PSL and MPIL for
the RB than for the CC. The more connected nature of RB pore network was associated with smaller measures (although not significant) of pore parameters (PSL and MPIL) (Table 9.2). MPIL was positively correlated with porosity and at T1 the MPIL of the RB had a much stronger relationship with porosity for RB (0.77) than the CC (0.46). Conversely MSIL was negatively correlated, but there was only a slight difference between the treatments for these parameters.

There was some similarity in the parameter relationships at T1 with those at T2. For instance porosity was more strongly correlated with PG for the RB (0.58) than the CC (0.12). This was surprising given that the mean values for PG and porosity were the same at T2. However there was little difference in the correlation between porosity with MPIL or MPSS and MPIL with SA. Nevertheless in the RB the MPIL was much more strongly correlated with PG than the CC at both sampling times. Thus the size of pores (MPIL) in the RB was such that it led to greater connectivity (PG) in the pore space. It is not clear by what means the RB contains a better connected pore network. It could have been the pore size as both the PSL and MPIL were strongly correlated (and significant) with PG, while for CC there was almost no correlation. Overall there was less difference in the correlation between parameters at T2 than at T1 which is partly a reflection of the measured mean values (Table 9.2).
<table>
<thead>
<tr>
<th>Treatment</th>
<th>Por</th>
<th>SA</th>
<th>PSL</th>
<th>SSL</th>
<th>MPIL</th>
<th>MSIL</th>
<th>MPSA</th>
<th>MPSS</th>
<th>PG</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA</td>
<td></td>
<td>0.88</td>
<td>1.00</td>
<td>-</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CC</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>PSL</td>
<td></td>
<td>0.46</td>
<td>0.08</td>
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<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
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<tr>
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<td>-0.71</td>
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</tr>
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<td>CC</td>
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<td>-0.70</td>
<td>0.22</td>
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<tr>
<td>MPIL</td>
<td></td>
<td>0.77</td>
<td>0.39</td>
<td>0.79</td>
<td>-0.28</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CC</td>
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<td>0.46</td>
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</tr>
<tr>
<td>MSIL</td>
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<td>-0.88</td>
<td>-0.96</td>
<td>-0.17</td>
<td>0.85</td>
<td>-0.45</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CC</td>
<td></td>
<td>-0.75</td>
<td>-0.96</td>
<td>0.23</td>
<td>0.72</td>
<td>0.19</td>
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<td></td>
</tr>
<tr>
<td>MPSA</td>
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<td>-0.97</td>
<td>-0.91</td>
<td>-0.35</td>
<td>0.72</td>
<td>-0.71</td>
<td>0.91</td>
<td>1.00</td>
<td>-</td>
</tr>
<tr>
<td>CC</td>
<td></td>
<td>-0.98</td>
<td>-0.72</td>
<td>-0.28</td>
<td>0.59</td>
<td>-0.43</td>
<td>0.79</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MPSS</td>
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<td>-0.87</td>
<td>-0.68</td>
<td>-0.46</td>
<td>0.46</td>
<td>-0.80</td>
<td>0.66</td>
<td>0.85</td>
<td>1.00</td>
</tr>
<tr>
<td>CC</td>
<td></td>
<td>-0.45</td>
<td>-0.01</td>
<td>-0.54</td>
<td>-0.16</td>
<td>-0.67</td>
<td>0.09</td>
<td>0.49</td>
<td></td>
</tr>
<tr>
<td>PG</td>
<td></td>
<td>0.90</td>
<td>0.79</td>
<td>0.39</td>
<td>-0.51</td>
<td>0.68</td>
<td>-0.74</td>
<td>-0.86</td>
<td>-0.86</td>
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<tr>
<td>CC</td>
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<td>0.60</td>
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<td>0.13</td>
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<td>0.20</td>
<td>-0.51</td>
<td>-0.57</td>
<td>-0.54</td>
</tr>
<tr>
<td>SG</td>
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<td>-0.08</td>
<td>0.30</td>
<td>-0.39</td>
<td>-0.45</td>
<td>-0.59</td>
<td>-0.29</td>
<td>0.06</td>
<td>0.39</td>
</tr>
<tr>
<td>CC</td>
<td></td>
<td>0.13</td>
<td>0.76</td>
<td>-0.60</td>
<td>-0.50</td>
<td>-0.74</td>
<td>-0.68</td>
<td>-0.16</td>
<td>0.35</td>
</tr>
</tbody>
</table>

NB. Correlations >0.33 are significant where P = 0.05
Table 9.4 Correlation coefficients ($r$) between structural parameters for RB and CC soil at the second sampling time

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Por</th>
<th>SA</th>
<th>PSL</th>
<th>SSL</th>
<th>MPIL</th>
<th>MSIL</th>
<th>MPSA</th>
<th>MPSS</th>
<th>PG</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA RB</td>
<td>0.70</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CC</td>
<td>0.77</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PSL RB</td>
<td>0.45</td>
<td>-0.17</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CC</td>
<td>0.42</td>
<td>-0.16</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SSL RB</td>
<td>-0.53</td>
<td>-0.88</td>
<td>0.22</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CC</td>
<td>-0.40</td>
<td>-0.72</td>
<td>0.33</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MPII RB</td>
<td>0.59</td>
<td>0.10</td>
<td>0.87</td>
<td>0.21</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CC</td>
<td>0.53</td>
<td>-0.05</td>
<td>0.89</td>
<td>0.25</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>MSII RB</td>
<td>-0.72</td>
<td>-0.92</td>
<td>0.06</td>
<td>0.87</td>
<td>&lt;0.01</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CC</td>
<td>-0.69</td>
<td>-0.89</td>
<td>0.12</td>
<td>0.87</td>
<td>0.04</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MPSII RB</td>
<td>-0.69</td>
<td>-0.77</td>
<td>-0.20</td>
<td>0.64</td>
<td>-0.16</td>
<td>0.75</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CC</td>
<td>-0.84</td>
<td>-0.79</td>
<td>-0.19</td>
<td>0.52</td>
<td>-0.31</td>
<td>0.76</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MPSS RB</td>
<td>-0.60</td>
<td>0.09</td>
<td>-0.77</td>
<td>-0.21</td>
<td>-0.91</td>
<td>-0.02</td>
<td>0.13</td>
<td>1.00</td>
<td>-</td>
</tr>
<tr>
<td>CC</td>
<td>-0.60</td>
<td>-0.05</td>
<td>-0.79</td>
<td>0.38</td>
<td>-0.79</td>
<td>-0.02</td>
<td>0.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PG RB</td>
<td>0.58</td>
<td>0.13</td>
<td>0.60</td>
<td>0.01</td>
<td>0.60</td>
<td>-0.21</td>
<td>-0.21</td>
<td>-0.67</td>
<td>1.00</td>
</tr>
<tr>
<td>CC</td>
<td>0.12</td>
<td>0.11</td>
<td>-0.02</td>
<td>0.09</td>
<td>0.01</td>
<td>-0.04</td>
<td>-0.05</td>
<td>-0.10</td>
<td></td>
</tr>
<tr>
<td>SG RB</td>
<td>0.02</td>
<td>0.53</td>
<td>-0.40</td>
<td>-0.49</td>
<td>-0.48</td>
<td>-0.48</td>
<td>-0.45</td>
<td>0.54</td>
<td>-0.26</td>
</tr>
<tr>
<td>CC</td>
<td>0.11</td>
<td>0.29</td>
<td>-0.08</td>
<td>-0.42</td>
<td>-0.14</td>
<td>-0.34</td>
<td>-0.24</td>
<td>0.13</td>
<td>-0.35</td>
</tr>
</tbody>
</table>

NB. Correlations >0.20 are significant where P = 0.05
Relationship between porosity and other structural parameters

Linear regression analysis was performed with porosity as the response variable and all the other structural parameters as explanatory variables to determine the relationship between these descriptors of structure. A pair-wise comparison of the slopes was calculated to test for significance differences between each treatment at two sampling times (Table 9.5).

Table 9.5 Significant pair-wise tests of structural parameters for RB and CC soil by four treatment: sampling time combinations

<table>
<thead>
<tr>
<th>Treatment</th>
<th>RB T1</th>
<th>CC T1</th>
<th>RB T2</th>
<th>CC T2</th>
</tr>
</thead>
<tbody>
<tr>
<td>RB T1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CC T1</td>
<td>MPIL ***</td>
<td>MSIL **</td>
<td>MPSS ***</td>
<td>SSL*</td>
</tr>
<tr>
<td>RB T2</td>
<td>MPIL ***</td>
<td>MSIL ***</td>
<td>MPSA **</td>
<td>MPSS **</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SA *</td>
<td>SSL **</td>
</tr>
<tr>
<td>CC T2</td>
<td>MPIL ***</td>
<td>PG *</td>
<td>MPSA *</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>MSIL ***</td>
<td></td>
<td>MPSA *</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>MPSS ***</td>
<td>PG ***</td>
<td>SSL *</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PG ***</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PSL *</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SSL ***</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NB. Where * = P <0.05, ** = P <0.01, *** = P <0.001

The SA parameter was significantly different between T1 and T2 for the RB samples, which suggests that the extent of the pore network declined with time in the RB. In addition, MPIL was found to be significantly different between RB at T1 and the other three treatment/time combinations. However the other pore size parameter PSL was significantly different only between RB at T1 and CC at T2. Perhaps the MPIL is a more sensitive measure of pore size. The MSIL was significantly different between RB T1 and
the other treatment/time combinations. This exactly reflects the differences as measured by the MPIL. The PG has an important functional meaning as a structural parameter and was found to be significantly different between CC at T2 with the other treatment/time combinations. Significant differences were also found with MPSS and MPSA but these are considered less important because of less functional relevance of these parameters. SG was the only parameter that a significant difference was not found between the four treatment/time combinations. Overall the linear regression analysis that is summarized in Table 9.5 and described above highlighted that most of the significant differences detected were between RB at T1 and the other three treatment/time combinations. This finding is not surprising given the differences in the mean values shown in Table 9.2.

**Relationship between different measurements of porosity**

At T2 soil cores were taken to measure the soil BD and total porosity was determined using equation 2.2. A comparison was undertaken between porosity estimated by image analysis with that calculated from the soil BD (Table 9.6).

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>Treatment</th>
<th>Method</th>
<th>Mean porosity (m³/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 75</td>
<td>RB</td>
<td>BD</td>
<td>0.48 (0.01)</td>
</tr>
<tr>
<td>0 – 70</td>
<td>RB</td>
<td>IA</td>
<td>0.30 (0.07)</td>
</tr>
<tr>
<td>75 - 150</td>
<td>RB</td>
<td>BD</td>
<td>0.34 (0.02)</td>
</tr>
<tr>
<td>80 - 140</td>
<td>RB</td>
<td>IA</td>
<td>0.32 (0.05)</td>
</tr>
<tr>
<td>0 – 75</td>
<td>CC</td>
<td>BD</td>
<td>0.33 (0.02)</td>
</tr>
<tr>
<td>0 – 70</td>
<td>CC</td>
<td>IA</td>
<td>0.30 (0.06)</td>
</tr>
<tr>
<td>75 - 150</td>
<td>CC</td>
<td>BD</td>
<td>0.31 (0.07)</td>
</tr>
<tr>
<td>80 - 140</td>
<td>CC</td>
<td>IA</td>
<td>0.32 (0.05)</td>
</tr>
</tbody>
</table>

NB. SE is shown in brackets; for BD n = 3, for IA n = 35.

The estimated porosity from image analysis was less than porosity measured from BD. The largest difference was for the RB at 0-75 mm. In comparison the difference was
much smaller at the 75-150 mm depth range and for the CC at both depths. Uncertainty exists regarding the reason for the magnitude of the difference between the two methods in the RB at 0-75 mm. One explanation is that the image analysis method only measured pores with a diameter >0.03 mm, while porosity measured from BD included both micro and macropores. Due to the similarity in the porosity estimates at the other depths this is unlikely to be the case. Indeed the measurement of macroporosity only is a shortcoming of the resin-impregnated method. Using the same method Mooney et al. (2001) also found large measurement differences between two methods of measuring the porosity of milled peat samples. Alternatively the difference in porosity may be a result of the sampling methods or the spatial variation in structure of RB surface soil.

9.4 Discussion

9.4.1 The distribution of pores and solid units

There was little difference detected in the pore size distribution between RB and CC. This was not expected and is in contrast to some significant differences found between the pore structural parameters (Table 9.2). The lack of difference in the pore size classes could be because the image analysis excluded pores with a diameter <0.03 mm or due to the range of pore size classes that were selected. The distribution of solid units was also similar between the treatments and they can be thought of like a range of different aggregate class sizes. However, Ringrose-Voase (1991) warned that the solid units may not equate with aggregates because the images may not be sectioned equatorially. Hence the actual aggregate diameter may not be correctly defined. Despite this shortcoming it was found that the RB (at T1 and T2) contained a greater proportion of small (0 to 0.5 mm) solid units than the CC which suggests that the soil matrix of the RB is more finely aggregated. This shows that the RB and CC are structured differently, despite the similarity in the pore size distribution that was found. Further confirmation of the different structural composition of RB and CC was the greater proportion of large solid units (0.5 to 1 mm and 1 to 2 mm) in the CC than the RB. This corresponds with the larger MSIL and SSL of the CC.
9.4.2 Factors affecting structure

As RB normally receive several cultivation passes during preparation and formation, it is possible that additional cultivation on the RB compared to the CC would have improved the structural condition of the RB soil (as seen at T1). Both treatments have been cultivated since 1999, but the RB has been cultivated more frequently (further details are given in chapter three). Other workers have found that increased tillage was associated with increased porosity (Hewitt and Dexter 1980; Pagliai et al. 1983; Shipitalo and Protz 1987). Nevertheless, some studies have found that cultivation actually results in decreased porosity (Moran et al. 1988; Pagliai et al. 2004) or reduced pore connectivity (Moran and McBratney 1992b), while other workers were not able to detect any significant differences in structure between different tillage treatments (Bakker and Barker 1998; Grevers and de Jong 1992; Roesner 1998). A fundamental difference between the RB and CC was the way they were trafficked. There was controlled traffic (CT) on the RB which was restricted to the furrows, whereas on the CC there was no CT. Therefore it is predicted that tillage and traffic together had a positive influence on the structural development of RB. Furthermore it is suspected that tillage has an effect on other soil properties such as soil texture.

Due to the deep ripping to initially form RB, it is speculated that the soil texture within the surface 20 cm is different between the RB and CC. It is possible that this cultivation brought up clay from the top of the B horizon and increased clay content in the RB. The characterization of the experimental site at Mt Pollock given in chapter three provides no data to support this and a more detailed description of each treatment is required for confirmation. Other properties that affect structure were similar and there was no difference in soil organic C or the ESP between the treatments.

Initially it was thought that the structure of RB could fluctuate seasonally. The difference in structure between RB and CC was large at T1, although these differences had mostly disappeared by T2. The decline in key structural parameters was most noticeable for the
RB structural parameters, but the CC hardly changed at all. The decline in structure at T2 was surprising as it was post-harvest and it was expected that the soil would have dried out and some cracking might have developed. Additional structural measurements would need to be taken over a longer period of time for seasonal trends to be determined.

The structural condition of the soil was affected by the $\theta_v$ before, and at the time of, sampling for analysis. In fact several workers (Bakker and Barker 1998; Mackie-Dawson et al. 1988; McKenzie 2001b; Roesner 1998) have suggested that $\theta_v$ was the likely cause in creating structural differences. Alternatively Peries et al. (2001) postulated there is a greater frequency of wetting and drying cycles on RB and this could positively influence soil structure. Therefore the differences that were found in $\theta_v$ (as shown in chapter four) could have improved the soil structural development of each treatment.

Vervoort and Cattle (2003) reported that $K_s$ was well correlated with porosity and PG. Thus, it is tempting to speculate on the effect on physical properties such as $K_s$ based on the structural parameters measured by image analysis. However further work is required to establish such a relationship for the soil type and tillage treatments at Mt Pollock. These relationships are complex and they are not always very strong. Therefore it is predicted that the improved structural form of the RB at T1 equated with greater $K_s$, although this cannot be confirmed.

9.5 Conclusion

Image analysis of resin-impregnated soil showed that the pore size distribution was similar for the RB and CC soil. The analysis of structural parameters showed that overall the RB contained a better connected network of smaller sized pore components (i.e. more finely aggregated) than the CC soil. There were no trends with depth found for the structural parameters of either treatment. Over the duration of the experiment the largest difference found was for RB at T1 compared to the three other treatment by time combinations. From T1 to T2 the structural parameters of the RB samples declined
noticeably. Consequently the longer-term ability of RB to maintain structure over time remains uncertain and structural stability may be a future issue.
10 Conclusion, recommendations and future research

The previous six experimental chapters have explored a range of soil physical properties of RB and comparative systems: CC and pasture. This chapter discusses the main findings from this work and seeks to link results from different chapters and thereby explore relationships between different soil properties. The findings are reviewed in three sections. First, the findings on soil water and crop growth/yield on RB and CC are reviewed. Second, the movement of soil water from field measurements and solute transport in laboratory experiments are discussed. Third, soil physical properties and structural measurements are evaluated. Finally, as a result of the findings in this study some recommendations are made on cropping with RB. During the course of the study additional areas that remain unknown have been identified and opportunities for future research on RB are suggested.

10.1 Soil water and crop production

The field measurement of soil water was a major experimental component of the thesis. Seasonal patterns in SWD were similar for RB, CC and pasture, but the RB were mostly drier than the CC treatment (but only sometimes drier than pasture), as shown by data in chapter four (Table 4.4 and Figure 4.5) and chapter five (Figure 5.2, 5.3 and 5.4). This suggests that the RB provided better drained soils for cropping, which is an advantage on soils that are prone to winter waterlogging, such as in south-western Victoria. However, given that all measurements were taken during years with less than average rainfall (section 4.3.1), there is uncertainty about how RB behave under wetter conditions; but it is expected that RB would remain drier than CC in years with higher rainfall. In this scenario the $\theta_v$ values would no doubt increase but the trends in SWD are predicted to be the same. The part of the soil profile found to be most different within RB was in the
surface 0-10 cm. Frequent measurement of the $\theta_v$ in the surface soil after rainfall showed that RB responded in a similar way to CC, but the RB always had a smaller $\theta_v$. The slightly drier conditions on RB should reduce the risk of waterlogging.

Due to the potential problems caused by waterlogging it was initially thought that the drier condition of the RB would always equate to better conditions for plant growth. However this was probably not always the case as the timing and duration of waterlogging must be critical to cause significant damage. In fact there is an indication that the drier conditions during 2003 may have partly reduced plant growth and resulted in lower grain yield on the RB compared to the CC (Table 5.2). However, even less rainfall in 2002 resulted in similar plant growth between the treatments and increased yield (of canola) on RB (Table 5.1). The most rainfall during the experiment was in 2004 and some waterlogging was observed on the CC but not on the RB. Thus in 2004 the final yield of the RB was greater than the CC although they were not significantly different (Table 5.3).

In chapter five the CC had an AFP <10 per cent for long periods (Figure 5.5 and 5.6), which was a reflection of the wetter soil in the CC than the RB. The percentage of AFP values <10 per cent (i.e. of the total number of measurements taken) was calculated and is presented in Table 10.1.

<table>
<thead>
<tr>
<th>Year</th>
<th>Depth (cm)</th>
<th>RB (%)</th>
<th>CC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>0-10</td>
<td>0</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>4</td>
<td>15</td>
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<td>2004</td>
<td>0-10</td>
<td>7</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>27</td>
<td>57</td>
</tr>
</tbody>
</table>

Table 10.1 shows there was a much greater percentage of AFP readings (i.e. a longer period) at critically low values for the CC than the RB. As the AFP values were derived
from $\theta_v$ measurements these data also confirm the wetter status of the CC. The distinctly lower AFP in 2004 was probably one factor in the poorer plant growth of the CC, whereas the RB was unaffected, while in 2003 waterlogging was not an issue for either treatment. Thus, the mixed results in the plant and yield measurements (Table 5.1, 5.2 and 5.3) from 2002 until 2004 were largely a function of changes in $\theta_v$ and the resultant effect on soil AFP.

Rainfall was probably the most influential factor on $\theta_v$ and rainfall was shown to be influential on crop yield in the regional survey (given in chapter five - section 5.3.6). Here crop yields on RB were found to be greater in high rainfall years than on CC type systems. This difference was probably due to the better aeration and drainage of RB compared with CC and hence less likelihood of waterlogged conditions in RB. The survey also showed that in years with below average rainfall there was no difference in yield between the treatments.

10.2 The movement of soil water and solute

Field measurement of $K_{sat}$ (chapter seven) showed that there was no significant difference between the RB and CC treatments in the soil surface. A controlled laboratory experiment measured the movement of solute (chapter eight) as an alternative method to field measurement of K. This approach has the advantage of characterising the solute flow descriptively and imposing particular flow conditions. There was no difference between the treatments in transport parameters under slightly unsaturated flow (-30 mm tension) and this corresponds to incomplete filling of fluid within the pore volume. Differences in pore arrangement were only detected when solute transport was measured at close to saturated flow. Under these conditions the BTCs and optimized parameters of the RB were more stable than for CC and the RB also produced less solute spreading. These differences suggest an increased degree of structural stability in the RB soil not found in the CC, as well the CC had a more tortuous and less well connected network of pores than the RB. Consequently the $\theta_{sat}:\theta_v$ ratio was smaller for the RB which indicates a greater proportion of preferential flow for the RB. Thus despite the lack of a measured
difference in field $K_{\text{sat}}$ the soil pore network of the RB was overall found to be better connected in comparison to CC. In addition there was significantly greater $K_s$ in the B horizon of the RB. Moreover it was predicted (from the run-off difference – chapter four; and the lack of field K difference – chapter seven) that the RB had superior external drainage. Thus overall the measurements on K and solute transport show an increased likelihood of leaching and reduced risk of waterlogging under RB.

10.3 Soil structural and physical overview

The soil structural and physical measurements taken in this study on RB indicate some mixed results. For instance some measurements did not show differences between the treatments (RB, CC and pasture), while other measurements were quite sensitive and showed distinct differences.

The laboratory-derived SWRC was measured twice and both times indicated that there was little difference between the RB, CC and pasture soils (chapter six). In contrast, the field-derived SWRC showed that the RB always represented a drier relationship than the CC, particularly at 60 cm depth where a saturated zone was detected in the CC, but not in the RB. This is in agreement with the field measurements of soil water (namely $\psi_m$ and SWD) that showed the RB were consistently drier than the CC (chapter four). A benefit derived from this was given in Table 10.1 with a greater frequency of good soil aeration (> 10 per cent AFP) in the RB than the CC.

Soil strength was strongly influenced by changes in $\theta$, for both CC and RB (chapter six). Consequently, the RB had a significantly lower soil strength characteristic between seven and 24 cm depth than the CC soil. It is predicted that the lower strength of the RB soil would be less restrictive to root growth and as a result beneficial for cropping. The integration of soil strength and SWRC data into a single parameter (LLWR) following the approach by da Silva et al. (1994) provided further confirmation of the improved physical condition in the RB soil, e.g. at 10-20 cm depth the LLWR of the RB was nearly twice that of CC.
The quantification of soil macropore structure (chapter nine) revealed further evidence of the improved soil physical condition of RB. One of the most distinct differences shown by resin-impregnated image analysis was the significantly greater pore connectivity (according to pore genus). The solute transport experiment (chapter eight) supported this finding as the RB had a greater proportion of more preferential flow close to saturation, a sign of a better connected pore network. The second time that macropore structure was quantified showed there was less difference in the structural parameters, but overall the RB were found to have improved soil structure. For instance the RB had several key structural parameters: porosity, surface area (SA) and pore genus (PG) that were improved compared to the CC soil.

10.4 Recommendations on cropping with raised beds

This thesis found that RB are recommended where there is limited external drainage, poor subsoil drainage and poor surface (topsoil) infiltration and aeration. It is the amount of growing season rainfall (GSR) that determines whether a yield benefit is derived from installing RB. In this study a GSR of at least 323 mm was required for RB to produce increased yield compared to CC. This amount (323 mm) was the GSR in 2004, but it was not enough rainfall to result in a significantly greater yield. Therefore it is predicted that a greater GSR is required (at least >340 mm) for a significant yield benefit. In addition to GSR, it is thought that crop type affects whether increased yield is realized.

With respect to the variables of soil type and rainfall, cropping with RB is recommended where there is:

1. a need to improve the internal and external drainage;
2. high soil strength in the topsoil which limits plant root growth;
3. low AFP (<10 per cent) which limits the soil aeration;
4. a likelihood that soil properties, such as soil structure, may deteriorate over time, e.g. due to structural instability.
The soils most likely to fall into these categories are those with the following attributes. Soils with heavy clay in the B horizon that are either clay throughout the profile or with a texture contrast profile. Typically these soils have poor internal drainage and infiltration is slow, especially between the A and B horizons for texture contrast soils. It is likely that these same soils will also have high soil strength (>2 MPa at field capacity) in the surface 20 cm, particularly soils with a shallow A horizon. Soils classified as sodic (>6 per cent exchangeable Na in the top 20 cm of the B horizon), are known to be unstable or structurally weak. Cropping on the soils previously described would benefit from the installation of RB, e.g. the soils described at Mt Pollock and Briandra (chapter three).

Likewise, with respect to soil type and rainfall, the installation of RB is not recommended if:

1. there are no historic observations or record of waterlogging;
2. it is likely that increased crop yields from RB will occur only in very wet years. A preliminary analysis of district data (chapter five) suggests that RB are not an economically viable option if the number of wet years is three or less in 10 years. In this case, over a 10 year period the average yield attainable from CC would be acceptable.

Therefore, the soils that would not benefit from RB have the following attributes. These soils are: free-draining, well-structured and non-sodic. A review of the measurements taken in this thesis and other studies (Bluett 2002; Peries 2005; SFS 1999; SFS 2000; SFS 2001; SFS 2002; SFS 2003; SFS 2004; SFS 2005) in south-western Victoria suggests that these soils have gradational soil profiles and are not high in clay content. Such soils have good internal drainage, especially in the B horizon and would maintain adequate AFP during the wettest periods of the year. Lastly, on wetting, these soils are stable and do not disperse.
10.5 Future research

From this thesis several opportunities for further research on RB have been identified. This thesis has focused on a selection of soil physical properties of RB and CC on one soil at Mt Pollock. However, it is not known for certain what the values are of those soil properties where RB are not required. Consequently there is a need for the measurements taken in this study to be repeated on distinctly different soil types across south-western Victoria. Currently RB seem to be recommended for most soil types, except where the slope is >1.5 per cent (GRDC et al. 2005). Indeed observations made in this study suggest that some soils do not require RB, although this needs to be confirmed by further measurements.

As this thesis paid attention to physical properties, key soil chemical properties were largely neglected. In south-western Victoria, RB have often been installed on soils classified as Sodosols (Isbell 2002). Soil sodicity causes hardsetting and poor aggregate stability (Naidu et al. 1995; So and Aylmore 1993). Hardsetting has been shown to cause problems for seedling germination and affects the infiltration of water into the soil. There have been no previous studies on the hardsetting nature of soils under RB in south-western Victoria. Thus, to what extent does hardsetting of the soil exist on RB compared to conventionally cultivated soils? Indeed, the formation of RB involves deep ripping of the subsoil (which is often sodic) and mixing it with the topsoil. Furthermore RB are being installed on some soils that have never previously been cultivated. Consequently the risk of hardsetting on soil under RB cropping must be determined.

It was found that RB provided some improved soil physical properties compared to CC. The solute transport experiment suggested that there was greater pore network stability in the RB. An assessment of soils in south-western Victoria by Robinson et al. (2003) claimed that aggregate stability was one of the most serious land degradation issues in this region. However there is a need to directly measure the soil aggregate stability on RB. Therefore it is recommended that research is directed towards determining the effect of RB cropping on aggregate stability. Aggregate stability can be measured with the
Emerson Dispersion Test (Emerson 1967) or by measuring the dispersive potential (Rengasamy et al. 1991) or clay dispersion (Rengasamy et al. 1984).

This thesis has covered the measurement of the SWD under RB and comparative land uses. Johnston (2005) also measured run-off volume from these treatments over the same period. Nevertheless there are deficiencies in our understanding of the pathways of water loss from RB and the soil water balance. Deep drainage from RB has not been directly measured. The measurement of deep drainage would be valuable in more completely evaluating the hydrology of RB.

Several soil management issues have been observed during this study on RB. For instance some farmers implement supplementary cultivation passes after RB are formed. These cultivations are usually done after two years (and repeated when necessary) and are referred to colloquially as ‘bed renovations’. Typically bed renovations involve the cultivation of soil along the furrows between the beds and sometimes they include shallow cultivation of the RB as well. The effect of and benefit accrued from bed renovations are not known. Similarly the influence of controlled traffic on RB has not yet been robustly established. However, in south-western Victoria RB are often adopted as part of controlled traffic cropping system.

Finally, research should investigate the application of fertiliser to RB, in particular N fertiliser in spring. There is a lack of knowledge on applying N at different crop growth stages. Data should be collected on plant density, tiller number, dry matter production, head number, grain size and profile SWD. This work should improve understanding of RB cropping so that crop yields might be optimized. Moreover it should increase the likelihood that N is applied at the correct time for crop uptake and not wasted or lost as run-off.
Neutron moisture meter calibration

The neutron moisture meter (NMM) was calibrated at each experimental site. At Mt Pollock a sprinkler system was connected to a nearby mains water supply and set up close to four calibration access tubes. This provided a reliable source of water which enabled the soil to be slowly wet up to saturation point. Duplicate neutron count readings were taken after a 16 second time interval at depths of 20, 40, 60 and 80 cm from the surface. Immediately afterwards undisturbed cores were collected from the corresponding depth intervals. From these samples the bulk density (BD) and gravimetric soil water content ($\theta_g$) were measured. Soil sampling and neutron count readings for the calibration were taken on three occasions: 24/10/2002, 14/01/2003 and 12/03/2003, corresponding to wet, intermediate and dry.

Greacen (1981) warned about difficulties when combining depth layers to determine the calibration equation. Inaccuracies can develop if there are significant changes in clay content or BD. Thus, in some cases a different calibration equation is required for each depth where there are major differences in texture or density. At Mt Pollock most pedological variation in the whole profile occurs in the A horizon, the depth of which varies from 10 to 18 cm. The B horizon was fairly uniform below this (see the Site Characterisation - Table 3.2.) and includes the depths intervals (i.e. 20, 40, 60 and 80 cm) that were measured using the NMM. A high percentage of gravel was found between 35 and 45 cm, e.g. close to one access tube up to 22 per cent gravel was measured. It is thought that gravel caused the BD to be overestimated and decrease the measured $\theta_g$. Consequently, the calibration calculated at 40 cm was not considered to be realistic. In contrast, the calibrations for 20, 60 and 80 cm were much better and were similar to each other. In fact a pair-wise linear regression analysis showed that there was no significant difference ($P < 0.05$) between these depths. Thus, it was decided to combine the calibration data together and use one calibration equation for all depths (Figure A.1).
At Briandra the gravel content of the soil was lower (<5 per cent) and thus the same problems as at Mt Pollock were not encountered. As no mains water was available, the calibration was undertaken when the profile was considered wet (09/09/2002) and when it had dried out (07/11/2003). Neutron counts were taken at several depths – 20, 30, 40, 50, 60 and 80 cm and samples were collected from the corresponding depth intervals. The calculated calibration equations at 40, 50 and 80 cm depths were poor and produced a low coefficient of determination ($R^2$) i.e. < 0.20. Consequently, the calibration equations used were: $y = 0.73x -0.06$ ($R^2 = 0.62$) at 20 cm for the 20 cm depth; $y = 0.91x - 0.17$ ($R^2 = 0.53$) at 30 cm for the 30 and 40 cm depths and $y = 0.81x - 0.03$ ($R^2 = 0.44$) at 60 cm for the 50, 60 and 80 cm depths.

![Graph](https://via.placeholder.com/150)

Figure A.1 Volumetric water content ($m^3/m^3$) and neutron count ratio at 20 (□), 60 (♦) and 80 (●) cm at Mt Pollock. Where $y = 0.8x - 0.13$, $R^2 = 0.58$. 

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APPENDIX B

The measurement of run-off

Surface runoff volume was measured and water run-off samples were collected from the RB and CC plots at Mt Pollock. This work was done by Mr T. Johnston, Victorian DPI, Geelong for a separate study using the same experimental site.

Plots were hydraulically isolated using compacted earth mounds and surface drains. Surface flows were measured using modified Repogle-Bos-Clemmens flumes, a hydrostatic water level sensor and a central data logger. A 100mm RBC flume (Clemmens et al. 1984) was installed at the lowest point of each of the 0.2 ha plots. Flow heights through the flumes were measured every 10 minutes with a liquid level sensor (Mindata 2100P, Mindata Aust. Pty Ltd; in conjunction with a multiplexer) and then recorded with a data logger (Handar 555, Mindata Aust. Pty Ltd). The flow heights enabled flow volume to be calculated for each measurement period. If the calculated flow volume exceeded a prescribed volume (usually 0.2 mm of runoff), an automatic water sampler (Isco 3700, ISCO Inc, USA) was triggered to collect a flow-weighted water sample (Figure B.1). Each sampler was able to collect a one litre water sample per run-off event. Within 24 hours water samples being taken they were collected from the field and placed in storage at -15°C. These water samples were then analysed for total nitrogen and total phosphorus.
Figure B.1 Autosampler collecting run-off samples at Mt Pollock
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