Soil physical degradation due to drip irrigation in vineyards:

Evidence and implications

Thesis submitted by

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This work is dedicated to Ian Parsons, Jim Scholfield and Tom Scholfield:

Three custodians of the land.

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Abstract

Drip irrigation is the most common method of water application used in Australian vineyards. However it places physical and chemical stress upon soil structure, which may affect soil physical properties, soil water availability and grapevine functioning. Common soil types within Australian vineyards appear vulnerable to soil degradation and there is emerging evidence of such degradation occurring.

Two South Australian vineyards (one located at Nuriootpa in the Barossa Valley, the other in the McLaren Vale winegrowing region) were used to examine evidence of altered soil physical properties due to irrigation. Significantly higher soil strength and lower permeability was found under or near the dripper in irrigated soils. There was also evidence that irrigation increased subsoil bulk density at Nuriootpa. It was uncertain how irrigation caused these changes. While sodicity was present at Nuriootpa, it appeared the physical pressures exerted by irrigation, such as rapid wetting and prolonged wetness, also contributed.

To gauge the severity of the degradation at Nuriootpa, a modelling study assessed the impact of higher soil strength and salinity on grapevine transpiration. The SWAP model (Soil-Water-Atmosphere-Plant) was modified and then calibrated using soil moisture data from Nuriootpa. Simulations were conducted for different irrigation regimes and the model output indicated that degradation led to a reduction in cumulative transpiration, which was almost entirely due to higher soil strength. However the reduction was relatively minor and there was evidence of water extraction by roots in all soil layers. Hence the degradation, in terms of higher soil strength and salinity, was not considered a significant management problem in the short-term. Evidence of increased waterlogging and its consequences require further investigation.

Roots were observed in soils at Nuriootpa with penetration resistance (*PR*) much greater than 2 MPa, which was thought to completely impede grapevine root growth. It was hypothesised that roots avoided the physically hostile matrix by using biopores or structural cracks. A pot experiment tested this hypothesis and examined the relationship between soil strength, biopores and root growth for grapevines. Grapevine rootlings (cv. Cabernet Sauvignon) were grown into pots with varying degrees of soil compaction, with and without artificial biopores. No root growth occurred when *PR* > 2 MPa unless biopores were present. Pores also improved root growth in non-compacted soil when *PR* approached 1 MPa, which

suggested biopores influence root growth in soils regardless of compaction levels. Therefore *PR* should not be the only tool used to examine the rooting-potential of a vineyard soil. An assessment of soil structure, such as biopore density and size, should be incorporated.

In drip-irrigated vineyards, there is a possibility that degraded clayey subsoils could be ameliorated by manipulating zones of soil drying. At distances away from the dripper, drying events could generate shrinkage cracks that improve drainage and provide opportunities for root growth. From a practical perspective, drying events could be manipulated by moving the dripper laterally or by changing the irrigation frequency and intensity. The potential of this simple, non-invasive, ameliorative approach was investigated. Large, intact cores were sampled from Nuriootpa subsoil where degradation had been identified. Individual core bulk density was calculated using a formula that was derived by solving two common soil physics equations simultaneously. This proved to be an accurate and non-invasive method. Half the cores were leached with a calcium solution, and the saturated hydraulic conductivity (K_s) was measured on all cores before and after drying to a matric potential of –1500 kPa. Soil drying led to a significant increase in K_s, which indicated an improvement in structure through the creation of shrinkage cracks and heaving. Calcium treatment had no impact on K_s, but that could change with more wetting and drying cycles. Results indicated the need for further investigation in the field, where different compressive and tensile forces operate. Harnessing this mechanism may provide an attractive soil management option for growers.

The soil physical degradation identified is concerning for sustainable production in irrigated vineyards. Given the sites were representative of typical irrigation practices, such degradation may be widespread. While modelling suggested the impact of higher soil strength and salinity was minimal, these properties should be monitored because they may worsen with continuing irrigation. Furthermore, the impact of irrigation on subsoil permeability needs to be defined more accurately. An increased incidence of waterlogging could significantly restrict production, which was evident when overly wet growing seasons were modelled. If subsoil permeability was found to be significantly lower in irrigated soils, amelioration may be required. In this instance, the use of drying events to generate structure provides an option. Ultimately, the impact of drip irrigation on soil physical quality warrants further attention, and it is imperative to monitor the physical quality of vineyard soils to ensure sustainable production.

Statement

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being made available in all forms of media, now or hereafter known.

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Publications arising from the thesis

At the time of writing, the following article describing work in this thesis has been submitted for publication:

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Chapter 1.

Introduction, Literature Review and Aims

1.1 Introduction

Irrigation is widely practised in Australian viticulture, however it can exert great pressure on the soil environment. It significantly alters the hydrologic cycle, which affects soil-changing processes. Changes can be beneficial (Artigao *et al.*, 2002), but history is replete with evidence of irrigation as a cause of soil degradation (Jacobsen and Adams, 1958; Khan *et al.*, 2006).

Soil structure is an important aspect of soil quality that can degrade with irrigation due to physical and chemical stress. This thesis aims to investigate the impact of irrigation on soil physical properties, which are a means of defining soil structure and can be related to grapevine functioning, within vineyards.

1.2 Literature Review

A review of the current understanding of soil structural processes and properties, in relation to irrigation, is presented. Soil physical properties are introduced, and their relationship to grapevine functioning is described. Finally, models of soil water availability are reviewed, which can be used to determine the impact of any degradation on crop performance.

1.2.1 Irrigation in Australian viticulture

Irrigation is widely practised in Australian viticulture to better manage yield and quality in a dry climate with unreliable rainfall. Over 80% of Australian vineyards are irrigated, which represents a land area of 149,960 ha (A.B.S., 2006) and a production value of over $1.2 billion per annum (N.S.W. Irrigators' Council, 2001). Consumptive water use varies according to season, climate, variety, method of application, and irrigation strategy. The national average is 3.76 ML/ha/yr (A.B.S., 2006), but water use ranges from more than 15 ML/ha/yr in the Murray Darling Basin to less than 0.5 ML/ha/yr in the groundwater dependent regions of

South Australia and Western Australia (Stringer and Wittwer, 2001). Application methods include drip, sprinkler, furrow and microspray irrigation systems. Drip irrigation is the most common method and together with microsprays accounts for 76 % of the total area irrigated (A.B.S., 2006). Its use is increasing as growers seek to improve water use efficiency and lessen adverse environmental impacts.

1.2.2 Soil structure

An integral aspect of soil quality is its structure because it controls many properties and processes that support plant growth. Its importance is reflected by the numerous research papers published over many years that are well summarised in comprehensive review papers (Hamblin, 1985; Dexter, 1988; Kay, 1990; Horn *et al.*, 1994; Kay and Angers, 2000).

While there is no one single definition of soil structure, it is commonly described as the arrangement of particles and the pores between them (Kladivko, 2006). Kay (1990) extends this definition to include temporal variability and describes three distinct aspects of soil structure. *Structural form* describes the heterogeneous arrangements of solid and void spaces at a given time and can be measured in terms of porosity, pore-size distribution, and continuity of the pore systems. *Structural stability* is the ability of a soil to retain its structural form when subjected to different stresses. *Structural resiliency* is the ability of a soil to recover its structural form through natural mechanisms after a stress has been removed.

Changes in soil structural form and stability are dependent on the inherent properties of the soil and extrinsic, time-dependent factors (Oster and Shainberg, 2001). Inherent soil properties that affect structure include texture, mineralogy (Goldberg *et al.*, 1988), organic matter (Oades, 1984; Nelson and Oades, 1998), bonding agents (Goldberg *et al.*, 1990), pH (Suarez *et al.*, 1984; Chorom *et al.*, 1994), surface charge density (Rengasamy and Sumner, 1998) and soil flora and fauna (Angers and Caron, 1998; Czarnes *et al.*, 2000). Extrinsic factors include cultivation and mechanical stress (Horn *et al.*, 2000), irrigation method and water quality (Halliwell *et al.*, 2001), wetting rate (Shainberg *et al.*, 2001), antecedent moisture content (Truman *et al.*, 1990), and chemical amendments (Jayawardane and Chan, 1994).

Changes in management practice, e.g. by introducing irrigation or changing water qualities and application rates, place stresses upon soil structural form. The extent to which structural form is altered is dependent upon soil structural stability and the nature of the stress applied. Ultimately changes in structural form affect the nature of the pore system, which controls the availability of water, nutrients and oxygen to plant roots, and provides opportunities for root growth (Hamblin, 1985). Therefore, it is important to ascertain the nature and extent to which irrigation is affecting soil structure to ensure long-term productivity is not being compromised.

1.2.3 Pressures exerted on soil structure by irrigation

A number of mechanisms can be identified whereby irrigation places stress upon soil structure. They can be broadly categorised as physical and chemical pressures. While much research has focussed on the chemical pressures of irrigation that are typically associated with water quality effects, comparatively little research has adequately dealt with the physical pressures of irrigation, which in many cases are ignored.

Physical pressures

The introduction of irrigation leads to fundamental changes in the soil hydrologic regime. Irrigated soils receive more water, experience rapid wetting, prolonged wetness, and undergo a greater number of wetting and drying cycles relative to natural rain-fed conditions. As outlined in the following paragraphs, such changes are conducive to structural degradation.

The amount of additional water, applied as irrigation, can be considerable even when it is to only ‘supplement’ rainfall. For example in the Barossa Valley wine region of South Australia, an average of less than 2.0 ML/ha/yr, or 200 mm, is applied with drip irrigation (Stringer and Wittwer, 2001) to supplement the annual mean rainfall of 502 mm (B.O.M., 2006). However it is misleading to quote application rates on a per hectare basis because the water is not applied evenly over the landscape. Rather it is concentrated beneath drippers, such that the soil volume immediately below a dripper receives considerably more irrigation than rainfall. The amount of additional water would be even greater in inland growing regions where irrigation rates are higher. It would appear that such extreme changes in hydrology place stress upon soil structure, yet no studies have examined this relationship in detail.

Additional water prolongs soil wetness, and increases the frequency and rate of wetting events. A soil is more unstable when wet due to reduced cohesion and the softening of cements (Marshall *et al.*, 1996), and two distinct processes, slaking and dispersion, are known to destabilise structure during wetting (Emerson, 1977). Dispersion is linked to the chemistry of the soil solution and the exchange complex, which will be discussed in detail as a chemical stress. However slaking can occur in the absence of chemical stress. It occurs because the stability of aggregates cannot withstand the pressures generated through wetting. Such pressures include uneven swelling, trapped air, shear stress and the heat of wetting (Emerson, 1977; Grant and Dexter, 1989; Grant and Dexter, 1990; Mullins *et al.*, 1990; Loch, 1994; Shainberg *et al.*, 2001). The magnitude of stresses produced and the extent of slaking increase with the rate of wetting (Panabokke and Quirk, 1957; Quirk and Panabokke, 1962; Kay, 1990). Despite drip irrigation being considered a 'gentle' wetting practice, it generates wetting rates significantly greater than those produced by most natural rainfall events. Again this is because the water application is concentrated at one point. For instance, a 4 L/h dripper typically infiltrates a disc of soil 30 cm in diameter and thus has an equivalent rainfall intensity of almost 60 mm/h. Therefore, it is probable that drip irrigation increases the likelihood of slaking.

Irrigated soils also experience more wetting and drying cycles, which contribute to the phenomenon of coalescence (Cockroft and Olsen, 2000; Lanyon *et al.*, 2000). Aggregate coalescence is a soil hardening process whereby the cementing of aggregates leads to increased soil strength. It can occur despite a high degree of water stability, suggesting that slaking and dispersion are not necessarily involved (Cockroft and Olsen, 2000; Lanyon *et al.*, 2000), it increases with more irrigation cycles (Lanyon *et al.*, 2000), and the rate of strength increase is greater than what is attributable to natural densification (Grant *et al.*, 2001). Consequences include lower hydraulic conductivity within the soil matrix, restricted root growth and diminished crop productivity (Cockroft and Martin, 1981; Cockroft and Olsen, 2000). The fact that coalescence can be widespread in zero-tilled soils where non-trafficked, water stable soil becomes hard (Cockroft and Olsen, 2000) has relevance to irrigated viticulture.

The extent to which structural form is altered by stress depends on inherent soil properties. Some soils resist change while others have properties making them more susceptible. Vulnerable soils have been labelled 'hardsetting' (Mullins *et al.*, 1990). They have properties such that during wetting, aggregates have insufficient strength to withstand the stresses of rapid water uptake, and structure is not regained upon drying which causes uniaxial shrinkage and/or development of increased strength (Mullins *et al.*, 1990). Red-brown earths, a common soil type in Australian wine growing regions, have A horizons known for their hardsetting tendencies due to naturally low salinity and organic carbon contents (Surapaneni and Olsson, 2002) and high contents of silt and fine sand, which create dense packing arrangements (Cockroft and Martin, 1981).

Chemical pressures

Irrigation can disturb the chemical equilibrium that exists between the soil solution and the exchange complex, which controls the stability of aggregates and pore systems (Rengasamy and Olsson, 1991). The mechanisms responsible for these interactions are explained at a basic level by diffuse double layer theory, outlined by van Olphen (1977). The diffuse double layer describes the arrangement of a net negatively charged clay surface and the exchangeable cations attracted to it. The thickness of the double layer is inversely related to the valency of the exchangeable cation, and inversely proportional to the square root of the ionic concentration of the soil solution (Blake, 1968). Hence double layer thickness for a Na-saturated clay is much larger than for a Ca-saturated clay, and the Na-saturated clay is less stable because of this. Also, the stability of a soil will decrease if the salinity of the soil solution is lowered.

As indicated, high levels of exchangeable sodium tend to destabilise soil structure. This condition is broadly known as sodicity for which comprehensive reviews exist (Naidu *et al.*, 1993; So and Aylmore, 1993; Levy *et al.*, 1998; Rengasamy and Sumner, 1998; Levy, 2000). The amount of exchangeable sodium within a soil is defined by either the exchangeable sodium percentage (ESP) or the sodium adsorption ratio (SAR) of the soil solution as shown:

$$\text{ESP} = 100(\text{Exchangeable Na}/\Sigma \text{ exchangeable cations}) \qquad \text{Eqn 1.1}$$

$$\text{SAR} = \text{Na}^{+}(\text{Ca}^{2+} + \text{Mg}^{2+})^{-1/2} \qquad \text{Eqn 1.2}$$

where Na^{+}, Ca^{2+} and Mg^{2+} represent concentration in millimoles per litre.

In Australia, a sodic soil is defined as one having an ESP of 6 or greater (McIntyre, 1979; Isbell, 1996). Indeed Australia has a vast area of land (28 %) affected by sodicity (Northcote and Skene, 1972), which is consistent with sodium chloride being the dominant salt in the Australian environment (Rengasamy and Olsson, 1991). Thus many Australian soils are naturally sodic or could become sodic if irrigated with waters that are quite often high in sodium.

The physical behaviour exhibited by sodic soils upon wetting with a low-salt solution is described by Rengasamy and Sumner (1998). Swelling and dispersion are regarded as the two main processes that alter soil physical properties. Dispersion occurs when clay particles spontaneously separate from one another during wetting. The detached particles can migrate and become lodged in conducting pores, thereby reducing the hydraulic conductivity of the soil (Oster and Shainberg, 2001). When ESP > 15, swelling becomes the more dominant process and reduced pore space lowers hydraulic conductivity (Shainberg and Letey, 1984). A key difference between swelling and dispersion is that swelling is a reversible process while dispersion is not. Dispersed particles cannot retain their original associations upon flocculation (Levy, 2000).

Swelling and dispersion are also controlled by the electrolyte concentration of the soil solution, which is often defined in terms of its electrical conductivity (EC). The relationship between SAR, EC and soil hydraulic conductivity has been examined by numerous studies on soil columns in the laboratory, which identify drastic reductions in hydraulic conductivity when waters of low EC are applied to soils of high sodicity (Quirk and Schofield, 1955; McIntyre, 1979; Oster and Schroer, 1979; Cass and Sumner, 1982a; Minhas and Sharma, 1986; Chaudhari and Somawanshi, 2004). However permeability can be maintained if adequate levels of electrolyte are present in the soil solution. Hence the concept of a threshold concentration was introduced and defined as the concentration required to prevent a >25% decrease in permeability for a given soil SAR (Quirk and Schofield, 1955). Rengasamy *et al.* (1984) defined this relationship for red-brown earths. However threshold concentration is not a unique function of EC and SAR (Curtin *et al.*, 1994). It varies with clay content, mineralogy, pH and organic matter (Rengasamy and Olsson, 1991). Therefore it is difficult to set definitive limits regarding SAR and EC that cause dispersion in the field.

Responses to sodicity can be quite different for surface and subsurface soils (Oster and Jayawardane, 1998). Surface soils are more affected by water drop impact, rapid wetting, irrigation water quality, mechanical compaction, tillage and mulches. Subsoils have lower wetting rates, higher antecedent water contents and lower organic matter contents. The sodicity problem can be quite acute at the top of B horizons in duplex soils, such as red brown earths (Fitzpatrick *et al.*, 1994). Sodium concentrations increase with depth in irrigated soils due to the uptake of water, which causes cations left in the soil solution to be concentrated (Halliwell *et al.*, 2001). Soil mineralogy plays a key role in determining the extent to which subsoils are affected by salinity, and the ability to produce salts by short-term weathering (minutes to hours) will buffer small increases in exchangeable sodium (Shainberg and Gal, 1982). The clay subsoil in red-brown earths produces only small amounts of electrolyte from mineral weathering and is sensitive to small increases in exchangeable sodium (Surapaneni and Olsson, 2002).

With respect to irrigation, exchangeable sodium may build up within the soil profile if sodic irrigation waters are used (Balks *et al.*, 1998; Bethune and Batey, 2002; Slavich *et al.*, 2002; Surapaneni and Olsson, 2002; Clark, 2004). To maintain structure in sodic soils, a minimum EC of irrigation water is required for clay particles to remain in a flocculated state (Quirk and Schofield, 1955; Cass and Sumner, 1982b). These conditions may be maintained throughout the irrigation season but a range of scenarios may cause the latent problems of sodicity to emerge- the onset of rainfall (low EC) in winter, the permanent cessation of irrigation, changing water sources, and altering land-use (Halliwell *et al.*, 2001). Salt-leaching caused by winter rainfall may be sufficient (Kienzler, 2001; Clark, 2004) or insufficient (Balks *et al.*, 1998; Bethune and Batey, 2002) to cause significant changes in soil physical properties. It is expected that unless ameliorative steps are taken, cessation of irrigation and the prolonged exposure of sodified soils to rainwater will result in structural decline (Bethune and Batey, 2002). Changing water quality to lower EC sources may also eventuate in degradation. For instance the introduction of the BIL-water* scheme in the Barossa Valley (Jackson, 2003), which replaces saline-sodic borewater with good quality surface water, could potentially have an adverse impact on soil structure.

Examples in viticulture

In the context of Australian viticulture, very few studies have examined changes in soil structure with irrigation. However there is some emerging evidence that structural degradation is occurring. For instance Clark (2004) investigated seasonal changes in soil salinity and sodicity resulting from drip irrigation with borewater (EC = 2-3dS/m) in a Barossa Valley vineyard, South Australia. Irrigation increased soil sodicity and salinity during the growing season, particularly at the edge of the sphere wet by a dripper, however winter rains leached salts and lowered the ionic concentration of the soil solution. Such conditions are conducive to colloid dispersion and structural decline when the ionic concentration drops below a certain

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[*] BIL-water refers to the Barossa Infrastructure Ltd scheme, which was established to increase water allocations for Barossa Valley growers. Water is accessed from the Murray River and local reservoirs.

threshold (Rengasamy et al., 1984). Indeed some evidence of structural decline was found by Clark (2004), with higher bulk densities and reduced pore space evident in thin sections. At the same site, a preliminary study by Kienzler (2001) found irrigation led to an increase in soil penetration resistance. A more complete assessment of soil physical properties is required at the site to determine the evidence and magnitude of any degradation, the timeframe over which it occurs and its impact on grapevine functioning.

Application of saline-sodic water was also found to elevate soil ESP, increase clay dispersion and reduce permeability in the Riverland growing region, South Australia (Prior *et al.*, 1992). The resultant waterlogging caused a number of rootstocks to lose their ability to exclude salt (Stevens and Walker, 2002).

Such findings have relevance for the future of Australian viticulture, where it is predicted that tighter water-licensing restrictions and greater demand across all horticultural sectors will limit access to quality water (N.L.W.R.A., 2002). Waters of marginal quality may be sourced to accommodate the heightened demand, potentially endangering soil physical conditions where applied (Hamilton *et al.*, 2005).

1.2.4 Soil physical properties and grapevine functioning

Changes in soil structure affect soil physical properties that have a direct relationship to crop functioning (Hamblin, 1985; Letey, 1985; Dexter, 1988; Horn *et al.*, 1994; Kay and Angers, 2000). Therefore such physical properties can identify changes in soil structure and provide insight into the potential impacts of any changes on crop performance. The relationship of these physical properties to grapevine functioning is described below. Other reviews on this topic can be found elsewhere (Richards, 1983; van Zyl and van Huyssteen, 1983; Seguin, 1986; Lanyon *et al.*, 2004).

Soil hydraulic properties

A fundamental role of soil in the crop cycle is to supply water to plants. For grapevines, a lack of available water can reduce vegetative growth, yield and quality (Smart *et al.*, 1974; Hardie and Considine, 1976), while excessive water contributes to high vigour that is often incompatible with good wine quality (Eynard and Gay, 1992; Smart, 1995) or leads to waterlogging, which has an adverse effect on root growth, shoot growth and fruitfulness (Stevens *et al.*, 1999). An ideal soil for the production of high quality wines supplies water at a steady, moderate and reliable rate (Seguin, 1986). Various soil hydraulic parameters control water storage, its availability to roots and drainage.

Water storage is determined by the pore system, which is influenced by texture, bulk density and organic matter content (Dexter, 2004). Different textures give rise to different pore sizes, and several models have been devised to calculate water storage based on texture (Schaap *et al.*, 2004). Texture has also been shown to influence the rooting pattern of grapevines (Nagarajah, 1987). Bulk density controls total porosity and compaction results in a loss of total pore volume, with a preferential loss of the largest pores (Richard *et al.*, 2001). Organic matter also influences water storage, with soils high in organic matter having significantly higher storage capacities (Hudson, 1994). It is conceivable that irrigation could alter all three of these factors, even texture (Presley *et al.*, 2004), and thereby alter the pore system and water storage capacity.

A means of describing both the pore system and water storage capacity is provided by the water retention curve, which is the relationship of water content to matric potential for a given soil. The curve is strongly affected by soil structure and can be used with the capillary equation to calculate pore size distributions (Hillel, 1998). Hence it can be used to identify changes in soil physical quality (Barlow and Nash, 2002; Dexter, 2004).

For practical vineyard applications, water storage is defined as total available water (TAW), which is the amount of water held between field capacity (≈ -10 kPa matric potential) and wilting point (≈ -1500 kPa). The optimum TAW for grapevines is depicted in Fig. 1.1 as a function of aeration, which will be elaborated upon later. TAW provides only a limited view of soil water supply because it does not describe water availability, which is not uniform from saturation to wilting point. For grapevines, a simplistic scheme of water availability (Fig. 1.2) has been devised to guide growers with regard to irrigation scheduling (Goodwin, 1995; Cass, 1999).

NOTE: This figure is included on page 10 of the print copy of the thesis held in the University of Adelaide Library.

Figure 1.1 – Classification of soil physical quality for grapevines, in terms of available water and root zone aeration . From Cass (1999).

NOTE: This figure is included on page 10 of the print copy of the thesis held in the University of Adelaide Library.

Fig. 1.2 A schematic representation of soil water availability for grapevines. From Goodwin (1995).

Water is most readily available from field capacity to -60 kPa (recommended to growers as the ‘refill point’) after which drought stress increases. The amount of readily available water (RAW) can be quantified over the rooting depth and this parameter is commonly used for site selection and irrigation system design (White, 2003). While the scheme has many practical applications, it is rather simplistic in that it ignores other factors such as hydraulic conductivity, aeration, salinity and mechanical impedance- factors that all influence water availability and may change with structural degradation. Therefore it is preferable to define water availability with a more physically based approach, as described later in this chapter.

Hydraulic conductivity directly influences water availability by affecting the rate of water movement to roots. Since Gardner (1960) produced a model describing the movement of water to a single root, there has been considerable debate over the relative importance of plant and soil hydraulic conductivities in limiting root extraction. Theoretical and experimental studies suggest that both hydraulic terms can be important, and that the minimum hydraulic conductivity of the bulk soil must be around 10^{-4}-10^{-5} mm/day so as not to be limiting (Cowan, 1965; Andrews and Newman, 1969; Newman, 1969b; Newman, 1969a; Taylor and Klepper, 1975; Reicosky and Ritchie, 1976). However Dexter (1988) points out that for the Urrbrae loam soil at the Waite Institute (a red brown earth), such low hydraulic conductivities are not reached until soil matric potential is less than wilting point. No studies have examined grapevine root uptake relative to low soil hydraulic conductivities.

Hydraulic conductivity also influences water availability indirectly by controlling infiltration and drainage characteristics. An adequate infiltration rate allows water to enter the soil without ponding on the surface that can lead to runoff and erosion. For vineyards, an infiltration rate >50 mm/hr is recommended (White, 2003). Low hydraulic conductivity may also cause ineffective drainage, which subjects roots to waterlogging and aeration stress after rainfall and irrigation.

Aeration

Soil aeration status plays a key role in crop performance. Root functioning is adversely affected if the oxygen status of a soil is deficient for metabolic processes (Armstrong and Drew, 2002), which can lead to reduced root growth, the formation of aerenchyma, and early nodal root emergence (Drew *et al.*, 1981). Low oxygen concentrations inhibit ion uptake by roots (Drew *et al.*, 1988) that leads to reduced nutrient concentrations in the foliage (Letey *et al.*, 1965). Anoxic conditions can also entrap ethylene and influence a range of other hormones and metabolites associated with root-shoot signalling to retard shoot growth (Jackson, 1985; Armstrong and Drew, 2002).

A commonly used index of soil aeration is air-filled porosity, which is the volume of air in a soil expressed as a percentage of the total volume. Because plants vary widely in their response to oxygen stress (Glinski and Lipiec, 1990), it follows that the critical value of air-filled porosity that limits root growth will vary with plant type. However in order to describe the physical status of soils, attempts have been made to quantify the point where the root growth of most plants is affected. Wesseling and van Wijk (1957) suggest a critical value of

10% air-filled porosity, which has been widely adopted (Glinski and Lipiec, 1990), although Grable and Siemer (1968) suggest 12 to 15% would present a safer limit.

Little literature deals directly with the effects of soil oxygen deficiencies on grapevine roots. Pot trials indicate that under waterlogged conditions overall vine growth declines, roots become concentrated in aerated parts of the soil and fruitfulness is reduced (Stevens *et al.*, 1999). Myburgh (1994) observed the majority of fine roots to be dead in a seasonally waterlogged vineyard in late spring, suggesting that a high proportion of fine roots die in waterlogged horizons during winter and spring. However grapevines appear to be more tolerant than other woody perennials. Stevens and Douglas (1994) found 25% of roots in soil with an air-filled porosity at field capacity of less than or equal to 6%, while Nel and Bennie (1984) found only minor citrus root growth in soils with an air-filled porosity of less than 15% at field capacity.

Mechanical impedance

Soil must have sufficient strength to provide anchorage to the plant and to prevent the collapse of air- and water-pathways by overburden pressure and external stresses. However dense regions of high strength limit root growth and crop yield (Bengough and Mullins, 1990). In the absence of pores of sufficient size, roots will only penetrate soil if they exert a force greater than the resistance they meet, and their growth will be inhibited in hard soil (Greacen *et al.*, 1969; Richards, 1983). The impact of high mechanical impedance on root growth has been examined by numerous studies that are summarised in review papers (Barley and Greacen, 1967; Greacen, 1986; Bengough and Mullins, 1990; Atwell, 1993; Unger and Kaspar, 1994; Masle, 2002; Clark *et al.*, 2003).

The elongation rate of roots is highly correlated with penetrometer resistance measurements, despite the different mechanisms by which they deform the soil (Passioura, 1991). Root tips tend to compress the soil cylindrically, whereas probes tend to compress the soil spherically (Cockroft *et al.*, 1969). Roots are also flexible, having the ability to follow tortuous paths, whereas penetrometers are rigid metal probes constrained to a limited path (Bengough and Mullins, 1990). As a consequence, penetrometer resistances tend to overestimate root resistances by a factor of between 2 and 8 (Bengough and Mullins, 1990). Despite the discrepancies, penetrometer resistance measurements remain the best method for estimating resistance to root growth in a soil. Fig. 1.3 demonstrates the strong linear relationship between penetrometer resistance and root growth over different soil types. Most studies report that a penetrometer resistance >2.0 MPa reduces root growth by at least 50% (Atwell, 1993).

NOTE: This figure is included on page 13 of the print copy of the thesis held in the University of Adelaide Library.

Fig. 1.3 Relationship between cotton root penetration and penetrometer resistance for various soil types. From Taylor et al. (1966).

While penetrometer measurements are a good indicator of mechanical impedance within the soil matrix, they do not quantify the overall resistance encountered by roots (Barley and Greacen, 1967). Most studies have examined root growth relative to penetration resistance using homogenous, repacked soil (e.g. Taylor et al., 1966; Veen and Boone, 1990; Tsegaye and Mullins, 1994). However in structured soils, roots can avoid an impenetrable matrix by exploiting biopores and cracks (Ehlers et al., 1983). Hence caution should be exercised when using penetrometer readings for anything other than comparative purposes.

Mechanically impeded roots are shorter, thicker, and more irregularly shaped than roots growing in low strength conditions (Richards and Greacen, 1986; Materechera et al., 1991). Their distribution can become clumped in biopores, where their functioning is not as efficient due to poor root-soil contact (Stirzaker et al., 1996) and exposure to higher populations of pathogens (Passioura, 1991). It appears that roots growing in hard soils may also send hormonal signals to the shoot, limiting shoot growth even when adequate supplies of water and nutrients are present (Masle and Passioura, 1987; Passioura and Gardner, 1990; Young et al., 1997; Masle, 1998). This response has been termed ‘feedforward’ where the plant is able to sense the unfavourable environment (hard soil) and slow shoot growth before the supply of nutrients and water are affected (Stirzaker et al., 1996).

As soil dries, its strength increases dramatically (Mullins *et al.*, 1992; Weaich *et al.*, 1992). Therefore plants growing in drying soil have to withstand both drought stress and higher mechanical impedance. Attempts have been made to understand the relative importance of each stress. In terms of root growth, Taylor and Ratliff (1969) found the elongation rate of cotton and peanuts in hard soils to be independent of water content, whilst Veen and Boone (1990) found the stresses to be additive for maize. The conflicting results may be due to the use of different species. In terms of shoot growth, studies in controlled environments have demonstrated the growth of wheat to be sensitive to increases in soil strength, but not to small changes in matric potential (Masle and Passioura, 1987; Young *et al.*, 1997; Masle, 1998; Whalley *et al.*, 2006). The factors are difficult to isolate in field studies (Whalley *et al.*, 2006).

Very few studies have examined the response of grapevines to strong soils. Strong negative correlations were found between vine root density and penetration resistance for a number of different soil types in France (Morlat and Jacquet, 1993). Pot studies indicate a linear decrease in root mass and shoot growth with increasing penetration resistance above 0.5 MPa (van Huyssteen, 1989; Ferree and Streeter, 2004), and some field observations support a critical penetration resistance of 2 MPa, above which root growth is abruptly or seriously impeded (Myburgh *et al.*, 1996). However other field studies have reported roots occupying even the densest subsoils with penetration resistances of up to 8 MPa at field capacity (Saayman, 1982; van Huyssteen, 1989). The discrepancy is probably related to varying soil structure between experimental sites.

Interrelationships

While it has been shown that soil physical conditions influence crop performance, the growth and functioning of root systems directly or indirectly influences these soil conditions. Angers and Caron (1998) provide an excellent review of this topic.

Root growth results in the enlargement of existing pores and the creation of new ones, many of which are macropores (>30 μm) (Gibbs and Reid, 1988). Macropores have a large influence on infiltration rates and contribute to preferential flow where water bypasses the soil matrix. The process of pore formation by roots is believed to be particularly important in no-till systems (such as vineyards) (Angers and Caron, 1998). Roots modify the soil-water regime by drying the soil through water extraction, leading to an increased number of wetting and drying cycles. This could lead to a cracking pattern developing at the outer edges of the rooted volume (Mitchell and van Genuchten, 1992), and the drying events may act synergistically with aggregate binding material produced in the rhizosphere to improve structural stability (Angers and Caron, 1998). Roots also contribute significantly to soil organic matter, which is known to affect aggregation in most soils (Oades, 1993).

Other significant interrelationships exist between soil physical properties themselves. For example, increasing soil water content may decrease mechanical impedance and aeration levels, increase nutrient availability and alter soil temperature (Wraith and Wright, 1998). Many of these individual changes have competing and contrasting effects, which can be difficult to disentangle. Therefore indices of soil physical properties that integrate these effects over a range of soil water contents may be more meaningful.

1.2.5 Models of soil water availability

Various models have been put forward to explain the availability of soil water to plants. Static models predominate the literature, however it is argued that future studies should examine the dynamic aspects of soil water availability by incorporating time as a variable.

Static models

The most widely used model is the available water capacity (AWC), otherwise known as TAW. It is the amount of water held between field capacity and permanent wilting point, and was first introduced by Veihmeyer and Hendrickson (1927). The concept of field capacity describes the amount of water held in a soil after excess water has drained and the rate of downward movement decreases (Israelson and West, 1922). Although it is defined as the water content after a thoroughly wetted soil has drained for two days (Marshall *et al.*, 1996), in effect it is an arbitrary concept, with the matric potential of field capacity varying between –5 kPa and –33 kPa (Groenevelt *et al.*, 2001). The permanent wilting point is the point of soil wetness where a wilted plant cannot recover its turgor when placed in a saturated atmosphere for 12 hours (Hillel, 1980). It is generally set at –1500 kPa (Groenevelt *et al.*, 2001), yet it can vary according to plant type and site-specific conditions. Plants have been included by calculating AWC over the depth of the rootzone to generate an amount of water that was termed the ‘plant available water capacity’ (PAWC) (Gardner *et al.*, 1984). However the main failing of the AWC and PAWC models is the assumption that all water held between two arbitrary limits is completely and equally available to the plant, and that all water outside the limits is completely unavailable (Hillel, 1980; Minasny and McBratney, 2003).

Other investigators drew upon empirical evidence that suggested water availability decreased with water content and plants suffered drought stress well before the wilting point was reached (Richards and Wadleigh, 1952). Hence schemes for 'readily available' water and 'stress available' water were outlined, as already discussed for grapevines (e.g. Goodwin, 1995; Cass, 1999). However such schemes are arbitrary and lack universal physical principles to work in a range of plant-soil scenarios.

Recognising the need to include physical factors that are directly related to plant growth, Letey (1985) combined aeration and mechanical resistance with AWC in a qualitative model termed the non-limiting water range (NLWR), as depicted in Fig. 1.4.

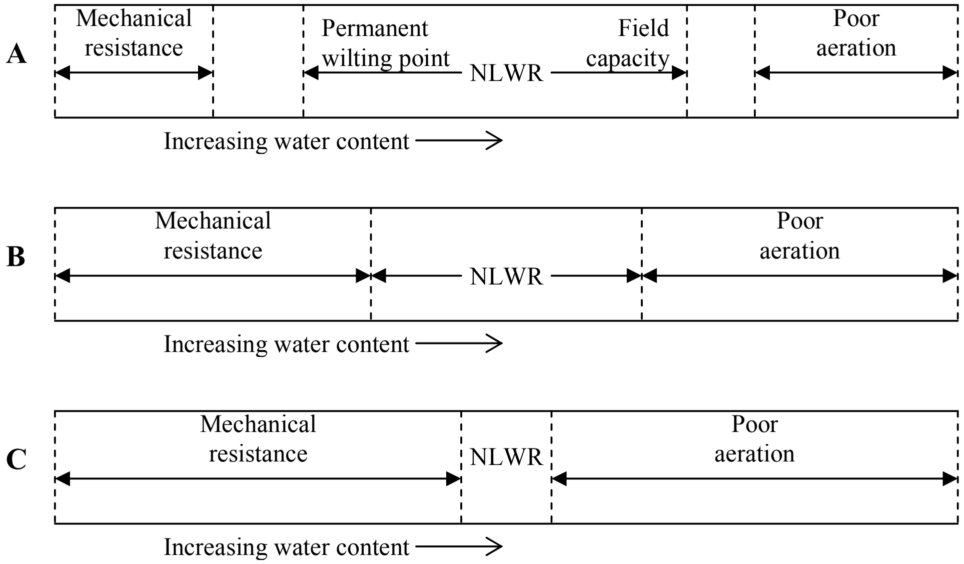

Fig. 1.4 Generalised relationship between soil water content and restricting factors for plant growth in soils, for soils with increasing bulk density and decreasing porosity from A to C. Adapted from Letey (1985).

Because low aeration occurs at high water contents, the upper limit of the NLWR corresponds either to field capacity or to the water content at which the degree of aeration becomes non-limiting, whichever is lower. Meanwhile mechanical resistance increases as soil dries, therefore the lower limit of NLWR corresponds to either the wilting point or the water content at which mechanical resistance becomes limiting, whichever is higher. The model was quantified as the least limiting water range (LLWR) by imposing critical values to describe aeration and mechanical resistance limits (da Silva *et al.*, 1994). An air filled porosity of 10% was chosen as the critical aeration limit, based on the work of Grable and Siemer (1968), and a penetration resistance of 2 MPa was chosen as the critical limit of mechanical resistance, based on the work of Taylor *et al.* (1966). The incorporation of several physical properties within a single index led to the use of LLWR as a comparative tool to study the impacts of different management systems on soil physical quality (e.g. Betz *et al.*, 1998; Tormena *et al.*, 1999; Semetsa, 2000; Zou *et al.*, 2000; McKenzie and McBratney, 2001). However the LLWR remains a flawed method for assessing plant-water availability because it implies water is equally available across a range of matric potentials until cut-off values are reached, when water becomes suddenly unavailable. This does not mimic empirical evidence.

Two approaches, both physically based, have been used to overcome the limitations of previous techniques. Minasny and McBratney (2003) use the shape of the water retention curve- volumetric water content (θ) versus matric potential (ψ)- to quantify the energy required to remove a unit of water from the soil. They termed the concept the integral energy. By integrating $\psi(\theta)$ with respect to θ, one is able to determine the energy required to remove a volume of water. This value will change continually over a range of water contents providing a realistic measure of soil water availability. Meanwhile, Groenevelt *et al.* (2001) introduced the integral water capacity (IWC) to refine the LLWR model. Continuous weighting functions, rather than sharp cut-off points, were included to define the soil physical conditions that limit plant growth. The concept implies a gradual reduction, or increase, in water availability as a physical limitation is approached, or departed from. Therefore not only does the IWC provide a more realistic measure of soil water availability, but it is able to include a range of soil physical properties within a single index. Hence it can be used as a comparative tool to assess the physical status of a soil, in terms of its capacity to supply water to plants.

The IWC can be obtained by integrating the weighted differential water capacity from zero to infinity, as follows:

$$\text{IWC} = \int_0^\infty \left(\prod_{i=1}^{n} \omega_i(h) \right) C(h)\,dh \qquad \text{Eqn 1.3}$$

where $C(h)$ = $-(d\theta/dh)$, the differential water capacity, $\omega_i(h)$ are weighting functions accounting for various limiting physical properties, *i* to *n*, Π indicates the weighting functions are multiplied, and *h* is the absolute value of the matric potential, expressed as a head (Groenevelt *et al.*, 2001). Essentially one measures the soil water retention curve $\theta(h)$, applies a differentiable fitting formula (e.g. van Genuchten, 1980; Groenevelt and Grant, 2004) and then differentiates $\theta(h)$ to obtain $C(h)$. Weighting functions, $\omega_i(h)$, are introduced to describe limiting soil physical properties and are multiplied by $C(h)$ to generate an 'effective' differential water capacity, which is then integrated to calculate IWC, expressed in m^3m^{-3}.

The weighting functions, $\omega_i(h)$, which may be linear or non-linear, are constructed to range from zero to unity between appropriate limits (Groenevelt *et al.*, 2001). This contrasts with the step functions used to calculate LLWR, which instantaneously switch from unity to zero as soil physical limitations are reached. In conjunction with the physical limitations imposed by a lack of aeration or high mechanical impedance, hydraulic conductivity and salinity relationships have been included as weighting functions in the IWC (Groenevelt *et al.*, 2001; Grant *et al.*, 2003; Groenevelt *et al.*, 2004). This is an important advance on other soil water availability concepts as not only is the store of water defined but also the rate at which a soil can supply water to roots. Furthermore, the salinity of the soil solution will increase with drying and exert increasing osmotic stress to lower the soil water potential.

Dynamic models

A major difficulty encountered with any attempt to quantify the supply potential of a soil, in terms of available water, is the dynamic nature of the soil-plant-atmosphere continuum (Hillel, 1980). While there has been considerable refinement of the traditional models of soil-water availability, they remain static and fail to include the significant variations in soil moisture and meteorological conditions encountered with time. These factors have a large bearing on root-water uptake and overall water availability.

The importance of meteorological conditions in influencing soil water availability is best highlighted by Denmead and Shaw (1962). On all days of their study on maize, the transpiration rate decreased as soil moisture decreased, which is in line with traditional concepts of soil water availability. However the level of soil suction (matric potential) where the relative transpiration rate (actual/potential) declined from 1 was found to vary according to meteorological conditions (Fig. 1.5). On days of high evaporative demand, the actual transpiration rate could be significantly less than the potential transpiration rate, despite adequate supplies of soil moisture. While on days of low evaporative demand, the actual transpiration rate was equivalent to the potential rate down to very low soil moisture contents.

NOTE: This figure is included on page 19 of the print copy of the thesis held in the University of Adelaide Library.

Fig. 1.5 Relative transpiration rate as a function of soil suction for different potential transpiration conditions. TFC is the transpiration rate at field capacity. From Denmead and Shaw (1962).

The findings of Denmead and Shaw (1962) suggest that plants can exert significant stomatal control on days of high evaporative demand to conserve water supplies. Similar behaviour has been reported for grapevines (Yunusa et al., 2000; Lu et al., 2003). However it appears that varieties respond differently to varying meteorological conditions, with Grenache exerting tighter stomatal control by comparison to Shiraz (Schultz, 2003; Soar et al., 2006). The varying plant responses bring yet another layer of complexity to understanding soil water relations.

The other deficiency of the static models is their failure to incorporate changes in soil moisture with respect to time. For instance the IWC or LLWR may identify diminished soil water availability for one soil compared to another over the complete range of moisture contents. However it is conceivable that soil moisture could be maintained at levels where aeration and soil strength are non-limiting by frequent irrigation or rainfall. Attempts have been made to examine the temporal dynamics, with a strong negative correlation found between shoot growth and the time the water content spends outside the LLWR (da Silva and

Kay, 1996). Furthermore the frequency with which the water content falls outside the LLWR was found to be related to the magnitude of the LLWR (da Silva and Kay, 1997). The results indicate that the LLWR itself can be a good index of soil physical quality, but these studies were carried out in dryland agriculture and a large range of soil moisture contents were encountered. In irrigated viticulture, there is much tighter control of soil moisture and a more refined model may be required to quantify water availability. For instance, one that integrates the time spent at different water contents.

Fluctuations of soil moisture and meteorological conditions with time make it difficult to derive meaningful representations of soil water availability from models that are static. However there is potential to embrace the dynamism of the system by using more powerful computer models, which simulate the transport and uptake of water and solutes in saturated/unsaturated soils over time, under changing meteorological conditions. An example of one such mechanistic model is SWAP (van Dam *et al.*, 1997; Kroes *et al.*, 2000; van Dam, 2000). SWAP is an acronym for *soil water atmosphere plant* and was developed from SWATR (*soil water actual transpiration*) (Feddes *et al.*, 1978). It is based, like most water transport models, on the well-known Richards' equation:

$$\frac{\partial \theta}{\partial t} = C(h)\frac{\partial h}{\partial t} = \frac{\partial\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right]}{\partial z} - S(h) \qquad \text{Eqn 1.4}$$

where θ is the volumetric water content (cm^3cm^{-3}), t is time (d), C is the differential water capacity, h is the soil water pressure head (cm), K is the hydraulic conductivity (cm d^{-1}), z is the depth (cm) taken positively upward, and S is the soil water extraction rate by plant roots ($cm^3cm^{-3}d^{-1}$). The modelling of water flow is combined with crop growth, solute flow, heat flow and irrigation subroutines, and is driven by daily meteorological data. Therefore one is able to track changes in transpiration and soil water content with time.

Of particular interest to simulations of soil water availability is the sink term (S) that describes root water uptake. Following logic similar to that of the LLWR and IWC models, Feddes *et al.* (1978) recognised that stresses due to dry or wet conditions and/or high salinity concentrations may reduce S_p(z)- the potential root water extraction rate at a certain depth. Hence various functions were developed to limit S_p(z) according to these stresses. The water stress function in SWAP was proposed by Feddes *et al.* (1978) (Fig. 1.6). For salinity stress, the response function of Maas and Hoffman (1977) is used (Fig. 1.7). Similar to the weighting functions of IWC, the stress functions range from unity to zero and are assumed to be multiplicative, such that the actual root water flux, $S_a(z)$ ($cm^3cm^{-3}d^{-1}$), is calculated from:

$$S_a(z) = \alpha_{rw}\alpha_{rs}S_p(z) \qquad \text{Eqn 1.5}$$

where α_{rw} and α_{rs} are the dimensionless reduction functions due to water and salinity stress, respectively.

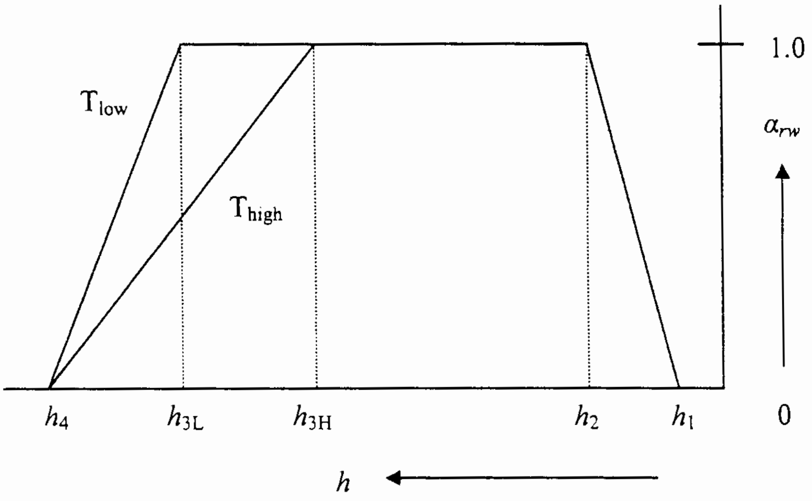

Fig. 1.6 Reduction coefficient for root water uptake, α_{rw}, as a function of soil water pressure head h and potential transpiration rate T_p (after Feddes *et al.*, 1978). h_1 and h_2 define the critical pressure heads for limitations due to poor aeration. On days of low T_p, the drought stress is defined by a linear function between h_{3L} and h_4, while on days of high T_p, the drought stress is defined by a linear function between h_{3H} and h_4. Thus SWAP is able to mimic the stomatal behaviour of a plant.

NOTE: This figure is included on page 21 of the print copy of the thesis held in the University of Adelaide Library.

Fig. 1.7 Reduction function for root water uptake, α_{rs}, as a function of soil water conductivity EC_{sw} (after Maas and Hoffman, 1977).

The Feddes sink-term reduction function for water extraction (Fig. 1.6) has been incorporated into other widely used modelling packages that simulate water and solute flow (e.g. Hydrus 1-D and Hydrus 2-D). Aside from the ability to mimic stomatal behaviour by switching between h_{3L} and h_{3H}, based on evaporative demand, the sink term follows an approach similar to the IWC. Hence there is potential to improve the sink term by including some of the refinements made to the static models by the IWC. For instance the Feddes sink term contains no weighting function for mechanical impedance, which has been shown to influence root growth, shoot growth and transpiration. With the inclusion of such a weighting function, SWAP could more accurately model changes in soil water availability over time, in a dynamic environment. Ultimately, if irrigation is seen to degrade soil structure and alter the weighting functions associated with mechanical impedance and aeration, the impact of this degradation upon grapevine transpiration could be modelled using SWAP.

1.2.6 Conclusion

The existing literature provides strong evidence that drip irrigation has the potential to structurally degrade soils, which could adversely affect soil physical properties, soil water availability and grapevine functioning. Common soil types within Australian vineyards appear vulnerable to these processes and there is emerging evidence of such degradation occurring. Hence there is a need to determine the nature and extent of soil structural degradation in drip irrigated vineyards to ensure sustainable production.

While specific data for grapevines is somewhat lacking, strong generic relationships between soil physical properties and crop functioning have been demonstrated. Therefore measurement of such physical properties can provide a link between soil structural quality and grapevine functioning. Furthermore, soil physical data can be input into dynamic simulation models, such as SWAP, to assess the impact of altered soil structure in terms of soil water availability and transpiration. The dynamic models provide a more realistic representation of soil water availability than static models due to the incorporation of changing soil moisture and meteorological conditions with time.

1.3 Aims of the thesis

Based on the major findings from the literature review, three broad objectives were established for the experimental investigations:

1. To characterise the impact of drip irrigation on soil physical properties in vineyards (Chapter 2).
2. To evaluate impacts on grapevine responses, including transpiration (Chapter 3) and root growth (Chapter 4).
3. To examine the potential to ameliorate any soil physical degradation, should it be identified, using novel, non-invasive methods (Chapter 5).

Chapter 2.

The impact of drip irrigation on soil physical properties in vineyards

2.1 Introduction

Irrigation is practised in over 80% of Australian vineyards (A.B.S., 2006) to better manage yield and quality in a dry climate with unreliable rainfall. Drip irrigation is the most common application method and its use is increasing as growers seek to improve water use efficiency and lessen adverse environmental impacts. While drip irrigation minimises evaporation and drainage, the existing literature suggests that it places significant physical and chemical pressures upon soil structure (Chapter 1.2.3). To manage vineyard soils sustainably, it is important to identify any changes in soil structure that result from drip irrigation. Such changes can be gauged through an assessment of soil physical properties.

Clark (2004) investigated seasonal changes in soil salinity and sodicity resulting from drip irrigation with borewater (EC = 2-3 dS m^{-1}, SAR = 8) in a Barossa Valley vineyard, South Australia. Irrigation increased soil sodicity and salinity during the growing season, particularly at the edge of the sphere wet by a dripper, however winter rains leached salts and lowered the ionic concentration of the soil solution. Such conditions are conducive to colloid dispersion and structural decline when the ionic concentration drops below a certain threshold (Rengasamy *et al.*, 1984; Quirk, 1994; Quirk, 2001). Indeed some evidence of structural decline was found by Clark (2004), with higher bulk densities and reduced pore space evident in thin sections. However, the extent to which irrigation altered other soil physical properties (e.g. hydraulic conductivity, water retention and soil strength) was not evaluated. These properties have a direct effect on vine growth by controlling the availability of water, nutrients and air to roots. It was also unknown what timeframe the degradation occurred over. Therefore, this study was undertaken to assess the impact of drip irrigation on soil physical properties and to identify a timescale for these changes.

2.2 Materials and methods

Field sites

The main site for this study was a vineyard at the Nuriootpa Research Station, Barossa Valley, South Australia. Soils at this site were well characterised from previous research efforts (Clark, 2004; Fares *et al.*, 2004). It was here that Clark (2004) identified irrigation-induced sodicity, which pointed to structural degradation. The soil was a red chromosol (Isbell, 1996), or red brown earth (Northcote, 1979), with the dominant feature being an abrupt texture contrast between the A and B horizons at a depth of about 35 cm. The A horizon was a fine sandy loam. The B horizon was a medium-to-heavy clay. Other properties included a favourable pH (~ 6.5) and a very low organic carbon content (~ 0.5%) in the A and B horizons (Clark, 2004). The red brown earth is the most common soil type within the Barossa Valley winegrowing region (Northcote *et al.*, 1954).

To help identify a timeframe for structural degradation at the Nuriootpa site, soil under vineyards of two different ages was compared to a non-irrigated soil. While more vineyards of different ages were desired, the experiment was limited to what was available at the field site. The two vineyards (a 2 y.o. vineyard (cv. Alberino Galicia) and a 15 y.o. vineyard (cv. Crouchen)) had both received above-ground drip irrigation with borewater since their establishment. They were immediately adjacent (<10 m) to a non-irrigated, non-planted control, which received identical inter-row management. Rows were 3.0 m wide and vines were planted 2.25 m apart along the rows. Irrigation was applied in weekly intervals throughout summer months with 4 L h^{-1} pressure-compensated drippers, spaced evenly along the vine row at each vine butt. An average yearly rate of 1.5 ML ha^{-1}, or 150 mm, was applied to supplement an average annual rainfall of 502 mm, which falls predominantly in the winter months. For each vine/dripper, there were typically about 20 applications of 48 L per season. The wetted areas were confined to 60 cm in diameter on the surface and did not overlap. The borewater had an average EC of 2.5 dS m^{-1} and SAR of 8. Irrigation with borewater was a common practice in the Barossa Valley, but better quality surface waters became available in 2001/02, with the introduction of the BIL (Barossa Infrastructure Ltd) irrigation scheme.

A second site was established at a private vineyard near Willunga, in the McLaren Vale growing region, South Australia. This site had also been studied by Clark (2004), and had a similar climate and soil type (also a red brown earth) to the Nuriootpa site. It was irrigated at similar rates with 4 L h^{-1} drippers, but with less saline water (1.2 dS m^{-1}), and gypsum had been applied evenly every second year since establishment at a rate of 2.6 tonnes ha^{-1}. Soil from the 16 y.o. vineyard (cv. Shiraz) was compared to soil in a grazing paddock, 10 m away, which had received no irrigation. Less intensive analysis was conducted at the McLaren Vale site because it was later found that the non-irrigated control soil had been compromised by possible contamination, which affected EC levels, and also by on-going grazing practices that promoted soil compaction. However some results from this site are presented here.

Sampling

Soil pits were established with a backhoe in both irrigated and non-irrigated soils during November 2003. Where appropriate, they were located to enable access to the soil profile directly under the vine row. There was no traffic-related compaction along the vine row, so any structural changes found could be attributed to irrigation. Intact soil cores were sampled from each pit-face using stainless steel rings (50mm high x 47mm diameter). Soil cores were manually extracted after the rings were pressed into the soil laterally with an hydraulic ram, which minimised structural artefacts that can be created by hammering. Six replicate cores were taken at 3 depths (representing the A1, A2 and B1 horizons at Nuriootpa, and the A1, B1 and B2 horizons at McLaren Vale) and at 0, 50 and 100 cm from the dripper along the vine row. The sampling strategy enabled comparisons of physical properties to be made at different distances from the dripper, where the influence of irrigation was thought to be different. For instance, soil directly beneath a dripper received much more irrigation than soil 100 cm away, which was mid-way between drippers. Soil cores were sealed in close-fitting airtight bags to maintain field moisture and returned to the laboratory, where they were kept in the dark at room temperature before analysis.

Laboratory measurements

The intact soil cores were trimmed to the dimensions of the steel ring that housed them. Care was taken to avoid smearing clay surfaces. In cases where small indentations were present in core surfaces, a fine sand of known bulk density was used to fill the indentations. The weight of fine sand required was recorded to calculate the volume of the indentation.

Soil water retention curves were determined for each core using the following soil suctions (h): 1, 3, 10, 33, 100, 300 kPa. Disturbed samples (air-dried and sieved < 2 mm) were used to measure water retention at 1000 and 1500 kPa. Hanging columns of water were used to set suctions from 1 to 10 kPa, and pressure chambers were used from 33 to 1500 kPa (Cresswell, 2002). Cores were wet gently from the base up with a 0.01 M $CaCl_2$ solution to minimise dispersion, 1 ppm $HgCl_2$ was used as a biological growth inhibitor, and ceramic plates were coated with a slurry of fine silica powder (Soil Water Solutions Pty Ltd, Daw Park, SA) to ensure hydraulic contact. To ensure equilibrium had been reached, cores were weighed daily on the hanging column apparatus until they reached constant weight, or left in pressure chambers for at least 3 weeks.

To quantify changes in soil strength during drying, penetration resistance (*PR*) was measured with a micro-penetrometer on cores equilibrated at four different soil suctions: 10, 33, 100 and 300 kPa. Penetrometer needles were machined (Simax Engineering Pty Ltd, Parkside, SA) to a base-diameter of 2.5mm, a cone angle of 30º, and a recessed shaft of 2 mm to minimise friction. During measurement, a needle was lowered at 2.5 mm/min into a soil core and resistance was measured by a load-cell, connected to a data logger (MicroScan Electronics Pty Ltd, Torrens Park, SA). Logged values were converted to pressure units (MPa) by dividing by the cone's basal area, and plotted against core depth. Average *PR* was calculated between 10 and 25mm core depth for each measurement. Where possible, one measurement was made for each core at all soil suctions. Four measurements were made on each core and care was taken to avoid artefacts by ensuring a minimum distance of 5 cone-diameters between each measurement point as recommended by Hignett (2002).

To calculate bulk density, the intact cores were oven dried (24h at 105ºC) and weighed at the conclusion of *PR* and water retention measurements. Particle density was measured, following the method of Blake and Hartge (1986). Particle density (ρ_s) and bulk density (ρ_b) were used to calculate total porosity (ε) or saturated volumetric water contents using the relation $\varepsilon = 1- (\rho_b / \rho_s)$ to anchor water retention curves at saturation.

Field measurements

A survey of field soil penetration resistance (*PR*) was undertaken at Nuriootpa in April 2005. The ground was prepared by irrigating all sites (a drip line was set up in the non-irrigated site) and allowing them to drain for 36 h to ensure consistent water contents at time of measurement- nominally field capacity. Penetrometer measurements were made using a 'Bush' cone penetrometer (Findlay Irvine Pty Ltd, Penicuik, Scotland), which had a base diameter of 12.8 mm and a cone angle of 30°. The penetrometer was pushed into the ground and *PR* was logged at 3.5 cm depth-increments. Twelve replicate measurements were made at each site and soil samples were collected at 4 depths to determine gravimetric water contents.

Saturated hydraulic conductivity (K_{sat}) was measured at all field sites during March and April 2004. Six replicate measurements were taken at all sites at the soil surface and at 50cm depth. Surface measurements were made using a CSIRO ponded-disc permeameter (Perroux and White, 1988). Infiltration rates were recorded until steady state conditions were reached. Attempts to calculate sorptivity proved too difficult due to rapid flow through the fine sandy loam topsoil. Therefore data was not corrected for sorptivity and the values presented here describe steady-state infiltration (*IR*), not K_{sat}. Guelph permeameters were used to measure field-saturated hydraulic conductivity K_{fs} in the subsoil (at 50cm depth) following the method of Reynolds (1993). Low flow rates in the clayey subsoil meant that in most cases permeameters were left for a number of days to reach steady state conditions. K_{fs} was calculated using the formula provided by Reynolds (1993) and the well-shape factor for clays as derived by Zhang *et al.* (1998).

Soil chemical data

Extensive soil chemical analyses were carried out by Clark (2004) for both the Nuriootpa and McLaren Vale vineyards. A small subset of this data is presented in Table 2.1.

NOTE: This table is included on page 28 of the print copy of the thesis held in the University of Adelaide Library.

Table 2.1 Average EC and SAR from saturated paste extracts of samples taken by Clark (2004) at Nuriootpa and McLaren Vale over 3 years (2001-2003).

Table 2.1 demonstrates higher EC and SAR in irrigated soil, particularly at Nuriootpa, due to irrigation histories. The averaged values do not indicate the significant fluctuations in EC that were encountered with time, due to salt accumulation in the growing season and salt leaching with winter rainfall. While it is difficult to relate this data to threshold concentrations values of EC that are required to maintain structure (Rengasamy *et al.*, 1984), Table 2.1 suggests there could be significant effects of sodicity on the physical properties of these soils.

2.3 Results and discussion

Penetration resistance

PR is a measure of soil strength and can be used to describe a soil's resistance to root growth. *PR* was found to be higher in irrigated soils during a field survey at Nuriootpa, measured at field capacity (Fig. 2.1). At depth (> 20cm), the irrigated soils exceeded the 2 MPa threshold that is commonly quoted as limiting to root growth of grapevines (e.g. Myburgh *et al.*, 1996). A smaller (but significant) increase in soil strength was evident 100 cm from the dripper.

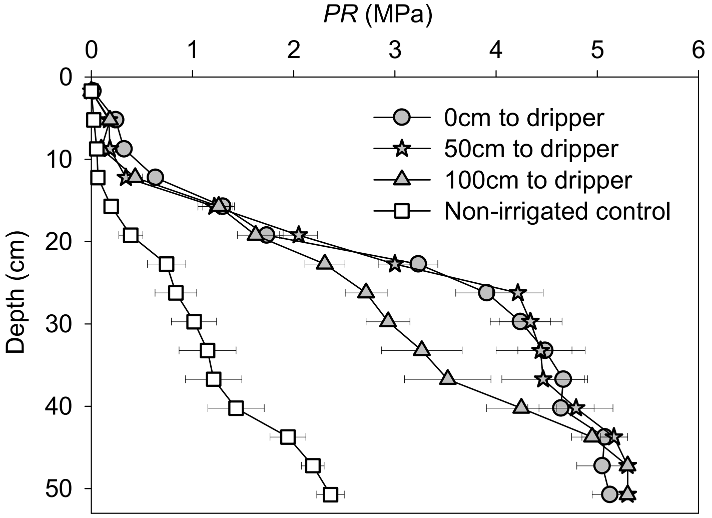

Fig. 2.1 Field survey of penetration resistance, *PR* (MPa), vs depth (cm) at Nuriootpa, for non-irrigated and irrigated soil at 0, 50 and 100 cm from dripper in the 15 y.o. vineyard.

Soil strength is strongly affected by water content and the tighter controls of soil moisture that were available in the laboratory were used to confirm trends in *PR* from the field survey.

Water content effects were minimised by analysing micro-penetrometer data collected on the intact cores that were used to measure water retention curves. Each core was equilibrated at common levels of soil suction so that comparisons of *PR* between sites became possible. Soil strength characteristics (curves of *PR* vs soil suction) were compared (Fig. 2.2).

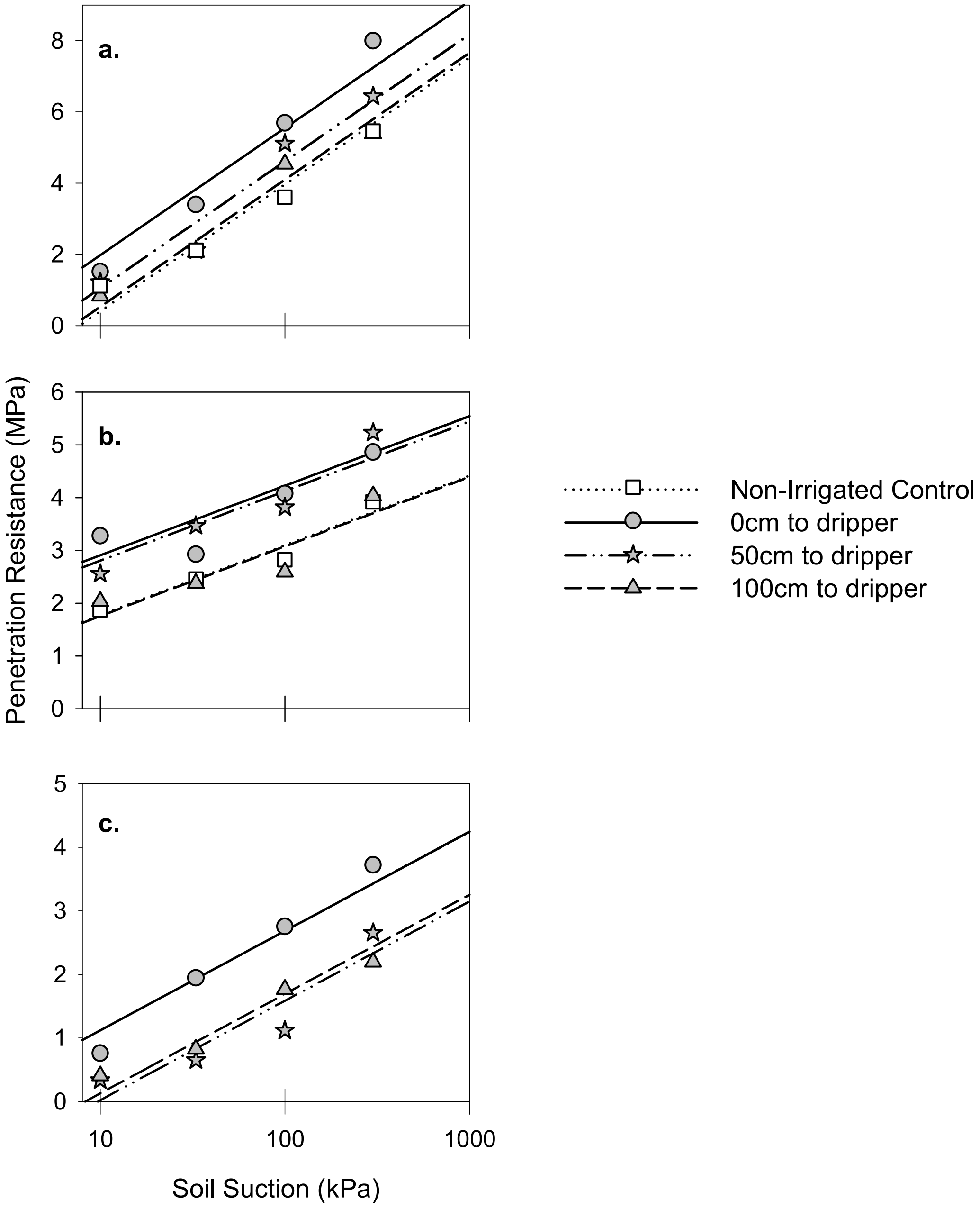

Fig. 2.2 Soil strength characteristics for: **a.** Nuriootpa A2 horizon, non-irrigated and irrigated soil at 0, 50 and 100 cm from dripper in 15 y.o. vineyard; **b.** Nuriootpa B1 horizon, non-irrigated and irrigated soil at 0, 50 and 100 cm from dripper in 15 y.o. vineyard; **c.** McLaren Vale A1 horizon, irrigated soil at 0, 50 and 100 cm from dripper in 16 y.o. vineyard. Lines indicate output from regression analysis.

To confirm the apparent differences between sites, regression analysis was performed using GENSTAT 6.1.0.2. By comparing variance ratios, the analysis isolated the most appropriate regression model to fit the data, which in this case was a set of parallel lines with different y-intercepts (Fig. 2.2). Therefore, at different sites with common soil suctions, there were significantly different levels of PR.

At Nuriootpa, there were some significant differences between soil strength characteristics. While no differences were found between non-irrigated soil and soil irrigated for 2 years, higher soil strength was found directly under the dripper and also at 50 cm from the dripper in soil irrigated for 15 years, in the A2 and B1 horizons (Fig. 2.2a and b respectively). *PR* increased more rapidly with suction in the A2 horizon because of a coarser texture, which causes more drainage over this range of soil suction.

The process whereby irrigation increased soil strength is unclear. No strength increases occurred in the 2 y.o. vineyard, nor at 100 cm from the dripper in the 15 y.o. vineyard, where one would expect the influence of drip irrigation to be smaller. This suggests degradation took time and that its impact was felt most strongly under or near the dripper. It was probable that the degradation was due to the sodicity identified by Clark (2004), however it appeared that other factors contributed. For instance strength increases occurred under the dripper at McLaren Vale, where gypsum had been regularly applied to minimise the build-up of exchangeable sodium (Fig. 2.2c). Furthermore, the strength increases were all located at positions in the profile where the physical pressures of irrigation were greatest, i.e. under or near the dripper. The soil under drippers experienced rapid wetting, prolonged wetness, and an increased number of wetting and drying cycles, relative to soil further along the vine row away from the influence of drippers. All of these factors exacerbate aggregate coalescence, a soil-hardening process that can act even on water stable soil (Cockroft and Olsen, 2000; Lanyon *et al.*, 2000; Grant *et al.*, 2001).

High soil strength diminishes the ability of grapevine roots to explore soil, which affects water and nutrient supplies for the plant, and may trigger inhibitory root to shoot signalling (Masle and Passioura, 1987). However the extent to which root growth was affected, due to higher *PR* in irrigated soils, was unclear. In the literature, there are few direct comparisons of soil strength and grapevine root growth. Pot studies show root and shoot growth to decline linearly with increasing PR above 0.5 MPa (van Huyssteen, 1989; Ferree and Streeter, 2004), and some field observations support a critical PR value of 2 MPa, above which root growth is abruptly or seriously impeded (Myburgh *et al.*, 1996). This suggests that subsoils in this study were impenetrable because a *PR* of 2 MPa was encountered at, or near, field capacity (Fig. 2.2b). However roots were observed in all soil horizons to indicate that a threshold of 2 MPa did not apply. Roots could have avoided the physically hostile matrix by exploiting biopores and other planes of weakness (Ehlers *et al.*, 1983). So while it appeared the elevated levels of PR could diminish crop performance, further investigation was required to determine the magnitude of this impact.

Permeability

A significant reduction in steady state infiltration rates (*IR*) was found under or near the dripper in irrigated A1 horizon soils at Nuriootpa (Fig. 2.3). The reduction also occurred in soil irrigated for only 2 years, which had consistently lower *IRs* than the 15 y.o. vineyard, however both exhibited a similar trend of increasing permeability with distance from the dripper. A similar reduction in *IR* under the dripper was found at McLaren Vale (Fig. 2.4).

IR is a measure of saturated flow, which is heavily dependent upon macropores. A reduction in *IR* indicates a reduction in the size, number or continuity of macropores. It was likely that irrigation diminished some or all of these properties. The rapid rate at which water was applied (relative to natural rain events) was probably responsible because the reductions in *IR* were evident under the dripper and not with increasing distance from the dripper, where little or no irrigation water passed. Rapid wetting of a dry soil encourages slaking, which blocks pores. It also exposes pore walls to high levels of shear stress that threaten their breakdown. Prolonged wetness within the zone under the dripper also lowers soil strength and therefore increases the vulnerability to physical damage. Sodicity was not seen as a major driver in these processes because *IR* also declined in the McLaren Vale vineyard, which received regular gypsum application (Fig. 2.4).

Spatial differences in soil properties may explain why the 2 y.o. vine had lower *IRs* than the older vine (Fig. 2.3), but the consistent trend of reduced *IR* closer to the drippers indicated that a similar degenerative process was at work that operated rapidly (<2 years).

The magnitude of *IR* in the irrigated soils at Nuriootpa was still high, despite the reduction, ensuring irrigation or rainfall passed quickly into the rootzone. However the reductions evident in McLaren Vale were of greater concern because they dropped to around

50 mm h^{-1}, which is the minimum *IR* desired for drip-irrigated vineyards (White, 2003). If *IR* drops to such a level, which is lower than dripper application rates, water may pond on the surface leading to run-off, erosion and evaporative losses.

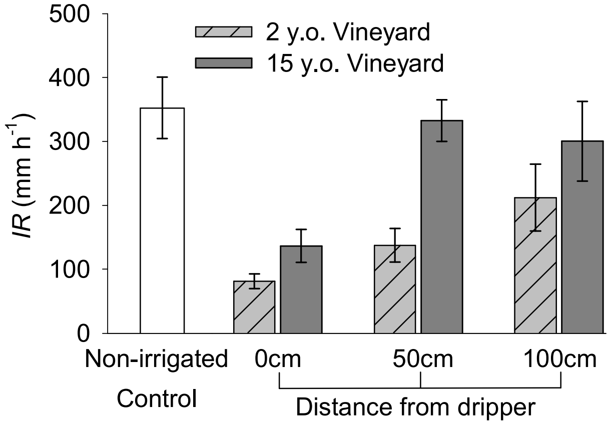

Fig. 2.3 Steady state infiltration rates, *IR* (mm h^{-1}) in Nuriootpa A1 horizon for non-irrigated and irrigated soil at 0, 50 and 100 cm from dripper in 2 y.o. and 15 y.o. vineyards.

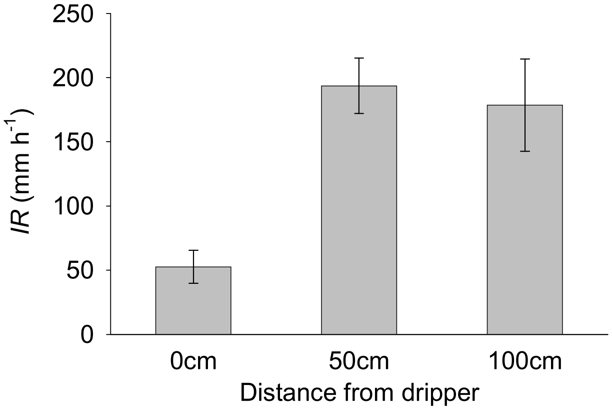

Fig. 2.4 Steady state infiltration rates (*IR*, mm h^{-1}) in McLaren Vale A1 horizon for irrigated soil at 0, 50 and 100 cm from dripper in 16 y.o. vineyard.

In the Nuriootpa subsoil, a similar trend of reduced permeability in irrigated soil was found (Fig 2.5). However differences could not be confirmed statistically due to high variability. K_{fs} values were low (~ 1.8 mm h^{-1}) which is typical for clayey subsoils and much less than the *IR* in the A1 horizon.

The high degree of variability was due to the uneven distribution of macropores, which were visible in the subsoil and positively skew measurements of K_{fs} if encountered. This was not a problem in the A1 horizon because measurements were made over a comparatively large surface area (319 cm^2) with a disc permeameter and macropores were encountered regularly. Macropores occurred more sporadically at depth and the Guelph permeameter, used to measure K_{fs} in subsoils, operates over a smaller surface area (123 cm^2). Therefore macropores were encountered with less regularity.

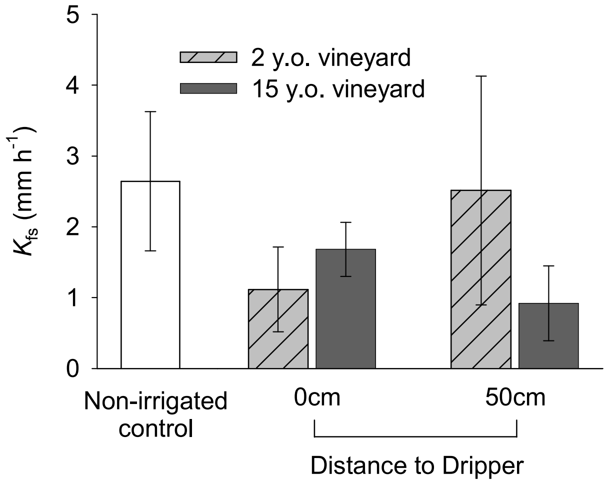

Fig. 2.5 Field-saturated hydraulic conductivity, K_{fs} (mm h^{-1}), in Nuriootpa B1 horizon for non-irrigated and irrigated soil at 0 and 50 cm from dripper in 2 y.o. and 15 y.o. vineyards. K_{fs} was not recorded at 100 cm from the dripper.

While subsoil K_{fs} data were inconclusive, it seems that irrigation may have reduced subsoil permeability. Clark (2004) found lower redox potentials and micromorphological features that indicated periodic reducing conditions in irrigated soils, which confirms the trends evident in K_{fs} data. Lower subsoil permeability encourages waterlogging that can lead to restricted spring growth, reduced nutrient uptake and a yield depression in grapevines (Stevens and Walker, 2002; White, 2003).

Bulk density

Average bulk densities at Nuriootpa suggested no major differences between irrigated and non-irrigated soils within common soil horizons (Table 2.2). This was unexpected because Clark (2004) had reported a 30 % increase in bulk density in the B1 horizon of the same soil due to irrigation.

Horizon	Control	2 y.o. vineyard *(cm to dripper)*			15 y.o. vineyard *(cm to dripper)*		
		0	*50*	*100*	*0*	*50*	*100*
A1	1.25	1.23	1.20	1.24	1.27	1.27	1.30
A2	1.66	1.60	1.64	1.62	1.68	1.63	1.55
B1	1.54	1.60	1.50	1.50	1.56	1.60	1.55

Table 2.2 Average bulk density (g cm^{-3}) in Nuriootpa A1, A2 and B1 horizons for non-irrigated control and irrigated soil at 0, 50 and 100 cm from dripper in 2 y.o. and 15 y.o. vineyards.

Closer analysis of B1 horizon data revealed a strong, negative, linear relationship between bulk density and moisture content at time of sampling (Fig. 2.6), described in the regression equation:

$$\rho_b = 1.97 - 1.80 \cdot \theta_g \quad (R^2 = 0.72) \qquad \text{Eqn 2.1}$$

where ρ_b is the bulk density, g cm^{-3}, and θ_g is the gravimetric water content, g g^{-1}, at time of sampling. The relationship was not evident in the sandy-textured A1 and A2 horizons and was due to shrinking/swelling in the clayey subsoil. It was also noted by Fares *et al.* (2004) in a separate study at the same site. Indeed the relationship presented in Eqn 2.1 compared closely with that of Fares *et al.* (2004).

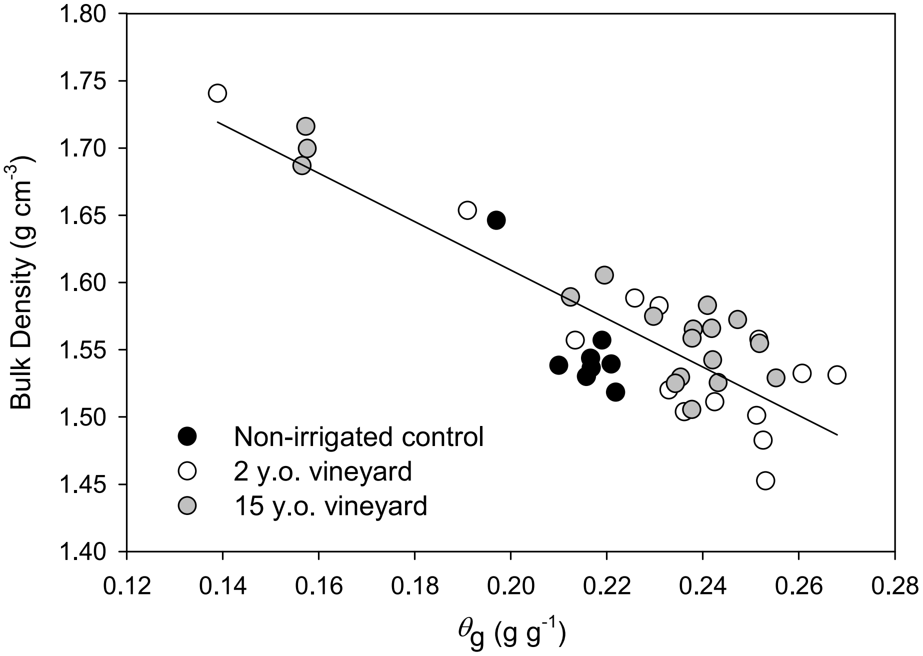

Fig. 2.6 Bulk density (g cm^{-3}) vs moisture content (g g^{-1}) at time of sampling in Nuriootpa B1 horizon for non-irrigated and irrigated soil in 2 y.o. and 15 y.o. vineyards. See Eqn 2.1 for fitted equation.

This relationship could have obscured differences in bulk density that existed between irrigated and non-irrigated soils. Nevertheless the majority of bulk densities for the non-irrigated soil lie below the regression line in Fig. 2.6, suggesting that it was in fact less dense. Adjusted means were compared using moisture content as a co-variate (GENSTAT 6.1.0.2), which again revealed higher bulk densities in the irrigated soils. However such an analysis was considered to be limited in its utility because the range of moisture contents was not evenly distributed among the treatments. That is most water contents for non-irrigated soil lay between 0.21 and 0.22 g g^{-1} while those for irrigated soil spanned the range from 0.14 up to 0.27 g g^{-1}. Hence while it appeared that irrigation increased subsoil bulk density, a more complete range of soil moisture contents needs to be examined to provide confirmation.

Water retention

No significant differences were found between sites for water retention curves in the A1 and A2 horizons (Appendix A). While all curves in the B1 horizon had a similar shape, some were slightly offset in terms of water content. This was probably due to differences in bulk density, but because of the shrinking/swelling nature of the soil (as explained above) no significant conclusions could be made. Future studies of this soil need to take account of their shrinking/swelling properties, and it is recommended that soil volume changes be measured in conjunction with gravimetric water content to develop (more) accurate volumetric water retention curves.

2.4 Conclusion

Drip irrigation adversely affected soil physical properties in the vineyards studied. Significantly higher soil strength and lower permeability were found in irrigated soils. There was also limited evidence of increased bulk density in subsoil layers. Such changes in physical properties can promote waterlogged conditions and limit the ability of roots to explore soil volumes to access resources. The extent to which this applies to grapevines is unknown, but anything that reduces the degree of control over water and nutrient uptake would be expected to be detrimental in vineyard management.

Reductions in permeability occurred rapidly (<2 years), but increases in *PR* took longer, suggesting that different processes were involved that operated at different rates. Or perhaps the same process that had an incremental effect on *PR* over a longer time period has a greater impact on permeability during the initial stages. While sodicity had been identified at Nuriootpa, it appeared that other processes, related to the physical pressures exerted by irrigation (such as rapid wetting and more wetting/drying cycles), also contributed to the degradation.

Further research is required to identify the extent to which these changes affect crop performance. Until more is known about the relative importance of the different soil changing processes and the extent to which crop performance has been impacted, it is difficult to make specific management recommendations to ameliorate the degradation identified.

This study did not suggest drip irrigation was capable of damaging soil structure any more than other irrigation methods (e.g. overhead sprinkler, microsprays) because they were not evaluated. However, it is hypothesised that other methods of irrigation impact less severely on soil structure, because their wetting patterns do not concentrate the water in such small soil volumes.

Chapter 3.

Modelling the impact of altered soil physical properties on grapevine transpiration

3.1 Introduction

An assessment of soil physical properties within vineyards revealed that irrigated soils were significantly stronger and less permeable than non-irrigated soils (Chapter 2). Such changes appeared to be undesirable for grapevine functioning given that high soil strength can retard root and shoot growth (van Huyssteen, 1989; Ferree and Streeter, 2004), and lower permeability increases the likelihood of waterlogging (White, 2003). However further investigation was required to understand the extent to which degraded soil physical conditions affect grapevine functioning.

The impact of the soil structural degradation could not be assessed in the field. Crop performance in irrigated and non-irrigated soils could not be compared because the non-irrigated soil was unplanted. Even if there was access to non-irrigated vines, valid comparisons between irrigated and non-irrigated vines cannot be made when their soil moisture regimes are so different. Furthermore root distributions within the irrigated soil could not be related to soil physical properties, because root growth is also affected by proximity to the dripper and associated soil moisture differences. For example soil at 100cm from the dripper was found to have lower penetration resistance (*PR*) than soil at 0 and 50cm from the dripper, but root length densities cannot be compared due to the different distances to the dripper.

Better controls are obtainable in the glasshouse. Pot trials can simulate the impact of altered soil physical properties and supplement existing data in the literature, which is somewhat lacking for grapevines. Indeed the pot experiment described in Chapter 4 examines the role of high soil strength and biopores in affecting grapevine root growth. However it is difficult to translate the results from pot trials into complex field situations, where soil moisture and meteorological conditions fluctuate with time, and where soil properties may change with depth.

An alternative approach is to use computer simulation modelling, which incorporates some of the complexities of the field environment. The review of literature (Chapter 1) suggested that the SWAP model (van Dam, 2000) could be used to assess the impact of soil degradation on grapevine transpiration, which is an integrated plant response to soil physical conditions. This chapter outlines a modelling study, using a modified version of SWAP, that assessed the impact of altered soil physical properties on grapevine transpiration at the Nuriootpa study site. It should be stressed that the objective of this study was to compare the performance of grapevines in degraded and non-degraded soil, rather than to quantify transpiration to a high level of accuracy.

3.2 Model description

SWAP is a physically based 1-D model that simulates the vertical transport of water, solutes and heat in saturated/unsaturated soils in relation to crop growth. It is specifically designed for integrated modelling of the soil-water-atmosphere-plant system. For this study, an altered version of SWAP2.0 was used, which is described in detail by Van Dam *et al.* (1997) and Kroes *et al.* (2002). More recent versions of the model can be obtained (e.g. SWAP3.03), however technical difficulties prevented their use here.

As indicated in Chapter 1, the core part of the SWAP program is the vertical transport of water, which is described by the Richards equation (Eqn 1.4). Water extraction by plant roots is governed by the sink term, S ($\text{cm}^3\text{cm}^{-3}\text{d}^{-1}$), which is limited according to water (Feddes *et al.*, 1978) and salinity stresses (Maas and Hoffman, 1977) that are assumed to be multiplicative (Eqn 1.5). The modelling of water flow is integrated with subroutines that simulate solute flow, heat flow, crop growth and irrigation. The entire program is driven by daily meteorological data.

Various modifications were made to the root-uptake subroutine for the purposes of this study. First and foremost, a stress function for high penetration resistance was introduced to limit S. Penetration resistance at a certain depth, $PR(z)$ (MPa), was defined by the following function:

$$PR\left[h(z)\right] = a(z) + b(z)\log_{10}\left[h(z)\right] \qquad \text{Eqn 3.1}$$

where z is depth (cm), a and b are fitting parameters that are input according to experimental data, and h is the absolute value of the soil matric potential (cm). Hence for each soil layer, SWAP could calculate PR, which was then used to calculate a dimensionless (-) reduction coefficient for high penetration resistance, α_{pr}, according to:

$$\alpha_{pr} = \frac{PR_{\lim 2}(z) - PR(z)}{PR_{\lim 2}(z) - PR_{\lim 1}(z)} \qquad \text{Eqn 3.2}$$

where α_{pr} is bound to range between 0 and 1 (i.e. $0 \leq \alpha_{\mathrm{pr}} \leq 1$), and PR_{lim1} and PR_{lim2} are the lower and upper limits of PR (MPa), where soil strength becomes limiting and completely limiting to water uptake, respectively. These values were input according to previous studies of grapevines growing in strong soils (van Huyssteen, 1989), but can be altered for different crops.

The SWAP model was limited in terms of how it defined aeration stress. The critical matric potentials for the Feddes' sink-term function for water stress (see Fig. 1.6) are input only once for the entire profile, and not for each soil layer. Hence for two soil layers that have very different hydraulic properties, such as the A and B horizons at Nuriootpa, SWAP would assume a similar aeration status if the layers were at similar matric potentials. Furthermore the reduction function for aeration stress (i.e. between h_1 and h_2 in Fig. 1.6) is linear with respect to h, when it would appear that a function based on water content is more appropriate. For instance air-filled porosity, AFP ($\mathrm{cm^3cm^{-3}}$), is calculated as the proportionate volume of air in a given volume of soil and is related in an inverse fashion to the volumetric water content, θ ($\mathrm{cm^3cm^{-3}}$). If the water retention curve, $\theta(h)$, is plotted on a linear scale near saturation, then θ drops rapidly with decreasing matric potential. Therefore AFP will increase rapidly over this range in a way quite different to what is described by the Feddes reduction function. Thus for each soil layer, AFP was calculated as follows:

$$AFP(z) = \theta_{sat}(z) - \theta(z) \qquad \text{Eqn 3.3}$$

where θ_{sat} is the saturated volumetric water content ($\mathrm{cm^3cm^{-3}}$). AFP was then incorporated into a function used to calculate the reduction coefficient for aeration stress, α_{air} (-), such that:

$$\alpha_{air} = \frac{AFP(z) - AFP_{\lim 1}(z)}{AFP_{\lim 2}(z) - AFP_{\lim 1}(z)} \qquad \text{Eqn 3.4}$$

where α_{air} is bound to range between 0 and 1, and $AFP_{\lim 1}$ and $AFP_{\lim 2}$ are the lower and upper limits of AFP (cm^3cm^{-3}), where aeration becomes completely limiting and non-limiting for water-uptake, respectively.

The two new reduction coefficients were incorporated to calculate the actual root extraction rate, $S_a(z)$ ($cm^3cm^{-3}d^{-1}$), by first assuming a multiplicative interaction under conditions where more than one stress applies, such that:

$$S_a(z) = \alpha_{air}\alpha_{pr}\alpha_{rs}\alpha_{rw}S_p(z) \qquad \text{Eqn 3.5}$$

where α_{rs} (-) and α_{rw} (-) are the reduction coefficients for salinity and water stress, respectively, and where $S_p(z)$ ($cm^3cm^{-3}d^{-1}$) is the potential root extraction rate based on evaporative demand. However it is unknown whether such stresses are multiplicative, additive or interact according to different functions (e.g. Homaee *et al.*, 2002; Skaggs *et al.*, 2006). The large number of coefficients in Eqn 3.5 may also restrict $S_a(z)$ too severely and unrealistically if multiplied. Therefore two other options for calculating $S_a(z)$ were introduced. One option applied an arithmetic average as follows:

$$S_a(z) = \left(\frac{\alpha_{air} + \alpha_{pr} + \alpha_{rs} + \alpha_{rw}}{4}\right)S_p(z) \qquad \text{Eqn 3.6}$$

Another option used a minimum function such that only the smallest of the four reduction coefficients applies at a given depth and moisture content- i.e.:

$$S_a(z) = \min(\alpha_{air}, \alpha_{pr}, \alpha_{rs}, \alpha_{rw})S_p(z) \qquad \text{Eqn 3.7}$$

The basis for choosing a given approach in such modelling warrants attention, but was beyond the scope of this thesis.

3.3 Input data

Modelling was conducted to simulate the environment at the Nuriootpa study site that was studied in Chapter 2. A description of the site and the methods used to collect much of the input data can be found in Chapter 2. Essentially, SWAP was used to compare the performance of grapevines, measured in terms of actual transpiration, if they were grown in non-degraded soil and in soil degraded by irrigation. The degraded soil was input as having the properties of the soil profile at 0 cm from the dripper in the 15 y.o. vineyard. The non-degraded soil was input as having the properties of the non-irrigated soil. To avoid confusion, these soils are now referred to as 'degraded' and 'non-degraded' rather than 'irrigated' and 'non-irrigated', because the model applied irrigation for both of these soils.

Soil data

The soil profile for both degraded and non-degraded soils was assumed to be 160cm deep, free draining with no groundwater interactions, and made up of 3 main horizons: the A1, A2 and B horizons described in Chapter 2. The B horizon properties were assumed to extend from the A/B boundary at 35cm to the bottom of the profile. There was assumed to be no hysteresis, swelling or bypass flow due to cracks and water repellence. While these processes may be important, particularly the swelling evident in Chapter 2, such assumptions are appropriate for the comparative nature of this study.

To solve the Richards equation, SWAP requires the soil hydraulic properties to be entered according to the analytical functions proposed by van Genuchten (1980), which describe the water retention and unsaturated hydraulic conductivity curves. The van Genuchten parameters were determined by entering tabular water retention data into the RETC fitting model (van Genuchten *et al.*, 1991). As indicated in Chapter 2, no significant differences were found between water retention curves for the degraded and non-degraded soil. Furthermore statistically significant differences were not established for subsoil hydraulic conductivity due to variability (Fig. 2.5). While differences were established for surface soil permeability (Fig 2.3), these were not modelled because the infiltration rates were not considered limiting. Therefore the same (averaged) hydraulic properties were input for degraded and non-degraded soil (Table 3.1).

It was unknown whether an unsaturated hydraulic conductivity (K_{unsat}) function should be incorporated to limit S_{a}. However there was no information regarding the relationship between K_{unsat} and grapevine functioning. Also, there would be no difference in K_{unsat} between degraded and non-degraded soils because the hydraulic properties were identically input. Therefore such a function was not included.

Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	O.M. ($g\ g^{-1}$)	θ_{res} (cm^3cm^{-3})	θ_{sat} (cm^3cm^{-3})	K_{sat} ($cm\ d^{-1}$)	α (cm^{-1})	λ (-)	n (-)
A1	0-16	80	5	15	0.005	0.038	0.516	532	0.054	0.5	1.582
A2	16-35	79	5	16	0.002	0	0.374	195	0.129	0.5	1.266
B	35-160	45	5	50	0.003	0	0.452	4.4	0.045	0.5	1.052

Table 3.1 Soil characteristics and soil hydraulic functions, where O.M. is organic matter content, θ_{res} is the residual water content, K_{sat} is the saturated hydraulic conductivity, and α, λ and n are fitting parameters according to van Genuchten (1980). Soil textural and O.M. data was taken from Clark (2004).

PR(*h*) data were input according to the regression analysis in Chapter 2. Parameters *a* and *b* in Eqn 3.1 were input for each horizon for both degraded and non-degraded soil (Table 3.2). No differences were isolated in the A horizon and average *PR*(*h*) data was input. For the A2 and B horizons, only the *a* parameter was different because the regression analysis indicated that the slopes of *PR*(*h*), if plotted on a log-linear scale, were not significantly different. The PR data inputs are depicted in Fig. 3.1.

	Non-degraded soil		Degraded soil	
Horizon	*a*	*b*	*a*	*b*
A1	-0.404	0.3415	-0.404	0.3415
A2	-6.729	3.564	-5.149	3.564
B	-0.906	1.3356	0.112	1.3356

Table 3.2 *PR*(*h*) input data where *a* (MPa) and *b* (MPa) are the fitting parameters in Eqn 3.1.

Defining the upper and lower limits of *PR* where transpiration is limited (PR_{lim1} and PR_{lim2}) required careful consideration. A lower limit of 0.5 MPa was chosen based on grapevine pot studies (Saayman, 1982; van Huyssteen, 1989). For an upper limit, 2 MPa is commonly used to define the least limiting water range (da Silva *et al.*, 1994) and is supported by grapevine root growth studies in homogenous soils (Ferree and Streeter, 2004). However the very high *PR* in both degraded and non-degraded soils (Fig. 3.1), even under moist conditions, suggested that an upper limit of 2 MPa would not be applicable. Roots were present in these strong soil layers, which suggested they were using biopores or structural cracks to grow deeper (Saayman, 1982; Ehlers *et al.*, 1983). Such behaviour has been noted in other vineyards and there is evidence of grapevine roots growing into layers of structured soil with PR as high as 8 MPa (van Huyssteen, 1989). Hence an upper limit of 8 MPa was used for this modelling study.

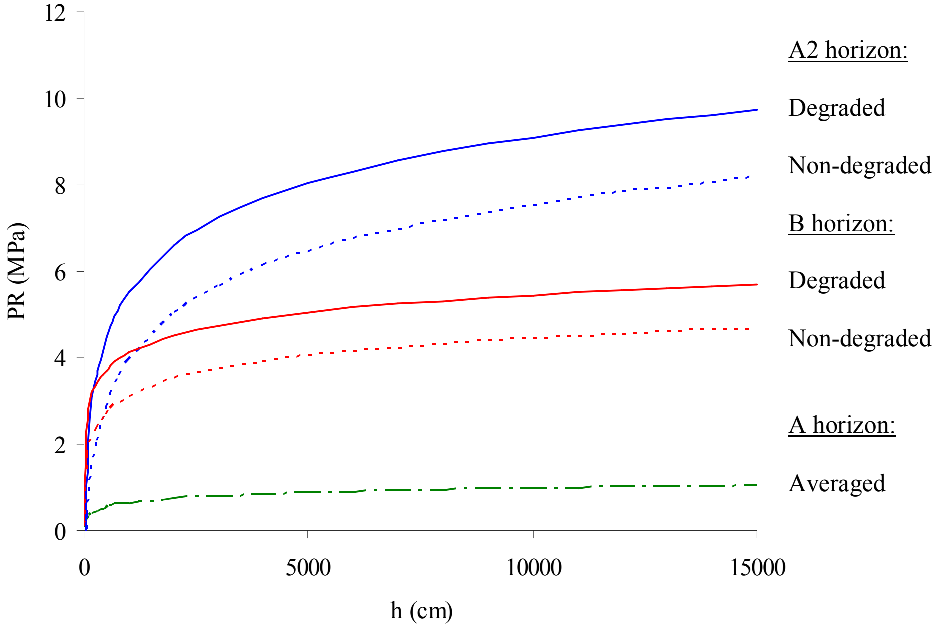

Fig. 3.1 *PR* (MPa) vs *h*, the absolute value of the soil matric potential (cm), for each soil horizon in degraded and non-degraded soils.

Critical *AFP* values for the lower and upper limits of aeration were input as 0.02 and 0.10 cm^3cm^{-3} respectively, based on the work of Wesseling and van Wijk (1957). No specific data was found that related grapevine functioning to such critical limits; however there should be no difference in aeration stress between the degraded and non-degraded soil because their hydraulic properties were the same.

Soil solute data was input using saturated-paste data from Clark (2004). The data had been collected between September and November in 2002 before irrigation commenced, at various depths and at 10 and 50cm from the dripper. This data was averaged in order to approximate root zone salinity in the degraded and non-degraded soil for any given year, before irrigation commences (Table 3.3). The averaged data points were extrapolated over the remaining soil depths. Salt accumulation during the growing season was modelled assuming no solute uptake by roots, and using the default parameters of the SWAP2.0 solute-flow subroutine.

NOTE: This table is included on page 45 of the print copy of the thesis held in the University of Adelaide Library.

Table 3.3 Averaged soil salinity data from Clark (2004). TDS is the total dissolved salts, which SWAP requires to be input.

Meteorological data

SWAP requires daily meteorological data to calculate the potential evapotranspiration rate, ET_{p0} (cm d^{-1}), which is then partitioned into a potential plant transpiration rate, T_p (cm d^{-1}), and a potential soil evaporation rate, E_p (cm d^{-1}). A patched-point dataset was obtained for the Nuriootpa research station from the SILO information reservoir at the Bureau of Meteorology (Jeffrey *et al.*, 2001). The dataset contained daily weather data from 1889 to present. No wind speed data was included so the Penman-Monteith equation could not be used to calculate ET_{p0}. However the dataset did contain a reference evapotranspiration rate, ET_{ref} (cm d^{-1}), that had been calculated according to the FAO modified Penman equation (Allen *et al.*, 1998). Hence a crop factor, k_c, was used to calculate ET_{p0} according to:

$$ET_{p0} = k_c ET_{ref} \qquad \text{Eqn 3.8}$$

Crop data

Grapevine functioning was simulated using the simple crop-growth model in SWAP. This represents a green canopy that intercepts precipitation, transpires and shades the ground. It was defined according to known grapevine characteristics. The length of the crop cycle was fixed at 212 days from September 1 to March 31, which is approximately the average length of a growing season at Nuriootpa (Pearce and Coombe, 2004). The leaf area index (m^2m^{-2}) was assumed to be 0 at budburst, increasing linearly to 1.8 at flowering, increasing less rapidly to 2.0 at the end of set, and then plateauing at 2.0, which is similar to reported values for grapevines (Sommer and Lang, 1994; Yunusa *et al.*, 1997). SWAP requires only the input of a single crop factor, taken to be constant from budburst to harvest (van Dam *et al.*, 1997).

A crop factor of 0.9 was input, which is quite high compared to typical k_c values for grapevines (Allen *et al.*, 1998), but has been reported to occur in vineyards when full cover is reached (Williams and Ayars, 2005). A high k_c was chosen based on the assumption that root uptake is higher directly under the vine, which is the portion of soil being modelled, compared to the average rate of the entire surface that is described by typical crop factors. A rooting depth of 100 cm was chosen based on field observations and a rectangular root distribution was assumed based on existing soil moisture data, which showed even water extraction occurring with depth (Fig. 3.3 and 3.4).

Critical matric potentials for the Feddes sink term (Fig. 1.6) are also input in the crop growth module. h_1 and h_2 were entered so as not to be limiting because aeration stress was defined according to Eqns 3.3 and 3.4. h_{3L} and h_{3H}, the critical values where drought stress becomes limiting on days of low and high evaporative demand respectively, were both entered as 1000cm based on previous grapevine research (Taylor and Ashcroft, 1972; Trambouze and Voltz, 2001). Hence varying stomatal control due to weather conditions was not modelled. In reality some varying stomatal control could be expected, however the hydraulic properties of both the degraded and non-degraded soils were identically input, so this would not affect comparisons between the two soils. Additionally some grapevine cultivars, e.g. Shiraz, are considered ‘optimistic’ plants that show little change in their stomatal response according to different evaporative conditions (Schultz, 2003; Soar *et al.*, 2006). The lower limit of water uptake (h_4) was input as 15000cm, which is supported by field observations in vineyards (Trambouze and Voltz, 2001). The parameters for the salinity stress function (Fig. 2.7) were input according to Maas and Hoffman (1977).

Irrigation

A limitation of the SWAP model is that it is 1-D. Therefore it was difficult to accurately simulate irrigation from a dripper, which is essentially a 3-D process. However attempts were made to model only the portion of soil beneath a dripper. Irrigation was simulated with an automated procedure that triggered irrigation when soil matric potential dropped below -80 kPa at a depth of 20 cm, to mimic ‘standard’ scheduling practices for vineyards (Goodwin, 1995). 20 mm of water was applied during each irrigation event, which is more than is typically applied in the Nuriootpa vineyard- 7.5 mm. However 7.5 mm is an average amount applied over the entire vineyard surface, when in reality this water is concentrated under the dripper and a higher amount should apply for this soil volume. Deficit irrigation was also simulated, because there is widespread interest in deficit irrigation practices that can improve grape quality and water use efficiency (Kriedemann and Goodwin, 2004). The 'deficit' strategy applied 20 mm of irrigation when the soil matric potential dropped below –300 kPa at 20 cm depth. The irrigation water was given a solute concentration of 1.4 mg cm^{-3} to simulate borewater application that has average EC of 2.5 dS m^{-1}. Hence soil salinity would build-up during the growing season for both the degraded and non-degraded soils, but the degraded soil would start with higher soil salinity (Table 3.3).

Key assumptions

The key assumptions made in this modelling approach involved the reduction of the actual transpiration rate, T_a (cm d^{-1}), according to the sink term reduction functions. Many of these functions were based on studies of stress relationships that infer a reduction in T_a, without directly measuring it. For instance the critical *PR* limits in Eqn 3.2 were defined according to studies of root growth, not T_a, because studies of transpiration rates have not been conducted. However there is strong evidence that T_a is reduced when *PR* is high, even in the absence of drought stress (Masle and Passioura, 1987). While such a relationship has not been calibrated for grapevines, it was reasonable to assume that the higher *PR* of the degraded soil would reduce T_a.

Another key assumption concerned soil hydraulic properties. While there was evidence that irrigation caused a reduction in subsoil permeability and resultant waterlogging, a statistically significant difference could not be isolated in K_{sat} data in Chapter 2. Hence the degraded and non-degraded soils were simulated as having identical hydraulic properties, which means that aeration and drought stresses were identically applied. Therefore this modelling study only analysed salinity and *PR* stresses, when different aeration stresses may also have been present.

Finally, this study used a 1-D model to simulate what is essentially a 3-D system. While it was suspected that the reduction coefficients and rooting patterns would vary three dimensionally, the study was focussed on comparing degraded and non-degraded soils rather than quantifying transpiration to a high degree of accuracy. Hence a simplified approach was appropriate.

3.4 Model calibration and evaluation

Because the sink-term reduction-functions depend on soil moisture content, it was important to accurately simulate changing soil moisture throughout a growing season. The model was calibrated using volumetric water content data for the Nuriootpa study site that had been collected by calibrated EnviroScan sensors (Sentek Sensor Technologies, Stepney, South Australia) over a typical growing season in 2003/04 (Fig. 3.2a). It was assumed that the degraded soil profile would exhibit similar trends in moisture content because its physical and chemical properties had been based on the soil monitored in Fig. 3.2a. SWAP simulated the 2003/04 growing season and the output water contents were compared to Fig. 3.2a. The performances of multiplicative (Eqn 3.5), average (Eqn 3.6) and minimum (Eqn 3.7) calculations of the sink term were analysed. The average function overestimated root extraction rates, presumably because when any of the stresses were non-limiting, the overall reduction coefficient would be large. The multiplicative calculation reduced root extraction too severely, probably because of the large number of coefficients. The minimum function performed best (Fig. 3.2b) and was used for all further simulations.

The SWAP model performed well in simulating the general trends of soil moisture in 2003/04 (Fig. 3.2a, b). For the topsoil (10 and 20cm depths) and subsoil (60 and 80cm), the reduction in θ over time due to root water extraction, and the upper and lower θ were well simulated. Fluctuations in θ were dampened due to simulated irrigation events not penetrating deeply, but the overall effect of this was minor. Use of the automated irrigation procedure during model calibration allowed for the simulation of all growing seasons, not only those where the irrigation scheduling had been recorded.

A comparison of the simulated water balance to data from other vineyards revealed that soil evaporation was low (Table 3.4) if we assume similar irrigation management was applied. The soil evaporation routines in SWAP are based on field crops with full ground cover that shade the soil and lower wind speeds at ground level more effectively than in vineyards; hence the lower soil evaporation rates, which contributed to less water extraction in the topsoil to trigger irrigation. However despite the magnitude of irrigation events being lower in the simulated soil, the time spent where measured θ was greater than modelled θ was not significant over the course of the season. Therefore the SWAP model was considered to be sufficiently accurate for comparative purposes in 2003/04.

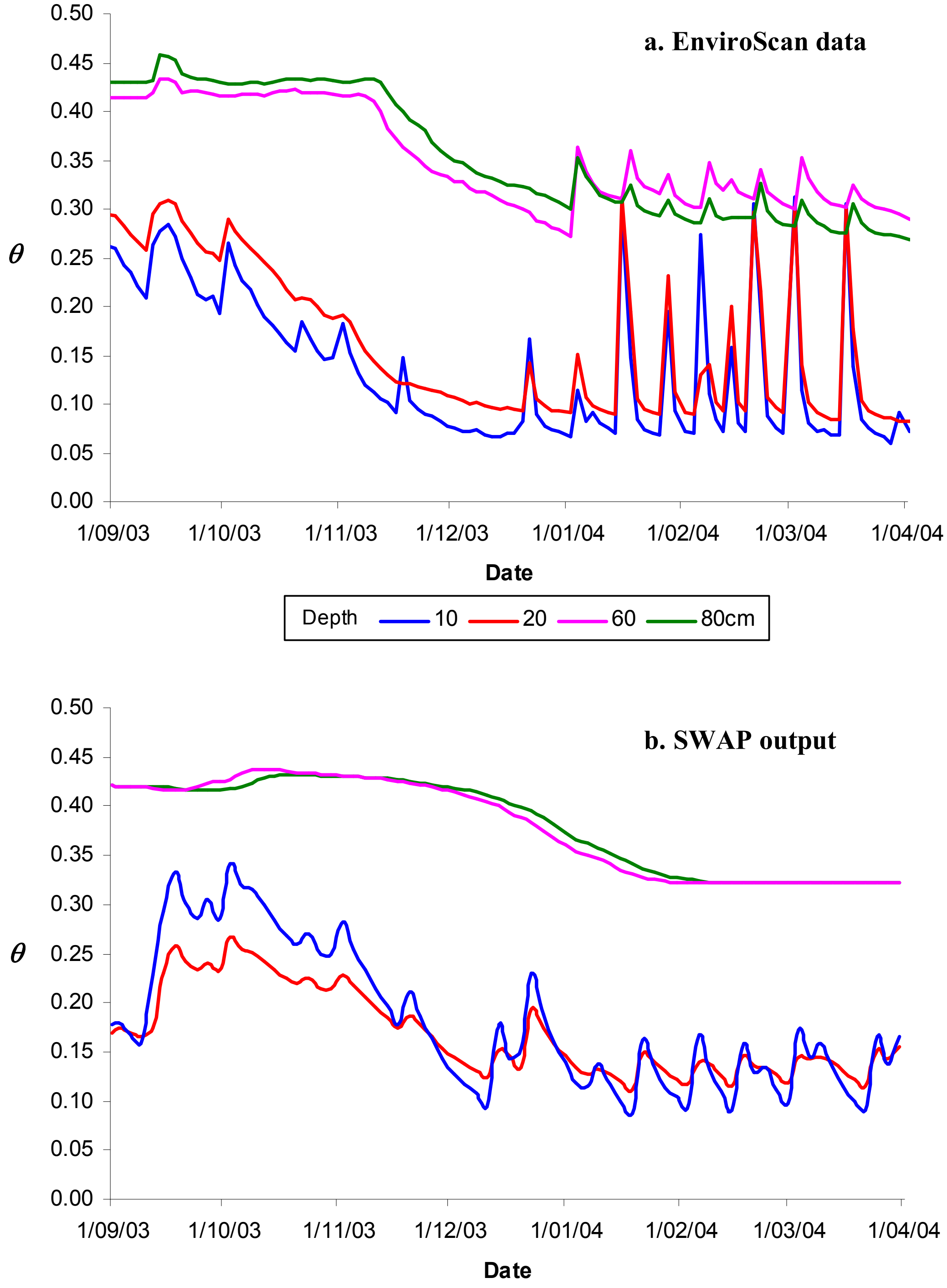

Fig 3.2 Volumetric water content, *θ* (cm^3cm^3), at various depths during the 2003/04 growing season showing: **a.** measured EnviroScan data from Mike McCarthy (pers. comm.); **b.** SWAP output for the degraded soil.

To evaluate the approach taken in 2003/04, the 2005/06 growing season was modelled using the same parameters and compared to a different θ dataset- measured with TDR (Fig 3.3). The TDR data from Dan Smith (pers. comm.) described average θ for the topsoil (0-30cm) and subsoil (30-60cm) and had been collected at the Nuriootpa site at approximately weekly intervals on days just before irrigation was applied. Hence the data had less variability than Fig. 3.2a. The modelled output was limited to the dates TDR was measured and averaged over the same depths.

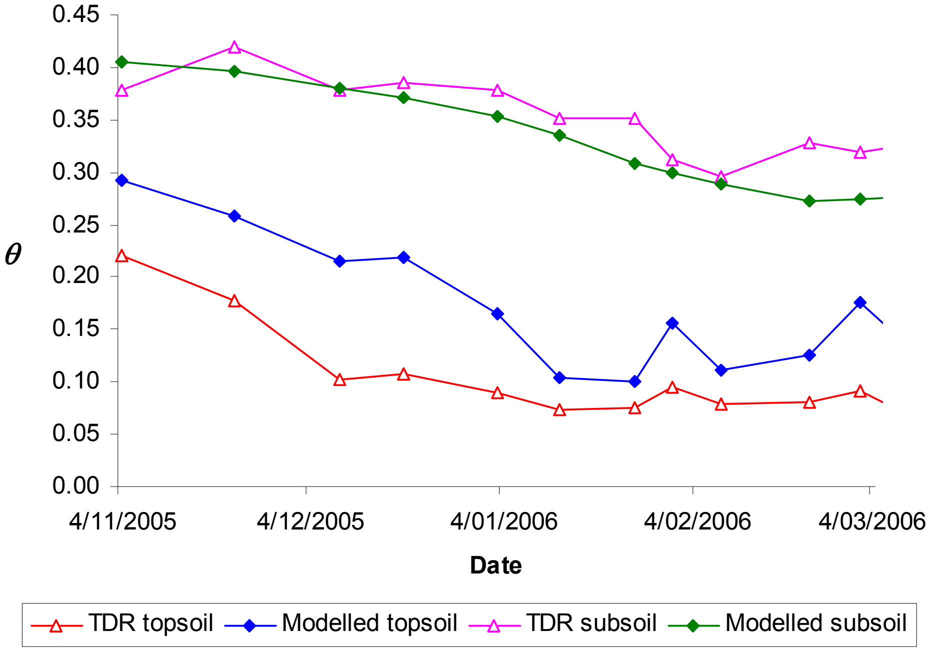

Fig 3.3 Modelled vs measured (TDR) volumetric water content data, θ (cm^3cm^{-3}), for the 2005/06 growing season at Nuriootpa.

There was good agreement between the measured and modelled θ for 2005/06, particularly in the subsoil. In the topsoil, the modelled θ was consistently higher than measured θ. However this was probably due to different antecedent water contents- the simulated antecedent water contents were somewhat arbitrarily input and identical for all simulated seasons. The rate that θ dropped was very similar for all measured and modelled profiles, suggesting that SWAP accurately described root water uptake.

A second evaluation was conducted by looking at the static performance of the model. Some data of grapevine transpiration vs matric potential was accessed for potted Merlot vines (Steve Green, pers. comm.), and compared to the combined reduction functions of the degraded and non-degraded soils, and to the original Feddes sink term (Fig 3.4). The experimental data for Merlot had been gathered on a soil with almost identical hydraulic properties to the A2 horizon at Nuriootpa and had been fitted with a two parameter equation similar to the van Genuchten (1987) S-shaped reduction function.

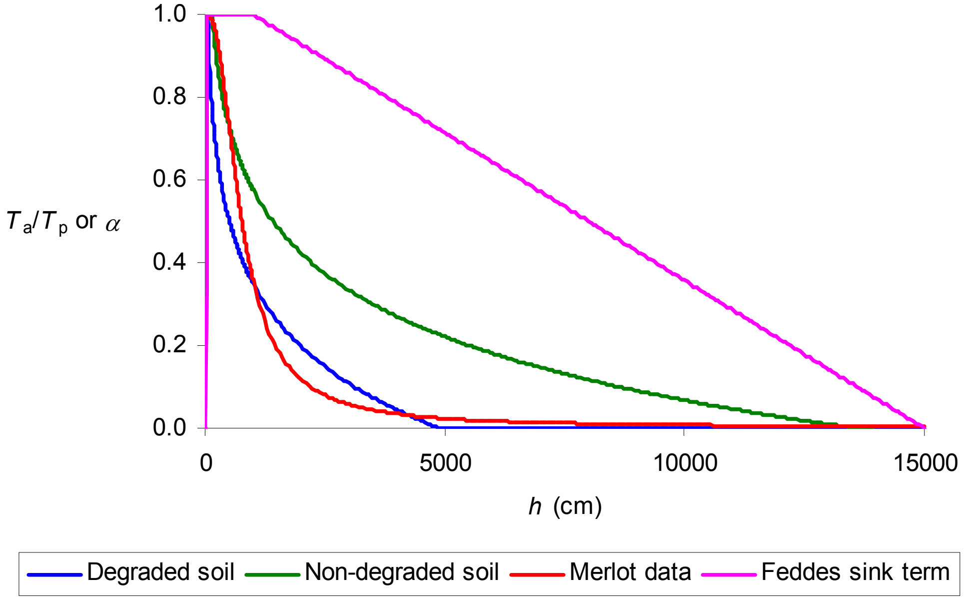

Fig 3.4 A comparison of the combined reduction functions used for degraded and non-degraded soils (Eqn 3.7) in the A2 horizon at Nuriootpa, versus experimental data for Merlot (Steve Green, pers. comm.) and the original Feddes sink term. The reduction functions are described by the relative transpiration rate, T_a/T_p, or the combined α term vs h, the absolute value of the soil matric potential (cm). The salinity reduction function is not included.

The reduction function for the degraded soil closely matched the experimental data for Merlot, and both soils significantly outperformed the Feddes sink term (Fig 3.4). A limitation of the Feddes sink term is that it is linear with respect to h. This does not mimic water retention curves, and the inclusion of $PR(h)$ function (Eqn 3.2) provides a more appropriate shape for the overall reduction function. The non-degraded soil was significantly less restrictive than the degraded soil. PR was not measured for the Merlot data so it was unknown what $PR(h)$ function applied for this data.

3.5 Model outputs

Simulations were conducted for degraded and non-degraded soils over five growing seasons that had near average summer rainfall (228.5 mm from September 1 to March 31).

For each season, differences in cumulative transpiration, T_{total} (mm), between the degraded and non-degraded soils were compared under 'standard' and 'deficit' irrigation practices, and under no irrigation. Average water use data for the five seasons simulated is presented in Table 3.4.

Regime	Rainfall	Irrigation (mm)		T_{total} (mm)			S_{total} (mm)	
	(mm)	D	ND	D	ND	Diff.	D	ND
Standard	215	104	104	250.6	262.9	12.2	137.9	138.6
s.e.	*9.2*	*7.5*	*7.5*	*1.5*	*2.2*	*1.0*	*4.5*	*4.3*
Deficit	215	68	72	244.1	252.8	8.8	120.3	119.6
s.e.	*9.2*	*8.0*	*8.0*	*1.1*	*1.1*	*0.6*	*4.4*	*4.1*
No irrigation	215	-	-	209.8	215.8	6.0	96.1	95.2
s.e.	*9.2*	-	-	*4.4*	*4.3*	*0.6*	*5.5*	*5.4*
Yanusa *et al.* (2004)				247.0			203.0	

Table 3.4 Average water use data for simulations conducted for degraded (D) and non-degraded (ND) soils at Nuriootpa under different irrigation regimes, where T_{total} and S_{total} are the cumulative transpiration and soil evaporation for a growing season (1 September – 31 March), 'Diff.' is the difference in T_{total} between the soils, and *s.e.* is the standard error of the mean. Outputs are compared to data from Yanusa *et al.* (2004), collected at Merbein, Victoria.

A thorough assessment of the water balance in Barossa Valley vineyards had not been studied previously. However simulated T_{total} compared well to published data from other irrigated regions (Table 3.4) (Yunusa *et al.*, 2004). Furthermore total water use, which would include T_{total}, S_{total} and change in soil water storage, was in line with findings from other vineyards (Evans *et al.*, 1993). As discussed previously, the simulated S_{total} was too low, but this was counterbalanced by irrigation also being lower than average for standard conditions at Nuriootpa (160mm).

Under standard irrigation, T_{total} was on average 12.2 mm higher in non-degraded soils (Table 3.4). When less irrigation was applied, the difference between the two soils also declined. The trend was evident in all seasons simulated (Fig 3.5), and suggests that vines growing in the degraded soil were already quite stressed when grown under well-watered conditions. Effectively in the degraded soil there was a smaller buffer against stress from water deficits that can be used to improve water use efficiency.

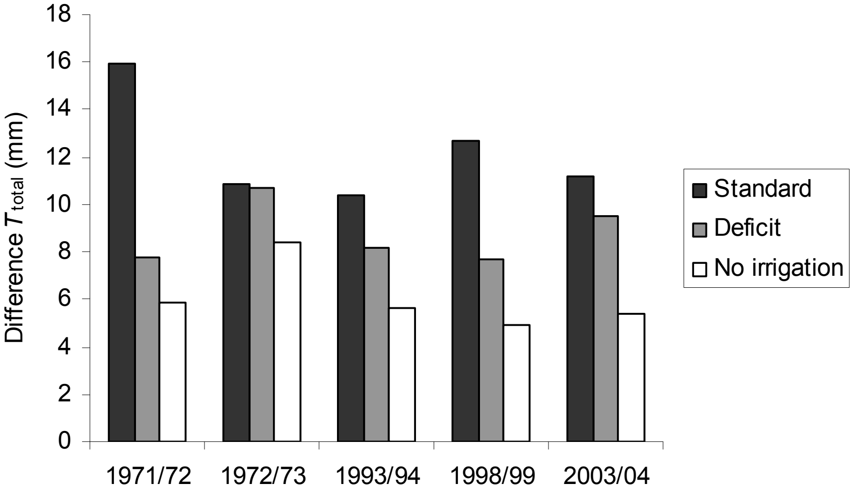

Fig 3.5 Difference in total transpiration, T_{total}, between degraded and non-degraded soils, over 5 growing seasons, under different irrigation regimes, at Nuriootpa.

T_{total} was also simulated in very wet and very dry seasons. Simulations were run in the three driest and wettest seasons on record (Table 3.5). The greatest reduction in T_{total} from standard conditions was evident in wet years due to aeration stress. Because this function acted identically for degraded and non-degraded soils, there was a smaller difference in T_{total} than what occurred under standard conditions. In very dry years, the impact of drought stress was negated by increased irrigation.

Season	Rainfall	Irrigation (mm)		T_{total} (mm)			S_{total} (mm)		Drainage (mm)	
	(mm)	D	ND	D	ND	Diff.	D	ND	D	ND
wet years										
1992/93	503	0	0	187.7	196.0	8.3	131.0	130.9	203.6	203.4
1973/74	423	20	20	207.9	217.0	9.1	137.3	137.9	60.7	54.2
2005/06	410	80	80	249.4	258.0	8.6	145.0	147.2	107.5	106.9
dry years										
1914-15	107	140	140	216.8	226.5	9.7	120.6	121.3	4.8	4.8
1904-05	128	140	160	240.3	250.7	10.4	128.5	133.8	5.0	5.0
1900-01	131	160	180	242.2	252.8	10.6	141.0	141.3	5.0	5.0

Table 3.5 Water use data for simulations conducted for degraded (D) and non-degraded (ND) soils at Nuriootpa, in very wet and very dry seasons.

The relative importance of the salinity and *PR* reduction functions was examined for the 2003/04 growing season by simulating different combinations of the two stresses (Fig 3.6). The reduction of T_{total} in the degraded soil (*+PR +Salt*) from the non-degraded soil (*-PR -Salt*) was almost entirely due to the *PR* stress. The higher solute content in the degraded soil had a negligible impact on T_{total}. There was no analysis of aeration or drought stresses because the same hydraulic properties were entered for both soils.

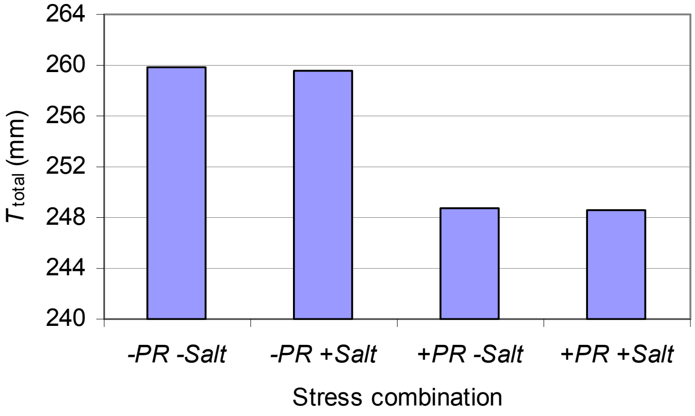

Fig 3.6 Relative importance of *PR* and salinity (*Salt*) stresses in 2003/04 at Nuriootpa, where + and – describe the presence and absence of the stresses respectively.

3.6 Discussion

In terms of assessing the impact of the soil degradation, the key question was not whether T_{total} was lower in the degraded soil but by how much. The higher *PR* and salinity in the degraded soil ensured that it would always be more restrictive for root water uptake. However from a management perspective, was an average difference of 12 mm for T_{total} significant? The reduction in available water and a smaller buffer against the controlled stress of deficit irrigation strategies was undesirable, but there were indications this may not be a large problem for management. A reduction of 12 mm was minor and represents < 5 % of T_{total} (262.9 mm). There had been no yield reduction noted at the Nuriootpa vineyard over the time where degradation increased (Mike McCarthy, pers. comm.). Soil moisture data indicated the vines extract water from all soil layers, despite the poor physical properties (high *PR* and low permeability) of these layers (Fig 3.2a and Fig 3.3). The non-degraded soil, while more desirable, had similarly poor physical properties. And given that grapevines are a crop in which limited stress can improve grape and wine quality, the reduction in T_{total} was not considered significant.

The above discussion should be qualified by considering some of the assumptions made in this modelling approach. For instance the impact of reduced subsoil permeability and resultant waterlogging was not modelled despite some evidence of its occurrence being presented in Chapter 2 and by Clark (2004). Given the reduction of T_{total} was greatest in overly wet seasons and that waterlogging reduces nutrient availability and leads to restricted spring growth (White, 2003), this aspect of soil degradation may have significant consequences in wet seasons. Therefore it could not be concluded that the degradation evident in Chapter 2 does not require some form of amelioration.

Reference should be made to other modelling approaches that examine crop growth in compacted soils. A variety of alternative approaches have been used and are reviewed by Lipiec *et al.* (2003). Many of these models simulate the impact of soil compaction on root growth, which then feeds back to influence transpiration (e.g. Jakobsen and Dexter, 1987; Stenitzer and Murer, 2003). While this approach is quite different from the one taken in this study, the reduction functions are quite similar. For example, the reduction function due to *PR* in Stenitzer and Murer (2003) is very similar to the description of α_{pr} in this study (Eqn. 3.2). Presumably the impact of the higher *PR* on transpiration would be similar if this different approach were taken.

3.7 Conclusion

The SWAP model was modified to examine the impact of soil degradation on grapevine transpiration at Nuriootpa. The modelling approach was restricted to an examination of salinity and *PR* stresses. The soil moisture regime at Nuriootpa was accurately simulated and T_{total} was in line with data collected at other vineyards. Simulations were conducted for different irrigation regimes with the model output indicating that degradation led to a reduction in available water and a smaller buffer against the controlled stress of deficit irrigation strategies. This reduction was almost entirely due to *PR* stress with the salinity stress seen to have a negligible impact. However in light of other factors, such as evidence of water extraction by roots in all soil layers and there being no yield reduction at the Nuriootpa vineyard over time, the < 5 % reduction in T_{total} was not seen to be significant. Hence the impact of higher *PR* and salinity was not considered to be a significant management problem.

An assessment of reduced subsoil permeability was not conducted in this study; however waterlogging and subsequent aeration stress was seen to significantly reduce T_{total} in wet seasons. Therefore if further research can isolate a statistically significant reduction in subsoil K_{sat}, the altered SWAP model could be used to examine the implications of this degradation.

Chapter 4.

Do grapevine roots use biopores to grow into strong soils?

Note: This chapter describes a collaborative study conducted by a fellow PhD student, Daniel Smith, and myself. We were both interested in the same aspect of grapevine root growth and approached the topic from different angles according to our primary research interests. Hence the collection of data was shared evenly, but the study has been written about separately and our interpretation of the data may be different.

4.1 Introduction

Drip irrigation was found to increase soil strength in vineyards (Chapter 2). However it was unclear what impact this was having on grapevine root growth, because the results did not match theoretical relationships between root growth and penetration resistance, *PR* (MPa). Roots were observed in soils with *PR* much greater than the 2 MPa threshold thought to severely impede grapevine root growth (Myburgh *et al.*, 1996; Ferree and Streeter, 2004). Similar observations have been made in other vineyards with roots occupying soil layers with *PR* as high as 8 MPa at field capacity (Saayman, 1982; van Huyssteen, 1989). Such findings support suggestions that *PR* is only a good indicator of mechanical impedance within the soil matrix, and does not quantify the overall resistance encountered by roots (Barley and Greacen, 1967).

It was hypothesised that roots avoided the physically hostile matrix by exploiting biopores or structural cracks. Studies have been conducted for a variety of crops (Ehlers *et al.*, 1983; Dexter, 1986; Stirzaker *et al.*, 1996; Hirth *et al.*, 1997; Pierret *et al.*, 1999; Hirth *et al.*, 2005), yet little is known about the relationship between soil strength, biopores and root growth for grapevines. This chapter describes a study that examined this relationship and tested the hypothesis that grapevines use biopores to grow into strong soil. Potted grapevines were grown in varying degrees of soil compaction, with and without artificial biopores.

4.2 Materials and methods

Experimental design

A 2 x 2 factorial experiment was designed to test the hypothesis that grapevines use biopores to grow into strong soils (Table 4.1). Grapevine rootlings (cv. Cabernet Sauvignon) were grown in pots that were compacted or not compacted, with or without artificial biopores. Six replicates were used for each treatment.

		Compaction	
		-	+
Artificial biopores	-	6 pots	6 pots
	+	6 pots	6 pots

Table 4.1 Experimental design.

Soil compaction treatments

A fine sandy loam soil from the A horizon of the Urrbrae loam, Waite Campus, Adelaide, was used. The soil was classified as a red brown earth and has been well characterised from previous studies (e.g. Oades *et al.*, 1981). It had similar properties to the surface horizons at Nuriootpa, described in Chapter 2, with a clay content of 17 %, an organic carbon content of 1.2 % and pH of 5.6. The soil was air-dried, sieved (<2 mm) and mixed thoroughly.

The air-dried soil was spray-wetted to yield a consistent volumetric water content of 0.22 cm^3cm^{-3} for all soil layers, regardless of their bulk density. This water content ensured adequate supplies of air and water for the plants. The moist soil was packed incrementally into pots using an hydraulic ram. Pots were made from PVC storm piping and were 15 cm diameter x 16 cm high. They were sealed on the base with a PVC end-cap. When packed, each pot consisted of 5 layers of soil. The top layer (layer 1) was 6 cm thick. Layers 2-5 were 2.5 cm thick. Non-compacted treatments were packed to a uniform bulk density of 1.30 g cm^{-3} for all layers. Compacted treatments were packed so that bulk density increased with depth (Fig. 4.1). The bulk densities were selected based on pilot studies of *PR* versus bulk density. Twenty-seven pots were packed for the experiment- 6 pots per treatment plus an additional 3 pots of non-compacted soil, which could be destructively sampled to gauge an appropriate harvest date for the remaining pots.

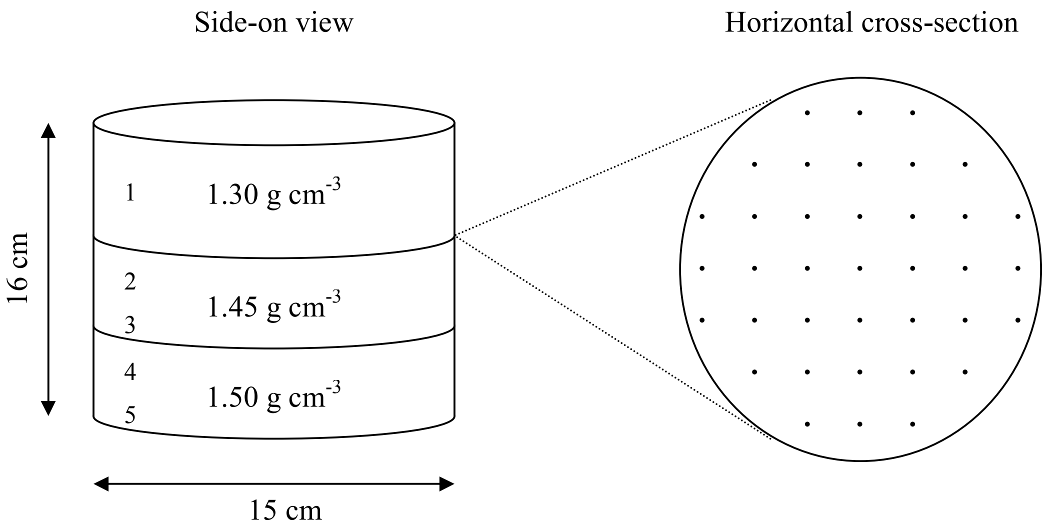

Fig. 4.1 Diagram representing a compacted treatment with biopores. The side-on view shows the pot dimensions, and increasing bulk density with depth (soil layers are represented by the numbers 1-5). The horizontal cross-section shows the pattern used for artificial biopores, which extended vertically through the compact layers (2-5).

The compacted treatments reflected field conditions at Nuriootpa. 'Non-compacted' topsoil with a bulk density of 1.30 g cm^{-3} (layer 1) provided non-limiting conditions for root growth to get started. A sharp increase in bulk density between layers 1 and 2 mimicked the A/B boundary at Nuriootpa (1.45 g cm^{-3}). Bulk density was higher again in layers 4 and 5 (1.50 g cm^{-3}). It was thought that increasing the bulk density with depth would force the vine roots to stop growing or else explore the grid of artificial biopores. This would allow us to determine a critical *PR* value above which root growth is completely impeded.

PR was measured using the micro-penetrometer described in Chapter 2. It was measured prior to planting in extra pots that were packed, and after harvest on a selection of cores from compacted and non-compacted treatments. There was no significant variability between replicates, or before and after plant growth. Average *PR* versus depth for both compaction treatments is presented in Fig. 4.2.

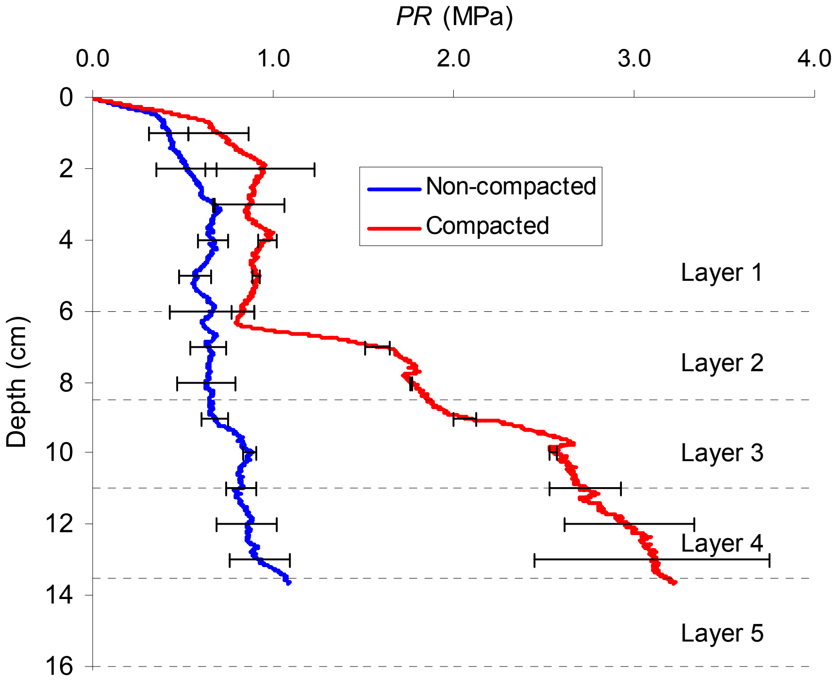

Fig. 4.2 *PR* (MPa) versus depth (cm) for compacted and non-compacted soil packed in pots in 5 layers. (The penetrometer needle was too short to measure layer 5).

Biopore treatments

The density and diameter of artificial biopores simulated field conditions at Nuriootpa. Biopores were visible on the surface of large, intact cores (also 15 cm diameter) that were collected for the study described in Chapter 5. Biopores were counted in each core (Fig. 4.3). The cores had an average of 37 biopores (excluding the outlier) that were typically 1 mm in diameter. Hence 37 artificial biopores of 1 mm diameter were inserted into pots prescribed as biopore treatments. The pore density (equivalent to roughly 2000 pores m^{-2}) was at the upper level and the pore diameter was at the lower level of treatments studied by Dexter (1986).

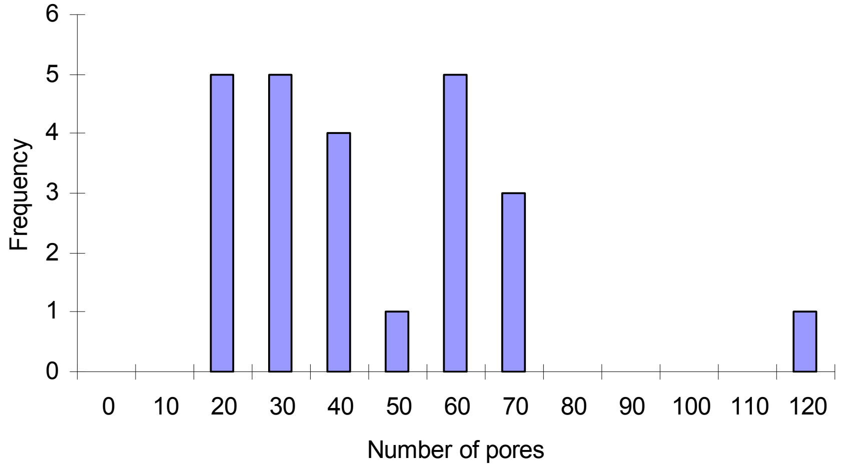

Fig. 4.3 Frequency histogram for the number of biopores visible on the surface of large, intact cores that were studied in Chapter 5.

The artificial biopores were inserted into pots from the mid-point of layer 1 (3 cm depth) to the base of the pot. The mid-point of layer 1 was chosen to allow some root growth before biopores were encountered. 0.9-mm-gauge wire was used to create pores of approximately 1 mm diameter. The wire was pushed vertically into layers 1-5 before the remainder of layer 1 was filled. An acrylic template was constructed and placed on the surface of the soil cores to guide the wire and ensure a uniform distribution of biopores (Fig. 4.1, cross-section).

Planting material

Own-rooted Cabernet Sauvignon rootlings were obtained (Yalumba Nursery, Nuriootpa, SA). These were generally 45 cm in length and were kept dormant in sealed plastic bags in a refrigerator until use (4°C). Twenty-seven rootlings of similar size were selected for planting from the 50 rootlings that were supplied. Pruning attempted to minimise sample variability and was required to fit the plants into pots. Rootlings were cane-pruned to 4 buds (2 x 2 bud spurs), and root-pruned to 10 roots < 2 mm diameter of 20 mm length (Fig. 4.4). Root-pruning also ensured that most of the roots sampled at the end of the experiment were new, rather than existing roots.

Fig. 4.4 Grapevine rootlings before (left) and after (right) pruning. The steel ring was used to create a hole in the soil for planting.

Vines were planted into holes, created with 5cm diameter steel rings that were pushed into the top layer to a depth of 4cm. The soil in the core was removed and broken up before refilling the hole around the rootling. The pot surface was covered with plastic film, which minimised evaporative losses and was draped over a wire 'cage' to maintain air space for gas exchange. Pots were weighed and transported to the glasshouse.

Growth Conditions

To minimise fluctuations in *PR*, pots were maintained at their initial weights and water contents by spray-wetting every second day. Glasshouse temperature was approximately 22 ± 5°C. Natural light was supplemented with sodium lamps that operated for 16 h each day (0400h – 2000h) to mimic summer day-length.

After planting, the vines showed signs of stress with delayed and variable bud-burst. Some vines grew normally, others produced water sprouts from the base (Fig. 4.5), and others produced no shoots. The stress was not related to compaction or biopore treatments (Fig. 4.5); nor was it related to poor planting material. Rather, it was considered primarily due to heavy root-pruning (Fig. 4.4) because bulk densities in layer 1 were low, soil moisture was ideal, and unpruned vines that had been left to hydrate in a bucket of water started to grow quite adequately in a cool, poorly-lit laboratory (18°C).

Fig. 4.5 Variable shoot growth due to root pruning. On the left, a compacted pot with no biopores shows standard shoot growth. On the right, a non-compacted pot with no biopores shows poor shoot growth from the base (water sprout). Both vines were grown for an identical amount of time (5 weeks).

Harvest

Based on the destructive sampling of additional pots, harvest was conducted 5 weeks after shoot growth had been initiated. The variable bud-burst meant plants were harvested on different dates. There was also an uneven number of replicates in each treatment that produced shoots: 5 replicates from 'non-compacted/no biopores', 4 from 'non-compacted/with biopores', and 3 each from both compacted treatments.

When harvested, the shoots were removed and weighed. Two vertical cuts were made through the PVC piping using a band saw to open the pots. Roots that grew down the side of pots were removed and discounted in further analyses. Soil was cut into the 5 separate layers using a knife, and roots were washed from each layer using a nest of sieves, the smallest of which was 1 mm. Roots were stored in 50 % ethanol.

Root analyses

Roots were spread out in trays of water on a flatbed scanner and scanned to create 16-bit greyscale images with a resolution of 400 dpi. Images were analysed using WINRHIZO software (Ver. 5.0A; Regent Instruments, Quebec, Canada), which calculates morphological root measurements based on Tennant's (1975) statistical line-intersect method. The following parameters were obtained for each soil layer: total root length (cm), average root diameter (mm), and root length density (cm cm^{-3}). The program also output other parameters that were not analysed in this study: total root surface area (cm^2), root volume (cm^3), root length (cm) in different diameter classes, and branching indices.

4.3 Results and discussion

Observations

Observations suggested that compaction and biopore treatments had a significant effect on root growth. Roots were seen to stop abruptly when compacted layers were reached and were commonly diverted sideways (Fig. 4.6). In the most compacted layers (4 and 5) roots were only found within biopores (Fig. 4.7). Their shape (perfectly straight) and their lack of branching confirmed their existence in biopores.

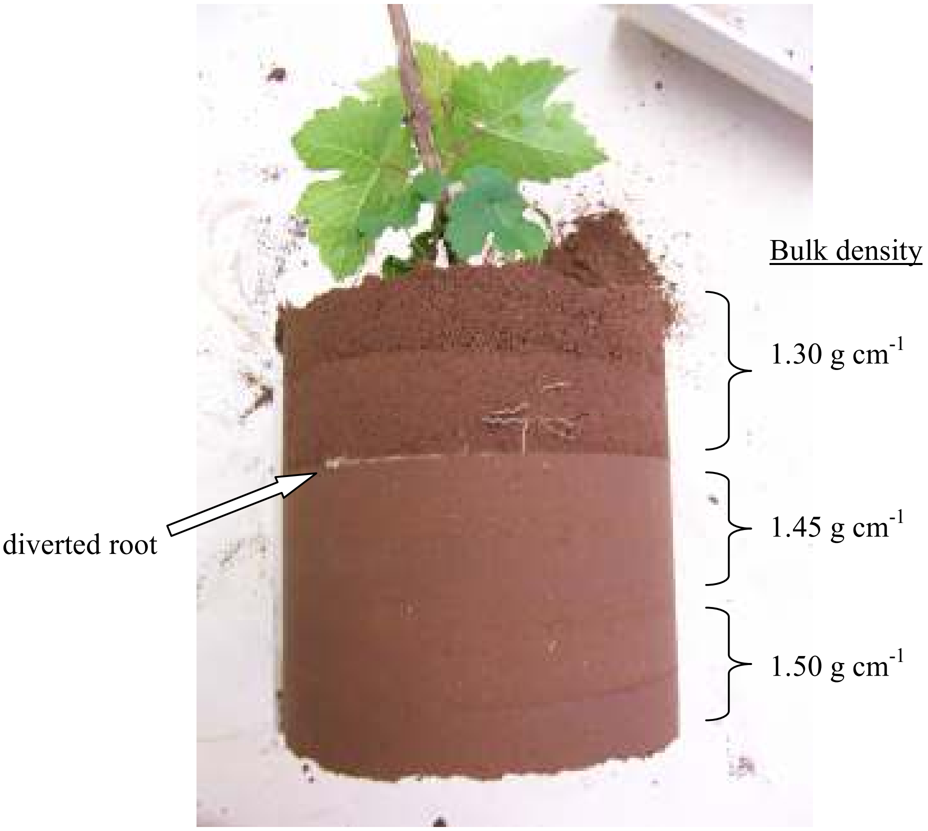

Fig. 4.6 An example of a root diverted sideways when compacted layers were reached.

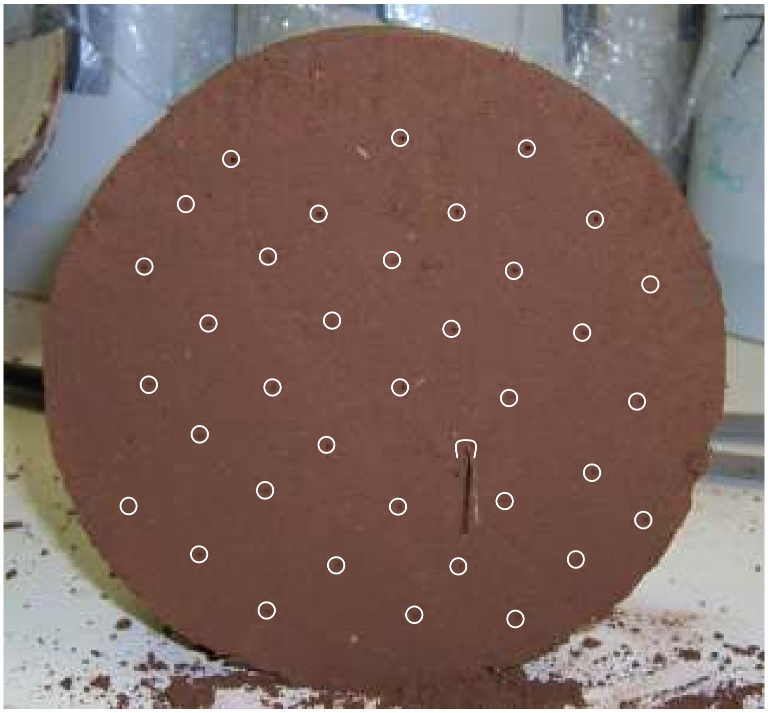

Fig. 4.7 A root growing through a biopore in a compacted layer. Note the straightness of the root, the lack of branching and the position of the root relative to pattern of biopores.

Root length

Despite clear observations that compaction and biopores had a significant effect on root growth, the data were difficult to interpret. The variable growth response to initial pruning (Fig. 4.5) prevented analysis of shoot growth according to soil treatments, and also caused significant variation in total root length between pots. Hence there were no clear responses of root length density to compaction or biopore treatments (Table 4.2).

	Non-compacted + biopores	Non-compacted - biopores	Compacted + biopores	Compacted - biopores
RLD (cm cm^{-3})	0.61	0.41	0.21	0.49
s.e.	*0.19*	*0.11*	*0.05*	*0.16*

Table 4.2 Total root length density, RLD (cm cm^{-3}), averaged for each soil treatment, where *s.e.* is the standard error of the mean.

Nevertheless the data was normalised to eliminate variable growth. Root length for each layer was converted to a percentage of the total root length in each pot and averaged for each treatment (Table 4.3).

Layer	Non-compacted + biopores	Non-compacted - biopores	Compacted + biopores	Compacted - biopores
1	69.9 b	72.9 b	88.3 a	93.1 a
2	13.6 a	17.1 a	5.5 b	6.3 b
3	7.7 a	6.8 a	2.8 b	0.6 c
4	4.7 a	2.2 b	1.2 b	0 c
5	4.1 a	1.0 b	2.2 ab	0 c

Table 4.3 Percentage of total root length in each soil layer, averaged for each treatment. Different letters correspond to significantly different percentages according to standard errors, within common soil layers.

For all treatments, roots were concentrated in the ‘non-limiting’ topsoil (Table 4.3). However there was a greater proportion of roots in the topsoil of compacted treatments and less root growth with depth. Root growth occurred only through artificial biopores- absolutely no roots were found in layers 4 and 5 of the compacted/no biopores treatment. Therefore the primary hypothesis of the study was accepted. The data also supported a critical *PR* of 2 MPa in homogenous soils where root growth was completely impeded. Furthermore, biopores appeared to play a role in assisting root growth in non-compacted soils, with proportionately higher root growth in layers 4 of 5 of the 'non-compacted/with biopore' treatment.

Treatment differences were highlighted when root length percentages were plotted as a function of depth (Fig 4.8). Average percentages of root length per layer relative to total root length (from Table 4.3) were plotted through the mid-point of each layer. A log-scale was chosen to examine treatment differences for all depths.

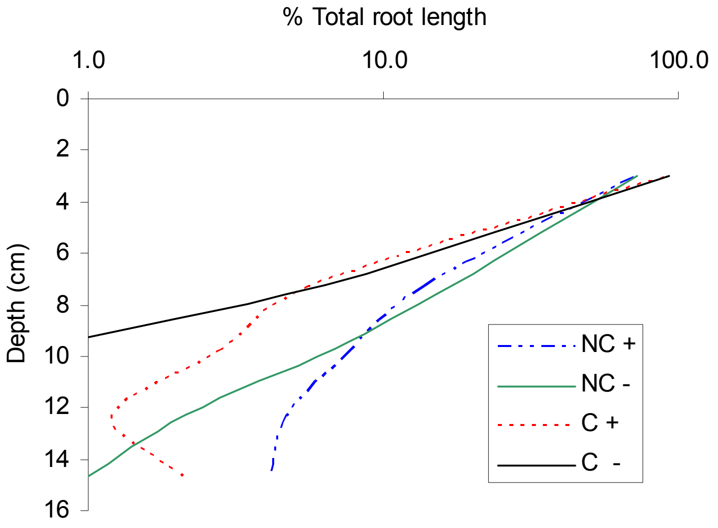

Fig. 4.8 Total root length (%) versus depth (cm) for different treatments: 'non-compacted/with biopores' (NC +); 'non-compacted/no biopores' (NC -); 'compacted/ with biopores' (C +); and 'compacted/no biopores' (C -).

In the top 8 cm of the profile, root growth declined more rapidly in compacted soils, but there was no effect due to artificial biopores- similar trends were evident in soils where the only difference was the presence or absence of biopores (Fig. 4.8). After this depth, however, there was a divergence in root growth due to biopores in both the compacted and non-compacted treatments. In compacted soils with no biopores there was a log-linear trend with depth until root growth was completely impeded. A similar log-linear trend, albeit a more gradual one, was noted in the non-compacted soils without biopores. Such behaviour contrasted to root growth in treatments that had biopores. In these treatments there was a log-linear decline in root growth until a certain depth was reached from which point root growth became more or less constant with depth. The trends indicated that biopores improved root growth not only in compacted soil, but also in non-compacted soil.

Root diameter

Root diameter is known to increase with soil strength for a range of plant species (Materechera *et al.*, 1991). It has been suggested that thickening results from roots compressing the soil radially to lower the soil resistance in front of elongating root tips (Greacen, 1986).

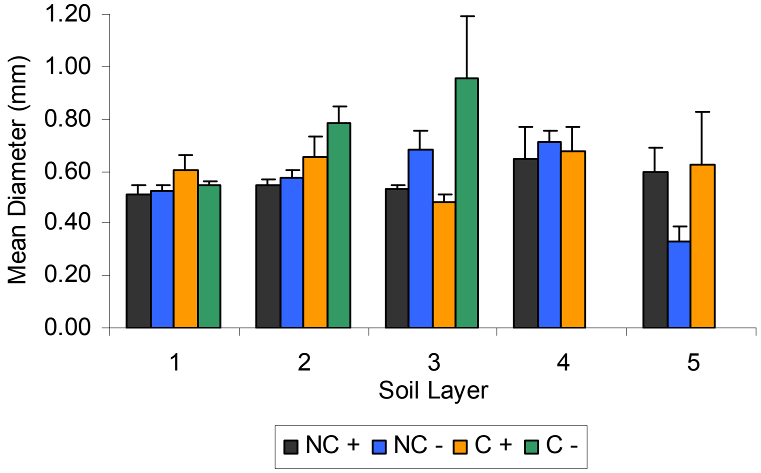

Fig. 4.9 Mean root diameter (mm) for each soil layer for different treatments: 'non-compacted/with biopores' (NC +); 'non-compacted/no biopores' (NC -); 'compacted/ with biopores' (C +); and 'compacted/no biopores' (C -).

Root diameter did not increase with soil strength in treatments with biopores (Fig. 4.9). However root diameter increased with depth in the compacted soil without biopores. Root diameter also increased with depth in non-compacted soil without biopores (excluding layer 5). Strength increase with depth was minor in non-compacted soils (Fig. 4.2); although root thickening coupled with smaller root lengths in layers 4 and 5 when no biopores were present (Table 4.3) suggested the non-compacted soil imposed some limitations on root growth.

4.4 Conclusion

Very little root growth occurred when *PR* > 2 MPa unless biopores were present. Hence the hypothesis that grapevine roots require biopores to grow into strong soil was supported. The presence of biopores also improved root growth in non-compacted soil when *PR* approached 1 MPa, which suggested that biopores influence root growth in soils regardless of compaction levels.

These findings supported the notion that vine roots had used biopores to grow into the Nuriootpa subsoil (Chapter 2). However the presence of roots does not necessarily indicate healthy root functioning. While this experiment examined the physical impact of biopores; in reality, biopores have very different chemical and biological properties to bulk soil (Pierret *et al.*, 1999). For instance roots clumped in biopores can be exposed to higher populations of pathogens (Passioura, 1991). Such factors could have a large bearing on vineyard production and may be affected by irrigation practices. Thus in light of the soil physical degradation evident in Chapter 2, it would be useful to examine the physical, chemical and biological status of biopores relative to drip irrigation.

The impact of biopores in compacted and non-compacted soils also suggested that it is misleading to focus solely on *PR* as a determinant of root growth. The critical limit of 2 MPa was supported, yet this is only relevant for homogeneous soils, which are uncommon in field situations. Therefore *PR* should not be the only tool used when assessing the rooting potential of soil in vineyards, which has been done in previous studies (e.g. Myburgh *et al.*, 1996). An assessment of soil structure, such as biopore density and size, should be incorporated.

Chapter 5.

The potential of drying events to generate structure in degraded, clayey subsoil

5.1 Introduction

Poorly structured, clayey subsoils can significantly limit vineyard productivity. Their low permeability encourages waterlogging. Their high soil strength retards root growth, shoot growth and transpiration. Such physically hostile subsoils are widespread throughout the Australian landscape and, in most cases, are the result of natural soil forming processes (Cockroft and Martin, 1981; Chittleborough, 1992; Naidu *et al.*, 1993). For instance many of the red brown earths used for viticulture in the Griffith irrigation area of New South Wales have naturally poor drainage, and water tables must be controlled to prevent restricted spring growth (White, 2003). Poor management practices can exacerbate these physical constraints through excessive cultivation with heavy machinery (Horn *et al.*, 2000) and/or improper irrigation practices (Chapter 2), and necessitate measures to ameliorate these soils.

Much research has been conducted to ameliorate physically hostile subsoils (Jayawardane and Chan, 1994). Deep tillage (Ellington, 1987; Blackwell *et al.*, 1991), application of chemical ameliorants such as gypsum and lime (Blackwell *et al.*, 1991; Clark, 2004), organic matter additions (Vance *et al.*, 1998), the promotion of biological activity (Cresswell and Kirkegaard, 1995; Lee and Smettem, 1995; Yunusa and Newton, 2003) and combined approaches (Baldock *et al.*, 1994; Olsson *et al.*, 2002; Wheaton *et al.*, 2002) have all been used with varying degrees of success. Comparatively little research has focussed on the potential of drying events to generate structure in clayey subsoils with shrink-swell properties (Grant and Dexter, 1989; Dexter, 1991).

In drip-irrigated vineyards, there is a possibility that degraded clayey subsoils could be ameliorated by manipulating zones of soil drying. At distances away from the dripper, drying events could generate shrinkage cracks that improve drainage and provide opportunities for root growth. Between-row cracking has been reported with furrow-irrigated cotton in New

South Wales (Chan and Hodgson, 1984), and such behaviour may explain why no increase in soil strength was evident at the mid-dripper position in Chapter 2. From a practical perspective, drying events could be manipulated by moving the dripper laterally or by changing the irrigation frequency and intensity. A better understanding of these mechanisms is required and the feasibility of this simple, non-invasive, ameliorative approach needs to be investigated. This chapter outlines a study that was undertaken as a preliminary assessment of the potential use of significant drying events to generate structure in degraded, clayey subsoil.

5.2 Materials and methods

The experiment involved sampling large intact cores from a vineyard, where subsoil degradation had been identified, and subjecting them to calcium treatments and a significant drying event in the laboratory. Hydraulic properties were measured before and after drying to a matric potential of –1500 kPa: chosen as the approximate limit to which grapevines could potentially dry soil at the edge of the rootzone, away from irrigation. Changes in hydraulic properties after drying would infer changes in structure. While it was recognised that cracking generated in soil cores may be quite different to cracking generated under field conditions, the logistical difficulty of a field trial prompted the laboratory approach as a first step.

Field site and sampling

Large intact cores were sampled from a vineyard at the Nuriootpa Research Station, Barossa Valley, South Australia, in November 2005. The soil was a Red Chromosol (Isbell, 1996) with the dominant feature being an abrupt texture contrast at 35 cm depth. The topsoil was fine sandy loam (~15 % clay). The subsoil was medium-to-heavy clay (~55 % clay). The 20 y.o. grapevines (cv. Chardonnay) had been drip irrigated at the rate of 150 mm year^{-1} to supplement an average annual rainfall of 502 mm, in a Mediterranean climate. Row and vine spacings were 3.0 and 2.25 m respectively. The site had a history of irrigation with borewater that had an EC of 2.5 dS/m and an SAR of 8. Such irrigation at this site was found to degrade soil structure in Chapter 2 and in other studies (Kienzler, 2001; Clark, 2004).

To expose the subsoil, a trench (30 m long x 0.35 m deep) was dug alongside a vinerow. Twenty-four PVC rings (150 mm diameter x 100 mm high) were pushed into the subsoil with a truck-mounted hydraulic drill-rig and manually extracted. The 24 large intact cores were taken in pairs under 12 adjacent vines- each core within 50 cm of the dripper, in the zone where structural degradation was identified (Chapter 2). At each vine, 4 replicates of small intact cores (50 x 50 mm) and a bulk soil sample were taken. All soil samples were kept dark and cool in air-tight bags before analysis.

Bulk soil properties

Bulk soil samples were air-dried and sieved to 2 mm. 1:5 soil water extracts were prepared. Electrical conductivity (EC) and pH were measured, and cation concentrations determined with ICP-AES, from which the sodium adsorption ratio (SAR) was calculated. Particle size analysis was conducted using the hydrometer method (Gee and Or, 2002), and particle density measured with pycnometers (Blake and Hartge, 1986). Water retention curves were measured with the small intact cores using hanging columns of water to set the matric potential at -10 kPa, and pressure chambers from -33 to -1500 kPa (Cresswell, 2002).

Bulk density measurement

Individual bulk densities of large intact cores were required to accurately determine the appropriate core weights that corresponded to various matric potentials during drying events. Density could not be determined by oven drying because this would compromise drying treatments. Hence the initial plan was to infer the bulk density of large cores from the measured values of small cores. However the bulk density of small cores was found to be highly variable with a non-normal distribution (Fig. 5.1).

An alternative, non-invasive measurement of bulk density was found by solving two common soil physics equations simultaneously. Eqn 5.1 describes the relationship between the saturated water content, θ_{sat} ($\mathrm{cm}^3\mathrm{cm}^{-3}$), and the ratio of the bulk density, ρ_{b} ($\mathrm{g\ cm}^{-3}$), and particle density, ρ_{s} ($\mathrm{g\ cm}^{-3}$):

$$\theta_{sat} = \frac{V_w}{V_t} = 1 - \frac{\rho_b}{\rho_s} \qquad \text{Eqn 5.1}$$

where V_w is the volume of water (cm^3) and V_t is the total volume (cm^3). Given that the bulk density is the ratio of the dry mass of soil, M_s (g), to the total volume (V_t), Eqn 5.1 can be rewritten in terms of V_w:

$$V_w = V_t - \frac{M_s}{\rho_s} \qquad \text{Eqn 5.2}$$

Meanwhile, a simple mass balance when the cores are saturated yields:

$$M_w = M_t - M_s \qquad \text{Eqn 5.3}$$

where M_w is the mass of water (g) and M_t is the total saturated mass (g). Now M_w can be converted to a volume by dividing by the density of water, ρ_w (g cm^{-3}), as such:

$$V_w = \frac{M_t}{\rho_w} - \frac{M_s}{\rho_w} \qquad \text{Eqn 5.4}$$

Eqn 5.4 can now be substituted into Eqn 5.2 and rearranged as follows:

$$M_s = \frac{\rho_s\left(V_t - \dfrac{M_t}{\rho_w}\right)}{1 - \dfrac{\rho_s}{\rho_w}} \qquad \text{Eqn 5.5}$$

Dividing Eqn 5.5 by V_t will yield the bulk density (ρ_b):

$$\rho_b = \frac{\rho_s\left(V_t - \dfrac{M_t}{\rho_w}\right)}{V_t\left(1 - \dfrac{\rho_s}{\rho_w}\right)} \qquad \text{Eqn 5.6}$$

Hence by using Eqn 5.6 the bulk density could be calculated based on the density of water, particle density, total volume and saturated mass, without the need to oven dry the samples. This approach gave more uniform measurements of bulk density (Fig. 5.2) that were used to calculate critical core weights in drying events. At the experiment's conclusion, all cores were oven dried and weighed to verify this approach.

Calcium and drying treatments

Table 5.1 describes the experimental design that was followed.

	Before drying	**After drying**
+ Calcium	K_{sat} of 12 cores	K_{sat} of 12 cores
- Calcium	K_{sat} of 12 cores	K_{sat} of 12 cores

Table 5.1 Experimental design for calcium and drying treatments

The 24 large cores were split into 2 groups of 12 cores. Half the cores were left in their original state, while the other half were leached with 140 mm (3 pore volumes) of 0.02 M $CaCl_2$. Leachates were analysed with ICP-AES, and additional volumes of calcium solution were passed through cores where preferential flow may have caused insufficient cation exchange. After measurement of hydraulic properties, all cores were dried to a matric potential of –1500 kPa, determined gravimetrically. Cores were left to dry on racks that exposed both ends; they were covered with a nylon sheet to minimise extreme gradients of relative humidity; they were weighed daily and sealed periodically to ensure drying rates did not exceed field conditions; and once critical weights were reached, which generally took 18 days, they were sealed and left to equilibrate for a week. Cores were gently re-wet from the base up until initial moisture contents were reached, and hydraulic measurements repeated.

Hydraulic measurements and K_{sat} calculation

Hydraulic measurements were made with disc infiltrometers that regulated air-entry tensions with hypodermic needles- using modified versions of those originally developed by Clothier and White (1981). Tensions were set to near saturation (-1 cm). A dishcloth and thin layer of fine sand covered the core surface to provide protection and hydraulic contact respectively. Petroleum jelly was smeared over core edges to prevent edge-flow. To minimise cation exchange, an isotonic solution (based on bulk soil analyses) was used as a wetting fluid for non-calcium treated cores, and 0.02M $CaCl_2$ was used for calcium-treated cores. Cumulative infiltration (I) was plotted against the square root of time ($t^{1/2}$) and fitted to a quadratic in the form of the Philip equation, i.e.

$$I = St^{1/2} + At \quad (= St^{1/2} + A(t^{1/2})^2) \qquad \text{Eqn 5.7}$$

where S is the sorptivity (mm $s^{-1/2}$) and A is the hydraulic conductivity of the transmission zone (mm s^{-1}), from which the saturated hydraulic conductivity, K_{sat} (mm d^{-1}), was calculated using the Darcy equation. For each core, K_{sat} was measured at the same water content before and after drying treatments. This allowed paired comparisons to be made between drying treatments to eliminate variability associated with hydraulic properties.

5.3 Results and discussion

Bulk soil properties

Bulk soil properties (Table 5.2) showed no significant variability or spatial trends across the sampling area. EC and SAR were low, however the irrigation water had been switched to BIL-water 2 years earlier; this had significantly lower EC and SAR than the borewater used previously. Over this time, the soil chemistry would have changed to reflect the chemistry of the new irrigation water. While there was no evidence of the saline-sodic borewater used previously, it was probable that the soil had properties similar to Table 2.1 before the switch was made.

	Clay %	Silt %	Sand %	EC dS m^{-1}	SAR	pH	ρ_s g cm^{-3}	ρ_b* g cm^{-3}
Average	57	4	39	0.15	1.5	8.02	2.759	1.46
s.e.	*1.4*	*0.5*	*1.3*	*0.01*	*0.1*	*0.06*	*0.003*	*0.01*

*determined using Eqn 5.6

Table 5.2 Bulk soil properties for the Nuriootpa subsoil. The EC, SAR and pH were determined on 1:5 soil water extracts. *s.e.* is the standard error of the mean.

Bulk density

Bulk densities obtained from small intact cores were highly variable with a non-normal distribution (Fig. 5.1). This was probably due to cores having different moisture contents, which affects the volume of soil contained due to clay shrinkage/swelling. The impact of moisture content on core bulk density was noted in Chapter 2 and in other studies at the site (Fares *et al.*, 2004).

A better, more rigorous technique for measuring bulk density was provided by Eqn 5.6. This simple method only required the measurement of a core's saturated mass, volume and particle density. The calculations were based on individual core measurements and not inferred from other cores taken at slightly different locations. Furthermore, the large cores had a greater sample volume compared to the small cores, which would minimise differences in moisture content. Hence it was not surprising that Eqn 5.6 provided a much more uniform distribution of bulk density (Fig. 5.2) in comparison to the small cores (Fig. 5.1).

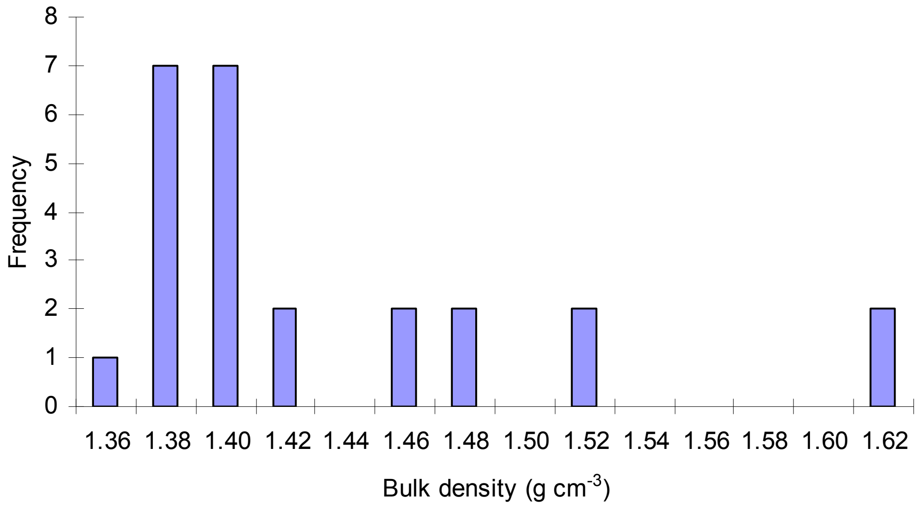

Fig. 5.1 Frequency histogram for bulk densities of small cores.

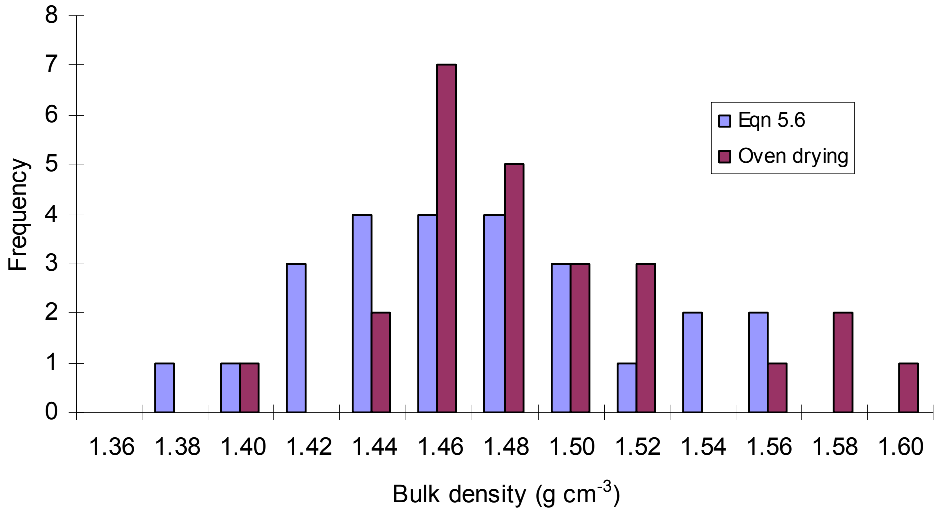

Fig. 5.2 Frequency histogram for bulk densities of large cores that were determined using Eqn 5.6 and by oven drying at the experiment's conclusion.

The approach was verified at the conclusion of the experiment when all 24 cores were oven dried and weighed. Bulk densities determined by Eqn 5.6 had a similar distribution and mean compared to those determined by oven drying (Fig. 5.2), and there was a close relationship between these two bulk density methods (Fig. 5.3). It appeared that Eqn 5.6 slightly underestimated bulk density (see 1:1 line in Fig. 5.3), probably because the cores were not completely saturated when weighed. However the average difference was minor (0.02 g/cm^3) and Eqn 5.6 provided a considerable improvement on the use of small cores.

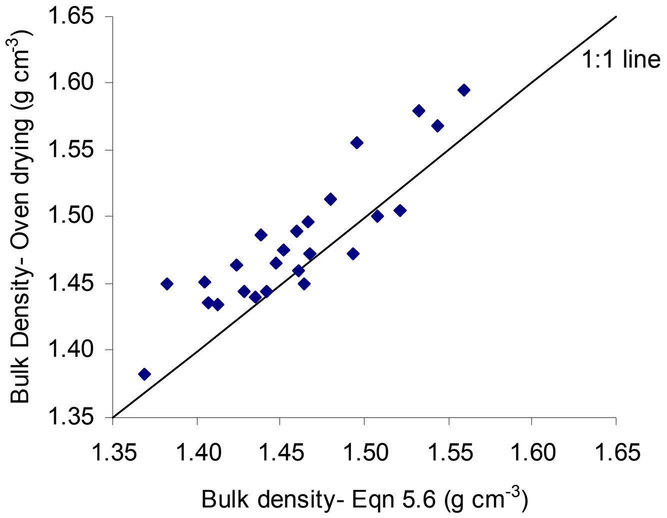

Fig. 5.3 A comparison of bulk densities (g cm^{-3}) determined by Eqn 5.6 and oven drying.

Hydraulic conductivity

Drying soil to –1500 kPa significantly increased its saturated hydraulic conductivity, K_{sat} (Fig 5.4). K_{sat} was log-normally distributed so a log transform was performed, which is commonly done for such data (e.g. Logsdon and Jaynes, 1996). Data from each core, before and after drying, was used for paired comparisons that confirmed the large increase in average K_{sat} despite variability (Table 5.3). While average K_{sat} was slightly higher for calcium treated cores, calcium addition had no significant impact on K_{sat} before or after drying.

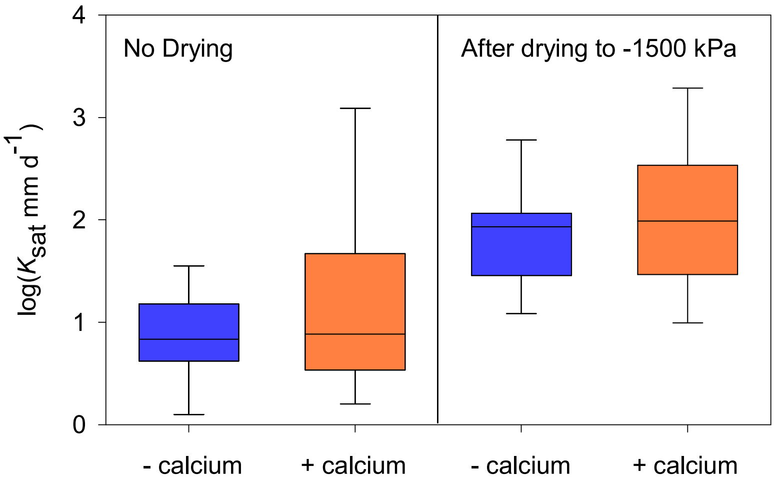

Fig. 5.4 Box plots of $\log_{10}(K_{sat})$ data, taken before and after drying to –1500 kPa on cores treated (+) and not treated (-) with calcium.

	Sample size	Mean ($mm\ d^{-1}$)	Variance	Standard deviation	Standard error of the mean
log(K_{sat} after drying) - log(K_{sat} before drying)	24	1.007	0.3326	0.5767	0.1177

95% confidence interval for mean: (0.7632, 1.250)

Test of null hypothesis that mean of K_{sat}(after drying) - K_{sat}(before drying) is equal to 0

Test statistic t = 8.55 on 23 d.f.

Probability < 0.001

Table 5.3 GENSTAT6.0 output for a paired-sample t-test, which rejected the null hypothesis that log(K_{sat} after drying) = log(K_{sat} before drying). Therefore drying significantly increased K_{sat} to the 0.1% significance level.

The large increase in K_{sat} by one order of magnitude suggested that drying soil to permanent wilting point (–1500 kPa) generated structure by creating new flow paths or enlarging existing ones. The creation of new shrinkage fractures during drying led to such changes. Large cracks were visible on the surface of some cores, but not continuous throughout the entire core length. Changes in K_{sat} reflect changes in pore structures that are continuous. Therefore it was likely that increased K_{sat} was due to the creation of a number of continuous mesopores and small macropores, rather than due to the creation of a few large, discontinuous macropores.

A second mechanism, which explained higher K_{sat} upon drying, was heaving. Significant shrinkage occurred with drying: an average volume loss of approximately 3.9%. When cores were re-wet to their initial moisture contents, most experienced heaving, whereby they swelled to volumes greater than their original dimensions because no overburden pressure was applied. The volume change was confirmed with most cores having a slightly larger saturated mass after drying and re-wetting. This translated to larger porosities and contributed, along with new shrinkage fractures, to greater K_{sat}.

Calcium treatment had no significant impact on K_{sat} (Fig. 5.4). The addition of calcium to the soil solution often improves hydraulic properties due to its ability to stabilise aggregates. Calcium encourages clay particles to flocculate by displacing sodium on the exchange phase and by increasing the electrolyte concentration of the soil solution (Oster, 1982). It was thought that calcium addition would stabilise shrinkage fractures that close when rewetted, and thereby maintain higher K_{sat} in calcium treated soil. This did not eventuate, probably because the soil had an initially low SAR (1.5) and the added calcium was not worked into the soil, which is typically done in the field when it is applied as gypsum or lime. Mechanical action is often required to remove detached particles that become lodged in conducting pores during dispersion and cannot retain their original associations through flocculation (Levy, 2000). Furthermore, the effects of time were not observed, and it is possible that differences in K_{sat} would emerge between calcium treatments if wetting and drying cycles were repeated, which are a form of mechanical action.

5.4 Conclusion

Drying soil cores taken from degraded, clayey subsoil, significantly improved their saturated hydraulic conductivity. Drying created shrinkage cracks, and rewetting caused porosities to increase through heaving. It is acknowledged that crack formation would be different under field conditions, where different compressive and tensile forces operate. However the significant shrinkage and swelling encountered here, over the plant-available range of soil moisture, indicated that structural improvement may be possible with such drying events in the field.

This laboratory trial was conducted as a preliminary assessment of the role soil drying could play in ameliorating degraded subsoil. Given the positive results, a field study within a drip-irrigated vineyard is the next logical step. Such a study could continuously monitor subsoil moisture and crack formation at different positions in the root-zone in relation to drippers, which could be moved. While many options are available to monitor soil moisture, studying crack formation at depth is more problematic. Visual observations and infiltration measurements at depth are useful, yet destructive. Cracks can be visualised in a non-invasive manner using electrical resistivity imaging (Samouelian *et al.*, 2003; Samouelian *et al.*, 2004), although this is a new technique requiring further refinement. Regardless of these difficulties, research should persist with field studies into the structural impact of soil drying events within drip-irrigated vineyards. Harnessing this mechanism may provide an attractive soil management option for growers.

Chapter 6.

General discussion and conclusions

6.1 Introduction

A review of the existing literature (Chapter 1) suggested that drip irrigation, the most common irrigation practice in Australian vineyards, exerts physical and chemical stress upon soil structure. Common soil types within Australian vineyards appeared vulnerable to these stresses and there was emerging evidence of soil structural degradation occurring. Soil structure affects soil physical properties which control soil water availability and grapevine functioning. This thesis has examined the evidence (Chapter 2) and implications (Chapters 3, 4) of soil physical degradation due to drip irrigation in vineyards. The potential of a simple, non-invasive ameliorative technique was also discussed (Chapter 5). A synthesis of these investigations is provided in this chapter.

6.2 General discussion

An assessment of soil physical properties was carried out in two South Australian vineyards (one at Nuriootpa in the Barossa Valley, the other in the McLaren Vale winegrowing region), where typical irrigation practices were applied (Chapter 2). It was revealed that irrigation led to increased soil strength in subsoils and lower permeability in topsoils. Changes in permeability occurred rapidly (< 2 years), while changes in subsoil strength took longer (2-15 years). It was unclear how irrigation caused these changes. The different rates at which permeability and soil strength declined suggested that different processes were involved. Sodicity had been identified at Nuriootpa (Clark, 2004), but other factors appeared to contribute because degradation was found even where gypsum was applied regularly (McLaren Vale) and the most degraded soil was always located under or near drippers, where the physical pressures of irrigation are greatest.

The changes in soil physical properties described in Chapter 2 appeared to be adverse for grapevine functioning, but further investigation was required to determine the significance of these changes. Hence a modelling study was conducted to assess the implications of the degradation (Chapter 3), and a pot experiment examined the role of biopores in mitigating the effect of higher soil strength on root growth (Chapter 4). Significant shrinkage/swelling was also noted in Chapter 2 for the Nuriootpa subsoil. It was hypothesised that such behaviour could potentially be harnessed to ameliorate the degradation (Chapter 5).

A modelling study gauged the severity of the degradation at Nuriootpa (Chapter 3). The literature review (Chapter 1) revealed an opportunity: recent concepts of static models (Groenevelt *et al.*, 2001) could be incorporated into the framework of dynamic simulation models to assess the impact of soil physical degradation. Hence the SWAP model was modified and the impact of higher soil strength and salinity on grapevine transpiration was studied. While the reduction in transpiration was almost entirely due to higher soil strength, the reduction was minimal (<5%) and there was evidence of water extraction by roots in all soil layers. Thus the degradation, in terms of higher soil strength and salinity, was not considered to be a significant management problem.

At Nuriootpa, roots were found growing through soil layers thought to be impenetrable (Chapter 2), so it was uncertain how increased soil strength had affected root growth. It was hypothesised that roots had avoided the physically hostile matrix by exploiting biopores or structural cracks. A pot study confirmed the importance of biopores for root growth (Chapter 4). Grapevine roots did not grow through soil when penetration resistance (*PR*) exceeded 2 MPa unless artificial biopores were present, and the presence of artificial biopores improved root growth when *PR* was only 1 MPa. Given the structural conditions in pots (biopore density and size) were similar to degraded soil at Nuriootpa, the impact of higher soil strength appeared to be mitigated by the presence of such pores. The pot study also highlighted limitations in focussing solely on *PR* as an index of rooting potential in vineyard soil.

When combined, Chapters 3 and 4 suggest the impact of higher soil strength in irrigated vineyards was minimal. High soil strength can directly affect transpiration by influencing root-shoot signalling (Masle, 2002). In effect, Chapter 3 studied this relationship and determined that transpiration in degraded soils was not significantly affected by higher soil strength. Meanwhile the impact of higher soil strength in retarding root growth was mitigated by the presence of biopores (Chapter 4). Therefore it does not appear that higher soil strength adversely affected grapevine functioning.

The significant shrinkage/swelling noted in Nuriootpa subsoil (Chapter 2), suggested drying events at distances away from the dripper could be used to generate structure within these soils. From a practical perspective, drying events could be manipulated by moving the dripper laterally or by changing irrigation frequency and intensity. The potential of this simple, non-invasive approach was investigated by applying drying and calcium treatments to large, intact cores sampled from degraded subsoil at Nuriootpa (Chapter 5). Soil drying and rewetting led to a significant increase in saturated hydraulic conductivity, which improved structure by creating shrinkage cracks, and by heaving. The positive results and the significant shrinkage/swelling encountered over the plant-available range of soil moisture indicated structural improvement may be possible with such drying events in the field.

6.3 Research opportunities

The impact of irrigation on soil physical properties should be studied on different soil types and in other irrigation districts where the irrigation to rainfall ratio is higher. Different application methods, such as microsprays and overhead sprinklers, should also be investigated, which may be more or less damaging for soil structure. Such information would aid the development of environmentally sound irrigation-practices.

Lower subsoil permeability, which can cause an increased incidence of waterlogging, requires further investigation. The trend of reduced subsoil permeability with irrigation (Fig. 2.5) needs to be confirmed. Permeability of irrigated and non-irrigated subsoils and their susceptibility to waterlogging could be evaluated by studying drainage. Drainage could be tracked over time, using an array of soil moisture sensors with logging capabilities, in the winter months when rainfall is usually higher. Such a method has several advantages over the use of permeameters: larger soil volumes are measured, thereby reducing the variability associated with macropores; temporal changes in permeability are defined; and waterlogging is measured directly, not inferred.

The effect of waterlogging or anaerobic conditions on production could be tested by comparing the application of normal water with oxygenated water to a degraded site (e.g. Bhattarai *et al.*, 2004). Direct measurement of yield or transpiration would benefit such an experiment.

Dynamic simulation models, such as the modified version of SWAP (Chapter 3), have several advantages over static models of soil water availability for assessing the impact of soil physical degradation. Such advantages include the incorporation of time, changing weather and soil moisture conditions, and the ability to link-in with field datasets such as soil moisture content. Only a small amount of additional data is required to obtain these benefits and much of this data is easily accessible; for example daily meteorological data. Continued use of dynamic models in this context is recommended. The performance of such models would be improved with more baseline data for grapevines. Pot and/or field experiments should study the direct response of grapevine transpiration to penetration resistance, soil aeration and unsaturated hydraulic conductivity. The impact of biopore density and size should be factored into these experiments. The model would also function more accurately with more precise details of root distribution (i.e. not simply rectangular) and activity, which can be measured by analysing water depletion rates (Nelson *et al.*, 2006).

Research should persist with field studies of the use of soil drying events to generate structure. There are different compressive and tensile forces in the field compared to isolated soil cores in the laboratory. Hence studying these interactions in the field is important. Crack formation at depth could be visualised with electrical resistivity imaging (Samouelian *et al.*, 2003; Samouelian *et al.*, 2004). The various ways of harnessing soil drying events should also be investigated. Moving the dripper laterally, withholding irrigation and astute management of cover crops are all ways of conceivably drying the soil to appropriate levels. Studying the response of grapevines to crack formation would then be encouraged. Root growth, shoot growth, yield and quality may all respond to the formation of new cracks, which may improve drainage and provide opportunities for root growth.

Another way of ameliorating degradation would be to increase biopore numbers. The different ways of achieving this (e.g. by cover crop management, soil fauna or artificial means) and their impact on production warrants attention.

6.4 Conclusion

The soil physical degradation identified in Chapter 2 is concerning for sustainable production in irrigated vineyards. Given the sites were representative of typical irrigation practices in the McLaren Vale and Barossa Valley regions, such degradation may be widespread. While Chapters 3 and 4 suggest the impact of higher soil strength and salinity to be minimal, these properties should be monitored because they may worsen with continuing irrigation. Furthermore, the impact of irrigation on subsoil permeability needs to be defined more accurately. An increased incidence of waterlogging could significantly restrict production, which was evident when overly wet growing seasons were modelled in Chapter 3. If subsoil permeability was defined more accurately and found to be significantly lower in irrigated soils, amelioration may be required. In this instance, the use of drying events to generate structure provides an option (Chapter 5).

Ultimately, the impact of drip irrigation on soil physical quality requires further attention. In the future, waters of marginal quality may be sourced to accommodate the heightened demand and tighter water-licensing restrictions, which are predicted across all sectors of irrigated agriculture (N.L.W.R.A., 2002; Hamilton *et al.*, 2005). Such waters may place even greater pressures on soil structure. Thus it will be imperative to monitor the physical quality of a wide range of vineyard soils to ensure sustainable production.

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Appendix A: Nuriootpa water retention data

Horizon	Suction kPa	Non-Irrigated		2 y.o. vineyard *cm to dripper*						15 y.o. vineyard *cm to dripper*					
				0		*50*		*100*		*0*		*50*		*100*	
		$\theta_{Ave.}$	*s.e.*	$\theta_{Ave.}$	*s.e.*	$\theta_{Ave.}$	*s.e.*	$\theta_{Ave.}$	*s.e.*	$\theta_{Ave.}$	*s.e.*	$\theta_{Ave.}$	*s.e.*	$\theta_{Ave.}$	*s.e.*
A1 horizon	0	0.522	0.003	0.533	0.006	0.541	0.004	0.524	0.005	0.514	0.006	0.511	0.009	0.503	0.005
	1	0.411	0.005	0.452	0.013	0.466	0.006	0.440	0.009	0.481	0.007	0.426	0.016	0.471	0.003
	3	0.342	0.003	0.371	0.010	0.388	0.006	0.365	0.009	0.371	0.006	0.361	0.008	0.378	0.004
	10	0.196	0.002	0.205	0.002	0.200	0.004	0.199	0.003	0.208	0.002	0.198	0.005	0.197	0.004
	33	0.127	0.003	0.128	0.003	0.115	0.002	0.118	0.002	0.130	0.005	0.113	0.003	0.116	0.003
	100	0.084	0.001	0.111	0.003	0.102	0.005	0.105	0.003	0.112	0.003	0.098	0.005	0.097	0.003
	300	0.066	0.002	0.073	0.001	0.066	0.001	0.066	0.001	0.071	0.001	0.063	0.001	0.065	0.001
	1500	0.037	0.000	0.039	0.001	0.037	0.000	0.038	0.000	0.042	0.000	0.038	0.001	0.039	0.000
A2 horizon	0	0.378	0.002	0.398	0.005	0.385	0.003	0.391	0.004	0.369	0.010	0.386	0.010	0.418	0.004
	1	0.293	0.005	0.303	0.003	0.300	0.006	0.293	0.004	0.275	0.007	0.281	0.010	0.296	0.003
	3	0.268	0.003	0.295	0.002	0.285	0.004	0.283	0.004	0.266	0.007	0.267	0.008	0.281	0.000
	10	0.193	0.002	0.192	0.002	0.189	0.002	0.190	0.001	0.190	0.001	0.190	0.003	0.190	0.002
	33	0.130	0.002	0.136	0.002	0.133	0.002	0.138	0.002	0.131	0.002	0.130	0.001	0.120	0.003
	100	0.104	0.002	0.111	0.001	0.111	0.003	0.113	0.002	0.106	0.003	0.099	0.001	0.093	0.005
	300	0.084	0.001	0.086	0.001	0.090	0.004	0.092	0.002	0.083	0.005	0.077	0.001	0.068	0.004
	1000	0.048	0.000	0.051	0.000	0.053	0.000	0.052	0.000	0.040	0.001	0.043	0.001	0.037	0.000
	1500	0.045	0.000	0.043	0.000	0.049	0.000	0.046	0.000	0.039	0.001	0.038	0.001	0.033	0.000
B1 horizon	0	0.445	0.002	0.434	0.012	0.458	0.007	0.457	0.003	0.435	0.004	0.419	0.011	0.438	0.004
	1	0.448	0.003	0.412	0.011	0.459	0.005	0.442	0.004	0.431	0.008	0.406	0.017	0.442	0.006
	3	0.444	0.003	0.400	0.010	0.441	0.007	0.427	0.003	0.423	0.009	0.392	0.018	0.424	0.003
	10	0.425	0.002	0.384	0.010	0.423	0.010	0.409	0.003	0.408	0.009	0.373	0.020	0.408	0.003
	33	0.408	0.002	0.370	0.009	0.409	0.011	0.394	0.003	0.394	0.010	0.356	0.021	0.393	0.004
	100	0.395	0.003	0.358	0.009	0.396	0.011	0.381	0.005	0.385	0.011	0.346	0.022	0.384	0.004
	300	0.376	0.002	0.339	0.008	0.382	0.007	0.363	0.005	0.370	0.010	0.330	0.021	0.366	0.003
	1000	0.346	0.001	0.300	0.006	0.344	0.004	0.326	0.002	0.322	0.002	0.327	0.006	0.339	0.003
	1500	0.330	0.001	0.282	0.006	0.332	0.004	0.311	0.002	0.306	0.002	0.319	0.006	0.325	0.002

* $\theta_{Ave.}$ is the average volumetric water content (g g^{-1}), *s.e.* is the standard error of the mean.

Appendix B: McLaren Vale water retention data

Horizon	Suction kPa	Non-Irrigated		16 y.o. vineyard *cm to dripper*					
				0		*50*		*100*	
		$\theta_{Ave.}$	*s.e.*	$\theta_{Ave.}$	*s.e.*	$\theta_{Ave.}$	*s.e.*	$\theta_{Ave.}$	*s.e.*
A1 horizon	0	0.450	0.008	0.506	0.005	0.512	0.005	0.497	0.007
	1	0.396	0.010	0.454	0.007	0.456	0.005	0.440	0.009
	3	0.372	0.011	0.403	0.004	0.364	0.005	0.377	0.008
	10	0.345	0.009	0.329	0.003	0.313	0.003	0.321	0.008
	33	0.341	0.009	0.286	0.003	0.279	0.002	0.285	0.007
	100	0.318	0.009	0.231	0.004	0.236	0.001	0.240	0.005
	300	0.250	0.002	0.186	0.004	0.189	0.003	0.196	0.004
	1000	0.136	0.001	0.127	0.001	0.116	0.000	0.126	0.001
	1500	0.117	0.001	0.116	0.000	0.101	0.001	0.112	0.001
B1 horizon	0	0.501	0.007	0.497	0.007	0.499	0.009	0.507	0.007
	1	0.479	0.004	0.464	0.004	0.421	0.007	0.455	0.002
	3	0.471	0.005	0.438	0.002	0.374	0.009	0.424	0.007
	10	0.457	0.004	0.418	0.002	0.357	0.009	0.398	0.009
	33	0.430	0.002	0.405	0.003	0.345	0.010	0.386	0.009
	100	0.400	0.003	0.394	0.002	0.338	0.009	0.373	0.009
	300	0.380	0.003	0.367	0.002	0.316	0.009	0.349	0.009
	1000	0.349	0.000	0.355	0.001	0.307	0.002	0.322	0.002
	1500	0.321	0.001	0.329	0.001	0.289	0.000	0.304	0.002
B2 horizon	0	0.450	0.006	0.409	0.006	0.431	0.007	0.423	0.006
	1	0.452	0.004	0.403	0.006	0.417	0.004	0.400	0.004
	3	0.444	0.004	0.392	0.005	0.405	0.005	0.387	0.003
	10	0.431	0.003	0.378	0.005	0.395	0.005	0.373	0.003
	33	0.405	0.002	0.364	0.005	0.382	0.006	0.360	0.003
	100	0.381	0.003	0.356	0.004	0.372	0.005	0.350	0.003
	300	0.360	0.003	0.338	0.004	0.353	0.006	0.333	0.004
	1000	0.337	0.003	0.342	0.002	0.341	0.002	0.326	0.003
	1500	0.315	0.003	0.317	0.003	0.322	0.000	0.310	0.002

Appendix C: Particle densities

Site	Horizon	Particle density ($g\ cm^{-3}$)
Nuriootpa	A1	2.61
	A2	2.66
	B1	2.76
McLaren Vale	A1	2.61
	B1	2.74
	B2	2.74

Appendix D: Nuriootpa micro-penetrometer data

Suction kPa	Non-Irrigated	2 y.o. vineyard *cm to dripper*			15 y.o. vineyard *cm to dripper*		
		0	*50*	*100*	*0*	*50*	*100*
	PR (MPa)	*PR* (MPa)	*PR* (MPa)	*PR* (MPa)	*PR* (MPa)	*PR* (MPa)	*PR* (MPa)
10	0.30	0.21	0.19	0.29	0.53	0.36	0.28
33	0.41	0.23	0.26	0.41	0.67	0.51	0.39
100	0.73	0.49	0.61	0.45	0.83	1.04	0.51
300	0.49	0.99	0.52	0.88	0.91	1.02	1.11
10	1.12	0.66	0.82	0.81	1.52	1.22	0.83
33	2.11	1.60	2.03	1.66	3.40	2.12	2.06
100	3.60	4.04	3.90	4.31	5.69	5.11	4.54
300	5.46	5.79	6.36	5.72	8.01	6.44	5.39
10	1.88	2.42	1.93	1.72	3.28	2.56	2.03
33	2.45	2.51	2.60	2.58	2.93	3.47	2.38
100	2.82	3.35	3.12	2.88	4.08	3.81	2.59
300	3.92	4.32	3.84	3.95	4.86	5.23	4.03

Appendix E: McLaren Vale micro-penetrometer data

Horizon	Suction kPa	Non-Irrigated	16 y.o. vineyard *cm to dripper*		
			0	*50*	*100*
		PR (MPa)	*PR* (MPa)	*PR* (MPa)	*PR* (MPa)
A1 horizon	10	1.09	0.76	0.34	0.40
	33	2.50	1.94	0.65	0.83
	100	3.43	2.75	1.12	1.77
	300	5.23	3.72	2.66	2.20
B1 horizon	10	1.95	1.54	1.12	0.82
	33	1.52	1.58	2.14	2.19
	100	2.72	2.40	2.03	1.90
	300	3.96	5.50	4.50	3.48
B2 horizon	10	2.90	2.76	3.09	1.62
	33	2.69	3.20	3.50	2.45
	100	3.16	3.95	3.63	4.10
	300	4.17	4.19	5.50	5.50