SOIL MANAGEMENT IN AN ESTABLISHED IRRIGATED VINEYARD,
ON A HARD RED DUPLEX SOIL

Submitted by

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Summary

Hard red duplex soils (HRDS) cannot sustain economically productive vineyards without careful management. An experiment was conducted at Rosbercon Vineyard, Picola from 1995 to 1998 in a vineyard block of Chardonnay on Ramsey rootstock planted in 1972. The hypotheses tested were: a) transient waterlogging decreases root growth and grapevine performance, and b) hardening of soil decreases root growth and grapevine performance.

Three soil managements were compared over 3 years, testing for improved soil physical and chemical properties, root growth and grapevine performance. Microjets irrigated the vine-line soil where randomised treatments of grown ryegrass (rye) (Autumn/Winter) or wheat straw (ws) (15 t/ha year round), gypsum application (+gyp or –gyp) (12 t/ha) and slow (slow) (5 mm/h) or fast wetting (fast) (15 mm/h) were applied.

Rye maintained soil macropores (> 30 μm diameter) 33 months after tillage, kept the soil soft (< 1 MPa) to a greater depth and had higher concentrations of grapevine roots than ws. +Gyp maintained the soil soft to a greater depth and improved water penetration to 250 mm depth compared with that of –gyp.

Soil electrical conductivity (EC) to 500 mm depth was increased by at least 36 %, approximately 15 months after application of 12 t/ha gypsum, and the effect was maintained at least 40 months after application. The increase in EC was associated with a decrease in spontaneous dispersion to 500 mm depth.

The concentration of water-soluble plus exchangeable Ca\(^{2+}\) at 0-100 mm depth, however, was decreased in ws compared with that of rye. This decrease may have been due to the formation of Ca\(^{2+}\)-organic complexes. Forty months after the application of gypsum, the exchangeable sodium percentage (ESP) was decreased by at least 26 % at a depth of at least 500 mm.
Grape yield increased markedly from year 1 (9.3 t/ha) to year 2 (34.0 t/ha), however, treatment differences in yield were not significant. Yield was stabilised in year 3 (16.7 t/ha), with no significant difference between treatments, however, the yield was greater than the commercial Chardonnay crop (5.3 t/ha) at Rosbercon Vineyard. The commercial Chardonnay crop in year 3 did receive 75% of the water applied to the experiment (4.5 ML/ha) due to water restrictions. Vegetative growth of grapevines in the experiment improved in year 2. Grapevines of rye treatments had significantly greater pruning weights (0.93 kg) than did those of ws treatments (0.81 kg). This was consistent with improved soil properties and root growth in these treatments. There were no significant differences for pruning weight between treatments in year 3, with the average weight across the experimental plot at 0.81 kg. Grapevines were in balance (yield to pruning weight ratio) in years 1 (9.0) and 3 (12.1), however, unbalanced in year 2 (23.5) due to a large increase in yields relative to pruning weights. There was no change to soil physical and chemical properties, root growth and grapevine performance in response to fast or slow treatments.

Vineyards with hard-setting and crusting surface soil can maintain soil physical and chemical properties in a condition that encourages root growth, if gypsum and a covercrop such as ryegrass are included in the management of the vine-line soil. Together with timely and appropriate volumes of irrigation, the porous surface soil will provide adequate aeration for growing roots. Thus, providing grapevines with the opportunity to achieve potential grape yield, vegetative growth and grape quality.
Statement of authorship

Except where reference is made in the text of the thesis, this thesis contains no material published elsewhere or extracted in whole or in part from a thesis by which I have qualified for or been awarded another degree or diploma.

No other person’s work has been used without due acknowledgment in the main text of the thesis.

This thesis has not been submitted for the award of any degree or diploma in any other tertiary institution.

Ashley D Wheaton

13 June 2001
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Chapter 1

Soil management in established irrigated vineyards, on hard red duplex soils - a literature review
1.1 Introduction

Hard red duplex soils (HRDS) occur in almost all grapegrowing districts in south-eastern and Western Australia (Northcote 1988). The HRDS are classified by Northcote (1979) as Dr 2 or 3, and have hard-setting surface soils. Northcote’s ‘A Factual Key for the Recognition of Australian Soils (1979)’ defines hard-setting surface soils as: ‘A horizons (surface soils) are considered hard-setting when a compact, hard and apparently apedal condition prevails on the periodic drying of the soil’. Without careful soil management, hard red duplex soils (HRDS) in Australia cannot sustain economically productive vineyards.

HRDS are by far the most agriculturally important hard-setting soils and occur in the higher rainfall districts (Mullins et al. 1990). Much of the work on these soils has been related to tillage for preparation of seed beds and the effect that crusting (section 1.2.4) and hard-setting have on the resultant annual crop. Growing winegrapes is a long term (> 20 years) investment, so eliminating or at least decreasing the rate of crusting and/or hard-setting will benefit viticulture.

HRDS have brownish surface soils ranging from loamy sand to clay loam of 100 to 500 mm thickness that overlay red-brown clay subsoils (Northcote 1988). Typical hard-setting soils have textures from loamy sand to sandy clay (Mullins et al. 1987). After tillage, the A horizons of such soils slump when wet rapidly by rain or irrigation, and then set hard when dried, often forming a crust or seal at the soil surface. Water penetrates only slowly into such a crusted surface or runs off or evaporates (Adem and Tisdall 1983). The A horizons of many Dr 2 soils can be anaerobic for longer than 24 hours after rain or irrigation and they can be hard at water potentials wetter than wilting point, inhibiting root growth. The properties of A horizons, however, are markedly modified by the nature of the B horizons that range from rock to clayey or sandy sediments (Northcote 1988). B horizons of HRDS can be slowly permeable (saturated hydraulic conductivity of $3.5 \times 10^{-7}$ m/s), poorly
drained (air-filled porosity of 0.06 cm$^3$/cm$^3$ at field capacity) and restrict most root growth (Olsson and Rose 1978; Olsson et al. 1995). These properties make the A horizon susceptible to poor aeration and decreased root growth.

As a basis to this research, limitations to growing perennial fruit crops on HRDS are discussed. The strategies to overcome these limitations, including modification of the soil to improve infiltration of water and aeration and increase root growth, are also discussed.

Unless stated otherwise, grapevines are *Vitis vinifera*, and from here on will be referred to by variety.

1.2 Characteristics of hard red duplex soils

1.2.1 Horizon depth

Soil surveys conducted on HRDS in southeastern Australia (Skene and Poutsma 1962) have identified a surface layer of soil (A horizon) varying in depth and generally a brown loam or sandy texture. Underlying the A horizon is a defined B horizon of heavier (more clay) texture. The B horizon is usually red-brown and clayey, changing in texture within a few centimetres of the A horizon.

The depth of soil horizons of HRDS, particularly the A horizon, limits the production of deciduous fruit (Cockroft and Wallbrink 1966). An A horizon less than 150 mm deep limits tree size. When the depth of the A horizon is around 250 mm or more, soil depth is not as important for tree growth as the mechanical composition of the A horizon.

In Stellenbosch, South Africa, Pinot Noir grapevines were grown in soil modified to depths of 200 mm, 400 mm, 600 mm, 800 mm and 1200 mm (Myburgh et al. 1996). For irrigated grapevines, vegetative growth and physiological activities responded positively to an increase in soil depth. Grapevines grown in soil modified to depths of 800 mm and 1200 mm had vegetative growth at the end of the second season equal to that of grapevines grown in 400 mm deep soil at the end of the third season.
1.2.2 Density and compaction

Hard-setting of cultivated soil usually involves slumping, which is a process of compaction (i.e. increase in bulk density) that occurs without the application of an external load (Mullins et al. 1990). Compaction of the A horizon may be an effect of an externally applied load, or the result of wetting structurally weak or unstable soil, or both.

Bulk density of soil is a quantitative measure of compaction (Blake and Hartge 1986), however, penetrometer resistance better relates the soil condition to root growth. There are no published values for penetrometer resistance that restrict root growth of perennial fruit crops, however, the relationship between bulk density and root growth of grapevines has been explored. At Nuriootpa, South Australia, one-year-old Chardonnay grapevines on Teleki rootstock were planted on a yellow duplex soil (dark brown sandy loam overlying clayey sand-clay loam brownish yellow mottled subsoil) of either raised beds or flat beds (Eastham et al. 1996). Root length of grapevines was greater when grown on raised beds of bulk density 1.25 g/cm$^3$ than on flat beds of bulk density 1.50 g/cm$^3$.

Hard red duplex soils (Dr 2.33) in the Goulburn Valley of Victoria, have been reported to have bulk densities of the A horizon between 1.4 and 1.6 g/cm$^3$ after 9 years under the Tatura system of soil management (Tisdall et al. 1984). Similarly, Emerson et al. (1994) sampled the surface soil (0 to 50 mm) of 17 orchards in the Goulburn Valley, Victoria and found bulk densities between 0.92 and 1.74 g/cm$^3$. The bulk densities were inversely related to percentage carbon in the soil. These findings suggest that the persistence of a soil at a bulk density favourable for root growth in orchards and vineyards depend on inputs of, and rate of breakdown of, organic matter.
1.2.3 Infiltration and aeration

The infiltration of water and diffusion of gases into soil are influenced by the soil as well as by the supply from the atmosphere and irrigation. The size and number of pores within the soil, particularly those continuous to the soil surface, play a major role in infiltration and diffusion.

Emerson et al. (1994) suggested that 0.10 cm$^3$/cm$^3$ of the soil filled with air was adequate for the growth of roots of peach trees (*Prunus persica*). High root concentrations (the length of root per volume of soil, known as root length density, RLD; 5.91 cm/cm$^3$ at 102 to 165 mm depth) in the tree-line of peach orchards on typical Goulburn Valley soils (HRDS) (Richards and Cockroft 1974) were attributed to the open stable structure (0.20 to 0.30 cm$^3$/cm$^3$ air-filled porosity at field capacity) of the untilled soil. Tisdall et al. (1984) found the surface soil (0 to 370 mm) in the tree-line of a peach orchard after 6 years under the Tatura system of soil management (Cockroft and Tisdall 1978), provided an air-filled porosity of 0.09 cm$^3$/cm$^3$ within 48 h of irrigation. The subsoil however, had an air-filled porosity of 0.07 to 0.09 cm$^3$/cm$^3$, but still provided sufficient oxygen for root and soil respiration. The stable surface soil at this site allowed 50 mm of water to infiltrate in 6 min, compared with that of average commercial orchards in the Goulburn Valley of 83 min.

Sultana grapevines grown in anaerobic soil (i.e. waterlogged) for as little as 3 days every 2 weeks for 8 weeks had decreased shoot growth compared with grapevines grown in aerobic soil (Stevens and Prior 1994). Similarly, 8 week old grapevines (cv. Sultana, Palomino and Doradillo) each consisting of a single shoot, waterlogged for 7 days, had deceased shoot length compared with that of grapevines grown in drained soil (West and Taylor 1984). Root dry weight, relative to total dry weight of the Sultana grapevine, was decreased from 25 % to 18 % by the 7 days of waterlogging.

Loveday (1976) found that 3 years after the application and incorporation by tillage of 12.5 t/ha of gypsum to a HRDS (Dr 2.33), infiltration of water increased 2 to 3-fold
compared with no gypsum and no tillage. Loveday (1981) emphasised the benefits of
gypsum on the infiltration of water into other HRDS (Stace et al. 1968) in Australia.
More recently, Baldock et al. (1994) found annual additions of gypsum (3.4 t/ha) and
wheat (*Triticum aestivum*) straw (10 t/ha) for 4 years to a Red-brown Earth (Dr 2.23,
Urrbrae fine sandy loam), increased the saturated hydraulic conductivity ($K_{sat}$) of the soil
surface. Individually, applications of gypsum and wheat straw increased $K_{sat}$, however,
applied together synergy resulted. However, at 200 mm depth, $K_{sat}$ increased with
gypsum and decreased with wheat straw application. This was explained by the
production of soluble organic anions from the decomposition of wheat straw, which were
leached and aided the dispersion of clay. Clay that dispersed easily from HRDS
contained a higher proportion of amino acids or proteins than did clay that did not
disperse, suggesting these materials acted as dispersants (Nelson et al. 1999).

The electrolyte concentration in applied water and the severity of soil sodicity impact
on infiltration rate and crust formation. Agassi et al. (1981) used a rainfall simulator to
quantify changes in infiltration rate with changes in electrolyte concentration of applied
water and exchangeable sodium percentage (ESP) of the soil. When soil ESP increased
from 1 to 5 % and irrigation was with distilled water, dispersion became apparent and the
infiltration rate dropped from 8 to 2 mm/h. In soils with an ESP of 5 %, an increase in the
electrolyte concentration of the applied water to 5 dS/m decreased the dispersion and
stabilised the infiltration rate at 8 mm/h. The infiltration rate was not as great (< 8 mm/h)
in soils with moderate-to-high ESP (13 to 26) when irrigated with water of electrolyte
concentration between 0.1 and 5.6 dS/m.

Shainberg et al. (1981), in a study similar to that of Agassi et al. (1981) related the salt
concentration of the soil solution to ESP of soil in the range 0 to 30 %, and measured the
resultant $K_{sat}$ and clay dispersion. When the concentration of salt in the soil solution was
1.8 dS/m, $K_{sat}$ decreased and clay dispersed only if ESP of the soil exceeded 12 %.
Conversely, a salt concentration of 10.8 dS/m in the soil solution led to clay dispersion
and decreased $K_{\text{sat}}$ at ESP values as low as 1 or 2 %. The findings of Shainberg et al. (1981) and Agassi et al. (1981), emphasise that even in soils with low ESP that are leached periodically with rainwater, $K_{\text{sat}}$ can be substantially decreased and a surface crust form.

The infiltration rate of 2.5 mm/h of sandy loam in a mature navel orange ($Citrus sinensis$) orchard was doubled when gypsum was applied weekly to the soil surface (Peacock et al. 1989). Calcium ($Ca^{2+}$) added to the irrigation water more than doubled infiltration rates compared with that of untreated water (0.1 dS/m).

1.2.4 Hard-setting and crusting

Hard-setting soils and soils that form crusts are both the result of the mobilisation and deposition of clay colloids, but the processes are not necessarily the same. The 3 factors making surface soil susceptible to crusting are: (a) the physical impact of raindrops; (b) the low electrolyte concentration of the soil solution due to leaching by rainwater; and (c) the absence of sand that slows clay dispersion and movement (Agassi et al. 1981). A hard-setting soil is also affected by these 3 factors, but in addition, the A horizon is so unstable that wetting causes disaggregation and fine material is deposited deeper in the profile (Mullins et al. 1990). A soil can weaken or mellow if wet quickly (Grant and Dexter 1990). Minimal mellowing occurs if soil is wet at suction greater than a critical mellowing suction (McKenzie and Dexter 1985).

A bed of soil aggregates that are water-stable, and have not been trafficked, gradually disaggregate and soil hardness increases during cycles of wetting and drying (Cockroft and Olsson 2000; Ghezzehi and Or 2000). This phenomenon, where aggregates are welded together, has been termed coalescence. Ghezzehi and Or (2000) suggested aggregate strength and plastic viscosity of aggregates contributed to coalescence. Lanyon et al. (2000), showed that slow irrigation (2 mm/h) decreased the rate of coalescence
compared with that with faster irrigation (5 mm/h). A possible mechanism for the effect of irrigation rate is a decrease in aggregate strength with an increase in irrigation rate.

Organic matter on the soil surface protects it from physical impact by water. The products of decomposition of organic matter help to stabilise surface aggregates to water (Tisdall and Oades 1982), although roots and vesicular-arbuscular mycorrhizal hyphae enhance the effect (Tisdall and Oades 1979; Andrade et al. 1998).

By incorporating 5 or 10 t/ha of wheat straw into the top 100 mm of an Urrbrae-type Red-brown Earth (Dr 2.23), Baldock et al. (1994) found decreased bulk density (1.18 to 1.06 g/cm³) and increased water-stable aggregates > 0.25 mm diameter after 4 years. Similarly, Emerson et al. (1994) identified an inverse relationship between bulk density and organic carbon of a HRDS (Dr 2.33) (section 1.2.2). Organic matter of 1.9 % did not prevent a surface crust in a silty clay loam after tillage and exposure of the soil surface to water (Pagliai 1983).

By decreasing the concentration of exchangeable sodium in the soil and increasing the electrolyte concentration, gypsum can decrease the dispersion of clay and minimise hard-setting and crusting of the surface soil (section 1.2.3) (Agassi et al. 1981; Shainberg et al. 1981; Rengasamy et al. 1984a; Baldock et al. 1994).

1.2.5 Soil strength

The strength of soil is a measure of resistance to deformation (Leeper and Uren 1993). An explanation for the development and increase in soil strength of a freshly cultivated bed of dry aggregates that exhibit hard-setting is outlined by Mullins et al. (1987). Their explanation of the increase in strength is as follows:

(a) wetting of aggregates mobilises silt and clay. This may occur through slaking and/or dispersion,
(b) during the early stages of drying, mobilised silt and clay move with the retreating water menisci to settle at contact points between sand grains or any remaining aggregates, often forming annular bridges between this larger stable material, and (c) as the drying continues, and despite air entering the soil, the mobilised material remains wet until large suctions of soil water are reached (values for kaolin reported as approaching 1 MPa). The contribution of suctions of soil water to effective stress provides a major component of the strength.

When the strength of soil is determined, the soil water content should be measured at the same time. There are many methods to determine soil strength (Marshall and Holmes 1988), including: penetrometer resistance, indirect measurement of tensile strength, direct shear, vane, triaxial compression, unconfined compression, and rupture. Penetrometer resistance is discussed here, as it is most relevant to root growth and thus to this thesis.

Haynes (1981) investigated the effects of grass retention, and the removal of grass (from October till mid-summer) by herbicide or by tillage on soil strength in a New Zealand apple (Malus domestica cv. Golden Delicious) orchard. In soil close to field capacity, penetration resistance (hand-held penetrometer) of the surface soil decreased in the order: herbicide > grass retention > tillage. The eradication of grass by the herbicide left the soil surface bare and exposed to rain drop impact and a surface crust developed. Haynes (1981) also found a positive correlation between penetrometer resistance and bulk density of the surface 200 mm for all treatments. Similarly, Obi (1999) found a decrease in penetrometer resistance (50 %) with grass covercrops compared with that of bare soil.

Emerson et al. (1994) determined penetration resistance and the Non Limiting Water Range (NLWR) of 9 surface soils (Dr 2.33) from orchards in the Goulburn Valley. The NLWR was defined by Letey (1985), as the difference between the maximum gravimetric water content at which aeration was adequate for root growth (10 % air-filled pore space, \( \omega_a \)), and the gravimetric water content at which the soil had become too hard for root growth (penetrometer resistance of 2.5 MPa, \( \omega_p \)). Only 2 of the 9 surface soils in the
study by Emerson et al. (1994) had a positive NLWR (the greatest approx. 15 to 35 g/100g).

da Silva et al. (1994) expanded the concept of NLWR to Least Limiting Water Range (LLWR) by identifying the limiting soil water suctions corresponding to \( \omega_a \) and \( \omega_p \) for different soil types. The LLWR is determined from water contents: field capacity (10 kPa suction), air-filled porosity (10 %), soil resistance (2.0 MPa), and permanent wilting point (1500 kPa suction). The LLWR has limits that are less rigid than those defined for the NLWR and will be used in this paper to describe any reference to either LLWR or NLWR.

Tisdall et al. 1984 working in the Goulburn Valley, at the then Irrigation Research Institute, Tatura studied the change in penetration resistance with time of a soil classified as Dr 2.33 (Northcote 1981). A soil management experiment testing the Tatura system of soil management as defined by Cockroft and Tisdall (1978) began in 1973, and measurements of penetrometer resistance were taken in 1976, 79 and 82. The penetrometer resistance at field capacity, of intact cores (76 mm diameter) taken 1m from the butts of 4 different peach trees is displayed in Fig. 1.1. The penetrometer resistance between 1979 and 1982 increased at all depths, although not significantly at 600 mm. This study suggests that the annual growth of roots of peach trees encountered increasingly hard soil, limiting their access to water and nutrients.
1.2.6 Chemical properties

The pH of HRDS typically increases down the profile. The A horizon (0 to 150 mm) is usually acidic to neutral (5.5 to 7.0) and the B horizon (150 to 700 mm) neutral to alkaline (7.0 to 8.5) (Skene and Freedman 1944; Loveday 1976; Rengasamy et al. 1984a). The increased pH with depth is associated with a general increase in electrical conductivity (EC), clay content and cation concentration (soluble and exchangeable) (Table 1.1).
Table 1.1. Selected chemical properties of 3 hard red duplex soils

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Horizon</th>
<th>pH</th>
<th>EC</th>
<th>TCC</th>
<th>CEC</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>(dS/m)</td>
<td>(me/l)</td>
<td>(cmolc/kg)</td>
<td>(g/100g)</td>
</tr>
<tr>
<td>Lemnos loam</td>
<td>A (0-150 mm)</td>
<td>5.7</td>
<td>0.081</td>
<td>0.72</td>
<td>6.9</td>
<td>28.5</td>
</tr>
<tr>
<td>(Dr 2.13)</td>
<td>B (150-450 mm)</td>
<td>6.2</td>
<td>0.161</td>
<td>1.73</td>
<td>14.2</td>
<td>55.8</td>
</tr>
<tr>
<td>Shepparton fine sandy loam</td>
<td>A (0-150 mm)</td>
<td>6.0</td>
<td>0.071</td>
<td>0.81</td>
<td>9.0</td>
<td>21.5</td>
</tr>
<tr>
<td>Marah clay</td>
<td>A (0-100 mm)</td>
<td>7.1</td>
<td>1.4</td>
<td>-</td>
<td>25.0</td>
<td>38.0</td>
</tr>
<tr>
<td>loam (Dr 2.33)</td>
<td>B (100-300 mm)</td>
<td>7.5</td>
<td>2.7</td>
<td>-</td>
<td>32.9</td>
<td>59.5</td>
</tr>
</tbody>
</table>


The ion-exchange complex of the clay B horizons is dominated by the cations in the order: Ca\(^{2+}\) >Mg\(^{2+}\) >K\(^+\) >Na\(^+\) (Table 1.2). Sodium ions have a greater alkaline producing ability than do the other cations (Leeper and Uren 1993).
Table 1.2. The proportion of exchangeable cations of 3 hard red duplex soils

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Horizon</th>
<th>CEC $^A$ (cmol$_c$/kg)</th>
<th>Exch. Ca (%)</th>
<th>Exch. Mg (%)</th>
<th>Exch. K (%)</th>
<th>Exch. Na (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lemnos loam</td>
<td>A (0-150 mm)</td>
<td>6.9</td>
<td>49</td>
<td>33</td>
<td>15</td>
<td>3</td>
</tr>
<tr>
<td>(Dr 2.13) $^B$</td>
<td>B (150-450 mm)</td>
<td>14.2</td>
<td>30</td>
<td>51</td>
<td>7</td>
<td>12</td>
</tr>
<tr>
<td>Shepparton fine sandy loam</td>
<td>A (0-150 mm)</td>
<td>9.0</td>
<td>57</td>
<td>24</td>
<td>18</td>
<td>1</td>
</tr>
<tr>
<td>(Dr 2.33) $^B$</td>
<td>B (150-450 mm)</td>
<td>17.3</td>
<td>43</td>
<td>41</td>
<td>9</td>
<td>7</td>
</tr>
<tr>
<td>Marah clay loam</td>
<td>A (0-100 mm)</td>
<td>25.0</td>
<td>34</td>
<td>35</td>
<td>24</td>
<td>7</td>
</tr>
<tr>
<td>(Dr 2.33) $^C$</td>
<td>B (100-300 mm)</td>
<td>32.9</td>
<td>42</td>
<td>37</td>
<td>9</td>
<td>12</td>
</tr>
</tbody>
</table>


The EC, a measure of soluble salts, can be determined on a saturated extract (EC$_{se}$) or soil suspension extract (EC$_{1:5}$) (Beatty and Loveday 1974). The more time consuming method of EC$_{se}$ is preferred and is related to the field water range of soils that vary widely in texture. However, experiments have determined a relationship between EC$_{se}$ and EC$_{1:5}$ for soils similar in texture (Shaw 1999).

The EC$_{se}$ of HRDS can inhibit grapevine growth at concentrations greater than 2 dS/m for own rooted grapevines and greater than 4 dS/m for salt tolerant rootstocks (Robinson 1992). Maas and Hoffman (1977) reviewed the salt tolerance of the grapevine, and concluded that the threshold concentration of soil salinity at which growth decreases was 1.5 dS/m (EC$_{se}$). A per unit increase in EC$_{se}$ beyond this concentration, decreases growth by 9.6 %. Generally, it is the chloride ion that becomes toxic to the grapevine and the sodium ion becomes detrimental to soil structure (Northcote 1988).
Clays dominated by Na\(^+\) on their exchange complex, disperse when exposed to water except when salt concentrations in the soil pores are high enough that the electrolyte effect causes coagulation to occur (section 1.2.3). An exchangeable sodium percentage (ESP) of 6 or more for Australian soils indicates it is sodic, and strongly sodic beyond an ESP of 15 (Northcote 1988). All HRDS in Table 1.2, as displayed in the Exch Na % column, have sodic B horizons.

Spontaneous dispersion of HRDS has been correlated with sodium concentration (sodium absorption ratio, SAR) (Rengasamy et al. 1984a). The soils used by Rengasamy et al. (1984a) with a SAR above 3 dispersed in the absence of mechanical stress.

HRDS in their virgin state are moderately fertile, but most have low concentrations of phosphorus (P) (< 0.04 g/100 g Total P) and nitrogen (N) (< 0.1 g/100 g Total N), while concentrations of potassium (K) (> 0.5 me/100 g exch. K) are moderate (Northcote 1988). Butler et al. (1942) suggested that phosphorus and nitrogen fertiliser should be applied for the economic production of wheat and oats (*Avena sativa*) on the soils of the County Moira (Numurkah, Victoria to south and Murray River to north). The vineyard referred to later in the thesis is located in County Moira.

1.3 Soil water

1.3.1 Soil water content

Knowing the soil water content and soil water suction is critical for decisions on tillage, irrigation scheduling and duration and keeping the soil within the LLWR so that it is neither waterlogged nor too hard for root growth. Table 1.3 presents 3 examples of the field capacity and permanent wilting point for HRDS.
Table 1.3. Field capacity and permanent wilting point of 3 hard red duplex soils

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Horizon</th>
<th>Wilting point (g/100g)</th>
<th>Field capacity (g/100g)</th>
<th>Bulk density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lemnos loam (Dr 2.13) A</td>
<td>A (20-80 mm)</td>
<td>9.8 D</td>
<td>28.5</td>
<td>1.4</td>
</tr>
<tr>
<td>(Dr 2.13) A</td>
<td>B (270-330 mm)</td>
<td>10.9 D</td>
<td>23.4</td>
<td>1.6</td>
</tr>
<tr>
<td>Trangie Cowal Pedoderm (Dr 2.33) B</td>
<td>A (0-200 mm)</td>
<td>6.0</td>
<td>20.0</td>
<td>1.4</td>
</tr>
<tr>
<td>Pedoderm (Dr 2.33) B</td>
<td>B (300-600 mm)</td>
<td>12.0</td>
<td>26.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Shepparton fine sandy loam (Dr 2.33) C</td>
<td>A (0-100 mm)</td>
<td>12.0</td>
<td>31.0</td>
<td>1.3</td>
</tr>
<tr>
<td>(Dr 2.33) C</td>
<td>B (300-460 mm)</td>
<td>26.0</td>
<td>38.0</td>
<td>1.5</td>
</tr>
</tbody>
</table>

A Data from Taylor and Olsson (1987). B Data from Hall et al. (1994). C Data from Stace et al. (1968). D Data from Skene and Poutsma (1962).

To identify the NLWR (section 1.2.5) Emerson et al. (1994) determined the gravimetric water content (ω) when 0.10 cm³/cm³ of the soil volume was air-filled and when the penetration resistance of the soil reached 2.5 MPa. The ω at 0.10 cm³/cm³ air-filled pore space and at a penetration resistance of 2.5 MPa varied from 15 to 27 g/100g and 14 to 44 g/100g respectively. The large variation in ω indicates the difference in structure of the surface soils and was a result of the bulk density and concentration of carbon.

1.3.2 Soil water suction

Williams et al. (1983) identified that the presence or absence of pedality, particle size composition, grade of structure, organic matter and field texture all influenced the form
and position of the water characteristic curve from 78 different soil types. An example of water characteristic curves for sand and loam, including the curve for the surface soil of a HRDS (Lemnos loam, Dr 2.33, from Finlay 1993), are presented in Fig. 1.2.

![Graph showing water content vs. soil water suction for sand, loam, and HRDS](image)

**Fig. 1.2.** The relationship between water content and suction (water characteristic curve) for sand and loam (Marshall and Holmes 1988), and the surface soil (20 to 84 mm) of a hard red duplex soil (HRDS) (Lemnos loam, Dr 2.33, from Finlay 1993). The curve of the HRDS assumes a bulk density of 1.0 g/cm³ for gravimetric to volumetric conversion.

Critical values of soil water suction have been identified for maximum root activity. Cockroft and Tisdall (1978) suggested frequent irrigations to maintain soil water suction of 30 kPa or less were appropriate for maximum root growth of peaches. Hardie and Martin (1990) proposed water management that balances grape yield and quality for winegrapes, by maximising bud fruitfulness and berry set while restricting berry size and vegetative growth. They proposed that different soil water suction during particular phases of grapevine growth could achieve optimal yield and quality of winegrapes.
Replicated experiments to test the validity of the water management proposed by Hardie and Martin (1990) have not been conducted, therefore, Table 1.4 is only a guide.

**Table 1.4. Water management for optimum yield and quality of winegrapes (from Hardie and Martin 1990)**

<table>
<thead>
<tr>
<th>Development phase</th>
<th>Soil water status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Budburst - flowering</td>
<td>Spring rains are predominant. Maintain soil water suction less than 30 kPa. Avoid waterlogging.</td>
</tr>
<tr>
<td>2. Flowering - fruit set</td>
<td>Maintain soil water suction at 10 kPa throughout the rootzone.</td>
</tr>
<tr>
<td>3. Fruit set - veraison</td>
<td>Dry rootzone to soil water suction of 80 kPa. If irrigation is necessary, wet no more than 25 % of the rootzone to 10 kPa.</td>
</tr>
<tr>
<td>4. Veraison - harvest</td>
<td>If water is available, maintain soil water suction at 80 kPa. If water is scarce, dry rootzone to a maximum of 200 kPa.</td>
</tr>
<tr>
<td>5. Harvest - leaf fall</td>
<td>Avoid soil water suctions greater than 200 kPa.</td>
</tr>
</tbody>
</table>

The above strategy maintains soil water suction between 10 and 200 kPa, which is within the limits of soil water suction for the LLWR (section 1.2.5). However, the LLWR could be exceeded if the air-filled porosity at 30 kPa were less than 0.10 cm³/cm³ or the penetration resistance at 200 kPa suction exceeded 2.5 MPa.

A range for soil water suction has been identified for water that is 'readily available' (10 to 60 kPa) and 'deficit available' (60 to 200 kPa) to grapevine roots. These ranges have been identified by work on regulated deficit irrigation (RDI) (Goodwin and Jerie 1992). RDI aims to decrease vegetative growth (shading of fruit), decrease berry size
(increase skin to juice ratio) with minimal effect on yield, while decreasing the volume of water applied to the grapevine.

1.3.3 Soil water flow

Approximately 57% of water applied to the soil evaporates or transpires, often through stomata on leaves (Clothier and Green 1997), the remaining water is lost from the soil as drainage or run-off. Of the water lost to the atmosphere (evaporation and transpiration per day) in an irrigated peach orchard, Olsson and Rose (1988) determined that 21% was evaporated from the soil surface during days 1 to 3 after irrigation. This value decreased to 13% during days 14 to 18 after irrigation.

The work above indicates that water available for uptake, after evaporation, drainage and surface run-off can be as low as 36% of the total water applied. This percentage varies considerably with temperature, slope, soil texture and structure, rooting characteristics and the rate and method of water application.

Duplex soils with heavy clay subsoils that are slowly permeable to water develop perched water tables. The positive pressure created by deep and extensive perched water tables increases drainage below the rootzone of most crops. Losses as high as 1.7 mm/day in yellow duplex soils of the wheat belt of Western Australia have been recorded (Eastham et al. 2000).

The Tatura system of soil management was implemented to overcome low hydraulic conductivities in subsoils of HRDS that result from high clay concentrations and low Ca:Mg ratios (Cockroft and Tisdall 1978). An increase in earthworm numbers from 150 to 2000 per m² in treated plots was associated with a 4-fold increase in macropores (empty at 4 kPa suction) (Tisdall 1978). Peach yields in the treated plots increased from the commercial yield of 18 to 75 t/ha.
Gypsum–enriched slots have been used on a HRDS to improve water infiltration and storage. Slots 0.15 m in diameter and 0.4 m deep, increased water infiltration 5-fold and water storage by 30 mm/m in a sodic Red-brown Earth (Jayawardane and Blackwell 1985).

1.4 Aspects of grapevine root physiology

1.4.1 Rootzone form

The grapevine root system has been reviewed by Richards (1983), Smart and Coombe (1983) and Van Zyl (1988), all of whom refer to the intensive study of the Sultana by Barnard (1932). Barnard (1932) identified main permanent roots, smaller permanent roots and feeder roots. The main roots originated from the base of the trunk at a depth of 300 to 350 mm, spreading radially and sloping downwards. These roots were up to 3.6 m in length and were found to 500 mm depth. The main permanent roots in this case were restricted by a heavy textured B horizon at 500 mm. Barnard (1932) did not find an increase in the length of main permanent roots system after the second or third year from planting.

Smaller permanent roots originating from the main root tended to grow towards the surface, however, some developed below the main system to 750 mm depth. Occasionally, ‘plunging’ roots were observed at depths of 1.2 m. The smaller permanent roots grew shortly after budburst with a peak at approximately 4 weeks after budburst. By week 5 to 6 after budburst, the small permanent roots were 180 to 200 mm in length, and covered by feeder roots less than 30 mm long.

Richards (1983) described the grapevine root system as highly divided and consisting of several classes of roots, most similar to that described by Barnard (1932). Richards (1983) suggested fibrous roots account for the majority of the root mass and are generally
found within the top 200 to 500 mm. The root structure depends on grapevine cultivar, rootstock, the soil type and physical condition, and age of the plant.

The concentration of roots per soil volume is important for nutrient and water acquisition. Freeman (1983) indirectly measured root length density (RLD) from root intercepts in a root observation laboratory (Freeman and Smart 1976). He found that the RLD of the Shiraz grapevines grown in the Southern Hemisphere increased from 0.74 to 1.25 cm/cm³ during the period October 14 1983 to November 22 1983. Six-year-old Chardonnay grapevines averaged a RLD of 0.40 cm/cm³ at 100 to 400 mm depth (Blackwell et al. 1988). Hughes et al. (1995) found that the mean RLD of Chardonnay and Cabernet Franc grapevines over 1 m depth was 0.09 cm/cm³. This was one-tenth the RLD of kiwifruit vines (Actinidia deliciosa) and peach at similar depths. Colombard grapevines irrigated by microjets had a RLD of 0.37 cm/cm³ in the top 200 mm of soil, declining to 0.23 cm/cm³ at 400 to 600 mm depth (Stevens and Douglas 1994). The maximum RLD for Thompson seedless grapevines was 0.04 cm/cm³ and 0.07 to 0.17 cm/cm³ grown in coarse (silt + clay < 20 %) and fine soils (silt + clay > 30 %) respectively (Nagarajah 1987).

The reviews of the root system of the grapevine mentioned here, all stress that soil structure (including porosity) is the most important factor for establishing the form of the root system.

1.4.2 Water and nutrient absorption

The absorption of water and nutrients by roots depends on many factors such as density and distribution of roots, hydraulic conductivity and water holding capacity of the soil and the evaporative demand of the grapevine. The uptake by parts of the root system, mycorrhizae, root hairs and suberised roots will be discussed here.
The main absorption zone of the grapevine root is white, can extend up to 100 mm from the root tip, and is covered with root hairs (Mullins et al. 1992). The absorption zone becomes brown and suberised (similar to bark formation in the shoot or cane) with age.

The absorptive ability of suberised versus unsuberised roots (section 1.4.3) is still somewhat unclear, however, both are important. Barnard's (1932) observation in the Sultana that roots started growing 5 weeks after the rise of sap, and 3 weeks after budburst, suggests that suberised roots conduct at least water. Other work suggests root growth begins around 10 weeks after budburst, when shoot growth is about half complete (Freeman and Smart 1976). This observation suggests that suberised roots supply water during flowering, when water stress can decrease berry numbers.

Grapevines infected with vesicular-arbuscular mycorrhizal fungi, compared with grapevines not infected, have shown enhanced growth and increased concentrations of phosphorus in their shoots when grown in soils with low concentrations of phosphorus (Possingham and Groot Obbink 1971). Forty-five vineyard soils across northern Greece displayed Olsen P concentrations in the range 6.0 to 60.0 mg/kg (Karagiannidis and Nikolaou 1999). The percentage infection of grapevine roots with mycorrhizal fungi ranged from 10 to 90 % and was strongly inversely related to Olsen P concentration of the soil. Mycorrhizal plants may also tolerate greater water stress than do non-mycorrhizal plants.

Root hairs, once thought to substantially increase the absorptive surface area and effective rooting diameter, have been suggested as more beneficial for the exudates they produce. Such exudates may assist uptake either by mobilising nutrients around the root apex or by encouraging the activity of organisms in the rhizosphere (Topp and Watt 1995).
1.4.3 Suberisation and root mortality

During suberisation, suberin is laid down inside cell walls in 3 types of tissue in the grapevine: the endodermis and hypodermis of roots during primary development and the external layers of the periderm in woody roots (Richards 1983). Suberisation is most extensive in the grapevine during mid-summer when temperatures are high and water content of soil is low. In dry soil, some roots can become suberised and brown to their tips. When soils become more favourable for growth, the roots may continue to grow from the tip or they may produce new lateral roots. In the root observation laboratory described by Freeman and Smart (1976), suberisation was more rapid during the growing season than during winter. They also observed some roots remained unsuberised over winter and that the number of intersections by roots began to decrease 15 weeks after budburst, indicating that the rate of suberisation was greater than the rate of new growth (Freeman and Smart 1976).

Barnard (1932) observed that feeder roots produced abundant root hairs early in the growing season, but by the end of November most roots were mature and no longer supported functional root hairs. The death of fine roots is a natural process in the grapevine, and many die within weeks of emerging (Reynolds 1975). Where soils are favourable, new lateral roots continually replace those that die. Richards (1983) suggested that the ephemeral roots of grapevines might be a principal source of organic matter, thus regulating microbial activity.
1.5 Grapevine yield, balance and berry chemistry

1.5.1 Grapevine yield and balance

Grapevine yield increases as nodes per grapevine, shoots per node, bunches per shoot, bunch weight, berries per bunch, berry weight, flowers per bunch and berries per flower increase. May (2000) measured the yield per grapevine at harvest of spur pruned Chardonnay at Piccadilly and Willunga, South Australian, as 4.23 and 13.10 kg/vine respectively. The corresponding yield of hedge pruned Chardonnay was 6.71 and 15.71 kg/vine respectively. These data demonstrate the variation in yield between regions and between canopy types within a region.

May (2000) also measured mean number of bunches per grapevine at harvest over 2 seasons for spur pruned Chardonnay grapevines at Piccadilly and Willunga as 49 and 85 respectively. Spur pruned Shiraz grapevines at Waikerie, South Australia produced 85 bunches per grapevine at harvest 1997 (Dry 2000). Coombe (1988) has published a range 29 to 286, median 143 for the number of bunches per grapevine in commercial vineyards.

A shoot that carries at least 1 bunch is termed a fruitful shoot (Antcliff and Webster 1955). A primary bud that contains at least 1 inflorescence primordia is termed a fruitful bud (Antcliff and Webster 1955). Shoot fruitfulness determined as mean bunch number per shoot is often used as an index of bud fruitfulness (Dry 2000), this convention will be followed in this thesis. Bunch number per shoot is easily measured shortly after flowering as part of a Merbein Bunch Count (MBC) (Antcliff et al. 1972) (section 2.6.3).

Freeman et al. (1979) recorded an average of 1.6 bunches per fruitful shoot over 5 years from spur pruned Shiraz grapevines in Griffith, New South Wales. Similarly, Dry (2000) found an average of 1.63 bunches per fruitful shoot over 3 years from spur pruned Shiraz at Waikerie, South Australia.
Smart and Robinson (1991) have established standards for grapevine balance (ratio yield/pruning weight) (Table 1.5). The authors suggest that for optimum grape yield, ripeness and quality, vigour and balance should be managed in the moderate range (Table 1.5).

**Table 1.5. The standards for grapevine balance (mean cane weight and grape yield/Pwt A ratio) as defined by Smart and Robinson (1991)**

<table>
<thead>
<tr>
<th>Vigour</th>
<th>Low</th>
<th>Moderate</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean cane wt (g)</td>
<td>&lt; 10</td>
<td>20-40</td>
<td>&gt; 60</td>
</tr>
<tr>
<td>Grape yield/Pwt A</td>
<td>&gt; 12</td>
<td>5-10</td>
<td>&lt; 3</td>
</tr>
</tbody>
</table>

A Pwt = Pruning weight

1.5.2 Berry chemistry

The pH of berry juice is important pre-harvest, as it can be used to determine grape ripeness. The strongest acid in berry juice is tartaric and is found in the largest concentrations and results in a low pH. As grapes ripen, the concentration of tartaric acid diminishes and juice pH increases (Ferroni and Scalabrelli 1995). Over several vintages sufficient data can justify setting standards from which to pre-determine optimum time to harvest. Most grapes are green at pH 2.7. Wines that require sharp, crisp acidity (i.e. sparkling wines) are often standardised at a pH between 2.9 and 3.1. For fresh, fruity white and blush wines berry juice of pH 3.1 to 3.3 is required (Vine et al. 1997). A pH of berry juice greater than 3.8 is unacceptable for the production of table wine (Hamilton and Coombe 1992).

Total acidity (includes acid compounds containing $\text{H}^+$ + $\text{K}^+$ + $\text{Na}^+$) or the titratable acidity (includes acid compounds containing $\text{H}^+$ only) (T.A.) are a measure of the
concentration of organic acids present in juice and wine. The predominant organic acids that occur in juice and wine are tartaric, malic, citric, acetic, succinic and lactic. The measure of T.A. often indicates less than the absolute concentration of wine or juice acids (total acidity) due to species of tartrate that have K\(^+\) and Na\(^+\) associated (Zoecklein et al. 1995). Concentrations of T.A. range from 5.0 to 8.0 g/L, in bland to sharp wines respectively (Vine et al. 1997).

Degrees Brix (°Brix) is defined as g soluble solids per 100 g of juice or wine and includes all soluble solids such as pigments, acids, glycerols and sugars. The fermentable sugar present in berry juice accounts for approximately 90 to 95 % of total soluble solids and °Brix is therefore, an approximate sugar concentration (Zoecklein et al. 1995). The concentration of soluble solids in berry juice used for the production of table wine should be at least 22 °Brix (Vine et al. 1997), and that for juice of Chardonnay approximately 22.0 to 23.5 °Brix (Wildman et al. 1976).

1.6 Interactions between perennial fruit crops and HRDS

The LLWR for root growth (Letey 1985; de Silva et al. 1994) determined by Emerson et al. (1994) in 9 orchards in the Goulburn Valley, suggests additional parameters for unrestricted root growth. For optimum root growth in the Goulburn Valley, surface soils require carbon concentrations between 1 and 3 % (section 1.2.5).

Greatest improvements in physical and biological fertility were apparent in treatments that returned the most organic matter and root production, namely perennial ryegrass (Francis et al. 1999). These findings are consistent with those of Watts and Dexter (1998), who established a direct positive relationship between aggregate friability (F) and soil organic carbon (SOC), \( F = 0.086 + 0.196 \text{SOC} \text{ (g/kg)}, (R^2 = 0.970). \)
A major restriction to root growth in HRDS is the naturally dense clay subsoil. A study of orchard soils in the Goulburn Valley by Cockroft and Wallbrink (1966), found that depth of the A horizon was significant in limiting tree size and production (section 1.2.1). The shallow A horizon of irrigated HRDS is often waterlogged because the clay B horizon restricts the penetration of water (Cockroft and Tisdall 1978; Taylor and Olsson 1987; Blackwell et al. 1988), and the LLWR is narrowed. When water enters the B horizon, root growth is limited by hard soil. Root growth in the B horizon that is unrestricted by aeration or strength in typical HRDS can be 10 to 20% of the root growth in the A horizon (Olsson et al. 1995).

Mulches, covercrops, gypsum, slotting, hilling, and deep ripping have been used to improve the soil physical and chemical environment for root growth.

1.6.1 The impact of mulching on root growth and fruit crop performance

Mulches of cereal straw have been used in many woody perennial fruit crops to protect the surface soil and minimise evaporation. Organic mulches supply carbon and nitrogen that increase soil fauna activity creating burrows and channels though the soil matrix (Russell 1971). Compost mulch of either municipal solid waste or sewage sludge increased cation exchange capacity and water holding capacity, and decreased bulk density (Roe 1998).

High root concentrations (5.6 to 5.9 cm/cm³) of peach in the top 10 to 165 mm of soils in the tree-line were attributed to 0.20 to 0.30 cm³/cm³ air-filled porosity at field capacity. This environment was created by the high biological activity (associated with organic matter) and the low rate of wetting by capillarity (Richards and Cockroft 1974).

Dense B horizons at 300 mm depth in Stellenbosch, South Africa, prevented root growth of grapevines. The application of straw mulch to the soil surface encouraged root growth to the surface increasing the total soil volume occupied by roots (Van Huyssteen
and Weber 1980). The resultant mass of shoots (1.8 t/ha) and yield (12.3 t/ha) was greater than for grapevines with soil treated with herbicide, tillage or a permanent sward. Similarly, the use of straw mulch as part of soil management in orchards in the Goulburn Valley, increased the root concentration of peaches by 0.42 cm/cm³, the butt circumference by 96 mm and trebled yield (Tisdall et al. 1984).

Compost mulch of sewage sludge and bark on the vine-line decreased the need for weed control by chemicals and required no application of synthetic fertilisers compared with grapevines grown in a bare vine-line (Pinamonti 1998). Grapevines with compost mulch applied suffered no loss in vigour, yield or quality of must compared with those grown in a bare vine-line. However, the concentration of exchangeable K increased in the soil slightly (39 mg/kg dry weight), K increased in the lamina (80 mg/kg dry weight) and total K increased in the must (130 mg/l), compared with grapevines grown in a bare vine-line. As the concentration of K in must increases, must pH increases due to the formation of salts and the insolubility of potassium acid tartrate in turn causing lower ionization of anthocyanins and greater likelihood of poor quality wine (Hamilton and Coombe 1992). The mixing of cereal and legume mulches in soil by earthworms initially increased the concentration of extractable P (Olsen P, 4.0 mg/kg), a long term increase in concentration of mineral N (1.5 times) but no change in the concentration of exchangeable K in soil (Haynes and Fraser 1998).

The positive effects of mulches, composted or raw, appear to outway any negative effect. Positive effects include: high infiltration and conservation of soil water, protection of the soil surface from water drops, food sources for soil fauna and roots plus cations for the soil exchange complex, water stable aggregates and minimal temperature fluctuations of the surface soil. All these parameters of soil encourage root growth at least to the soil surface (Stewart et al. 1998; Mosaddegghi et al. 2000).

Mulches can be detrimental in frost prone regions by insulating the soil surface and preventing radiant heat from warming the night air. The decomposition of mulches on
soil that adequately supplies K to the grapevine can increase the concentration of K in the must and decrease wine quality.

1.6.2 The impact of covercrops on root growth and fruit crop performance

Rotations of annual crops including varieties with deep roots increase the number of biopores that encourage growth of roots in the succeeding crop (Singh and Sainju 1998). The growth of covercrops in the vine-line or voluntary plants during the non-growing season in woody perennial crops can improve soil structure for root growth in the following season (Van Huyssteen and Weber 1980). Cresswell and Kirkegaard (1995) detailed work on crops that provide ‘biological drilling’ (creation of macropores in subsoil that benefit the following crop). An example was tree roots that improved rooting depth, root concentration and water storage for the following maize crop.

However, Goss (1987) detailed evidence that uptake of mineral nutrients (eg. iron and aluminium) by roots deceased the stability of soil aggregates. Therefore, replacing stabilising (eg. calcium) cations to the soil may prevent disaggregation. Italian ryegrass was used as a nitrate catch crop in spring barley (*Hordeum vulgare* L.) grown on a sandy loam (Thomsen and Christensen 1999). The ryegrass catch crop halved the leaching of nitrate that was applied however, the nitrate associated with the catch crop was leached during subsequent years when ryegrass was not grown.

1.6.3 The impact of gypsum on root growth and fruit crop performance

Gypsum applied to sodic and marginally sodic soils that have poor physical properties improve tilth and water acceptance, often improving crop productivity (Keren and Shainberg 1981; Shanmuganathan and Oades 1983; Harrison *et al.* 1992). Most experimental work on the application of gypsum for improvement of soil physical properties has been conducted with annual crops and pastures, with no reference to
changes in root growth. Yield response of crops from the application of gypsum to soil is shown in Table 1.6.
### Table 1.6. Yield response of crops after gypsum applied to soil

<table>
<thead>
<tr>
<th>Location</th>
<th>Soil type</th>
<th>ESP</th>
<th>Time after application (years)</th>
<th>Rainfall or Irrigation</th>
<th>Crop type</th>
<th>Gypsum applied (t/ha)</th>
<th>Change in Crop Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macquarie Valley, NSW</td>
<td>Red-brown Earth (Db 1.13)</td>
<td>3-6</td>
<td>2.0 &amp; 3.0</td>
<td>Furrow irrigation</td>
<td>Cotton (Gossypium hirsutum)</td>
<td>2 of 5</td>
<td>+ 300</td>
</tr>
<tr>
<td>Griffith, NSW</td>
<td>Red-brown Earth C</td>
<td>&gt; 6</td>
<td>3.0</td>
<td>Flood Irrigation</td>
<td>Maize (Zea mays)</td>
<td>8</td>
<td>+ 60</td>
</tr>
<tr>
<td>Kyabram, Vic Red-brown Earth</td>
<td>Red-brown Earth (Dr 2.13)</td>
<td>0.7</td>
<td>0.8</td>
<td>Flood Irrigation</td>
<td>Lucerne (Meticago sativa) (second cut)</td>
<td>11.2</td>
<td>+ 60</td>
</tr>
<tr>
<td>Condoblin, NSW</td>
<td>Scalded sodic clay (Dr 2.13)</td>
<td>5.0</td>
<td>Rainfall (477 mm ave.)</td>
<td>Wheat (Triticum aestivum)</td>
<td>2.5</td>
<td>+ 280</td>
<td></td>
</tr>
<tr>
<td>Strathalbyn SA</td>
<td>Pot exp. Sandy loam F</td>
<td>9.1</td>
<td>0.25</td>
<td>Irrigation</td>
<td>Wheat (442 mm)</td>
<td>2.8</td>
<td>+ 10-20</td>
</tr>
</tbody>
</table>

The major benefits for root growth from gypsum applied to soil were the improvement in water penetration and holding capacity, aeration and lowered soil strength (Shainberg et al. 1989). These benefits resulted from an increase in soil electrolyte supplied by the gypsum to minimise clay dispersion and the development of a crust on the soil surface (section 1.2.3). The benefits of gypsum on soil physical and chemical properties have been found to directly increase the LLWR of soil (section 1.2.5, Hall et al. (1994)).

The specific benefits of gypsum on soil and thus on root growth of woody perennial fruit crops have not been widely studied. Root weights of avocado seedlings (*Persea sp.* cv. Topa Topa) were not significantly increased by gypsum addition however, significant decreases in root weight and infection by *Phytophthora cinnamomi* were largely eliminated by the addition of gypsum to soil (Messenger et al. 2000). The decrease in infection by *Phytophthora cinnamomi* of avocado seedlings in gypsum-amended soil was not caused by increased root growth, root resistance or improved drainage.

### 1.6.4 The impact of slotting on root growth and fruit crop performance

Gypsum slotting in soil with a sodic subsoil (Jayawardane et al. 1987) decreased the time (compared with non-gypsum slotted soil) that the soil (0.2 m depth) had an air-filled porosity less than 0.08 cm$^3$/cm$^3$. The LLWR (section 1.2.5) of the gypsum slots (0.26 to 0.47 cm$^3$/cm$^3$) was greater than that in the non-gypsum slotted soil (0.35 to 0.44 cm$^3$/cm$^3$). A greater LLWR created in the soil that was gypsum slotted would ultimately improve root growth of grapevines.

The technique of slotting with lime to ameliorate soil acidity, as opposed to gypsum slotting for the amelioration of soil sodicity, was successful in a 6-year-old commercial vineyard at Port Macquarie located on an acid clay soil (Kirchhof et al. 1991). Lime slotting (2 t/ha lime incorporated in slot and 8 t/ha surface applied) to 0.40 m depth, at
0.50 and 0.80 m from the vine-line, combined with raised beds (0.35 m high) in the vine-line, increased the yield of grapes from 4.8 to 8.2 t/ha. Relative soil volumes of the slot, raised beds and undisturbed soil were 8, 36 and 56 % respectively, while root length densities were 30, 50 and 20 % respectively. The pH_{\text{CaCl}_2} of the soil in the limed slot and the non-ameliorated soil was 5.0 and 4.3 respectively for the 0.40 m depth. The modification of a small proportion, compared with a large proportion, of the available soil to grapevine roots can have a marked effect on grape yield, and is probably more economical than modification of the entire rootzone.

1.6.5 The impact of hilling (raised beds) on root growth and fruit crop performance

The use of raised beds (1.24 m wide at base, 0.45 m on top of subsoil) to increase the growth of young grapevines, provided a greater depth of surface soil and improved soil physical and hydraulic properties that optimised root and shoot growth (Eastham et al. 1996). Root length per unit soil surface area, similar at 0.30 m and 0.75 m from the grapevine, was greater in raised beds than that without beds. Canopy growth 2 and 4 months after planting was greater on raised beds than that without beds through increased length of main shoots and increased number and length of lateral shoots.

Two-year-old Chenin Blanc on 99 Richter rootstock grown on raised beds at least 1.5 m wide and 0.4 m high and irrigated by micro sprinkler, significantly increased vegetative growth and yield compared to the unripped control (Myburgh 1994). In the raised beds the majority of the fine roots were active due to improved drainage and aeration (Myburgh and Moolman 1991), whilst fine roots found in cracks in flat beds were dead due to waterlogging. Unirrigated grapevines grown on raised beds that had surface to volume ratios less than 1.0 had lower yields than the unripped control.

The yields of Shiraz grapevines grown in soil with a depth of surface soil of 800 mm was greater than those grown in 350 mm of surface soil, irrespective of irrigation type and
frequency (Freeman 1990). The yield of grapevines in the shallow surface soil was increased by 41% when grapevines were grown in raised beds and irrigated with microjets compared with drip irrigated grapevines without raised beds.

Height (< 0.4 m) and irrigation, plus a surface cover are critical to the success of raised beds, particularly for young grapevines. Careful management of raised beds, surface covers and irrigation can enhance the rate at which grapevines become established on a trellis.
1.7 Conclusions

Grapevine root growth is restricted if:

(a) the soil is hard-set and penetration resistance at field capacity is greater than 2 MPa;
(b) the soil in which they grow is saturated for 3 days;
(c) the LLWR is close to zero;
(d) the suction of soil water exceeds 60 kPa.

The main aim of my thesis is to identify the changes in chemical and physical properties of a hard-setting red duplex soil in the Goulburn Valley of Victoria, and their influence on grapevine root growth, grapevine performance and water penetration. The experiment was to improve root growth and grapevine performance by minimising hard-setting and crusting of the surface soil and decrease susceptibility to waterlogging by improving water flow into the sodic subsoil.

The null hypotheses: a) transient waterlogging decreases root growth and grapevine performance, and b) hardening of soil decreases root growth and grapevine performance were tested.
Chapter 2

Materials and methods
2.1 Soil and site description

The grapevine block (0.3 ha) at Picola, within the Rosbercon Vineyard, Victoria, Australia (35°59’S, 145°6’E) covers 3 soil types. These soil types are Moira loam, Waaia loam and Waaia sandy loam (Cockroft pers. comm. 1996), generally classified as Dr 2.33 (Northcote et al. 1975). These soils are collectively known as Red-brown Earths (Stace et al. 1968), Haplic, Eutrophic, Red Chromosol or Sodosol (medium loamy surface) (Isbell 1996), and Natrixeralf (Soil Taxonomy 1975). The soil profile is 120 mm greyish-brown fine sandy loam (A1), overlying 50 mm greyish-brown and light greyish-brown fine sandy to clay loam (A2), overlying 330 mm red-brown medium clay (B) overlying parent material of mottled yellowish-brown and brown fine sandy loam to clay - some concretionary carbonate (Skene and Poutsma 1962).

Before this experiment the vineyard was irrigated by overhead sprinklers each spanning 7 rows and approximately 15 grapevines along the row. The vineyard had been through continuous tillage for weed control in the 1970’s, minimum tillage with soil hilled and ryegrass grown in the vine-line in the early 1980’s, and no-tillage with cover cropping (volunteer species) and a vine-line cover of straw mulch from mid-late 1980’s. Chardonnay grapevines chosen for the experiment were established on Ramsey (Vitis champini) rootstock and a wide-T trellis system in 1972.

An experiment was conducted from May 1995 to September 1998 to test the hypotheses: a) transient waterlogging decreases root growth and grapevine performance, and b) hardening of soil decreases root growth and grapevine performance. The experiment of 5 rows (replicates) with 8 treatments in each row was used to test the hypotheses (Fig. 2.1). Each treatment contained 7 grapevines (5 treatment and 2 guard) and was 1.5 m wide and 13.0 m long. Grapevines were numbered 1 to 5 in each treatment, with grapevine 1 at the northern end of each treatment and grapevine 5 at the southern end of the treatment.
Treatments were spaced along the row according to groupings of grapevines (at least 7) of similar size and age (avoiding replants). In May 1995, the surface soil between the rows of all treatments was rotary-hoed to a depth of approximately 150 mm. The soil when rotary-hoed was at the lower plastic limit (LPL) (25 g water per g soil), and was then hilled into beds under the grapevines with a V-delver pulled behind a tractor. The beds were approximately 1.5 m wide and provided a depth of surface soil at the peak of the vine-line of approximately 400 mm. The treatments implemented at the experiment are presented in Table 2.1.

As a result of soil analysis for gypsum requirement, gypsum was applied by hand to the soil surface in the +gyp treatments, along the 1.5 m wide vine-line. Italian ryegrass (*Lolium multiflorum* v. Concord) was sown to the rye treatments in the vine-line (after the gypsum had been applied) and the mid-row in May 1995. Ryegrass was re-sown in the vine-line in April 1996 and 1997. Wheat straw (*Triticum aestivum*) was applied to the vine-line in the ws treatments at 15t/ha, at the beginning of the growing season each year (October).
Fig. 2.1. Treatments applied in a randomised block design.
<table>
<thead>
<tr>
<th>Input</th>
<th>Type (label)</th>
<th>Application rate</th>
<th>Timing</th>
<th>Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum (CaSO$_4$.2H$_2$O)</td>
<td>By-product (+gyp)</td>
<td>12 t/ha</td>
<td>One application, May 1995</td>
<td>Calcium exchanges with sodium on clay. Gypsum increases the electrolyte concentration and coagulates clay.</td>
</tr>
<tr>
<td>None (-gyp)</td>
<td></td>
<td>0 t/ha</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vine-line cover (ws)</td>
<td>Wheat straw</td>
<td>15 t/ha</td>
<td>All year</td>
<td>Wheat straw conserves water and provides opposite conditions to those of ryegrass.</td>
</tr>
<tr>
<td>Ryegrass seed (rye)</td>
<td></td>
<td>30-40 kg/ha</td>
<td>Herbicide applied to vine-line, growing season</td>
<td>Ryegrass roots stabilise soil aggregates and use excess soil water.</td>
</tr>
<tr>
<td>Wetting rate</td>
<td>Slow (slow)</td>
<td>5 mm/h</td>
<td>Growing season</td>
<td>A slow wetting rate decreases the rate of slumping of soil.</td>
</tr>
<tr>
<td></td>
<td>Fast (fast)</td>
<td>15 mm/h</td>
<td>Growing season</td>
<td>A fast wetting rate increases the rate of slumping of soil.</td>
</tr>
</tbody>
</table>

$^A$ The factorial combination of all inputs (2x2x2) provides the 8 treatments.
The overhead sprinklers mentioned previously were not used in the experiment. The irrigation system was a lateral system of polyethylene tubing (diameter 19, 25, 32 and 50 mm) in which riser tubes were inserted, with support stakes and Tornado® Rayjet emitters attached. The Tornado® Rayjet (21 L per hr @ 100 kPa) was selected for its slow precipitation rate (5 mm/h) and the relatively small area of spray coverage (2.1 m diameter at 100 kPa). An emitter with a slow rate of water application was required so that the rate of soil slumping and compaction, under fast and slow wetting rates could be determined. Ideally, the desired water coverage would be limited to the vine-line (1.5 m wide). Although, the Tornado Rayjet did not meet this specification, it was the closest commercially available product. Water applied to the vine-line is more efficient than a wider spread, because the majority of grapevine roots in this vineyard are in the vine-line and not in the mid-row (Hunt 1994). In the treatment with the slow application rate (5 mm/h) the rayjets were spaced along the vine-line at 2 m, and in the treatment with the fast application rate (15 mm/h) the rayjets were spaced at 0.66 m. All treatments were installed and in use early in the growing season, October 1995.

The time for irrigation plus the time between irrigation events is defined as an irrigation cycle. The start of an irrigation cycle is considered as the day water application starts. Irrigation cycles throughout any 1 season varied in length to allow for changes in water requirements of the grapevines. The average volume of water applied per season was 4 ML/ha.

Each season, grapevine growth and development began in early spring (September). Water use by the grapevine began when bud burst occurred (approx. mid September at Picola), at which time root growth also began (for 2 to 3 months). From bud burst in September to veraison (berry softening) in mid January, water use by the grapevine increased as shoot growth and leaf number increased (Fig. 2.2). Leaf number and water use then reached a plateau, and water requirements depended predominantly on the weather.
Fig. 2.2. Typical shoot length (mm) and berry fresh weight (g) versus growth stage from bud burst to harvest (Rosbercon, Picola).

Table 2.2 presents rainfall, evaporation and temperature data from Rosbercon Vineyard, Picola.
Table 2.2. Meteorological data for Rosbercon Vineyard, Picola. Monthly rainfall, mean daily temperatures and evaporation (pan evaporation class A) over the 3 seasons in which data were collected. Long-term monthly means are also presented.

<table>
<thead>
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</thead>
<tbody>
<tr>
<td>Rainfall (mm) 1995</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>79</td>
<td>89</td>
<td>28</td>
<td>15</td>
<td>42</td>
<td>39</td>
<td>0</td>
</tr>
<tr>
<td>Max temp. (°C) 1995</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>12.0</td>
<td>12.0</td>
<td>15.0</td>
<td>16.0</td>
<td>18.0</td>
<td>22.0</td>
<td>24.0</td>
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<tr>
<td>Max temp. (°C) 1996</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.0</td>
<td>3.0</td>
<td>2.9</td>
<td>3.4</td>
<td>5.0</td>
<td>6.0</td>
<td>10.0</td>
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<tr>
<td>Daily evap. (mm) 1995</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.6</td>
<td>0.3</td>
<td>1.3</td>
<td>1.45</td>
<td>2.17</td>
<td>3.3</td>
<td>5</td>
</tr>
<tr>
<td>Rainfall (mm) 1996</td>
<td>30</td>
<td>31</td>
<td>18</td>
<td>27</td>
<td>16</td>
<td>72</td>
<td>70</td>
<td>74</td>
<td>54</td>
<td>25</td>
<td>30</td>
<td>8</td>
</tr>
<tr>
<td>Max temp. (°C) 1996</td>
<td>24.0</td>
<td>26.0</td>
<td>24.0</td>
<td>18.0</td>
<td>19.0</td>
<td>15.0</td>
<td>13.0</td>
<td>15.0</td>
<td>150</td>
<td>18.0</td>
<td>20.0</td>
<td>25.0</td>
</tr>
<tr>
<td>Min temp. (°C) 1996</td>
<td>14.0</td>
<td>12.0</td>
<td>10.0</td>
<td>7.0</td>
<td>4.0</td>
<td>4.0</td>
<td>3.0</td>
<td>2.9</td>
<td>5.4</td>
<td>5.0</td>
<td>7.0</td>
<td>11.0</td>
</tr>
<tr>
<td>Daily evap. (mm) 1996</td>
<td>6.3</td>
<td>4.8</td>
<td>2.7</td>
<td>1.7</td>
<td>1.1</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.6</td>
<td>1.8</td>
<td>4.2</td>
<td>6.0</td>
</tr>
<tr>
<td>Rainfall (mm) 1997</td>
<td>44</td>
<td>6</td>
<td>20</td>
<td>4</td>
<td>64</td>
<td>39</td>
<td>9</td>
<td>59</td>
<td>75</td>
<td>19</td>
<td>47</td>
<td>4</td>
</tr>
<tr>
<td>Max temp. (°C) 1997</td>
<td>29.0</td>
<td>30.0</td>
<td>22.0</td>
<td>21.0</td>
<td>17.0</td>
<td>15.0</td>
<td>12.0</td>
<td>13.0</td>
<td>15.0</td>
<td>19.0</td>
<td>24.0</td>
<td>27.0</td>
</tr>
<tr>
<td>Min temp. (°C) 1997</td>
<td>16.0</td>
<td>10.0</td>
<td>10.0</td>
<td>7.0</td>
<td>4.0</td>
<td>3.0</td>
<td>2.5</td>
<td>2.3</td>
<td>4.0</td>
<td>5.0</td>
<td>11.0</td>
<td>12.0</td>
</tr>
<tr>
<td>Daily evap. (mm) 1997</td>
<td>7.2</td>
<td>7.9</td>
<td>3.0</td>
<td>1.8</td>
<td>0.7</td>
<td>0.4</td>
<td>1.8</td>
<td>0.6</td>
<td>0.9</td>
<td>5.3</td>
<td>5.5</td>
<td>6.3</td>
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<tr>
<td>Long term ave. ^</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
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<tr>
<td>Rainfall (mm) 1995</td>
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<td>27</td>
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<td>33</td>
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<td>30.8</td>
<td>30.6</td>
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<td>13.5</td>
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<td>14.8</td>
<td>14.9</td>
<td>12.9</td>
<td>9.6</td>
<td>6.8</td>
<td>4.3</td>
<td>3.6</td>
</tr>
<tr>
<td>Daily evap. (mm) 1995</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Long term data were collected from Echuca (36° 9' S, 144° 46' N), approximately 40 km SW of Rosbercon Vineyard, Picola.</td>
<td></td>
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</tr>
</tbody>
</table>
2.2 Soil sampling

Over the course of the experiment the soil was sampled for a range of physical and chemical analyses (Table 2.3). A total of 7 sampling dates were used. The sampling method varied depending on the analysis to be performed.

In March 1995, before the experiment was established, 6 locations were chosen randomly in the experiment to collect soil for analysis of the requirement of gypsum. Samples were taken approximately 91 m south from the start of row 1 (sample 1), 28 m south from the start of row 2 (sample 2), 39 m (sample 3) and 81 m (sample 4) south from the start of row 4, and 23 m (sample 5) and 59 m (sample 6) south from the start of row 5.

In November 1995, cores were taken daily on days 1 to 4 of the irrigation cycle in which 20 to 25 mm was applied. Cores were taken from between grapevines 1 and 2 in each treatment (see Fig. 2.1). The corer was a stainless steel double-cylinder with a protruding 1 m rod (Blake and Hartge 1986). The corer was driven into the soil with a steel post impeller.
Table 2.3. Soil samples collected in the vine-line for physical and chemical analysis during the soil management experiment at Rosbercon Vineyard, Picola (May 1995 - September 1998)

<table>
<thead>
<tr>
<th>Sample date</th>
<th>Depth (mm)</th>
<th>Diameter (mm)</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 1995</td>
<td>50-113, 289-352, 489-552</td>
<td>32</td>
<td>Gypsum requirement</td>
</tr>
<tr>
<td>Nov. 1995</td>
<td>20-114, 250-344, 450-544</td>
<td>73</td>
<td>Bulk density</td>
</tr>
<tr>
<td>Aug. 1996</td>
<td>0-100, 200-300, 400-500</td>
<td>32</td>
<td>pH, EC, WSC $^A$+ExC $^B$</td>
</tr>
<tr>
<td>Jan. 1997</td>
<td>20-114</td>
<td>73</td>
<td>Bulk density,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>macroporosity</td>
</tr>
<tr>
<td>July 1998</td>
<td>0-100, 200-300, 400-500</td>
<td>32</td>
<td>Grapevine root</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>concentration</td>
</tr>
<tr>
<td>Sept. 1998</td>
<td>0-100, 200-300, 400-500</td>
<td>32</td>
<td>pH, EC, WSC, ExC</td>
</tr>
</tbody>
</table>


To extract the cores, soil was removed in 3 stages from the eastern side of the newly formed beds (Fig. 2.3). In stage 1 a section of soil 20 mm deep and 250 mm wide was removed outward (east) from the hill peak. This resulted in a ledge from which a core was extracted, close to the peak of the hill. In stage 2 a larger section of soil was removed...
from 20 mm to 250 mm depth to maintain the width of extraction at 250 mm. A core was taken at 250 mm depth. This process was repeated until cores were extracted from 20, 250 and 450 mm depth. Each extracted core had 12 mm of soil trimmed from the base and 19 mm trimmed from the top, leaving a 63 mm x 73 mm sample. The extracted soil was then replaced to approximately the depth from which it had been removed.

**Fig. 2.3.** Diagram of a hilled vine-line, with circles depicting the location of each core [94 mm long x 73 mm diameter] extraction at the depths 20, 250 and 450 mm below the peak of the hill.

In August 1996 a soil core was extracted from each treatment. These cores were collected and analysed for an undergraduate project (Cook 1996). Soil sampling was over 3 days, with 40 soil cores collected and each divided into 3 sections. Each 500 mm x 32 mm core was vertically extracted from the bed along the vine-line, 300 mm south of grapevine 1 (Fig. 2.1) and 150 mm west of the peak of the hilled vine-line. Each sample (120 in total) was air-dried, ground and sieved (< 2 mm) before analysis. In September 1998, cores were taken as per Cook (1996). In this case, the cores were taken from the eastern side of the hilled vine-line to avoid taking samples in the same location.

In January 1997, cores were taken as in November 1995, at a depth of 20 to 114 mm. A sample was taken from each treatment between grapevines 2 and 3, and between grapevines 4 and 5, at the peak of the hilled vine-line. Organic litter plus a small amount of the topsoil (20 mm) were removed from the surface prior to taking samples.
In January 1996 and July 1998, soil cores were taken for determination of root concentration. In January 1996, 2 cores were taken from soil around grapevine 1 and grapevine 5 of every treatment for a total of 1600 soil samples (40 samples per treatment x 40 treatments). One core was taken 400 mm north-east from the base of each grapevine. The other core was taken 400 mm south-west from the base of each grapevine. In July 1998, 1 core was taken from soil around grapevine 3 and 4 of every treatment for a total of 400 soil samples (10 samples per treatment x 40 treatments). The cores were taken 400 mm north-east from the base of each grapevine.

2.3 Soil measurements - physical properties

2.3.1 Penetrometer resistance

A field penetrometer designed and made by the Cooperative Research Centre for Soil and Land Management (Alf Cass, PMB 2, Glen Osmond, S.A. 5064), was used to determine soil resistance to penetration (soil strength). The penetrometer was mounted on a frame designed to maintain stability and supply a constant penetration rate. The steel cone (6 mm diameter, 30° inclusive angle) and shaft (4 mm diameter) of the apparatus penetrated the soil propelled by a motor (rate of penetration, 250 mm per min). A force transducer (maximum force 250 N) at the top of the steel shaft measured the force required for the cone to be driven into the soil. With the cross sectional area of the cone considered, pressure data were recorded every 6 mm.

On March 6 and 7 and 28 and 29 1996, volumetric water content and penetrometer resistance were measured. All treatments were irrigated 12 to 20 h before measurements were taken. Twenty-five mm of water was applied on March 5 and 15 mm on March 27. The volumetric water content was determined with Time Domain Reflectometry (TDR) via buried waveguides and coaxial cables (section 2.5). The steel cone, aligned vertically, entered the soil at the peak of the hilled vine-line within 200 mm of the buried TDR
waveguides. The penetrometer resistance at each sampled grapevine was measured 3 times in each treatment, (except when obstacles at depth eg. grapevine roots, stones, prunings prevented penetration) and the mean determined. The maximum depth of penetration varied between 180 and 400 mm.

On February 5 and 6 1998, penetrometer resistance was measured as per season 1 (1995/96). However, the corresponding volumetric water content was not measured due to breakdown of TDR equipment. All treatments were irrigated with 20 mm of water 30 to 35 h before penetrometer resistance was measured in replicates 1 and 2, and 10 mm of water 10 h before measurements of replicates 3, 4 and 5. The maximum depth of penetration varied between 200 and 390 mm.

2.3.2 Bulk density and macroporosity

Samples collected in November 1995 (section 2.2), each encased by a stainless steel ring, were each placed separately into a labelled freezer bag, and gravimetric water content (Gardner 1986) and bulk density (Blake and Hartge 1986) determined. Total porosity (total core volume - soil volume) was also calculated to determine the air-filled porosity (total porosity - volumetric water content) of the soil at a given time after irrigation.

Given the high initial bulk density at 250 to 344 mm and 450 to 544 mm depths in November 1995 (section 3.3), I presumed that the change in bulk density at these depths at later sampling times would be minimal and have no additional restriction on root growth. Macroporosity of soil cores (section 2.2) collected in January 1997 was determined by equilibration of cores at known matric suction (-10 kPa), before being oven-dried. Total porosity (total core volume - soil volume), the volumetric water content at field capacity and macroporosity (total porosity - volumetric water content at field capacity) were each calculated (Leeper and Uren 1993).
2.3.3 Spontaneous dispersion and soil texture

Spontaneous dispersion was determined on samples collected in August 1996 (section 2.2). Particle size analysis by hydrometer method (Gee and Bauder, 1986) was also determined on 6 samples taken approximately 50 m along rows 3 and 4.

Spontaneous dispersion was determined on 20 g of air-dried soil placed in a 120 mL transparent jar and 100 mL distilled water slowly added down the side of the jar. The suspension was then left undisturbed for 16 h. The dispersed clay in suspension was mixed with a mechanical stirrer (Dynamix Laboratory Stirrer) placed mid-way into the suspension and stirred at a speed of 0.16 rev/s for 30 s. After 20 min of sedimentation, 10 mL of the clay suspension was collected from a depth of 25 mm by pipette. The concentration of dispersed clay was measured spectrophotometrically at a wavelength of 600 nm against a distilled water control. Results were converted to absorbance and percentage dispersion with a transmission scale (Rengasamy *et al.* 1984a, as modified by Cook 1996).

Remoulded aggregate dispersion of 3 aggregates per treatment was determined from samples collected in September 1998 (section 2.2). The analysis followed that of the modified Emerson Dispersion Test (Loveday and Pyle 1973) and the results are reported as a rating (0 = none, 6 = strong).
2.4 Soil measurements - chemical properties

2.4.1 Gypsum requirement

For the requirement of gypsum, samples were collected in March 1995 (section 2.2) and analysed by the analytical laboratory, NRE Tatura. The collected soil was air-dried and the fine earth fraction (< 2 mm) analysed (Rayment and Higginson 1992). Briefly, a suspension of 1:5 soil:distilled water was shaken for 1 hour and the following determined on the soil solution:

(a) pH by detection of change in potential of a glass-calomel electrode of a pH meter,

(b) Electrical conductivity (EC), and

(c) Concentration of chloride, (Cl⁻), sodium (Na⁺), potassium (K⁺), calcium (Ca²⁺) and magnesium (Mg²⁺) by atomic absorption spectrophotometry.

Results of the chemical analysis were used to calculate the Sodium Adsorption Ratio (SAR) of the soil solution (Method M1a; Rayment and Higginson 1992), Total Cation Concentration (TCC, mmolc/L) (Rengasamy et al. 1984a) and Ca/Mg ratio. The mechanical dispersion of each sample was also determined (Rengasamy et al. 1984a). The SAR was calculated by equation (3) where concentrations are in mmolc/L.

\[
SAR = \frac{[Na^+]}{([Ca^{2+} + Mg^{2+}]/2)^{1/2}}
\]  

The TCC was calculated as the sum of the concentration (mmolc/L) of cations Ca²⁺, Mg²⁺, Na⁺ and K⁺. The Ca/Mg ratio was calculated as the concentration of Ca²⁺ divided by the concentration of Mg²⁺.

The above results together with a flow-chart developed by Rengasamy et al. (1984b) were used to determine the gypsum requirement.
2.4.2 pH

Samples collected in August 1996 and September 1998 (section 2.2) were analysed for pH in a suspension of 1:5 soil:distilled water. (Method 4A1; Rayment and Higginson 1992).

2.4.3 Electrical conductivity

Samples collected in August 1996 and September 1998 (section 2.2) were analysed for EC in a suspension of 1:5 soil:distilled water (Method 3A1; Rayment and Higginson 1992).

2.4.4 Exchangeable cations and water soluble cations

Samples collected in August 1996 (section 2.2) were analysed for the concentration of exchangeable cations plus water-soluble cations (WSC+ExC) (Ca$^{2+}$, Mg$^{2+}$, Na$^{+}$ and K$^{+}$) by the method of Rayment and Higginson (1992). Samples collected in September 1998 (section 2.2) were analysed for the concentration of water-soluble cations (WSC) (Ca$^{2+}$, Mg$^{2+}$, Na$^{+}$, K$^{+}$) by the method of Rengasamy et al. (1984a), and exchangeable cations (ExC) (Ca$^{2+}$, Mg$^{2+}$, Na$^{+}$, K$^{+}$) by the method of Gillman and Sumpter (1986).
2.5 Soil measurements - soil water

Time Domain Reflectometry (TDR, Topp et al. 1980) waveguides were installed under the vine-line on the days (November 1995) that bulk density cores were taken from the hilled vine-line (section 2.2). An exposed soil face, created in the hilled vine-line while the cores were taken, allowed 200 mm long waveguides to be inserted horizontally (parallel to the vine-line). Each waveguide consisted of 3 stainless steel prongs, 3 mm in diameter, and 25 mm apart. A plastic mould supported the waveguides in position and secured a 2 m long coaxial cable to the waveguides. The TDR unit was a Trase™ constructed by Soil Moisture Corporation, Santa Barbara, CA. USA. and supplied by Irricrop Technologies Pty. Ltd. Narrabri, N.S.W., Australia (Table 2.4) The TDR processor was housed in a lightweight metal-box with battery attached at the base and storage compartment on top. All compartments were sealed to protect the internal electronics from field conditions. The unit was run on two 6 V, 7 A Yuasa batteries which could be recharged with a battery charger of 220 V, 50 Hz input and 18 V, 2.2 A output (Trase operating instructions, Version 2000 Soil Moisture Corp. Santa Barbara, CA. USA.).

The waveguides were installed at depths 250 mm and 450 mm below the peak of the hilled vine-line. To keep the waveguide prongs parallel during insertion, a strengthened prototype with prongs slightly narrower in diameter was constructed. The prototype with sharpened ends was pushed into the soil, parallel to the vine-line, to provide holes for the waveguide prongs to follow. Once the waveguides had been inserted into the bed, the excavated soil was replaced to approximately the location in which it came. Each coaxial cable was run horizontally from the base of the waveguide for 250 mm, then run vertically along the opposite soil face until the cable reached the surface. The remaining length of coaxial cable was wrapped around the nearest grapevine, away from the path of machinery.
**Table 2.4. General specifications of Trase TDR (Trase operating instructions, Version 2000. Soil Moisture Corp. Santa Barbara, CA. USA)**

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measuring range</td>
<td>0-100% Volumetric Water Content.</td>
</tr>
<tr>
<td>Measuring accuracy</td>
<td>2% Full scale.</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>0 to +45°C.</td>
</tr>
<tr>
<td>Power supply</td>
<td>2 sealed, gelled electrolyte batteries. Total capacity: 7 A hr.</td>
</tr>
<tr>
<td></td>
<td>Recharge time: 12 h.</td>
</tr>
<tr>
<td></td>
<td>Auxiliary power input 18-24 V AC or DC, 2 A for battery recharge or independent operation.</td>
</tr>
<tr>
<td>Connecting ports</td>
<td>BNC Port - For waveguide connection.</td>
</tr>
<tr>
<td></td>
<td>RS-232 Serial port - For data transfer.</td>
</tr>
<tr>
<td></td>
<td>Multiplex Port - 15 pin D-SUB, for Sequence switch access and for unattended logging of multiple sites using external equipment.</td>
</tr>
<tr>
<td></td>
<td>Power port - 8 pin DIN.</td>
</tr>
<tr>
<td>Memory</td>
<td>Standard 256 kb memory with storage capacity, 170 graphs per 5400 readings.</td>
</tr>
<tr>
<td></td>
<td>Automatic data tagging of reading time/date/reading.</td>
</tr>
<tr>
<td></td>
<td>Autologging capabilities with reading interval range from 1 per min to 1 per day.</td>
</tr>
<tr>
<td>Electronic particulars</td>
<td>Measuring pulse amplitude 1.5 V peak.</td>
</tr>
<tr>
<td></td>
<td>Sampling resolution, 10 ps.</td>
</tr>
<tr>
<td></td>
<td>Graphic display - 128 x 256 Dot Super Twist Matrix, Backlighted LCD.</td>
</tr>
<tr>
<td></td>
<td>Circuit breaker protection.</td>
</tr>
<tr>
<td></td>
<td>Hardware - 8 slot card cage, 3 system boards, 5 optional slots.</td>
</tr>
</tbody>
</table>
2.5.1 Period of measurements

The buried waveguides (November 1995) together with a TDR unit were used to determine soil volumetric water content (Topp et al. 1980). Coaxial cable extensions and the multiplexing capabilities of the TDR unit were used to measure the volumetric water content every hour.

For season 1995/96, volumetric water content was used predominantly to schedule irrigation. To schedule irrigation, the volumetric water content was measured at least every 3rd day on randomly chosen treatments across the experiment. Measurements were taken at depths 250 and 450 mm, and the information guided irrigation scheduling.

During March and April 1996, as well as November 1996 through March 1997, hourly measurements were taken 3 h prior to, and for 2 to 3 days after, irrigation. These measurements showed changes in volumetric water content with time, at each depth and each treatment was measured at least once. For each treatment measured, the volumetric water content before irrigation was subtracted from the largest volumetric water content after irrigation, and then divided by the time (h) between the 2 water contents. The resulting data, the change in volumetric water content per hour (Δvolumetric water content/h), were then compared between treatments.

2.5.2 Volumetric versus gravimetric measurement

To test the accuracy of the TDR measurements, on 3 occasions (January 17 1996, February 1 1996 and April 22 1996) in 4 to 5 treatments the volumetric water content was measured and at the same time gravimetric water content samples were taken. The samples were taken with a screw auger to 250 and 450 mm depth within 200 mm of a TDR waveguide. From bulk density measured in November 1995, gravimetric water contents were converted to volumetric water content.
2.6 Grapevine measurements

Few grapevine measurements, particularly vegetative growth, were made during season 1995/96. Treatments in the experiment were not established until October 1995, therefore, any influence of treatments on the productive capacity of the grapevines would not be realised before the following season (1996/97).

2.6.1 Grape yield

Grapes were harvested by hand on March 13 1996, March 19 1997, and March 4 1998. Bunches were counted for each treatment of 5 grapevines and weighed (±1 g) fresh in 100 bunch lots. One hundred berries were taken from each treatment (20 from each grapevine, 5 from each of 4 bunches). The berries were selected as 2 from the top (each shoulder), 2 from the middle and 1 from the tail of the bunch (Jordan and Croser 1984). Berry samples were collected on the day of harvest in 1996, 4 days before harvest in 1997, and 2 days before harvest in 1998.

2.6.2 Grape quality

The juice from each 100 berry sample collected at harvest was analysed for pH, titratable acidity, °Brix and potassium concentration (Iland 1988).

2.6.3 Grapevine fruitfulness

In October 1995, 1996 and 1997 when shoots were about 500 to 600 mm long and inflorescence development was between stages of flower separation and flowering, a MBC (Antcliff et al. 1972) was undertaken on 1 grapevine per treatment. The grapevines were selected as representative of their treatment. They were visually selected to take into account general size (i.e. with similar butt thickness, cordon length and vegetative
growth at the time of measurement). A MBC assembles data from buds on one-year-old wood of grapevines. The MBC method aids predictions of yield, with approximations of % bud burst, % fruitful shoots per total nodes, % fruitful shoots per burst nodes, % fruitful shoots per total shoots, mean bunches per node and mean bunches per fruitful shoot (fruitfulness of grapevine shoots) (Smart and Coombe 1983). In October 1998, a partial MBC was conducted, which collected data on the number of bunches per grapevine and the number of bunches per fruitful shoot.

2.6.4 Vegetative growth and grapevine balance

In May 1995, all grapevines in the experiment were hand pruned to a uniform bud number per m. To achieve a full canopy without excess shade on leaves and fruit, Smart and Robinson (1991) suggested 15 to 20 buds per m of row for a single wire trellis system. This pruning level equates to 10 spurs per m with 2 buds per spur. The grapevines in this work were on a T-trellis system, which provided 2 parallel cordons per row length, approximately 0.8 m apart. To be consistent with Smart and Robinson (1991), the grapevines were pruned at 15 to 20 buds per m of cordon, equivalent to 30 to 40 buds per m of grapevine along the row. Grapevines were pruned in mid-July 1996, 1997 and 1998 by the same method as that used in 1995 and the prunings from each grapevine were weighed fresh (±1 g). Mean cane weight was calculated as total pruning weight per grapevine divided by the number of shoots counted during the MBC in October. The ratio of grape yield to pruning weight was calculated to indicate the balance between crop load and vegetative growth (Smart and Robinson 1991).

In 1995, 1996 and 1997, butt circumference, cane length and leaf number per cane were determined on the same grapevine in each treatment as used for MBCs (MBC). These measurements were taken at 1 to 2 week intervals from October when shoot length was approximately 100 to 200 mm, until shoot growth stopped around January 1. Two
canes from the selected grapevine from each treatment were tagged with fluorescent tape for identification. A location on each grapevine trunk was chosen for butt circumference measurements. Stringy bark was removed from the trunk and a single streak of fluorescent paint sprayed to mark the location. Length and circumference were measured with a dressmaker’s tape.

2.6.5 Grapevine root growth

The collected soil cores (section 2.2) were sealed in plastic bags and stored at 4°C to minimise decomposition of the organic material. Over 12 months, the roots were washed from the soil, firstly with Calgon® (sodium poly meta phosphate) to disperse the clay, then with water at high pressure, and sieved to separate the roots. The roots were stored in water in plastic vials at 4°C, until they were scanned for total root length with an automatic root-length scanner (ARLS) (Commonwealth Aircraft Corporation Ltd, Melbourne). The ARLS had its own stationary calibration system that was identified as inaccurate (A Wheaton pers. comm. 1996). When roots were scanned, they moved within the liquid medium under centrifugal forces. Therefore, a known length of wire, approximately 0.25 mm diameter, was scanned and a calibration equation was established relating the scanned length and the actual length.

Average root length density, L (cm/cm³) was calculated as total root length divided by the core volume (Stevens and Douglas 1994).
2.7 Reflection of seasonal influences

At the beginning of the first growing season, August-October 1995, the rainfall was below the long-term mean (Table 2.2). I suggest that grapevine growth was limited in rye treatments.

From July 15 to September 15 1996, there was 157 mm of rain. The resulting soil volumetric water content was in excess of 0.20 cm$^3$/cm$^3$ (less than 100 kPa for surface soil and 80 kPa for subsoil) to 450 mm depth, prior to bud burst in early September. Bud burst was earlier than that of the previous seasons (September 15) (Norm Lummis pers. comm. 1995). Effective rainfall persisted through September (Table 2.2). Irrigation started on October 11 when soil water contents were typically less than 0.20 cm$^3$/cm$^3$ in the top 450 mm of soil. The rye treatments had a stand of ryegrass less than 100 mm high. This poor stand resulted from a dry autumn (March-May 1996) when soil volumetric water content at 250 mm depth was often less than 0.15 cm$^3$/cm$^3$. Rainfall during winter was 216 mm for the 3 months, however, as maximum daily temperatures were less than 15 °C (Table 2.2) ryegrass growth was poor. As well as being short (<100 mm) the ryegrass covered approximately 60 % of the area of the hilled beds. Wheat straw was re-applied to ws treatments on October 4 at a rate of 15t/ha (Table 2.1). Wheat straw applied in 1995 was depleted. In all +gyp treatments, gypsum particles were still evident on the soil surface in March 1997.

Season 3 (1997/98) had below average rainfall for July-August 1997 (Table 2.2). The volumetric water content of soil was below 0.20 cm$^3$/cm$^3$ at 450 mm depth, before bud burst in mid-September. Bud burst occurred on September 15 within a week of that in previous years. The first irrigation was applied on August 10, however, rain in mid-August (Table 2.2) meant that irrigation was not re-started until October 6 when volumetric water content was typically less than 0.20 cm$^3$/cm$^3$ in the top 450 mm of soil. The rye treatments had an 80 to 100 mm stand of ryegrass, and provided 80 to 90 % cover when desiccated with
herbicide before bud burst. Wheat straw was re-applied to ws treatments on November 20 and 21 at a rate of 15 t/ha (Table 2.1) because that applied in 1996 had disappeared from the surface.

2.8 Statistical analysis

The experimental design was a randomised block and the data were analysed by ANOVA, GENSTAT V5.4.1 (Lawes Agricultural Trust, IACR-Rothamsted 1998). The means and LSDs presented in chapters 3 to 6 were generated ANOVA tables. The data were analysed for multiple comparisons between treatments and a large ANOVA table was generated. A table of means and table of least significant differences of means at 5% level (LSD5%) accompanied the ANOVA table.
Chapter 3

Soil physical properties
3.1 Introduction

Soil physical properties of the vine-line soil, namely penetrometer resistance, bulk density, macroporosity, texture, spontaneous and remoulded aggregate dispersion were determined throughout the experiment (section 2.3). The physical properties were analysed for differences between treatments in reference to decreasing the impact of slumping and hardening soil on root growth and performance of grapevines.

3.2 Penetrometer resistance

Penetrometer resistance was determined in March 1996 and February 1998 to identify the impact of treatments on soil resistance to penetration. The method and penetrometer used are described in section 2.3.1. In March 1996, treatments 1 (rye +gyp slow), 2 (ws +gyp slow) and 3 (ws –gyp slow) in replicate 5 were not measured due to equipment failure. Results are presented as the depth at which penetrometer resistance reached 1 and 2 MPa, Table 3.1.
Table 3.1. The depth (mm) at which penetrometer resistance (a) reached 1 MPa and (b) reached 2 MPa. The combined effect of wetting rate and vine-line cover

(March 1996)

rye = ryegrass grown in vine-line April-September, ws = wheat straw cover of vine-line all year, fast = fast rate of wetting (15 mm/h), slow = slow rate of wetting (5 mm/h)

(a)

<table>
<thead>
<tr>
<th>Wetting rate</th>
<th>fast</th>
<th>slow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vine-line cover</td>
<td>rye</td>
<td>122</td>
</tr>
<tr>
<td></td>
<td>ws</td>
<td>139</td>
</tr>
</tbody>
</table>

LSD$_{5\%}$ = 30.

(b)

<table>
<thead>
<tr>
<th>Wetting rate</th>
<th>fast</th>
<th>slow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vine-line cover</td>
<td>rye</td>
<td>178</td>
</tr>
<tr>
<td></td>
<td>ws</td>
<td>191</td>
</tr>
</tbody>
</table>

LSD$_{5\%}$ = 39.

For slow treatments, the depth at which penetrometer resistance reached 1 and 2 MPa was greater in rye than in ws treatments (Table 3.1). Wheat straw conserved water and kept the soil wetter than where ryegrass was established and subsequently killed. Wheat straw may have contributed to compaction due to a greater overburden mass in ws treatments. In September and October 1996, the volumetric water content (250 mm depth) was measured in all treatments before irrigation had commenced for the season (Table 3.2). Treatments with ws had on average 0.05 cm$^3$/cm$^3$ greater volumetric water content than did rye treatments. The additional mass of water added for the depth 0-250 mm in ws treatments amounted to 1.25 g/cm$^2$. Given a wet bulk density of rye
treatments of 1.84 g/cm³, the extra 0.03 g water/g soil added was considered insufficient by itself to have caused compaction and increase penetrometer resistance.

**Table 3.2. Volumetric water content (cm³/cm³) at 250 mm depth in treatments with wheat straw applied and where ryegrass was grown**

The water content was measured on September 27 and October 8 1996; this was before the commencement of irrigation (October 11) and after ryegrass was killed (September 1).

rye = ryegrass grown in vine-line April-September, ws = wheat straw cover of vine-line all year

<table>
<thead>
<tr>
<th>Vine-line cover</th>
<th>Date</th>
<th>September 27 1996 A</th>
<th>October 8 1996 B</th>
</tr>
</thead>
<tbody>
<tr>
<td>rye</td>
<td></td>
<td>19.2</td>
<td>20.3</td>
</tr>
<tr>
<td>ws</td>
<td></td>
<td>23.5</td>
<td>26.2</td>
</tr>
</tbody>
</table>

A LSD₅% = 2.4.  B LSD₅% = 2.5.

For ws treatments, the depth at which penetrometer resistance reached 1 MPa was greater in fast than in slow treatments (Table 3.1 a). There was no difference for depth at which penetrometer resistance reached 2 MPa between fast and slow treatments where ws was applied. There was a difference between rye slow and ws slow treatments. From Table 3.1, I suggest that the stabilising effect of the roots of ryegrass (Tisdall and Oades 1979) overcomes the inter-aggregate weakening caused by fast wetting, providing a greater depth of soil with penetrometer resistance less than 2 MPa compared with a vine-line cover of wheat straw. The implication of this is that irrigators using systems that apply water at high rates (> 5 mm/h), should consider ryegrass that will stabilise soil and slow the onset of hardening.

The depth at which penetrometer resistance reached 1 MPa was greater in +gyp treatments than in –gyp treatments (+gyp 149.9, –gyp 98.7 mm and LSD₅% = 21.2). The addition of gypsum to dispersive soil promotes coagulation (Loveday 1976). By promoting coagulation, gypsum helps to maintain a stable pore network, maintain
hydraulic conductivity, and minimise soil strength and surface crusting (Loveday 1981). The results for depth at which penetrometer resistance reached 2 MPa are consistent with those for the depth at which penetrometer resistance reached 1 MPa (+gyp 212.6, –gyp 166.6 mm and LSD5% = 27.6).

Penetrometer resistance was determined in all treatments on February 5 and 6 1998. Treatments in which the depth that penetrometer resistance reached 1 and 2 MPa were significantly different, are shown in Table 3.3.

Table 3.3. The depth (mm) at which penetrometer resistance reached 1 and 2 MPa.

The effects of gypsum and of vine-line cover (February 1998)

rye = ryegrass grown in vine-line April-September, ws = wheat straw cover of vine-line all year, 
gypsum = 12 t/ha gypsum applied to vine-line in May 1995

<table>
<thead>
<tr>
<th></th>
<th>Depth to 1 MPa (mm)A</th>
<th>Depth to 2 MPa (mm)B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>–</td>
<td>– 87</td>
<td>134</td>
</tr>
<tr>
<td>+</td>
<td>+ 120</td>
<td>180</td>
</tr>
<tr>
<td>Vine-line cover</td>
<td></td>
<td></td>
</tr>
<tr>
<td>rye</td>
<td>rye 133</td>
<td>184</td>
</tr>
<tr>
<td>ws</td>
<td>ws 73</td>
<td>131</td>
</tr>
</tbody>
</table>

A LSD5% = 27. B LSD5% = 35.

The surface application of gypsum in May 1995 maintained a greater depth of soil with penetrometer resistance less than 1 MPa than did no gypsum. This effect of gypsum was consistent with that in March 1996.

The ability for ryegrass roots and associated fungal hyphae to maintain soil in an aggregated (water-stable) state (Tisdall and Oades 1979; Andrade et al. 1998), probably provided a greater depth of soft soil than that of soil under wheat straw. The results for the depth at which penetrometer resistance reached 2 MPa are consistent with those for the depth at which penetrometer resistance reached 1 MPa.
Results of penetrometer resistance imply that gypsum coagulates clay and ryegrass and hyphae stabilise soil aggregates and maintained the soil vine-line in a soft state (< 2 MPa). Therefore, to get value from hillling soil onto the vine-line there is a need to have both these processes (coagulation and stabilisation).

Relationships between penetrometer resistance and root length or root mass were explored. All gave poor, non-significant correlations. Possible reasons include that the grapevine was an established perennial crop with an already developed root system and the range of penetrometer resistance data was small.

3.3 Bulk density and macroporosity
Soil bulk density was determined in November 1995 and January 1997, and macroporosity was determined in January 1997. These determinations were to identify the bulk density of soil layers and any impact of treatments on bulk density or macroporosity. The method used to determine bulk density and macroporosity is detailed in section 2.3.2. Table 3.4 displays soil bulk densities that were determined on cores taken at 3 depths (20-114, 250-344 and 450-544 mm) below the vine-line during November 1995.
Table 3.4. Bulk density (g/cm$^3$) of intact soil cores (94 mm long x 73 mm diameter)

taken within the vine-line between vines 1 and 2 in each treatment (November 1995)

Samples were taken at depths 20-114 mm, 250-344 mm and 450-544 mm. rye = ryegrass grown
in vine-line April-September, ws = wheat straw cover of vine-line all year, gypsum = 12 t/ha
gypsum applied to vine-line in May 1995, fast = fast rate of wetting (15 mm/h), slow = slow rate
of wetting (5 mm/h)

<table>
<thead>
<tr>
<th>Gypsum</th>
<th>Depth (mm)</th>
<th>Wetting rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>rye</td>
<td>fast</td>
</tr>
<tr>
<td>−</td>
<td>20-114 $^A$</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>250-344 $^B$</td>
<td>1.72</td>
</tr>
<tr>
<td></td>
<td>450-544 $^C$</td>
<td>1.83</td>
</tr>
<tr>
<td>+</td>
<td>20-114 $^A$</td>
<td>1.21</td>
</tr>
<tr>
<td></td>
<td>250-344 $^B$</td>
<td>1.61</td>
</tr>
<tr>
<td></td>
<td>450-544 $^C$</td>
<td>1.78</td>
</tr>
</tbody>
</table>

$^A$ LSD$_{5\%}$ = 0.16. $^B$ LSD$_{5\%}$ = 0.06. $^C$ LSD$_{5\%}$ = 0.08.

Table 3.4 shows the bulk density of each soil layer. The bulk densities at 250-344 mm
and 450-544 mm corresponded to the A (or old surface soil) and B horizons respectively,
before the soil in the inter-row was cultivated and hilled into beds on the vine-line. These
bulk densities were greater than 1.50 g/cm$^3$, beyond which root growth of perennial fruit
crops becomes limited (Tisdall et al. 1984, Eastham et al. 1996). One reason for the poor
performance of grapevines prior to the experiment was probably the high bulk density of
the existing A and B horizons (Norm Lummis pers. comm. 1996). Mean bulk density of
all treatments in the newly formed beds (20-114 mm) was 1.22 g/cm$^3$. 
Macroporosity and bulk density determined in January 1997 are presented in Table 3.5. Macroporosity in rye treatments was greater than in ws treatments (rye 0.35, ws 0.31 cm³/cm³ and LSD₅₀% = 0.03). I noted enhanced earthworm activity in ws treatments. Cass et al. (1993) speculated that excessive earthworm activity found under mulches could lead to intense remoulding of soil aggregates and the destruction of macro- and meso-pores (30-100 µm diameter). The resulting soil structure would be dense, compact and hard enough to limit root growth. Lee and Foster (1991) reviewed work on the stability of earthworm casts and concluded that freshly deposited wet casts seemed to be less stable than other soil aggregates, however, with time, organic matter and resultant digestive gums and bacteria the stability of casts improved beyond other soil aggregates. Hindell et al. (1997) found that fresh earthworm casts were significantly more dispersive than uningested soil despite the addition of gypsum and organic matter. However, casts that were aged-moist (30 days) or air-dried were no more dispersive than was uningested soil.

Ryegrass grown in disturbed soil increased percentage of water-stable aggregates and was directly related to the length of ryegrass roots in the soil and the length of hyphae associated with ryegrass roots (Tisdall and Oades 1979). In this experiment, the greater macroporosity in rye treatments than in ws treatments, may have resulted partly from the roots of ryegrass stabilising aggregates and, thus maintaining the macroporosity that resulted from tillage and hilling soil into beds.
Table 3.5. (a) Macroporosity (cm³/cm³) and (b) bulk density (g/cm³) of intact soil cores (94 mm long x 73 mm diameter) for the surface soil (20-114 mm depth) of the vine-line in each treatment (January 1997)

rye = ryegrass grown in vine-line April-September, ws = wheat straw cover of vine-line all year, gypsum = 12 t/ha gypsum applied to vine-line in May 1995, fast = fast rate of wetting (15 mm/h), slow = slow rate of wetting (5 mm/h)

(a)

<table>
<thead>
<tr>
<th>Vine-line cover</th>
<th>rye</th>
<th>ws</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wetting rate</td>
<td>fast</td>
<td>slow</td>
</tr>
<tr>
<td>Gypsum –</td>
<td>0.34</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>0.34</td>
<td>0.34</td>
</tr>
</tbody>
</table>

LSD₅₉ = 0.06.

(b)

<table>
<thead>
<tr>
<th>Vine-line cover</th>
<th>rye</th>
<th>ws</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wetting rate</td>
<td>fast</td>
<td>slow</td>
</tr>
<tr>
<td>Gypsum –</td>
<td>1.19</td>
<td>1.12</td>
</tr>
<tr>
<td></td>
<td>1.13</td>
<td>1.15</td>
</tr>
</tbody>
</table>

LSD₅₉ = 0.12.

In January 1997, bulk density was not different between treatments (P = 0.25), indicating no differences in total porosity. Mean bulk density of all treatments in the beds (20-114 mm) was 1.17 g/cm³. There was no change in bulk density at 20-114 mm depth from November 1995 (Table 3.4) to January 1997 (Table 3.5 b), and bulk density remained low following the formation of beds in the vine-line in May 1995. Work in the Goulburn Valley (Tisdall et al. 1984) and in South Australia (Baldock et al. 1994) on
Red-brown Earths found decreases in bulk density of surface soil where organic matter was applied. Tisdall et al. (1984) applied organic matter (11 t/ha) and observed a decrease in bulk density from 1.5 to 1.4 g/cm$^3$ in the top 12 mm. Similarly, Emerson et al. (1994) sampled the surface soil (0-50 mm) of 17 orchards in the Goulburn Valley (section 1.2.4) and established an inverse relationship between percentage carbon (1-4 %) and bulk density (1.4-1.8 g/cm$^3$). Emerson et al. (1994) attributed this relationship in part to a proportion of the carbon present being in the form of bonding gel, that in turn provided for a more porous and less dispersed structure. Even in the absence of initial measurements of concentrations of soil organic matter, it is likely that the organic matter applied to the vine-line in this experiment, as wheat straw or ryegrass, would have increased concentrations of soil organic matter.

In August 1997, the concentration of organic matter of the surface 150 mm of soil in the vine-line was below optimum for a porous and stable Red-brown Earth. Three rye and 3 ws treatments were analysed for organic matter (Alamgir 1997), and ranged between 0.022 g/g and 0.027 g/g, corresponding to 0.013 g/g and 0.016 g/g organic carbon, respectively (Walkley 1947). An irrigated Red-brown Earth in northern Victoria displayed minimal hard-setting and good percentage water-stable aggregation (up to 90 %) when organic carbon was at least 0.018 g/g (Adem and Tisdall 1984).

The loss of macroporosity under ws means there may have been an increase in volume of pores of smaller sizes. These smaller pores may include mesopores; that hold plant available water within the soil matrix, implying a possible increase in water holding capacity. There may also be an increase in micropores; that holds water unavailable to the grapevine. The macroporosity under ws of 0.31 cm$^3$/cm$^3$ is well in excess of the critical value of 0.15 cm$^3$/cm$^3$ for macroporosity (Tisdall and Adem 1988). From these measurements I conclude, the longevity of macropores may be greater where soil aggregates are stabilised by fine roots such as ryegrass, than in systems with no fine roots eg. where wheat straw is applied.
Carter (1990) found a direct positive relationship between macroporosity and penetrometer resistance in a study comparing tillage for cereal production on Charlottetown fine sandy loam over 2 years. Carter (1990) produced a regression equation \( \text{Penetrometer resistance} = 2.69(0.928^{\text{macroporosity}}) \) that accounted for 50.5% of the variation when penetrometer resistance (field penetrometer) and macroporosity (estimated on undisturbed soil cores) were compared. The data of macroporosity recorded by Carter (1990) covered the range 0.05-0.22 cm\(^3\)/cm\(^3\), while the above macroporosity data are between 0.27-0.37 cm\(^3\)/cm\(^3\). Data of penetrometer resistance collected in March 1996 and February 1998 (section 3.2) together with the above macroporosity data, enable a similar relationship to be examined. The relationship between penetrometer resistance in February 1998 and macroporosity in January 1997 for rye treatments produced a regression equation \( \text{penetrometer (MPa) resistance} = 9.966e^{-0.086\text{macroporosity}} \) that accounted for 51% of the variation.

Further examination of the relationship between macroporosity and penetrometer resistance is important to be able to predict the magnitude of one parameter from the measurement of the other. For example, for the soil used in this experiment, measurement of penetration resistance can predict macroporosity, an indicator of soil aeration.

### 3.4 Texture

Soil texture was determined in August 1996 (section 2.3.3) and is displayed in Table 3.6. The soil samples taken for particle size analysis were Waaia loam (Fig. 2.1). With the 200 mm increase in depth of the A horizon in the vine-line as a result of profile modification, the Waaia loam includes 400 mm of brown loam or fine sandy loam overlying 500 mm of dark red-brown nutty heavy clay (Johnston 1952).
Table 3.6. Texture of soil samples (section 2.2), determined by particle size analysis, hydrometer method (Gee and Bauder 1986). Data presented are a fraction of total (Modified from Cook 1996)

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>Clay (g/g)</th>
<th>Silt (g/g)</th>
<th>Fine sand (g/g)</th>
<th>Coarse sand (g/g)</th>
<th>Soil texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-100</td>
<td>0.21</td>
<td>0.18</td>
<td>0.38</td>
<td>0.23</td>
<td>Loam</td>
</tr>
<tr>
<td>200-300</td>
<td>0.26</td>
<td>0.17</td>
<td>0.34</td>
<td>0.23</td>
<td>Clay loam</td>
</tr>
<tr>
<td>400-500</td>
<td>0.41</td>
<td>0.15</td>
<td>0.27</td>
<td>0.17</td>
<td>Clay</td>
</tr>
</tbody>
</table>

3.5 Spontaneous dispersion

Spontaneous dispersion of air-dry aggregates (August 1996) and remoulded aggregate dispersion (September 1998) was determined to identify the impact of treatments. The methods used to determine spontaneous dispersion are described in section 2.3.3. Spontaneous dispersion, as determined by Cook (1996) on samples taken in August 1996 (section 2.2), for depths 0-100, 200-300, and 400-500 mm is shown in Fig. 3.1.
Fig. 3.1. Spontaneous dispersion (g/100 g) versus treatment for depths 0-100 mm, 200-300 mm and 400-500 mm (August 1996). Error bars are 2x the standard error. T1 rye +gyp slow, T2 ws +gyp slow, T3 ws -gyp slow, T4 rye -gyp slow, T5 rye +gyp fast, T6 ws +gyp fast, T7 ws -gyp fast, T8 rye -gyp fast. rye = ryegrass grown in vine-line April-September, ws = wheat straw cover of vine-line all year, gypsum = 12 t/ha gypsum applied to vine-line in May 1995, fast = fast rate of wetting (15 mm/h), slow = slow rate of wetting (5 mm/h) (Modified from Cook 1996).

For all treatments, except T5 (rye +gyp fast), there was a non-significant trend for spontaneous dispersion (g/100 g) to increase with depth. Increased dispersion may relate directly to the increase in clay with depth (Table 3.6). Spontaneous dispersion (g/100 g) of the subsoil (400-500 mm) appeared to be less in treatments T1 (rye +gyp slow) and T5 (rye +gyp fast) than in other treatments, however, this difference was not significant due to the large LSD5% of 28.2. The combination of surface applied gypsum and the growth of ryegrass during autumn and winter may have promoted the dissolution of gypsum and transportation of Ca²⁺ to depth (400-500 mm). The greater macroporosity in rye treatments than in ws treatments (rye 0.35, ws 0.31 cm³/cm³ and LSD5% = 0.03) supports
this. Vance et al. (1998) found a similar relationship in the subsoil of Lemnos loam (Skene and Poutsma 1962) with annual applications of gypsum and a pasture mix (ryegrass, white clover (Trifolium repens) and red clover (T. pratense)) grown over 3 years. Another explanation for the observed differences in spontaneous dispersion (T1 and T5 compared with other treatments at 400-500 mm depth) may be the binding of calcium with products of decomposition of organic matter (such as wheat straw in T2, T3, T6 and T7) to form Ca\(^{2+}\)-organic complexes. Baldock et al. (1994) suggested that Ca\(^{2+}\)-organic complexes may have prevented the leaching or exchange of ions and limited any dissolution of gypsum and transportation of Ca\(^{2+}\) to depth (400-500 mm).

In August 1996, air-dry aggregates in +gyp treatments had a lower spontaneous dispersion (g/100 g) at depths 0-100 mm and 200-300 mm, than did –gyp treatments (Table 3.7). The lower spontaneous dispersion (g/100 g) may be explained by the exchange of Ca\(^{2+}\) for sodium ions on clay colloids and the increase in electrolyte concentration (section 4.3.1).

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>–gyp</th>
<th>+gyp</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-100 A</td>
<td>5.6</td>
<td>3.8</td>
</tr>
<tr>
<td>200-300 B</td>
<td>13.5</td>
<td>4.3</td>
</tr>
<tr>
<td>400-500 C</td>
<td>25.9</td>
<td>17.3</td>
</tr>
</tbody>
</table>


Table 3.7. Spontaneous dispersion (g/100 g) of soil aggregates (Rengasamy et al. 1984a as modified by Cook 1996) at 0-100 mm, 200-300 mm and 400-500 mm depth, the effect of gypsum (August 1996)
At 400-500 mm depth there was no difference in spontaneous dispersion (g/100 g) between +gyp and –gyp treatments. This may indicate that at the time of sampling few Ca\(^{2+}\) ions from the gypsum had reached 400 mm. The large LSD\(_{5\%}\) at the 400-500 mm depth indicates that more samples are required for future sampling. Variability in dispersion can arise from differences in cation and electrolyte composition between individual aggregates (Rengasamy et al. 1984a).

In September 1998, the impact of gypsum persisted in decreasing remoulded aggregate dispersion at all depths (Table 3.8).

**Table 3.8. Remoulded aggregate dispersion (0 = none, 6 = strong) of soil aggregates (Loveday and Pyle 1973) at 0-100 mm, 200-300 mm and 400-500 mm depth, the effect of gypsum (September 1998)**

Gypsum = 12 t/ha gypsum applied to vine-line in May 1995

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>−gyp</th>
<th>+gyp</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-100 (^A)</td>
<td>0.9</td>
<td>0.3</td>
</tr>
<tr>
<td>200-300 (^B)</td>
<td>3.8</td>
<td>1.1</td>
</tr>
<tr>
<td>400-500 (^C)</td>
<td>5.5</td>
<td>4.1</td>
</tr>
</tbody>
</table>

\(^A\) LSD\(_{5\%}\) = 0.3. \(^B\) LSD\(_{5\%}\) = 1.1. \(^C\) LSD\(_{5\%}\) = 1.3.

In September 1998, at 0-100 mm depth, ws treatments caused greater remoulded aggregate dispersion than did rye treatments (ws 0.8, rye 0.4, and LSD\(_{5\%}\) = 0.3). Use of remoulded aggregates simulates the effect of strong mechanical stress such as tillage of wet soil (Rengasamy et al. 1984a). Baldock et al. (1994) identified a trend of increasing mechanical dispersion with applications of wheat straw and identified increased concentrations of K\(^+\) (which has a low coagulation value compared with that of Ca\(^{2+}\)) that could have been released by decomposing wheat straw. Mechanical dispersion
simulates the effect of moderate mechanical stress such as raindrop impact on bare soil (Rengasamy et al. 1984a). Baldock et al. (1994) also observed decreased concentrations of Ca$^{2+}$, which they explained as Ca$^{2+}$-organic complexes formed with products of decomposition of organic matter decomposition. Results here differed from those of Baldock et al. (1994), and therefore, I speculate that dispersion in ws treatments was caused by the presence of organic anions and/or organic matter with a high proportion of amino acids or proteins that acted as dispersants (Nelson et al. 1999).

Given that the EC of soil at 0-100 mm depth in ws and rye treatments was similar (approximately 0.29 dS/m), the lower remoulded aggregate dispersion in rye treatments may have been because ryegrass roots and associated fungal hyphae prevented slaking (Tisdall 1995). By stabilising macroaggregates, the roots and hyphae may have decreased the surface area from which clay could disperse. Ryegrass roots produce acidic exudates (Oades 1978) that could have increased the dissolution of gypsum into Ca$^{2+}$ and SO$_4^{2-}$ to further prevent dispersion.

Fifteen months after the application of gypsum, spontaneous dispersion was decreased to 300 mm depth, and sometime between 15 and 40 months spontaneous dispersion was decreased to at least 500 mm depth in the vine-line. Remoulded aggregate dispersion was also decreased after 40 months at 0-100 mm depth where ryegrass was grown compared with the application of wheat straw. The ability of ryegrass to stabilise soil aggregates decreased the surface area from which clay could disperse, while organic acids and/or a high concentration of amino acids or proteins released from the decomposing straw would have assisted dispersion.
3.6 Summary and conclusions

The physical properties of soil in the vine-line were improved for the growth of grapevine roots by treatments applied. The application of 12 t/ha of gypsum and growth of ryegrass in autumn and winter maintained the soil soft (< 2 MPa) to a greater depth than non-gypsum-treated soil or soil with wheat straw applied. Greater volumes of macropores were maintained in the surface soil (20-114 mm depth) where ryegrass was grown compared with where wheat straw was applied. Gypsum decreased spontaneous dispersion of soil to at least 500 mm depth sometime between 15 and 40 months after gypsum was applied. Ryegrass also decreased the dispersion of the surface soil (0-100 mm depth) compared with that of wheat straw.

To increase the longevity of soil in a state appropriate for root growth, freshly tilled aggregates of soil in the vine-line should be stabilised by a fine-rooted species of grass and clay should be coagulated by the application of Ca^{2+} in a form such as gypsum.
Chapter 4

Soil chemical properties
4.1 Introduction

Soil chemical properties of the vine-line, namely gypsum requirement (including mechanical dispersion, SAR\textsubscript{1,5}, TCC\textsubscript{1,5} and Ca\textsuperscript{2+}/Mg\textsuperscript{2+} ratio), pH\textsubscript{1,5}, EC\textsubscript{1,5}, water soluble plus exchangeable cations (Ca\textsuperscript{2+}, Mg\textsuperscript{2+}, Na\textsuperscript{+} and K\textsuperscript{+}), water soluble cations (Ca\textsuperscript{2+}, Mg\textsuperscript{2+}, Na\textsuperscript{+} and K\textsuperscript{+}), and exchangeable cations (Ca\textsuperscript{2+}, Mg\textsuperscript{2+}, Na\textsuperscript{+} and K\textsuperscript{+}) were determined throughout the experiment (section 2.4). The chemical properties were analysed between treatments in reference to treatment impact on cation movement through the soil and subsequent changes in sodicity status.

4.2 Gypsum requirement

Soil samples were taken in March 1995 (section 2.2) prior to the establishment of the experiment and analysed for gypsum requirement (section 2.4.1). The results of the gypsum requirement (Table 4.1), particularly, whether the soil was dispersive or not, the SAR\textsubscript{1,5}, the TCC\textsubscript{1,5} and the Ca\textsuperscript{2+}/Mg\textsuperscript{2+} ratio, and a flow chart developed by Rengasamy \textit{et al.} (1984b), were used to determine the rate of application of gypsum. The rate identified was 2 t/ha gypsum per 100 mm depth of surface soil. So that enough gypsum would dissolve and be leached to a depth of approximately 600 mm, the identified rate of 2 t/ha gypsum was increased to 12 t/ha in May 1995.
Table 4.1. Results of gypsum requirement taken before the experiment was established (March 1995)

Samples were taken in the vine-line at 3 depths (50-113 mm, 289-352 mm and 489-552 mm), and from 6 locations. The approximate locations were 91 m from the start of row 1 (sample 1), 28 m from the start of row 2 (sample 2), 39 m (sample 3) and 81 m (sample 4) from the start of row 4, and 23 m (sample 5) and 59 m (sample 6) from the start of row 5 (Fig. 2.1)

<table>
<thead>
<tr>
<th>Sample, depth (mm)</th>
<th>pH</th>
<th>EC dS/m</th>
<th>Na 1:5 mmol/L</th>
<th>K 1:5 mmol/L</th>
<th>Ca 1:5 mmol/L</th>
<th>Mg 1:5 mmol/L</th>
<th>SAR</th>
<th>TCC mmolc/L</th>
<th>Ca/Mg</th>
<th>Texture</th>
<th>Disp %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 50</td>
<td>6.6</td>
<td>0.06</td>
<td>0.2</td>
<td>0.04</td>
<td>0.2</td>
<td>0.08</td>
<td>0.5</td>
<td>0.5</td>
<td>2.5</td>
<td>FSCL</td>
<td>5</td>
</tr>
<tr>
<td>1, 289</td>
<td>6.0</td>
<td>0.08</td>
<td>0.28</td>
<td>0.04</td>
<td>0.26</td>
<td>0.08</td>
<td>0.7</td>
<td>0.7</td>
<td>3.3</td>
<td>CL</td>
<td>5</td>
</tr>
<tr>
<td>1, 489</td>
<td>6.5</td>
<td>0.08</td>
<td>0.28</td>
<td>0.02</td>
<td>0.38</td>
<td>0.16</td>
<td>0.5</td>
<td>0.8</td>
<td>2.4</td>
<td>CL</td>
<td>7</td>
</tr>
<tr>
<td>2, 50</td>
<td>6.3</td>
<td>0.07</td>
<td>0.24</td>
<td>0.06</td>
<td>0.26</td>
<td>0.12</td>
<td>0.6</td>
<td>0.7</td>
<td>2.2</td>
<td>FSCL</td>
<td>4</td>
</tr>
<tr>
<td>2, 289</td>
<td>6.0</td>
<td>0.06</td>
<td>0.26</td>
<td>0.04</td>
<td>0.18</td>
<td>0.08</td>
<td>0.7</td>
<td>0.6</td>
<td>2.1</td>
<td>CL</td>
<td>6</td>
</tr>
<tr>
<td>2, 489</td>
<td>7.1</td>
<td>0.08</td>
<td>0.16</td>
<td>0.16</td>
<td>1.78</td>
<td>1.98</td>
<td>0.4</td>
<td>4.5</td>
<td>0.9</td>
<td>LMC</td>
<td>10</td>
</tr>
<tr>
<td>3, 50</td>
<td>5.5</td>
<td>0.04</td>
<td>0.16</td>
<td>0.02</td>
<td>0.16</td>
<td>0.08</td>
<td>0.5</td>
<td>0.4</td>
<td>2.0</td>
<td>CL</td>
<td>5</td>
</tr>
<tr>
<td>3, 289</td>
<td>5.7</td>
<td>0.06</td>
<td>0.36</td>
<td>0.02</td>
<td>0.2</td>
<td>0.12</td>
<td>0.9</td>
<td>0.7</td>
<td>1.7</td>
<td>CL</td>
<td>7</td>
</tr>
<tr>
<td>3, 489</td>
<td>6.7</td>
<td>0.19</td>
<td>1.68</td>
<td>0.1</td>
<td>1.62</td>
<td>2.34</td>
<td>1.2</td>
<td>5.7</td>
<td>0.7</td>
<td>LMC</td>
<td>10</td>
</tr>
<tr>
<td>4, 50</td>
<td>6.5</td>
<td>0.05</td>
<td>0.16</td>
<td>0.04</td>
<td>0.22</td>
<td>0.08</td>
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<td>0.5</td>
<td>2.8</td>
<td>FSCL</td>
<td>5</td>
</tr>
<tr>
<td>4, 289</td>
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<td>0.16</td>
<td>0.02</td>
<td>0.26</td>
<td>0.08</td>
<td>0.4</td>
<td>0.5</td>
<td>3.3</td>
<td>LSCL</td>
<td>7</td>
</tr>
<tr>
<td>4, 489</td>
<td>6.4</td>
<td>0.05</td>
<td>0.24</td>
<td>0.02</td>
<td>0.34</td>
<td>0.2</td>
<td>0.5</td>
<td>0.8</td>
<td>1.7</td>
<td>SCL</td>
<td>9</td>
</tr>
<tr>
<td>5, 50</td>
<td>6.2</td>
<td>0.04</td>
<td>0.16</td>
<td>0.04</td>
<td>0.2</td>
<td>0.08</td>
<td>0.4</td>
<td>0.5</td>
<td>2.5</td>
<td>CL</td>
<td>5</td>
</tr>
<tr>
<td>5, 289</td>
<td>5.9</td>
<td>0.06</td>
<td>0.24</td>
<td>0.02</td>
<td>0.22</td>
<td>0.12</td>
<td>0.6</td>
<td>0.6</td>
<td>1.8</td>
<td>LSCL</td>
<td>6</td>
</tr>
<tr>
<td>5, 489</td>
<td>6.9</td>
<td>0.12</td>
<td>1.2</td>
<td>0.18</td>
<td>2.44</td>
<td>3.04</td>
<td>0.7</td>
<td>6.9</td>
<td>0.8</td>
<td>LMC</td>
<td>10</td>
</tr>
<tr>
<td>6, 50</td>
<td>5.9</td>
<td>0.04</td>
<td>0.12</td>
<td>0.06</td>
<td>0.18</td>
<td>0.06</td>
<td>0.4</td>
<td>0.4</td>
<td>3.4</td>
<td>CL</td>
<td>6</td>
</tr>
<tr>
<td>6, 289</td>
<td>5.5</td>
<td>0.04</td>
<td>0.2</td>
<td>0.02</td>
<td>0.62</td>
<td>0.12</td>
<td>0.3</td>
<td>1.0</td>
<td>5.2</td>
<td>LC</td>
<td>7</td>
</tr>
<tr>
<td>6, 489</td>
<td>6.5</td>
<td>0.08</td>
<td>0.44</td>
<td>0.06</td>
<td>0.82</td>
<td>0.76</td>
<td>0.5</td>
<td>2.1</td>
<td>1.1</td>
<td>LMC</td>
<td>9</td>
</tr>
</tbody>
</table>
4.3 Composition of soil solution

4.3.1 Soil solution (August 1996)

The pH and electrical conductivity (EC) were determined in August 1996 as part of an undergraduate research project (Cook 1996), to identify the depth and magnitude of the impact that gypsum had on water penetration and soil chemistry following the application of 12t/ha gypsum in May 1995. Ms Cook’s project originated from my observation of improved water penetration into soil where gypsum had been applied. Therefore, the hypothesis for Ms Cook’s project was that gypsum applied to the surface of a hard-setting red duplex soil does not effect the penetration of water.

The pH (1:5, soil:distilled water, section 2.4.2) of the soil as determined by Cook (1996) on samples (section 2.2) taken from depths 0-100 mm, 200-300 mm, and 400-500 mm is displayed in Table 4.2. The treatment average pH of 7.0 in the subsoil, 400-500 mm depth, was greater than in the topsoil layers, 0-100 mm (6.4) and 200-300 mm (6.4). The pH was lower in ws treatments than in rye treatments at depths of 0-100 mm (ws 6.2, rye 6.5 and LSD5% = 0.2) and 400-500 mm (ws 6.8, rye 7.2 and LSD5% = 0.3). At 0-100 mm depth rye –gyp fast treatments had the highest pH (Table 4.2). In contrast, at 0-100 mm depth rye +gyp fast, ws +gyp fast and slow had the lowest pH.
Table 4.2. pH 1:5, soil:distilled water of soil in the vine-line, the interaction between all treatments (August 1996)

A sample was taken in the vine-line at 3 depths (0-100 mm, 200-300 mm and 400-500 mm) from each treatment. rye = ryegrass grown in vine-line April-September, ws = wheat straw cover of vine-line all year, gypsum = 12 t/ha gypsum applied to vine-line in May 1995, fast = fast rate of wetting (15 mm/h), slow = slow rate of wetting (5 mm/h) (after Cook 1996).

<table>
<thead>
<tr>
<th>Gypsum</th>
<th>Vine-line cover</th>
<th>Wetting rate</th>
<th>rye</th>
<th>ws</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>fast</td>
<td>slow</td>
<td>fast</td>
</tr>
<tr>
<td>–</td>
<td>0-100&lt;sup&gt;A&lt;/sup&gt;</td>
<td>6.9</td>
<td>6.6</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td>200-300&lt;sup&gt;B&lt;/sup&gt;</td>
<td>6.8</td>
<td>6.6</td>
<td>6.4</td>
</tr>
<tr>
<td></td>
<td>400-500&lt;sup&gt;C&lt;/sup&gt;</td>
<td>7.7</td>
<td>7.7</td>
<td>7.0</td>
</tr>
<tr>
<td>+</td>
<td>0-100&lt;sup&gt;A&lt;/sup&gt;</td>
<td>6.1</td>
<td>6.5</td>
<td>6.1</td>
</tr>
<tr>
<td></td>
<td>200-300&lt;sup&gt;B&lt;/sup&gt;</td>
<td>6.0</td>
<td>6.1</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>400-500&lt;sup&gt;C&lt;/sup&gt;</td>
<td>6.5</td>
<td>6.9</td>
<td>6.6</td>
</tr>
</tbody>
</table>

<sup>A</sup> LSD<sub>5%</sub> = 0.4. <sup>B</sup> LSD<sub>5%</sub> = 0.2. <sup>C</sup> LSD<sub>5%</sub> = 0.3.

At all depths +gyp treatments had a lower pH than did –gyp treatments (Table 4.3). At all depths the addition of Ca<sup>2+</sup> (from gypsum) will cause an increase in the concentration of H<sup>+</sup> ions in solution (resulting in a decrease in pH) due to the exchange of H<sup>+</sup> by Ca<sup>2+</sup> on the colloid surfaces.
Table 4.3. pH 1:5, soil:distilled water of soil in the vine-line, the effect of gypsum application (August 1996)

A sample was taken in the vine-line at 3 depths (0-100 mm, 200-300 mm and 400-500 mm) from each treatment. gypsum = 12 t/ha gypsum applied to vine-line in May 1995 (after Cook 1996)

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>–gyp</th>
<th>+gyp</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-100 A</td>
<td>6.6</td>
<td>6.2</td>
</tr>
<tr>
<td>200-300 B</td>
<td>6.7</td>
<td>6.1</td>
</tr>
<tr>
<td>400-500 C</td>
<td>7.4</td>
<td>6.7</td>
</tr>
</tbody>
</table>

A LSD5% = 0.2. B LSD5% = 0.2. CLSD5% = 0.3.

From Table 4.2 I conclude that at 0-100 mm and 400-500 mm depths ws treatments decreased the pH relative to that in rye treatments. This could be a result of increased microbial activity (particularly bacteria) associated with wheat straw application, and the oxidisation of ammonia (NH₃) and sulphur (S) (Leeper and Uren 1993). Also, +gyp treatments decreased the pH relative to that of –gyp treatments (Table 4.3). Baldock et al. (1994) proposed that this effect was due to the exchange of Ca²⁺ with H⁺ on the clay colloids, thus increasing the H⁺ concentration in solution. The low pH in rye +gyp fast treatments (Table 4.2) may have been due to the greater area wet, observed (not measured) under fast treatments relative to that in slow treatments. The greater area wet, combined with the limited ground cover (observed in rye treatments relative ws treatments) may have allowed faster dissolution of Ca²⁺ from the gypsum, and thus more exchange with H⁺ on the clay colloids.

The EC (1:5, soil:distilled water, section 2.4.3) of the soil, was determined by Cook (1996) for depths 0-100 mm, 200-300 mm, and 400-500 mm. The EC of the soil at all depths was greater in +gyp treatments than in –gyp treatments (Table 4.4).
Table 4.4. EC (dS/m) 1:5, soil:distilled water of soil in the vine-line, the effect of gypsum application (August 1996)

A sample was taken in the vine-line at 3 depths (0-100 mm, 200-300 mm and 400-500 mm) from each treatment. gypsum = 12 t/ha gypsum applied to vine-line in May 1995 (after Cook 1996)

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>–gyp</th>
<th>+gyp</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-100 A</td>
<td>0.09</td>
<td>0.54</td>
</tr>
<tr>
<td>200-300 B</td>
<td>0.04</td>
<td>0.15</td>
</tr>
<tr>
<td>400-500 C</td>
<td>0.11</td>
<td>0.15</td>
</tr>
</tbody>
</table>

A LSD5% = 0.26. B LSD5% = 0.03. C LSD5% = 0.03.

Gypsum dissociates to Ca$^{2+}$ and SO$_4^{2-}$ and would thus be expected to increase the EC of the soil (Baldock et al. 1994; Vance et al. 1998). Table 4.4 indicates that over approximately 15 months, some salts, either the gypsum applied to the surface or those exchanged by the Ca$^{2+}$, have been redistributed down the profile.

The EC of the soil was less for ws treatments than for that of rye treatments, at 200-300 mm (ws 0.07, rye 0.13 dS/m and LSD5% = 0.03) and 400-500 mm (ws 0.11, rye 0.15 dS/m and LSD5% = 0.03) depths. The binding of Ca$^{2+}$ with products of decomposition of organic matter to form Ca$^{2+}$-organic complexes, as suggested by Baldock et al. (1994), may have prevented the leaching or exchange of ions and limited any increase in EC of the soil at depth. Alternatively, acidic mucilage produced by ryegrass roots as well as the macroporosity the roots maintained (section 3.3), may have assisted the dissolution of gypsum to Ca$^{2+}$ and SO$_4^{2-}$ and increased EC at 200-300 and 400-500 mm depth in rye treatments. Data in Table 4.5 support these suggestions.
Table 4.5. EC (dS/m) 1:5, soil:distilled water of soil in the vine-line at 200-300 mm depth, the interaction between gypsum and vine-line cover (August 1996)

rye = ryegrass grown in vine-line April-September, ws = wheat straw cover of vine-line all year, gypsum = 12 t/ha gypsum applied to vine-line in May 1995 (after Cook 1996)

<table>
<thead>
<tr>
<th>Vine-line cover</th>
<th>rye</th>
<th>ws</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum –</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>+</td>
<td>0.21</td>
<td>0.10</td>
</tr>
</tbody>
</table>

LSD<sub>5%</sub> = 0.04.

4.3.2 Soil solution (September 1998)

The pH and EC were determined in September 1998 as for samples in August 1996, to identify any impact of treatments over the 2 years. At 0-100 mm, 200-300 mm, 400-500 mm depth, the pH for +gyp treatments was less than that for –gyp treatments (Table 4.6).

Table 4.6. pH 1:5, soil:distilled water of soil in the vine-line, the effect of gypsum application (September 1998)

A sample was taken in the vine-line at 3 depths (0-100 mm, 200-300 mm and 400-500 mm) from each treatment. gypsum = 12 t/ha gypsum applied to vine-line in May 1995

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>–gyp</th>
<th>+gyp</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-100&lt;sup&gt;A&lt;/sup&gt;</td>
<td>6.8</td>
<td>6.2</td>
</tr>
<tr>
<td>200-300&lt;sup&gt;B&lt;/sup&gt;</td>
<td>6.9</td>
<td>6.1</td>
</tr>
<tr>
<td>400-500&lt;sup&gt;C&lt;/sup&gt;</td>
<td>7.1</td>
<td>6.6</td>
</tr>
</tbody>
</table>

<sup>A</sup> LSD<sub>5%</sub> = 0.3. <sup>B</sup> LSD<sub>5%</sub> = 0.3. <sup>C</sup> LSD<sub>5%</sub> = 0.4.
At 200-300 mm depth, there was an interaction between gypsum application and vine-line cover (Table 4.7). The decrease in pH in ws treatments that occurred at 200-300 mm depth (September 1998) also occurred in ws fast treatments at 0-100 mm depth in August 1996 (section 4.3.1). Therefore, the effect of decomposing wheat straw on pH had occurred at a greater depth over time and probably as a result of the extra water that was applied.

**Table 4.7. pH 1:5, soil:distilled water of soil in the vine-line at 200-300 mm, the interaction between gypsum and vine-line cover (September 1998)**

rye = ryegrass grown in vine-line April-September, ws = wheat straw cover of vine-line all year, gypsum = 12 t/ha gypsum applied to vine-line in May 1995

<table>
<thead>
<tr>
<th>Vine-line cover</th>
<th>rye</th>
<th>ws</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum</td>
<td>–</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td>+</td>
<td>6.1</td>
</tr>
</tbody>
</table>

LSD<sub>5%</sub> = 0.4.

The EC of the soil at all depths was greater in +gyp treatments than that in −gyp treatments (Table 4.8). Gypsum persisted in the surface soil 3 years after its application and maintained a high EC (compare with Table 4.4).
Table 4.8. EC (dS/m) 1:5, soil:distilled water of soil in the vine-line, the effect of gypsum application (September 1998)

A sample was taken in the vine-line at 3 depths (0-100 mm, 200-300 mm and 400-500 mm) from each treatment. gypsum = 12 t/ha gypsum applied to vine-line in May 1995

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>–gyp</th>
<th>+gyp</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-100 A</td>
<td>0.09</td>
<td>0.51</td>
</tr>
<tr>
<td>200-300 B</td>
<td>0.08</td>
<td>0.13</td>
</tr>
<tr>
<td>400-500 C</td>
<td>0.09</td>
<td>0.17</td>
</tr>
</tbody>
</table>

^A LSD<sub>5%</sub> = 0.24. ^B LSD<sub>5%</sub> = 0.04. ^C LSD<sub>5%</sub> = 0.04.

4.4 Water-soluble cations and exchangeable cations

4.4.1 Water soluble cations plus exchangeable cations (August 1996)

The concentration of WSC+ExC (calcium (Ca<sup>2+</sup>), magnesium (Mg<sup>2+</sup>), sodium (Na<sup>+</sup>) and potassium (K<sup>+</sup>)) (cmol<sub>c</sub>/kg) were determined by Cook (1996) (section 2.4.4) on soil samples taken in August 1996 (section 2.2), for depths 0-100 mm, 200-300 mm, and 400-500 mm. Water-soluble cations plus exchangeable cations (WSC + ExC) are those associated with the inorganic and organic exchange complex as well as those cations associated with salts.

At 0-100 mm depth, +gyp treatments had greater concentrations of WS Ca<sup>2+</sup> + Ex Ca<sup>2+</sup> than did –gyp treatments (+gyp 13.59, –gyp 8.60 cmol<sub>c</sub>/kg and LSD<sub>5%</sub> = 2.54). Also at 0-100 mm depth, +gyp treatments had a lower concentration of WS Na<sup>+</sup> + Ex Na<sup>+</sup> than did –gyp treatments (+gyp 0.11, –gyp 0.20 cmol<sub>c</sub>/kg and LSD<sub>5%</sub> = 0.03). Greater concentrations of WS Ca<sup>2+</sup> + Ex Ca<sup>2+</sup> and lower concentrations of WS Na<sup>+</sup> + Ex Na<sup>+</sup> in +gyp treatments were expected in the surface soil, because Ca<sup>2+</sup>, the cation in gypsum, exchanges readily with Na<sup>+</sup> on clay colloids (Loveday 1976; Greene and Ford 1985).
At 200-300 mm depth, fast treatments had greater concentrations of WS Ca\(^{2+}\) + Ex Ca\(^{2+}\) than did slow treatments (fast 10.87, slow 6.18 cmol_c/kg and LSD\(_{5\%}\) = 1.92). An interaction between vine-line cover and wetting rate also occurred at 200-300 mm depth (Table 4.9).

### Table 4.9. Water-soluble plus exchangeable calcium (cmolc/kg) of the soil in the vine-line at 200-300 mm, the interaction between vine-line cover and wetting rate (August 1996)

<table>
<thead>
<tr>
<th>Wetting rate</th>
<th>fast</th>
<th>slow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vine-line cover</td>
<td>rye</td>
<td>8.90</td>
</tr>
<tr>
<td></td>
<td>ws</td>
<td>12.84</td>
</tr>
</tbody>
</table>

LSD\(_{5\%}\) = 2.76.

The greater area wet that was observed and faster rate of water application under fast treatments than those of slow treatments probably contributed to an increase in the dissolution of Ca\(^{2+}\) from gypsum. The greater WS Ca\(^{2+}\) + Ex Ca\(^{2+}\) found in ws fast treatments may have resulted, not only from gypsum application, but also from the decomposition of wheat straw. The above ground parts (vegetative) of oven-dried wheat may contain up to 0.5 g/100 g Ca\(^{2+}\) (Reuter et al. 1997), contributing 75 kg/ha from one application of wheat straw of 15 t/ha. The amount of Ca\(^{2+}\) applied as wheat straw is small compared with that of 12 t/ha of gypsum (23 g/100 g Ca\(^{2+}\)) which contributes approximately 2760 kg/ha of Ca\(^{2+}\).

The interaction between gypsum and vine-line cover also produced differences in WS Ca\(^{2+}\) + Ex Ca\(^{2+}\) at 200-300 mm depth (Table 4.10).
Table 4.10. Water-soluble plus exchangeable calcium (cmolc/kg) of soil in the vine-line at 200-300 mm depth, the interaction between gypsum and vine-line cover (August 1996)

<table>
<thead>
<tr>
<th>Vine-line cover</th>
<th>rye</th>
<th>ws</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum</td>
<td>5.96</td>
<td>9.66</td>
</tr>
<tr>
<td>+</td>
<td>9.48</td>
<td>9.01</td>
</tr>
</tbody>
</table>

LSD$_{5\%}$ = 2.76.

The concentration of WS Ca$^{2+}$ + Ex Ca$^{2+}$ at 200-300 mm depth in rye +gyp treatments, being equal to that of ws –gyp treatments, suggests that wheat straw supplied Ca$^{2+}$ (Table 4.10). However, wheat straw contributes a maximum of 75 kg/ha of Ca$^{2+}$ from one application of wheat straw of 15 t/ha (Reuter et al. 1997), which is much less than that contributed by gypsum (2760 kg/ha of Ca$^{2+}$). Another contributing factor to the difference in concentration of WS Ca$^{2+}$ + Ex Ca$^{2+}$ between rye –gyp treatments and particularly ws –gyp, may have been that the ryegrass grown during May-September 1995 and May-August 1996 had temporarily bound these cations before the desiccated ryegrass had decomposed. A conservative yield of 800 kg/ha of ryegrass growth contains approximately 2.0 kg/ha of Ca$^{2+}$ (Pinkerton et al. 1997) again a small contribution compared with that of 12 t/ha gypsum. The difference in concentration of WS Ca$^{2+}$+ Ex Ca$^{2+}$ between rye –gyp treatments and particularly ws –gyp is not easily explained. Therefore WSC and ExC were determined later in the experiment (Sept. 1998, section 4.4.2) to identify if the trend continued. No evidence was apparent of either WS Ca$^{2+}$ or Ex Ca$^{2+}$ being greater in soil under ws treatments compared with +gyp treatments.
There was a non-significant trend for WS Na\(^+\) + Ex Na\(^+\) to increase with depth. From a mean WS Na\(^+\) + Ex Na\(^+\) of all treatments of 0.16 cmol/kg at 0-100 mm depth to 1.44 cmol/kg at 400-500 mm depth.

The WS Mg\(^{2+}\) + Ex Mg\(^{2+}\) at 0-100 mm depth, was greater in ws treatments than in rye treatments (ws 2.67, rye 2.21 cmol/kg and LSD\(_{5\%}\) = 0.41). Like Ca\(^{2+}\), Mg\(^{2+}\) can constitute up to 0.5 g/100 g of the oven-dried weight of a wheat plant (Reuter et al. 1997). The use of Mg\(^{2+}\) by ryegrass and the grapevine may also have temporarily contributed to the difference between ws and rye treatments.

At 200-300 mm depth, the concentration of WS Mg\(^{2+}\) + Ex Mg\(^{2+}\) was greater in +gyp treatments than –gyp treatments (+gyp 2.73, –gyp 2.21 cmol/kg and LSD\(_{5\%}\) = 0.39). The increase is likely to have resulted from the WS Mg\(^{2+}\) + Ex Mg\(^{2+}\) that had moved from 0-200 mm depth, although difference at this depth were not detected. After 12.5 t/ha of gypsum had been applied to the surface soil of a sodic Red-brown Earth (Dr 2.33), Loveday (1976) identified that the Ca\(^{2+}\) exchange (40-50 % of total applied) was predominantly with Na\(^+\) (20-33%) and Mg\(^{2+}\) (13-25%).

Greene and Ford (1985) found no change in concentration of Ex Mg\(^{2+}\) in the surface soil of a non-irrigated sodic Red-brown Earth (0-100 mm) (Dr 2.23) 2 years after 15 t/ha of gypsum had been applied. However, after 5 years, the concentration of Ex Mg\(^{2+}\) had significantly decreased with one application of gypsum of 2.5 t/ha.

### 4.4.2 Water-soluble cations (September 1998)

The Sodium Absorption Ratio (SAR) and Total Cation Concentration (TCC) (section 2.4.1) were calculated from the concentrations of cations in soil solution (section 2.4.4) for all treatments and depths sampled (section 2.2). The SAR at 0-100 mm and 200-300 mm depth was lower in +gyp treatments than in –gyp treatments (Table 4.11).
Table 4.11. Sodium Absorption Ratio of soil in the vine-line at 0-100 mm and 200-300 mm, the effect of gypsum application (September 1998)
gypsum = 12 t/ha gypsum applied to vine-line in May 1995

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>–gyp</th>
<th>+gyp</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-100 A</td>
<td>0.81</td>
<td>0.23</td>
</tr>
<tr>
<td>200-300 B</td>
<td>1.05</td>
<td>0.44</td>
</tr>
<tr>
<td>400-500 C</td>
<td>0.77</td>
<td>0.71</td>
</tr>
</tbody>
</table>

A LSD5% = 0.14. B LSD5% = 0.28. C LSD5% = 0.25.

The application of gypsum in May 1995 markedly decreased the ratio of Na⁺ to [Ca²⁺ + Mg²⁺] (SAR) to a depth of at least 200-300 mm in the vine-line. At 0-100 mm depth, TCC was greater in +gyp treatments than in –gyp treatments (+gyp 6.58, –gyp 0.86 mmol/L and LSD5% = 3.65).

4.4.3 Exchangeable cations (September 1998)
Exchangeable cations (ExC) were determined on samples taken in September 1998 (section 2.2) and the Exchangeable Sodium Percentage (ESP) was calculated (section 2.4.4). At 0-100 mm depth, +gyp treatments had greater concentrations of Ex Ca²⁺, greater sum of the ExC, Na⁺, K⁺, Ca²⁺, and Mg²⁺, lower ESP, and lower concentrations of Ex Mg²⁺ than did –gyp treatments (Table 4.12). The ESP was lower in +gyp treatments than in –gyp treatments at depths 200-300 mm and 400-500 mm. The concentration of Ex Na⁺ at 400-500 mm depth was lower in +gyp treatments than in –gyp treatments (Table 4.12). Hence +gyp transformed the subsoil from sodic (ESP > 6) to non-sodic (ESP = 2.9).
The application of gypsum in March 1995 changed the SAR at depths no greater than 400 mm (Table 4.11), whereas the impact on EC (Table 4.8) was to a depth of at least 500 mm. This increase in EC, may have been associated with other ions (not measured) leached to 400-500 mm depth. These other ions would have become mobile due to exchange with Ca$^{2+}$ and SO$_{4}^{2-}$ ions from gypsum. The data in Table 4.12 confirm this, as the concentration of ExC did not increase to depths greater than 200 mm, and the increase in ESP and absolute concentrations of Na$^{+}$ suggest that Na$^{+}$ must have been exchanged on the clay by other cation(s).

**Table 4.12. Concentration (cmol/kg) of exchangeable Ca$^{2+}$, Mg$^{2+}$ and Na$^{+}$, Exchangeable Sodium Percentage (ESP), and the sum of exchangeable Na$^{+}$, K$^{+}$, Ca$^{2+}$, and Mg$^{2+}$ (4 cations), of soil in the vine-line, the effect of gypsum application (September 1998)**

<table>
<thead>
<tr>
<th>Gypsum</th>
<th>Depth (mm)</th>
<th>Na$^{+}$</th>
<th>Ca$^{2+}$</th>
<th>Mg$^{2+}$</th>
<th>ESP</th>
<th>4 cations</th>
</tr>
</thead>
<tbody>
<tr>
<td>–</td>
<td>0-100</td>
<td>6.18 C</td>
<td>0.62 D</td>
<td>1.46 E</td>
<td>8.45 H</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200-300</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>400-500</td>
<td>0.70 B</td>
<td></td>
<td></td>
<td>7.14 G</td>
<td></td>
</tr>
<tr>
<td>+</td>
<td>0-100</td>
<td>8.26 C</td>
<td>1.95 D</td>
<td>1.08 E</td>
<td>9.35 H</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200-300</td>
<td></td>
<td></td>
<td>1.77 F</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>400-500</td>
<td>0.23 B</td>
<td></td>
<td>2.89 G</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A Only data with statistical differences between treatments are shown.

B LSD$_{5\%}$ = 0.31. C LSD$_{5\%}$ = 0.44. D LSD$_{5\%}$ = 0.60. E LSD$_{5\%}$ = 0.30. F LSD$_{5\%}$ = 1.84. G LSD$_{5\%}$ = 2.65. H LSD$_{5\%}$ = 0.39.
4.5 Summary and conclusions

Initially (August 1996), at 0-100 mm depth and later (September 1998) at 200-300 mm depth, decomposing ws decreased the pH of soil compared with rye treatments. Gypsum-treated soil had a lower pH and higher EC than did non-treated soil to at least 500 mm depth by August 1996, and remained so until at least September 1998.

In August 1996, rye treatments had higher EC than did ws treatments, suggesting that the formation of Ca$^{2+}$-organic complexes that prevented the leaching of ExC and limited any increase in EC of soil at depth. Data from August 1996 suggest that decomposing ws released Ca$^{2+}$ to 200-300 mm depth of similar concentrations to gypsum-treated soil. Data from September 1998 did not support the release of Ca$^{2+}$ from decomposing ws.

In September 1998, SAR was deceased in gypsum-treated soil to at least 300 mm depth compared with non-gypsum-treated soil. Also at this time, ESP was decreased to at least 500 mm depth in gypsum-treated soil and transformed the sodic subsoil (ESP > 6) to non-sodic (ESP = 2.9).

Frequent applications of wheat straw or gypsum in vineyard systems should be accompanied by monitoring of soil pH, and therefore, lime applied if soil pH drops to critical levels. Increases in EC and decreases in ESP can be achieved to depths of at least 500 mm within 3 years of the application of 12 t/ha of gypsum, therefore, increasing potential for soil hydraulic properties to also improve. Soil EC can increase faster in soil supporting ryegrass compared with soil covered by wheat straw.
Chapter 5

Soil water
5.1 Introduction

Porosity, water content and depth of wetting of the vine-line soil were determined throughout the experiment (section 2.3 and 2.5). Air-filled porosity in the rootzone was determined to compare the degree of aeration and occurrence of waterlogging between treatments. The impact of treatments on soil hydraulic properties was determined as a change in water content with time after irrigation.

5.2 Soil water measurements

5.2.1 Air-filled porosity in the rootzone

The air-filled porosity of vine-line soil was determined (section 2.3.2) after irrigation to identify whether the rootzone was exposed, for extended periods (> 24 h) to air-filled porosities that are below optimum for root growth. Air-filled porosities, determined 16-17 h after the beginning of an irrigation of 25 mm on January 3 1996, are shown in Table 5.1.
Table 5.1. Air-filled porosity ($cm^3/cm^3$) of the soil at 250-344 mm depth, 16-17 h after the beginning of an irrigation of 25 mm on January 3 1996

rye = ryegrass grown in vine-line April-September, ws = wheat straw cover of vine-line all year, gypsum = 12 t/ha gypsum applied to vine-line in May 1995, fast = fast rate of wetting (15 mm/h), slow = slow rate of wetting (5 mm/h)

<table>
<thead>
<tr>
<th>Vine-line cover</th>
<th>Wetting rate</th>
<th>rye</th>
<th>ws</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>fast</td>
<td>slow</td>
<td>fast</td>
</tr>
<tr>
<td>Gypsum</td>
<td>–</td>
<td>0.14</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>+</td>
<td>0.13</td>
<td>0.17</td>
</tr>
</tbody>
</table>

LSD$_{5\%}$ = 0.08.

Treatments of rye –gyp slow had a lower air-filled porosity than rye +gyp slow treatments, the latter value is similar to that of ws –gyp slow treatments that had a greater air-filled porosity than did ws +gyp slow treatments. The electrolyte effect of gypsum that probably encouraged coagulation of clay and increased the pore network and stability within the soil matrix, may explain the higher air-filled porosity in rye +gyp slow treatments compared with those of rye –gyp slow. However, the mechanisms for the differences between ws –gyp slow and ws +gyp slow treatments are not obvious.

There were no significant differences between treatments for air-filled porosity at 450-544 mm depth, 16-17 h after the beginning of a 25 mm irrigation with the mean air-filled porosity being 0.11 $cm^3/cm^3$.

Critical values below which air-filled porosity becomes detrimental for root respiration and growth have been published for different crops in the Goulburn Valley, Victoria. Richards and Cockroft (1974), found large concentrations of peach tree roots (5.0-6.0 $cm/cm^3$) in the topsoil (13-165 mm) of a tree-line. They attributed these large concentrations to an air-filled porosity of 0.20-0.30 $cm^3/cm^3$ when the soil was at field capacity. Like data in Table 5.1, Tisdall et al. (1984) found in the tree-line of a peach
orchard, that within 48 h of irrigation the air-filled porosity in 0-370 mm depth averaged 0.095 cm³/cm³.

The surface soils (0-250 mm) of HRDS have limited shrink-swell characteristics (Emerson et al. 1994), and, based on Richards and Cockroft (1974) and Tisdall et al. (1984), the critical air-filled porosity for root growth will be taken in this thesis as 0.10 cm³/cm³. The subsoil (450 mm) however, which has greater shrink-swell characteristics than does the surface soil, may require more air-filled porosity than the surface soil for root growth. A larger critical air-filled porosity would allow for pores to become constricted when the soil is wet and swollen.

Given some low (< 0.10 cm³/cm³) air-filled porosities 16-17 h after the beginning of an irrigation (Table 5.1), detailed changes after irrigation were investigated (Fig. 5.1). At approximately 35.5 h after the beginning of an irrigation of 40 mm on January 9 1996, the air-filled porosity in ws +gyp slow and ws –gyp fast treatments at 250 mm and ws +gyp slow, rye +gyp fast and ws +gyp fast at 450 mm depth was less than the critical value of 0.10 cm³/cm³ (Fig. 5.1). An irrigation of 40 mm had been applied as a one-off attempt to induce wet conditions in the vine-line to assess air-filled porosity and run-off, because conditions in winter and spring were not excessively wet.

The common features of the treatments that were associated with air-filled porosities below critical levels were ws at 250 mm depth and +gyp at 450 mm depth. The loss of macroporosity under wheat straw identified in section 3.3 suggests an increase in the volume of pores of smaller sizes, thus, decreasing the rate of drainage and air-filled porosity after irrigation. The improved penetration of water into gypsum-treated surface soil (at least 250 mm depth) (section 5.2.2), may have induced a perched watertable (and therefore, low air-filled porosity) on top of the subsoil due to its low hydraulic conductivity compared with the surface soil (Taylor and Olsson 1987; Blackwell et al. 1988).
The air-filled porosity is probably higher in most commercial vineyards, than those in my experiment, after irrigation with sprinkler, microsprays or drip, because the irrigation applied is generally less than 40 mm. For example, most vineyards in the Goulburn Valley apply less than 25 mm per irrigation. The low air-filled porosities (< 0.10 cm$^3$/cm$^3$) in Fig. 5.1 also reflect the low total porosities used to calculate the air-filled porosity (data not shown). The mean total porosity was 0.35 cm$^3$/cm$^3$ at 250 mm depth and 0.32 cm$^3$/cm$^3$ at 450 mm depth.
Fig. 5.1. Air-filled porosity (cm$^3$/cm$^3$) at (a) 250-344 mm depth and (b) 450-544 mm depth below the vine-line, 11.5 h before and 13.5 and 35.5 h after starting a 40 mm irrigation (8 h for slow and 2.66 h for fast treatments) on January 9 1996. The horizontal line shows the critical air-filled porosity of 0.10 cm$^3$/cm$^3$. T1 rye +gyp slow, T2 ws +gyp slow, T3 ws –gyp slow, T4 rye –gyp slow, T5 rye +gyp fast, T6 ws +gyp fast, T7 ws –gyp fast, T8 rye –gyp fast. rye = ryegrass grown in vine-line April-September, ws = wheat straw cover of vine-line all year, gypsum = 12 t/ha gypsum applied to vine-line in May 1995, fast = fast rate of wetting (15 mm/h), slow = slow rate of wetting (5 mm/h).
Air-filled porosities were below critical levels in no more than 3 out of the 8 treatments at 16-17 or 35.5 h after the beginning of irrigation. The surface soil (250-344 mm depth) of +gyp treatments had air-filled porosities greater than 0.10 cm³/cm³ except where ws and slow were also applied. The subsoil (450-544 mm depth) in +gyp treatments had not yet benefited in air-filled porosity from the effect of gypsum (applied 7 months earlier) and had similar air-filled porosities to –gyp treatments. The subsoil appeared to act as a throttle to water flowing from the permeable surface soil.

5.2.2 Water penetration to depth

Initially, TDR waveguides were installed to measure volumetric water content for irrigation scheduling and to identify excess water in the rootzone. However, when the measurements taken daily after irrigation were analysed over time, water penetration to a greater depth in +gyp treatments than in –gyp treatments (Fig. 5.2) became evident.

More water at 250 mm depth and 450 mm depth in +gyp treatments than in –gyp treatments suggested improved water penetration. The 12t/ha application of gypsum (section 2.1) probably increased the hydraulic conductivity of the soil. Loveday (1976, 1981) and Baldock et al. (1994) noted an increase in hydraulic conductivity of gypsum-treated soil.
Fig. 5.2. Mean of volumetric water contents (cm³/cm³) for (a) +gyp treatments and (b) -gyp treatments at 250 mm depth and 450 mm depth below the vine-line in 1996. IR specifies a 25 mm irrigation to 3.00 am, measurements were taken between 9.00 and 12.00 am. Each horizontal line depicts the volumetric water content of 0.20 cm³/cm³.
To further investigate the effect of gypsum on water penetrating to 250 mm depth and 450 mm depth, a multiplexing device was used with the TDR to enable volumetric water content to be monitored hourly (section 2.5.1). During March and April 1996, 28 of the 40 treatments were monitored from 2 h before irrigation up to 4-5 days after irrigation. Six treatments (2 +gyp fast, 1 +gyp slow, 2 –gyp fast and 1 –gyp slow) were selected and the mean data for +gyp and –gyp treatments plotted against time (Fig. 5.3). Only 6 treatments were selected because other treatments were measured with long cables (> 10 m) from the waveguides to the TDR. Data from treatments measured with long cables were variable and the data unreliable (Logsdon 2000).
Fig. 5.3. Mean volumetric water content versus time after an irrigation of 25 mm, for (a) 3+gyp treatments and (b) 3–gyp treatments in 1996. Arrows labelled, 'fw' and 'sw' indicate the end of irrigation for fast and slow treatments respectively. Each horizontal line depicts the volumetric water content of 0.20 cm³/cm³.
The application of gypsum to soil increased the penetration of water to 250 mm depth and to a lesser extent to 450 mm depth. A more intensive investigation of the impact of gypsum on the soil hydraulic capacity was undertaken during season 1996/97.

TDR waveguides were used to intensively monitor volumetric water content at 250 mm and 450 mm depth over time (section 2.5.1). The change in volumetric water content per hour ($\Delta$volumetric water content/h) between treatments was then compared (Table 5.2). Change in water content over time has been used elsewhere to determine infiltration and hydraulic characteristics of soil (Hundal and De Datta 1984; Baker and Allmaras 1990).

**Table 5.2. The change in volumetric water content (cm$^3$/cm$^3$) per hour during irrigations (from 2 h before up to 24 h after irrigation) between November 11 1996 and March 3 1997, at 250 mm and 450 mm depth, for all treatments (except T1 rye +gyp slow Rep 3, T3 ws –gyp slow Rep 3, T5 rye +gyp fast Rep 4 and T8 rye –gyp fast Rep 3)**

rye = ryegrass grown in vine-line April-September, ws = wheat straw cover of vine-line all year, gypsum = 12 t/ha gypsum applied to vine-line in May 1995, fast = fast rate of wetting (15 mm/h), slow = slow rate of wetting (5 mm/h)

<table>
<thead>
<tr>
<th>Vine-line cover</th>
<th>rye</th>
<th>ws</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wetting rate</td>
<td>fast</td>
<td>slow</td>
</tr>
<tr>
<td>Gypsum Depth (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>−</td>
<td>250 $^A$</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>450 $^B$</td>
<td>0.05</td>
</tr>
<tr>
<td>+</td>
<td>250 $^A$</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>450 $^B$</td>
<td>0.39</td>
</tr>
</tbody>
</table>

$^A$ LSD$_{5%}$ = 2.14. $^B$ LSD$_{5%}$ = 0.49.
At 250 mm depth, +gyp treatments had greater $\Delta$volumetric water content/h than did –gyp treatments (+gyp 1.68, –gyp 0.43 $\Delta$(cm$^3$/cm$^3$)/h and LSD$^{5\%}_v = 1.07$). As water arrived at 250 mm depth (in +gyp compared with –gyp treatments) more quickly, or more water arrived over the same period, the 12 t/ha application of gypsum increased the hydraulic conductivity of the soil.

At 450 mm depth, there was a non-significant trend for $\Delta$volumetric water content/h to be greater in rye +gyp treatments than in other treatments.

5.2.3 Verification of TDR accuracy

Fig. 5.4 shows that only 9 waveguides (T1R1 450 mm, T3R3 250 mm, T5R5 450 mm, T8R5 250 mm, T2R4 250 mm and 450 mm, T1R4 250 mm and 450 mm, and T4R4 450 mm) were within 2-3% of the volumetric water content converted from gravimetric water content. These tests were undertaken 6.5 (17/1/96), 8.5 (1/2/96) and 19.5 (22/4/96) weeks respectively, after the waveguides were installed. The additional time, for test 22/4/96 (Fig. 5.4), for the soil to settle around the waveguides may have improved their accuracy. The difference recorded between TDR and the gravimetric sample method as a percentage of the TDR value, on each occasion was 27% on the 17/1/96, 31% on the 1/2/96, and 18% on the 22/4/96.

Verstricht et al. (1994) reported water contents from TDR waveguides in situ after only 11 months after installation. The published data varied up to 0.04 cm$^3$/cm$^3$ volumetric water content from adjacent waveguides. In an intensive study, Baker and Allmaras (1990) monitored 4 sites each with 4 waveguides (500 mm apart) at each of 3 depths (100 mm, 300 mm and 500 mm), after 22.4 mm of rain. They noted substantial differences between and within the 4 profiles, indicating nonuniformities in infiltration, even though the rainfall was not sufficiently intense to produce surface ponding.
However, the mean change in water content for the 4 profiles was remarkably close to the total rainfall recorded.

The data in Fig. 5.4 suggest that the variability in volumetric water content is large, not only between TDR waveguides in different locations but between the different methods (TDR v gravimetric) in approximately the same locations (within 200 mm). However, 200 mm may not constitute the same location, as large differences have been noted within 500 mm (Baker and Allmaras 1990). The differences observed in volumetric water content in this experiment might collectively be a result of equipment error, sampling error and inherent variability within the soil matrix. With regard to the variability observed and the consistency of installation of TDR waveguides in each treatment and the replication of each treatment 5 times, data collected are credible for analysis between treatments.
Fig. 5.4. Comparison between measurement of volumetric water content by gravimetric method and TDR on (a) 17/1/96, (b) 1/2/96 and (c) 22/4/96. T1 rye +gyp slow, T2 ws +gyp slow, T3 ws –gyp slow, T4 rye –gyp slow, T5 rye +gyp fast, T6 ws +gyp fast, T7 ws –gyp fast, T8 rye –gyp fast. Each horizontal line depicts the volumetric water content of 0.20 cm$^3$/cm$^3$. 
5.2.4 Fast versus slow wetting

This section investigates the difference found for some variables between fast and slow treatments. There was a greater area (observed, not measured) of soil wet in fast than in slow treatments. Based on my observations I estimate that the area wet as a percentage of the total area occupied per grapevine (2100 mm x 1850 mm) in fast and slow treatments was 90% and 50% respectively. There was also a greater depth of soil wet in +gyp than in –gyp treatments for an irrigation of 25 mm (section 5.2.2). More water penetrated to at least 250 mm depth in +gyp than in –gyp treatments and therefore, I estimate the depth of soil wet in +gyp and –gyp treatments was 300 mm and 200 mm respectively.

Based on the assumptions made above, the volume of soil wet for the combination of gypsum and wetting rate treatments is shown in Table 5.3.

<table>
<thead>
<tr>
<th>Wetting rate</th>
<th>fast</th>
<th>slow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum –</td>
<td>699</td>
<td>388</td>
</tr>
<tr>
<td>Gypsum +</td>
<td>1049</td>
<td>583</td>
</tr>
</tbody>
</table>

The same volume of water was applied to each treatment during irrigation which, based on the estimated volumes of soil wet in Table 5.3, suggests for example, –gyp slow treatments would have had more water run-off during irrigation than would other combinations of gypsum and wetting rate treatments. Water was noted lying in the inter-row adjacent to some treatments after irrigation, but was not measured. The estimates of
volumes of soil wet (Table 5.3) may have implications for vine performance discussed in chapter 6.

To further investigate whether run-off during irrigation was likely, the volume of water applied to the soil was compared with the volume of pore space available in the estimated volumes of soil wet in Table 5.3. Run-off was likely to have occurred if the volume of water applied (Vapplied) exceeded the volume of pore space available (Vavailable). The Vapplied and Vavailable for the combination of the gypsum and wetting rate treatments are displayed in Table 5.4.

Based on the calculations in Table 5.4, run-off was not likely to have occurred in any combination of gypsum and wetting rate treatments, as Vapplied did not exceed Vavailable. These calculations assume that the physical condition of the surface soil was permeable and infiltration of water was not limited.

Table 5.4. Likelihood of run-off (LRO) to occur during a 25 mm irrigation, estimated as Vapplied > Vavailable. Where Vapplied = volume of water applied \((\text{cm}^3 \times 10^3)\), and Vavailable = volume of pore space available \((\text{cm}^3 \times 10^3)\) for the estimated volume of soil wet for the combination of gypsum and wetting rate treatments.

<table>
<thead>
<tr>
<th>Wetting rate</th>
<th>fast</th>
<th>slow</th>
<th>LRO</th>
<th>fast</th>
<th>slow</th>
<th>LRO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wetting rate</td>
<td>Vapplied</td>
<td>Vavailable</td>
<td>LRO</td>
<td>Vapplied</td>
<td>Vavailable</td>
<td>LRO</td>
</tr>
<tr>
<td>Gypsum –</td>
<td>98</td>
<td>308</td>
<td>No</td>
<td>98</td>
<td>171</td>
<td>No</td>
</tr>
<tr>
<td>+</td>
<td>98</td>
<td>472</td>
<td>No</td>
<td>98</td>
<td>268</td>
<td>No</td>
</tr>
</tbody>
</table>

Given the observed area wet in fast and slow treatments was less than 100 %, then the original wetting rates (calculated on an area wet of 100 %) for fast and slow wetting were
probably greater than 15 and 5 mm/h respectively. Based on the percentage of the total area occupied per grapevine (1500 mm x 1850 mm), the area wet in fast and slow treatments was estimated as 90% and 50% respectively, therefore, resultant wetting rates would have been 24 and 17 mm/h for fast and slow wetting respectively.

The specific rate of wetting applied in fast and slow treatments is not as important as the difference between them. The re-calculated difference in rate of wetting is not as great as calculated originally from the manufacturer specifications, however, the difference between the wetting rates should be sufficient to induce differences between treatments (section 2.1).
5.3  Relationships between soil water measurements

5.3.1 Water penetration to depth

During season’s 1995/96 and 1996/97, I identified more water penetrating to 250 mm depth in the vine-line in +gyp than in –gyp treatments (section 5.2.2). A trend of more water penetrating to 450 mm depth in rye +gyp treatments than in any other treatment, became apparent in season 1996/97. The relationship between \( \Delta \) volumetric water content/h and the spontaneous dispersion (g/100 g) at 450 mm depth is shown in Fig 5.5.

There was a significant (\( P = 0.036 \)), but weak, negative linear relationship (\( R^2 \approx 0.10 \)) between water penetration and spontaneous dispersion (log\(_e\) transformed). Treatments of rye +gyp (T1 and T5) had a low spontaneous dispersion and a high \( \Delta \) volumetric water content/h (Fig. 5.5). The inhibiting effect of gypsum on spontaneous dispersion was identified in section 3.5, and is likely to be the contributing factor here. However, ws +gyp treatments (T2 and T6) that also had gypsum applied, displayed less water penetration and higher spontaneous dispersion (%) than with rye +gyp treatments. As suggested previously (section 4.3.1), Ca\(^{2+}\) movement down the profile in T2 and T6 may have been inhibited by the formation of Ca\(^{2+}\)-organic complexes (Baldock et al. 1994) that developed between products of decomposition of straw mulch in ws +gyp treatments.
Fig. 5.5. Relationship between the change in volumetric water content/h (cm³/cm³)/h at 450 mm depth, determined from 2 h before irrigation to 8 h after irrigation (monitored between 11/96 and 3/97) and spontaneous dispersion (g/100 g) at 400-500 mm depth (measured 8/96). T1 rye +gyp slow, T2 ws +gyp slow, T3 ws –gyp slow, T4 rye –gyp slow, T5 rye +gyp fast, T6 ws +gyp fast, T7 ws –gyp fast, T8 rye –gyp fast. rye = ryegrass grown in vine-line April-September, ws = wheat straw cover of vine-line all year, gypsum = 12 t/ha gypsum applied to vine-line in May 1995, fast = fast rate of wetting (15 mm/h), slow = slow rate of wetting (5 mm/h).
5.4 Summary and conclusions

Gypsum applied to the surface soil improved the air-filled porosity at 250-344 mm depth, 16-17 and 35.5 h after the beginning of irrigation. However, the subsoil (450-544 mm depth) which had not yet benefited from the application of gypsum 7 months earlier had low air-filled porosities (< 0.10 cm³/cm³), possibly as a result of the permeable surface soil and water perched at the surface soil-subsoil interface.

Water arrived at 250 mm depth more quickly or more water arrived over the same period where gypsum was applied than where it was not applied, suggesting an increase in the hydraulic conductivity of the surface soil with gypsum.

There was variability between volumetric water contents measured by TDR and gravimetrically. However, TDR waveguides had been installed for only 2 months, with consistency likely to improve as soil settled around each waveguide. The 200 mm distance between TDR and gravimetric measurements may also have provided substantial variation due to inherent variability within the soil matrix. Irrespective of the variation between methods of determining volumetric water content, with the consistency of installation of waveguides and treatment replication the data collected are credible for comparison between treatments.

The volume of soil wet after irrigation was estimated for the combination of gypsum and wetting rate treatments and was identified as different. Real differences in the volume of soil wet may have implications for grapevine growth and performance (chapter 6). Based on the pore space of the estimated volumes of soil wet and the volume of water applied, run-off was not likely to occur in any combination of gypsum and wetting rate treatments.

The ability of gypsum to decrease dispersion of a HRDS via the electrolyte effect and improve infiltration was reinforced by the weak relationship between the Δvolumetric water content/h and spontaneous dispersion.
The application of gypsum to the vine-line of HRDS can improve air-filled porosity and hydraulic conductivity of the surface soil. These changes in soil characteristics are likely to improve the environment for root growth and decrease run-off of water into the inter-row and improve vehicle access throughout the vineyard.
Chapter 6

Grapevine characteristics
6.1 Introduction

The grapevine characteristics measured throughout the experiment were yield and its components, composition of berry juice, grapevine fruitfulness, vegetative growth and balance and root growth (section 2.6). The grapevine characteristics were analysed for differences between treatments in reference to their response to changes in soil conditions. The treatment responses for each year of the experiment will be discussed first, and then changes between seasons will be considered.

6.2 Grape yield

6.2.1 Yield (March 1996)

Mean grape yield per grapevine at harvest for all treatments in March 1996 was 5.3 kg fruit/vine (data not shown). This grape yield was similar to that of the commercial Chardonnay crop at Rosbercon Vineyard and consistent with my expectations of no productivity increases from treatment grapevines in March 1996. Grape yields of 5.3 kg fruit/vine (approx. 9.0 t/ha) appear to be average for the region for Chardonnay, however, the product is sold at a price comparable to Chardonnay grown in hotter climates where grape yields are more than double (> 20 t/ha) (G Wellman pers. comm.). There were no expected productivity increases from treatments because bud development for the next season occurs within the current season, and any external effect on the grapevine during or before the current season affects setting of leaf primordia and inflorescence primordia for the following season (Mullins et al. 1992). However, grape yield for the current season can be changed during the current season, by the environment and by grapevine management.
Grape yield was greater for grapevines in ws treatments than for rye treatments (ws 6.0, rye 4.7 kg fruit/vine and LSD5% = 1.0). There was also an effect of interaction between vine-line cover and gypsum on grape yield (Table 6.1). The rye +gyp treatments had higher grape yield than did rye –gyp treatments.

Table 6.1. Grape yield per grapevine (kg fruit/vine) at harvest in March 1996, effect of vine-line cover and gypsum

<table>
<thead>
<tr>
<th>Vine-line cover</th>
<th>rye</th>
<th>ws</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum –</td>
<td>3.9</td>
<td>6.4</td>
</tr>
<tr>
<td>+</td>
<td>5.5</td>
<td>5.6</td>
</tr>
</tbody>
</table>

LSD5% = 1.4.

Competition for water between the grapevines and ryegrass at bud burst (September 15-16), combined with a late start to the irrigation season on October 4, was the likely cause of low grape yield in rye treatments. Water stress from bud burst to veraison (September 15-16 to early January, at Rosbercon) decreases grape yields through decreased berry numbers and berry fresh weight (Hardie and Considine 1976; Freeman et al. 1979; Goodwin and Jerie 1992).

The rye +gyp treatments had similar grape yield to ws +gyp and ws –gyp treatments. The improved soil conditions (greater depth of soft soil and less clay dispersion) and greater hydraulic conductivity of soil in +gyp treatments (sections 3.2, 3.5, and 5.2.2), may have improved the environment for root growth compared with –gyp treatments when irrigation did start. The similar yields in ws –gyp to rye +gyp and ws +gyp treatments are a likely result of water conservation by ws and greater hydraulic conductivity created by +gyp.
The mean number of bunches per grapevine at harvest in March 1996 for all treatments was 64.8 (data not shown). The number of bunches per grapevine was greater in ws–gyp treatments than in rye–gyp treatments (Table 6.2), which is consistent with treatment effects on grape yield and shows that the number of bunches is a component of grape yield.

Table 6.2. The number of bunches per grapevine at harvest in March 1996, effect of vine-line cover and gypsum

<table>
<thead>
<tr>
<th></th>
<th>Vine-line cover</th>
<th>rye</th>
<th>ws</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gypsum</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>–</td>
<td>57.5</td>
<td>69.9</td>
<td></td>
</tr>
<tr>
<td>+</td>
<td>67.2</td>
<td>64.7</td>
<td></td>
</tr>
</tbody>
</table>

LSD<sub>5%</sub> = 10.6.

Mean bunch weight at harvest for all treatments in March 1996 was 80.9 g (data not shown). Mean bunch weight was greater in ws than in rye treatments (ws 88.2, rye 73.6 g and LSD<sub>9%</sub> = 8.7). Bunch weights of commercial vineyards range from 40 g (low), 52 g (median) and 100 g (high) (Coombe 1988). Bunch weights here in March 1996 were above the median weights identified by Coombe (1988). Bunch weights for Chardonnay grapevines have been reported as high as 165 g (May 2000), because Chardonnay naturally has a large bunch structure.

Mean berry weight at harvest for all treatments in March 1996 was 1.35 g (data not shown). There were no differences between treatments for berry weight in March 1996, therefore, there was no effect of water stress on berry weight in rye treatments as there was for grape yield (Table 6.1), contradicting findings of Hardie and Considine (1976), Freeman et al. (1979) and Goodwin and Jerie (1992). The absence of a water stress effect
on berry weight may indicate the stress was not severe during cell division (about middle of December to middle of January at Rosbercon Vineyard) and cell expansion (about end of January to end of February at Rosbercon Vineyard) in the berry.

The mean number of berries per bunch for all treatments, calculated as the bunch weight for each treatment divided by the berry weight for each treatment, was 60.0 (data not shown). Therefore, the data presented in Table 6.3 are the calculated number of berries per bunch for each treatment. Like the number of bunches per grapevine, there were more berries per bunch in ws treatments than in rye treatments (ws 65.0, rye 55.0 and \[\text{LSD}_{5\%} = 5.9\]). There was also an effect of interaction between vine-line cover and gypsum for the number of berries per bunch. Treatments of rye –gyp had fewer berries per bunch than did ws +gyp and ws –gyp treatments (Table 6.3).

Table 6.3. The calculated number of berries per bunch at harvest in March 1996, effect of vine-line cover and gypsum

<table>
<thead>
<tr>
<th>Vine-line cover</th>
<th>rye</th>
<th>ws</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum –</td>
<td>51.4</td>
<td>68.0</td>
</tr>
<tr>
<td></td>
<td>58.6</td>
<td>62.1</td>
</tr>
</tbody>
</table>

\[\text{LSD}_{5\%} = 8.4.\]

May (2000) identified the mean number of berries per bunch of Chardonnay, for seasons 1989/90 and 1990/91 in commercial vineyards at Piccadilly in the Adelaide Hills (altitude 500 m) and Willunga, south of Adelaide (altitude 50 m) as 22 and 36 respectively. The mean percentage fruit set at these vineyards was similar (44 % and 41 % respectively) suggesting that a greater number of branches per inflorescence and flowers per inflorescence contributed to the greater number of berries per bunch. My
results are nearly twice these means and I suggest the number of berries per bunch described by May (2000) are extremely low, and are the result of a calculation error.

6.2.2  Yield (March 1997)

Mean grape yield per grapevine at harvest for all treatments in March 1997 was 19.5 kg fruit/vine (data not shown) and triple that of grape yield per grapevine in March 1996 (section 6.2.4). Grape yield per grapevine was greater in fast treatments than in slow treatments (fast 20.27, slow 18.77 kg fruit/vine and LSD$_{5\%}$ = 1.44). The greater area wet that was observed (not measured) in the vine-line, in fast treatments than in slow treatments (section 5.2.4) may have encouraged a greater volume of fibrous (or absorbing) roots in the surface soil. With more absorbing roots in the top 200-300 mm of soil, more water may have been taken up. Buttrose (1974) exposed grapevines grown in potting compost to gravimetric water contents greater than 60 % and approximately 20 % of the water content at field capacity (reference point of 75 % of field capacity = 412.5 g water/kg potting compost). Grapevines supplied with adequate water (> 60 % of field capacity) had a greater number and size of inflorescence primordia compared with those exposed to low potting compost water contents (20 % of field capacity).

There were no differences between treatments for the number of bunches per grapevine. The mean number of bunches per grapevine at harvest for all treatments in March 1997 was 211 (data not shown).

Mean bunch weight at harvest for all treatments in March 1997 was 92.7 g (data not shown). As bunch weight contributes to grape yield per grapevine, it was not surprising that a similar effect of wetting rate on grape yield per grapevine was also found for wetting rate on bunch weight (Table 6.4). In this case, bunch weight was lowest for grapevines in –gyp slow treatments.
Table 6.4. Bunch weight (g) at harvest in March 1997, the interaction between wetting rate and gypsum

gypsum = 12 t/ha gypsum applied to vine-line in May 1995, fast = fast rate of wetting (15 mm/h), 
slow = slow rate of wetting (5 mm/h)

<table>
<thead>
<tr>
<th>Wetting rate</th>
<th>fast</th>
<th>slow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum –</td>
<td>96.1</td>
<td>88.3</td>
</tr>
<tr>
<td></td>
<td>92.5</td>
<td>94.1</td>
</tr>
</tbody>
</table>

LSD$_{5\%}$ = 5.7.

The bunch weight from grapevines of +gyp slow treatments was not different to that of –gyp fast treatments (Table 6.4). The greater volume of water that penetrated to 250 mm depth in +gyp treatments (section 5.2.2) probably provided more water to the grapevine roots than in –gyp treatments. The greater depth of soil wet in +gyp treatments may have counteracted the observed lower area of soil that was wet in slow compared with fast treatments. This is confirmed by the similar estimated volumes of soil wet in +gyp slow and –gyp fast treatments (section 5.2.4).

Mean berry weight at harvest for all treatments in March 1997 was 1.13 g (data not shown). Berry weight was greater in ws treatments than in rye treatments (ws 1.17, rye 1.10 g and LSD$_{5\%}$ = 0.05). The conservation of water by wheat straw covering the soil surface compared with growing ryegrass using water probably provided the grapevine roots access to more water. The volume of water supplied to the grapevine is positively correlated to berry weight through the number of cells developed during early stages of berry growth and the expansion of these cells during ripening (Hardie and Considine 1976; Freeman et al. 1979; Ussahatanonta et al. 1996). The coefficient of variation (CV) for berry weight within treatments ranged from 4 % to 15 %. A CV as great as 15 % for berry weight is likely to reflect the high variability in berry weight that is possible within a single bunch. May (2000) visually categorised the berries of bunches at harvest 1990 of
Chardonnay grapevines at Willunga, South Australia into 4 sizes. The mean berry weight of each category, 1.55 g, 1.23 g, 1.00 g, and 0.63 g, contributed 42 %, 37 %, 18 %, and 3 % of total bunch weight respectively. These data are the only published values I could find of the range of berry weights collected from whole Chardonnay bunches. The data of May (2000) suggest that a CV of 4 % to 15 % within treatments for my experiment is low.

The calculated (section 6.2.1) number of berries per bunch at harvest for all treatments in March 1997 was 82.1 (data not shown). The calculated number of berries per bunch was greater in +gyp treatments than in –gyp treatments (+gyp 83.5, –gyp 80.6 and LSD5% = 2.4). The calculated number of berries per bunch was greater in ws treatments than in rye treatments (ws 84.0, rye 80.2 and LSD5% = 2.4). There was also an effect of interaction between vine-line cover and gypsum application on calculated number of berries per bunch (Table 6.5).

**Table 6.5. Calculated number of berries per bunch at harvest in March 1997, the interaction between vine-line cover and gypsum**

<table>
<thead>
<tr>
<th>Vine-line cover</th>
<th>rye</th>
<th>ws</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum –</td>
<td>79.5</td>
<td>87.6</td>
</tr>
<tr>
<td>+</td>
<td>80.9</td>
<td>80.3</td>
</tr>
</tbody>
</table>

LSD5% = 3.5.

It may be expected that ws +gyp treatments would generate more berries per bunch than –gyp rye treatments because of the individual, positive effects of +gyp and ws treatments on the number of berries per bunch. However, ws –gyp treatments had the greater number of berries per bunch. The application of Ca2+ (gypsum in this case) to the
soil results in exchange with cations, including NH$_4^+$, that may be subsequently leached to greater depths. Leaching of N compounds generally due to higher permeability with Ca$^{2+}$ addition may cause fewer berries per bunch. Ussahatanonta et al. (1996) found fewer berries per bunch in Cabernet Sauvignon grapevines supplied with a low concentration of nutrients compared with those supplied with Osmocote Plus® (0.15 g/g N, 0.048 g/g P, 0.108 g/g K). The leaching of such cations (NH$_4^+$) (not measured here) may explain the increase in soil EC to at least 500 mm depth in +gyp compared with –gyp treatments (section 4.3.2). The cations Ca$^{2+}$, Mg$^{2+}$ and K$^+$ did not contribute to increases in EC because their concentrations were not different below depths of 200 mm, in +gyp compared with –gyp treatments (sections 4.4.2 and 4.4.3).

6.2.3 Yield (March 1998)

There were no differences between treatments for grape yield per grapevine. Mean grape yield per grapevine at harvest for all treatments in March 1998 was 9.6 kg fruit/vine (data not shown).

There were no differences between treatments for the number of bunches per grapevine at harvest. The mean number of bunches per grapevine at harvest for all treatments in March 1998 were 115 (data not shown).

There were no differences between treatments for bunch weight. Mean bunch weight at harvest for all treatments in March 1998 was 82.7 g (data not shown).

There were no differences between treatments for berry weight. Mean berry weight at harvest for all treatments in March 1998 was 1.17g (data not shown). The variation in berry weight within each treatment as indicated by the CV was different between treatments, as shown in Table 6.6.
**Table 6.6. The coefficient of variation (CV) (%) for berry weight at harvest for each treatment in March 1998**

rye = ryegrass grown in vine-line April-September, ws = wheat straw cover of vine-line all year, gypsum = 12 t/ha gypsum applied to vine-line in May 1995, fast = fast rate of wetting (15 mm/h), slow = slow rate of wetting (5 mm/h)

<table>
<thead>
<tr>
<th>Vine-line cover</th>
<th>rye</th>
<th>ws</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wetting rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>fast</td>
<td>14.3</td>
<td>16.2</td>
</tr>
<tr>
<td>slow</td>
<td>13.8</td>
<td>19.8</td>
</tr>
<tr>
<td>fast</td>
<td>16.2</td>
<td></td>
</tr>
<tr>
<td>slow</td>
<td>19.8</td>
<td></td>
</tr>
<tr>
<td>Gypsum –</td>
<td>9.9</td>
<td>8.7</td>
</tr>
<tr>
<td></td>
<td>9.0</td>
<td>11.9</td>
</tr>
</tbody>
</table>

The CV’s in Table 6.6 are small compared with those of berry weights of whole bunches (up to 70 %) collected from Chardonnay at harvest 1990, Willunga, South Australia (May 2000). The actual variation in berry weight may not have been realised in my experiment as the sampling method used (Jordan and Croser 1984, section 2.6.1) removed berries from outside the bunch at top, middle and tail. May (2000) removed all berries from the sampled bunches and randomly selected a sample for berry weight, concluding that variation in berry weight per bunch was significant and techniques for crop sampling should include whole bunches, especially for cultivars with tight bunches such as Chardonnay and Pinot Noir. Contrary to May’s (2000) suggestion, a representative sample may still be achieved following the method of Jordan and Croser (1984).

The calculated number of berries per bunch at harvest (section 6.2.1) for all treatments in March 1998 was 70.4 (data not shown). The number of berries per bunch was greater in ws –gyp treatments than in ws +gyp treatments (ws –gyp 73.2, ws +gyp 67.4 and LSD$_{5\%}$ = 4.4). This was a similar finding to that for berry weight and bunch weight in March 1997 (section 6.2.2). The application of Ca$^{2+}$ (gypsum in this
case) to the soil probably resulted in $\text{Ca}^{2+}$ exchange with other cations, including $\text{NH}_4^+$, that may have been subsequently leached to greater depths. Water stress at flowering can decrease the number of berries that set on bunches (Hardie and Considine 1976). Soil water measurements taken here (chapter 5) suggest no water stress occurred and that all treatments were near to the optimal soil water content of between $0.20 - 0.27 \text{ cm}^3/\text{cm}^3$. Differences here, though significant, are not large as indicated by the range in berry number per bunch for Shiraz (Dry 2000) and Cabernet Sauvignon (Ussahatanonta et al. 1996) of 105-110 and 58-72 respectively.

The luxurious water contents ($0.20 - 0.27 \text{ cm}^3/\text{cm}^3$) maintained within the rootzone of treatment grapevines may have outweighed any stresses the roots would experience as a results of sub-optimal soil physical or chemical properties. Such a deficiency of soil related stresses may explain the lack of significant difference between treatments for grape yield.

6.2.4 Yield summary and conclusion

Decreased grape yield at harvest in 1996 in rye treatments compared with ws treatments was attributed to water stress between bud burst and flowering. Grape yield components affected were fewer bunches per grapevine, fewer berries per bunch and lower bunch weight, which is consistent with responses to water stress observed by others (Hardie and Considine 1976; Freeman et al. 1979; Goodwin and Jerie 1992). Contradictory to these authors, there was no effect in my experiment on berry weight in rye compared with ws treatments, which indicates the stress was probably not severe during cell division and cell expansion in the berry. Treatments with rye +gyp had higher grape yields than did rye –gyp treatments, possibly from the combined increase in number of bunches per grapevine, and number of berries per bunch. This +gyp response is probably from
improved soil conditions and greater hydraulic conductivity in these treatments (sections 3.2, 3.5, and 5.2.2), which may have improved the environment for root growth.

Greater yield and bunch weight at harvest in 1997 for fast treatments was attributed to the greater volume of soil wet in fast than that in slow treatments as estimated in section 5.2.4. Berry weight was greater in ws than in rye treatments and was probably a result of water conservation under ws as shown in Table 3.2. Treatments with +gyp and ws had a positive effect on the calculated number of berries per bunch, however, the combination of ws–gyp had the greatest number of berries per bunch compared with other treatment combinations of gypsum and vine-line cover. The conservation of water by ws and the probable increased concentration of mineral nutrients in the absence of +gyp probably increased berry numbers per bunch.

At harvest in 1998, there was no significant effect of treatments on grape yield or the components of grape yield. However, mean grape yield per grapevine for all treatments decreased compared with that in March 1997. The mean grape yield per grapevine for all treatments for season’s 1995/96, 1996/97 and 1997/98 respectively are shown in Table 6.7.

### Table 6.7. Summary of means of grape yield (kg fruit/vine), number of bunches per grapevine, bunch weight (g), berry weight (g), and number of berries per bunch at harvest for each year of the experiment

<table>
<thead>
<tr>
<th>Harvest in March</th>
<th>Grape yield (kg fruit/vine)</th>
<th>Bunches per vine</th>
<th>Bunch weight (g)</th>
<th>Berry weight (g)</th>
<th>Berries per bunch</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>5.3</td>
<td>64.8</td>
<td>80.9</td>
<td>1.35</td>
<td>60.0</td>
</tr>
<tr>
<td>1997</td>
<td>19.5</td>
<td>211</td>
<td>92.7</td>
<td>1.13</td>
<td>82.1</td>
</tr>
<tr>
<td>1998</td>
<td>9.6</td>
<td>115</td>
<td>82.7</td>
<td>1.17</td>
<td>70.4</td>
</tr>
</tbody>
</table>
The large increase in grape yield at harvest from March 1996 to March 1997 was attributed to improved conditions for root growth, and probably water and nutrient uptake and shoot fruitfulness through changes in irrigation system (microspray), a change to hand-pruning and formation of vine-line beds. The subsequent decrease in grape yield at harvest in March 1998 reflects the inconsistent behaviour of grape yield from season to season (Coombe 1988). The grapevine probably expended large reserves of carbohydrates to more than triple grape yield from season 1995/96 to 1996/97, therefore lowering carbohydrate reserves available for the following season (1997/98) (Mullins et al. 1992). The marked increase in yield at harvest from March 1996 to March 1997, is an indication of the potential production of the Chardonnay crop at Rosbercon Vineyard. However, to achieve grapes of a more desirable ripeness and quality I suggest a regulated deficit irrigation strategy that should marginally decrease grape yield through smaller berries (section 1.3.2).

The relationships between components of grape yield were explored for consistency between years and identification of ratios for Chardonnay crops. Berry weight and the number of berries per bunch explained the variation in bunch weight. At harvest in 1996, 1997 and 1998, berry weight explained 26 %, 29 % and 66 % and berries per bunch explained 67 %, 41 % and 42 %, of the variation in bunch weight, respectively.

The ratios established for Chardonnay at harvest 1996 to 1998 were, [bunch weight (g)/berry weight (g)] ranged from 55 to 75 and [bunch weight (g)/(berries/bunch)] ranged from 0.80 to 1.33.

6.3 Grape quality

6.3.1 Berry composition (March 1996)
The quality components measured on the juice of 100 berries at harvest from each treatment were pH, titratable acidity and soluble solids (Table 6.8). Section 1.5 describes optimal values for Chardonnay grapes for these characters.

There were no differences between treatments for juice pH or titratable acidity. Mean juice pH and titratable acidity at harvest for all treatments in March 1996 were 3.47 and 6.82 respectively (data not shown), within the acceptable range for the production of table wine (section 1.5).

Treatments with rye had greater soluble solids than did ws treatments (rye 23.54, ws 23.13 °Brix and LSD$_{5\%}$ = 0.36) within the acceptable range for the production of table wine (section 1.5). Given the likely cause for lower grape yields in rye treatments was water stress, this finding is similar to Goodwin and Jerie (1992), but contradictory to those of Hardie and Considine (1976), who found a slight delay in the maturity of grapevines that were water stressed between bud burst and veraison.
Table 6.8. Quality components of the juice of 100 berries at harvest from each treatment in March 1996

rye = ryegrass grown in vine-line April-September, ws = wheat straw cover of vine-line all year,
gypsum = 12 t/ha gypsum applied to vine-line in May 1995, fast = fast rate of wetting (15 mm/h),
slow = slow rate of wetting (5 mm/h)

<table>
<thead>
<tr>
<th>Berry composition</th>
<th>Wetting rate</th>
<th>Gypsum +</th>
<th>Gypsum -</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vine-line cover</td>
<td>rye</td>
<td>ws</td>
</tr>
<tr>
<td>PH ^</td>
<td>slow</td>
<td>3.50</td>
<td>3.51</td>
</tr>
<tr>
<td></td>
<td>fast</td>
<td>3.48</td>
<td>3.50</td>
</tr>
<tr>
<td>Titratable acidity (g tartrate equiv./L) ^</td>
<td>slow</td>
<td>6.70</td>
<td>6.55</td>
</tr>
<tr>
<td></td>
<td>fast</td>
<td>6.96</td>
<td>6.56</td>
</tr>
<tr>
<td>Soluble solids (°Brix) ^</td>
<td>slow</td>
<td>23.92</td>
<td>23.14</td>
</tr>
<tr>
<td></td>
<td>fast</td>
<td>23.60</td>
<td>23.28</td>
</tr>
</tbody>
</table>

^ LSD5% = 0.12. ^ LSD5% = 0.82. ^ LSD5% = 0.70.

6.3.2 Berry composition (March 1997)

The quality components measured on juice of 100 berries at harvest from each treatment were pH, titratable acidity and soluble solids (Table 6.9).

Juice pH was greater in rye treatments than in ws treatments (rye 3.66, ws 3.58 and LSD5% = 0.04). The concentration of soluble solids (°Brix) in the berry juice was greater in rye treatments than in ws treatments (rye 21.87, ws 20.86 °Brix, and LSD5% = 0.45). This effect may have been directly due to dilution, as berries from ws treatments were heavier than those from rye treatments (ws 1.17, rye 1.10 g and LSD5% = 0.05) (section 6.2.2). Alternatively, higher soluble solids and pH in rye than in ws treatments suggest that rye treatments were probably at an advanced stage of ripeness, as berries
were smaller and there were fewer per bunch (ws 84.0, rye 80.2 and LSD\textsubscript{5\%} = 2.4) (section 6.2.2). Most treatments failed to reach 22.00 °Brix because the crop load was excessively high (greater than 30 t/ha) compared with the commercial Chardonnay crop (12 t/ha). Treatment grapevines were harvested when the commercial Chardonnay crop was harvested so that grapes could be included with those harvested from the commercial crop. For treatment grapes to ripen fully they should remain on the grapevine until the concentration of soluble solids is acceptable (achieve 22.0 °Brix) (Hamilton and Coombe 1992).

### Table 6.9. Quality components of the juice of 100 berries at harvest from each treatment in March 1997

<table>
<thead>
<tr>
<th>Berry composition</th>
<th>Wetting rate</th>
<th>Gypsum</th>
<th>Vine-line cover</th>
<th>rye</th>
<th>ws</th>
<th>rye</th>
<th>ws</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH\textsuperscript{A}</td>
<td>slow</td>
<td>3.56</td>
<td>3.58</td>
<td>3.70</td>
<td>3.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>fast</td>
<td>3.60</td>
<td>3.59</td>
<td>3.66</td>
<td>3.61</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Titratble acidity (g tartrate equiv./L)\textsuperscript{B}</td>
<td>slow</td>
<td>5.00</td>
<td>4.85</td>
<td>4.91</td>
<td>5.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>fast</td>
<td>5.42</td>
<td>5.35</td>
<td>5.40</td>
<td>5.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soluble solids (°Brix)\textsuperscript{C}</td>
<td>slow</td>
<td>22.04</td>
<td>21.18</td>
<td>21.76</td>
<td>20.64</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>fast</td>
<td>22.00</td>
<td>21.08</td>
<td>21.70</td>
<td>20.54</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\textsuperscript{A} LSD\textsubscript{5\%} = 0.07. \textsuperscript{B} LSD\textsubscript{5\%} = 0.67. \textsuperscript{C} LSD\textsubscript{5\%} = 0.49.

### 6.3.3 Berry composition (March 1998)
The quality components measured on juice of 100 berries at harvest from each treatment were pH, titratable acidity and soluble solids (Table 6.10).

Table 6.10. Quality components of the juice of 100 berries at harvest from each treatment in March 1998

rye = ryegrass grown in vine-line April-September, ws = wheat straw cover of vine-line all year, gypsum = 12 t/ha gypsum applied to vine-line in May 1995, fast = fast rate of wetting (15 mm/h), slow = slow rate of wetting (5 mm/h)

<table>
<thead>
<tr>
<th>Berry composition</th>
<th>Wetting rate</th>
<th>Gypsum +</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vine-line cover</td>
<td>rye</td>
<td>ws</td>
</tr>
<tr>
<td>pH A</td>
<td>slow</td>
<td>3.66</td>
<td>3.71</td>
</tr>
<tr>
<td></td>
<td>fast</td>
<td>3.62</td>
<td>3.64</td>
</tr>
<tr>
<td>Titratable acidity (g tartrate equiv./L) B</td>
<td>slow</td>
<td>6.15</td>
<td>5.64</td>
</tr>
<tr>
<td></td>
<td>fast</td>
<td>6.15</td>
<td>6.04</td>
</tr>
<tr>
<td>Soluble solids (°Brix) C</td>
<td>slow</td>
<td>26.42</td>
<td>26.14</td>
</tr>
<tr>
<td></td>
<td>fast</td>
<td>26.56</td>
<td>26.24</td>
</tr>
</tbody>
</table>

^A LSD_{5%} = 0.11. ^B LSD_{5%} = 0.74. ^C LSD_{5%} = 0.26.

Juice pH was greater in slow treatments than in fast treatments (slow 3.69, fast 3.63 and LSD_{5%} = 0.05). Juice pH is directly related to the content of soluble solids (°Brix) and organic acids (predominantly titratable acidity) in the juice (Hamilton and Coombe 1992). The non-significant trend for soluble solids (slow 26.31, fast 26.17 °Brix, and LSD_{5%} = 0.25) and titratable acidity (slow 5.83, fast 5.98 g tartrate equiv./L, and LSD_{5%} = 0.37) of berry juice, in slow treatments compared with those of fast probably contributed to the greater pH. The resulting components of berry juice could be due to
the greater volume of soil wet that was estimated under fast compared with slow treatments (section 5.2.4), allowing a greater volume of water uptake, causing a dilution in the berries.

The mean value for all treatments for the soluble solids of berry juice at harvest in March 1998 was 26.24 °Brix (data not shown). This concentration of soluble solids is high compared with the range of 18-24 °Brix when grapes are usually harvested in Australia (Hamilton and Coombe 1992). This high concentration of soluble solids was reached, because harvest was delayed. The delay was due to the commercial crop adjoining this experiment ripening later. For commercial reasons harvests coincided.

The mean concentration for all treatments for titratable acidity was 5.90 g tartrate equiv./L (data not shown), which is at the lower end of the ideal range (5-9) (section 1.5) and a result of grapes more ripe than optimum.

6.3.4 Grape quality summary and conclusion

The concentration of soluble solids (°Brix) of grapes at harvest in 1996 was greater in rye than in ws treatments which is consistent with lower grape yields in rye than in ws treatments. These findings are similar to those of Goodwin and Jerie (1992) who imposed water stress between flowering and veraison.

The heavy crop carried by all treatments in March 1997 lead to less than desirable concentration of soluble solids of grapes at harvest. At harvest, as indicated by higher °Brix and higher pH, grapes from rye treatments were at a more advanced stage of ripeness compared with grapes from ws treatments. This was probably a result of smaller and fewer berries per bunch in rye than in ws treatments.

The greater volume of soil wet in fast than in slow treatments probably diluted soluble solid concentrations and decreased juice pH in the berry at harvest 1998. The wetting
effect on pH may have been affected by the delayed harvest and resultant low pH, low
titratable acid and high soluble solids of berry juice.

6.4 Grapevine fruitfulness

6.4.1 Merbein Bunch Counts (October 1995)

Data from MBCs performed in October 1995 on 1 grapevine per treatment were used to
calculate mean number of bunches per grapevine and mean number of bunches per
fruitful shoot (fruitfulness of grapevine shoots). Because the experiment was established
during winter 1995, the MBC performed in season 1995/96 does not reflect the treatments
implemented. However, the data show the state of the vineyard when the experiment
began.

The mean number of bunches per grapevine for all treatments in October 1995 is
shown in Table 6.11. The CV for the number of bunches per grapevine between
treatments was 24.8 %, and considered low compared with that of others (Coombe 1988;
Dry 2000; May 2000). These data correlate well with the actual number of bunches per
grapevine (65) at harvest and CV (17.8 %) between treatments. Data from this experiment
show that mean number of bunches per grapevine for all treatments was in the lower half
of the range described by Coombe (1988).

Mean number of bunches per fruitful shoot for all treatments in October 1995 was 1.2
and CV of 7.7 % between treatments (data not shown). I have found no published data
for bunches per fruitful shoot for Chardonnay in Australia, however, Freeman et al.
(1979) and Dry (2000) for spur pruned Shiraz found 1.6 and 1.63 bunches per fruitful
shoot, respectively. Compared with the above authors, fruitfulness of shoots of
Chardonnay grapevines at Picola in 1995/96 was less than Shiraz grapevines grown in
warmer climates (Griffith, NSW (Freeman et al. 1979) and Waikerie, SA (Dry 2000)).
6.4.2 Merbein Bunch Counts (October 1996)

Data from MBCs performed in October 1996 on 1 grapevine per treatment were used to calculate mean number of bunches per grapevine and mean number of bunches per fruitful shoot.

The mean number of bunches per grapevine for all treatments in October 1996 is shown in Table 6.11. The CV for the number of bunches per grapevine between treatments was 21.5 %, and considered low compared with that of others (Coombe 1988, Dry 2000, May 2000). These data correlate well with the actual number of bunches per grapevine (211) at harvest and CV (21.5 %) between treatments. The data from October 1996 for this experiment show mean number of bunches per grapevine for all treatments were in the third quartile of the range described by Coombe (1988). The CV between all treatments for number of bunches per grapevine in October 1996 was similar to that in October 1995. This indicates that variation between treatments for bunches per grapevine was not markedly affected from season 1995/96 to 1996/97 by the application of treatments. This is strengthened by the lack of significant differences found between treatments for bunches per grapevine.

Mean number of bunches per fruitful shoot for all treatments in October 1996 is shown in Table 6.11 and had a CV of 11.1 % between treatments. The magnitude of fruitfulness achieved across treatments in October 1996 is closer to that found by Freeman et al. (1979) and Dry (2000) (section 1.5), than that achieved in my experiment in October 1995. This increase in fruitfulness may have resulted from improved light and heat on latent buds by the change to spur pruning at 15-20 buds per m of cordon in July 1995 compared with hedging (> 40 buds per m) used previously (Smart and Robinson 1991).

Treatments with ws –gyp had more bunches per fruitful shoot than did rye –gyp treatments (ws –gyp 1.7, rye –gyp 1.4 LSD5% = 0.16), probably because there was a greater volume of available soil water under ws than under rye treatments (section 3.2) (Williams and Matthews 1990).
6.4.3 Merbein Bunch Counts (October 1997)

Data from MBCs performed in October 1997 on 1 grapevine per treatment were used to calculate mean number of bunches per grapevine and mean number of bunches per fruitful shoot.

The mean number of bunches per grapevine for all treatments in October 1997 is shown in Table 6.11. The CV for the number of bunches per grapevine between treatments was 15.1 %, and considered low compared with that of others (Coombe 1988; Dry 2000; May 2000). These data correlate well with the actual number of bunches per grapevine (115) at harvest and CV (10.8 %) between treatments. The data from October 1997 for this experiment show mean number of bunches per grapevine for all treatments were in the second quartile of the range described by Coombe (1988). The CV between all treatments for number of bunches per grapevine in October 1997 was lower than those in October 1995 and 1996. This indicates that variation between treatments for bunches per grapevine was decreased from season 1995/96 to 1997/98 by the application of treatments. This is strengthened by the lack of significant differences found between treatments for bunches per grapevine in October 1997.

Mean number of bunches per fruitful shoot for all treatments in October 1997 is shown in Table 6.11 and had a CV of 6.7 % between treatments. The magnitude of fruitfulness achieved across treatments in October 1997 decreased from that in October 1996 and was lower than that found by Freeman et al. (1979) and Dry (2000) (section 1.5). The decrease in fruitfulness from October 1996 to October 1997 may have been due to the heavy crop in season 1996/97 (section 6.2.2) resulting in low reserves of carbohydrates (Mullins et al. 1992). In October 1997, there were no significant differences found between treatments for number of bunches per fruitful shoot.
6.4.4 Merbein Bunch Counts (October 1998)

A partial MBC was conducted in October 1998 (section 2.6.3) to explore the impact of treatments on bunches per grapevine and mean number of bunches per fruitful shoot in the 4th season of the experiment (1998/99).

The mean number of bunches per grapevine for all treatments in October 1998 is shown in Table 6.11. The CV for the number of bunches per grapevine between treatments was 13.5 %, and considered low compared with that of others (Coombe 1988; Dry 2000; May 2000). The experiment ceased in October 1998 therefore, grape yield at harvest was not measured. The data from October 1998 for this experiment show mean number of bunches per grapevine for all treatments were in the third quartile of the range described by Coombe (1988). The CV between all treatments for number of bunches per grapevine in October 1998 was lower again than those in October 1995, 1996 and 1997 (Table 6.11, section 6.4.5). This shows that variation between treatments for bunches per grapevine decreased over the experiment. This suggests that management of the experiment decreased variation between treatments to a greater degree, more than treatments affected the number of bunches per grapevine. Management of the experiment consisted of pruning to a uniform number of buds per m of cordon, hilling soil into beds along the vine-line and applying the same volume of water to each vine. This is strengthened by the lack of significant differences found between treatments for bunches per grapevine in October 1998.

Mean number of bunches per fruitful shoot for all treatments in October 1998 is shown in Table 6.11 and had a CV of 4.5 % between treatments. The magnitude of fruitfulness achieved across treatments in October 1998 increased from that in October 1997 and was similar to that found by Freeman et al. (1979) and Dry (2000) (section 1.5).

In October 1998, mean number of bunches per fruitful shoot was greater in +gyp treatments than that in –gyp treatments (+gyp 1.5, –gyp 1.6 and LSD_{5%} = 0.05). The improved hydraulic properties of the surface soil (section 5.2.2) probably contributed to
better aeration and benefits for root growth and shoot fruitfulness. Shoot fruitfulness depends on grapevine water status (Williams and Matthews 1990), and inflorescence primordia die in the absence of functioning roots (Mullins 1966). However, fruitfulness of shoots depends on air temperature (Coombe 1988) and incidence of solar radiation on latent buds (Smart 1987), that were not measured.

6.4.5  Grapevine fruitfulness summary and conclusion

Data from October 1995 were indicative of the state of the vineyard when the experiment began. The number of bunches per grapevine and corresponding CV between treatments (Table 6.11) were low compared with those of other Chardonnay crops in the Goulburn Valley and Rutherglen districts (Martin and Dunn pers. comm. 2001). Fruitfulness of grapevine shoots (Table 6.11) was also considered low when compared with that of Shiraz crops from warmer climates (Griffith, NSW (Freeman et al. 1979) and Waikerie, SA (Dry 2000)).

Table 6.11. Summary of means and coefficients of variation (CV’s) for the number of bunches per grapevine and number of bunches per fruitful shoot from Merbein

<table>
<thead>
<tr>
<th>Harvest in March</th>
<th>Bunches per grapevine</th>
<th>CV for bunches per grapevine</th>
<th>Bunches per fruitful shoot</th>
<th>CV for bunches per fruitful shoot</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>65</td>
<td>24.8</td>
<td>1.2</td>
<td>7.7</td>
</tr>
<tr>
<td>1996</td>
<td>206</td>
<td>21.5</td>
<td>1.5</td>
<td>11.1</td>
</tr>
<tr>
<td>1997</td>
<td>109</td>
<td>15.1</td>
<td>1.4</td>
<td>6.7</td>
</tr>
<tr>
<td>1998</td>
<td>173</td>
<td>13.5</td>
<td>1.6</td>
<td>4.5</td>
</tr>
</tbody>
</table>
In October 1996, the number of bunches per grapevine (Table 6.11) was higher than that of others in the Goulburn Valley and Rutherglen districts (Martin and Dunn pers. comm. 2001), while the CV between treatment grapevines (Table 6.11) remained low and similar to that in October 1995. There were no significant differences between treatments for number of bunches per grapevine, which is consistent with the low CV between treatment grapevines. Fruitfulness of grapevine shoots increased from October 1995 (Table 6.11), probably from an improved pruning method (compared with hedging) and irrigation system (compared with overhead sprinkler). The estimated volume of soil wet was greater in ws –gyp treatments and probably increased fruitfulness of grapevine shoots compared with rye –gyp treatments.

The number of bunches per grapevine in October 1997 (Table 6.11) was lower than in October 1996, however, higher than others in the district were. The corresponding CV for the number of bunches per grapevine (Table 6.11) was again low in October 1997 and strengthened by the lack of significant differences between treatments. Fruitfulness of grapevine shoots decreased from October 1996 to October 1997 (Table 6.11), probably because of the high crop load in season 1996/97 and low reserves of carbohydrates.

The number of bunches per grapevine in October 1998 (Table 6.11) increased from October 1997, but not to the numbers reached in October 1996. The fruitfulness of grapevine shoots in October 1998 (Table 6.11) was the highest for the 4 years of the experiment. The improved hydraulic properties of the surface soil in +gyp treatments probably contributed to the greater shoot fruitfulness than in –gyp treatments (section 6.4.4).

The number of bunches per grapevine determined in October always correlated well with those picked from grapevines at harvest of that season. The CV between all treatments for number of bunches per grapevine became progressively lower from October 1995, 1996, 1997 to 1998 (Table 6.11), showing that variation decreased over the life of the experiment. This implies that management of the experiment decreased
variation between treatments to a greater degree than treatments affected bunches per grapevine. Compared with the commercial vineyard, the management of the experiment, which consisted of pruning to a uniform number of buds per m of cordon, hilling soil into beds along the vine-line and applying the same volume of water to each grapevine indicates that grape yield can be increased and be less variable.

6.5 Vegetative growth and grapevine balance

6.5.1 Pruning weight (July 1996)

Mean pruning weight per grapevine on July 10 1996 for all treatments for season 1995/96 was 0.6 kg/vine (Table 6.12). Mean pruning weight was greater for ws than rye treatments (ws 0.67, rye 0.52 kg and LSD$_{5\%}$ = 0.08). The low vegetative growth in rye treatments may have resulted from water stress from bud burst to flowering, as affected grape yield (section 6.2.1). This finding is similar to that of Goodwin and Jerie (1992) who found pruning weight was decreased by 25 % of the control when water stress was imposed pre-veraison.

Industry standards for vegetative growth (pruning weight) and the balance between grape yield and vegetative growth (grape yield/pruning weight ratio) have been developed by Smart and Robinson (1991). Table 6.1.2 shows treatment means for pruning weights and grape yield/pruning weight ratios in my experiment and industry standards are shown in Table 1.5.

Mean cane weights from Table 6.12 show that vegetative vigour in all treatments was low in season 1995/96. The method used to calculate mean cane weight (section 2.6.4) may have underestimated mean cane weight, as all shoots counted in October during a MBC may not have been weighed at pruning or small shoots included in a MBC may not have developed into mature shoots. Shoots counted in October were used to calculate mean cane weight instead of those pruned in July because of time restraints at pruning.
Mean cane weights were typically 6 g below that required for low to moderate vigour. Grape yield to pruning weight ratio was in the moderate range, indicating pruning weights and grape yields in all treatments were low.

Table 6.12. Mean grape yield, pruning weight, mean cane weight and grape yield to pruning weight ratio for each treatment for season 1995/96

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Wetting rate</th>
<th>Vine-line cover</th>
<th>Grape yield B (kg/vine)</th>
<th>Pwt A,C (kg/vine)</th>
<th>Mean cane wt D (g)</th>
<th>Ratio Grape yield/Pwt E</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>slow</td>
<td>rye +gyp</td>
<td>5.6</td>
<td>0.5</td>
<td>3.3</td>
<td>9.8</td>
</tr>
<tr>
<td>2</td>
<td>slow</td>
<td>ws +gyp</td>
<td>5.3</td>
<td>0.6</td>
<td>3.8</td>
<td>8.9</td>
</tr>
<tr>
<td>3</td>
<td>slow</td>
<td>ws –gyp</td>
<td>6.1</td>
<td>0.7</td>
<td>3.6</td>
<td>9.1</td>
</tr>
<tr>
<td>4</td>
<td>slow</td>
<td>rye –gyp</td>
<td>3.4</td>
<td>0.4</td>
<td>2.4</td>
<td>8.3</td>
</tr>
<tr>
<td>5</td>
<td>fast</td>
<td>rye +gyp</td>
<td>5.5</td>
<td>0.5</td>
<td>2.5</td>
<td>10.3</td>
</tr>
<tr>
<td>6</td>
<td>fast</td>
<td>ws +gyp</td>
<td>5.9</td>
<td>0.7</td>
<td>3.7</td>
<td>9.0</td>
</tr>
<tr>
<td>7</td>
<td>fast</td>
<td>ws –gyp</td>
<td>6.6</td>
<td>0.7</td>
<td>4.2</td>
<td>9.1</td>
</tr>
<tr>
<td>8</td>
<td>fast</td>
<td>rye –gyp</td>
<td>4.3</td>
<td>0.6</td>
<td>3.3</td>
<td>7.3</td>
</tr>
</tbody>
</table>

A Pwt = Pruning weight. B LSD5% = 1.9. C LSD5% = 0.2. D LSD5% = 1.4. E LSD5% = 2.2.

6.5.2 Shoot growth, leaf number, butt circumference and pruning weight (season 1996/97)

There were no differences between treatments in shoot growth per week. Shoot growth rate was greatest at 100 mm per week around October 21 when shoot length was approximately 330 mm (data not shown). Williams and Matthews (1990) observed a peak in shoot growth per week for Colombard grapevines of 170 mm approximately 20 days after bud burst. Total shoot length on November 29 1996 (last reading for the season) was approximately 730 mm (data not shown). Shoot growth per week had decreased considerably by the end of November and was less than 20 mm. Smart and
Robinson (1991) suggested that shoot length for a grapevine of moderate vigour is approximately 1000 mm.

There were no differences between treatments for leaf number per shoot on November 29, 1996. The mean number of leaves per shoot at this time was 27 (data not shown). Butt circumference did not change over the measurement period (October 14 to November 29, 1996).

Mean pruning weight per grapevine on July 2, 1997 for all treatments for season 1996/97 was 0.9 kg/vine (Table 6.13). Pruning weight was greater in rye treatments than in ws treatments (rye 0.9, ws 0.8 kg and LSD$_{0.05}$ = 0.09). The difference (120 g) here is small even when compared with the low pruning weights observed across all treatments (Table 6.13). The vineyard was hedged with a mechanical trimmer (vertical arm consisting of 2 serrated blades oscillating in opposite directions) attached to a tractor during December 1996 to trim the long shoots growing into the row, thus providing access for tractors. During winter pruning (May-June 1997) in the vineyard, a vertical and horizontal saw (toothed blades that were round and spin) was used to prune the majority of canes from the commercial grapevines. The saw accidentally pruned the western side of row (rep) 2 of the experiment. The stimulation of lateral growth by the trimming during December 1996 probably made up for some of the growth lost during trimming, however, the 2 events (trimming and sawing) described probably decreased the pruning weight of grapevines determined on July 2, 1997.

Table 6.13 shows treatment means for pruning weight and grape yield/pruning weight ratio. Values in Table 6.13 can be compared with industry standards for vigour level and grapevine balance, as defined by Smart and Robinson (1991) (Table 1.5).
Table 6.13. Mean grape yield, pruning weight, mean cane weight and grape yield to pruning weight ratio for grapevines from each treatment for season 1996/97

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Wetting rate</th>
<th>Vine-line cover</th>
<th>Grape yield B (kg/vine)</th>
<th>Pwt A,C (kg/vine)</th>
<th>Mean cane wt D (g)</th>
<th>Ratio Grape yield/Pwt E</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>slow</td>
<td>rye +gyp</td>
<td>19.9</td>
<td>0.9</td>
<td>4.2</td>
<td>22.2</td>
</tr>
<tr>
<td>2</td>
<td>slow</td>
<td>ws +gyp</td>
<td>18.9</td>
<td>0.8</td>
<td>4.2</td>
<td>25.8</td>
</tr>
<tr>
<td>3</td>
<td>slow</td>
<td>ws –gyp</td>
<td>19.4</td>
<td>0.8</td>
<td>4.8</td>
<td>23.0</td>
</tr>
<tr>
<td>4</td>
<td>slow</td>
<td>rye –gyp</td>
<td>16.8</td>
<td>0.8</td>
<td>3.5</td>
<td>23.3</td>
</tr>
<tr>
<td>5</td>
<td>fast</td>
<td>rye +gyp</td>
<td>19.8</td>
<td>0.9</td>
<td>4.7</td>
<td>21.0</td>
</tr>
<tr>
<td>6</td>
<td>fast</td>
<td>ws +gyp</td>
<td>20.0</td>
<td>0.8</td>
<td>4.0</td>
<td>26.2</td>
</tr>
<tr>
<td>7</td>
<td>fast</td>
<td>ws –gyp</td>
<td>21.5</td>
<td>0.8</td>
<td>4.2</td>
<td>26.6</td>
</tr>
<tr>
<td>8</td>
<td>fast</td>
<td>rye –gyp</td>
<td>19.8</td>
<td>1.0</td>
<td>5.0</td>
<td>19.7</td>
</tr>
</tbody>
</table>

A Pwt = Pruning weight. B LSD5% = 2.9. C LSD5% = 0.2. D LSD5% = 1.6. E LSD5% = 4.4.

Mean cane weights show that vegetative vigour in all treatments was low in season 1996/97 (Table 6.13), compared with industry standards (Table 1.5). Mean cane weight was typically 5 g less than that required for low to moderate vigour. The large grape yield in 1996/97 compared with that of vegetative vigour resulted in a grape yield to pruning weight ratio greater than 12, indicating vigour was low (Table 6.13). Low vegetative vigour indicates low leaf area, therefore, limits the grape yield the grapevine can ripen (Smart and Robinson 1991).

6.5.3 Shoot growth, leaf number, butt circumference and pruning weight (season 1997/98)

There were no differences between treatments for shoot growth per week. Shoot growth per week peaked between 140 and 160 mm around November 3 1997 when shoots were approximately 450 mm (data not shown). Total shoot length on January 6 1998 (last
reading for the season) was approximately 850 mm. Many shoots had stopped growing as indicated by their brown tips.

There were no differences between treatments for leaf number per shoot on December 9 1997. The mean leaf number per shoot at this time was 37 (data not shown). No significant differences were identified between treatments for butt circumference. Changes in butt circumference were small with a maximum of 6.0 mm per month (data not shown).

There were no differences between treatments for pruning weight per grapevine. Mean pruning weight per grapevine on July 9 1998 for all treatments for season 1997/98 was 0.8 kg/vine (Table 6.14). Table 6.14 shows treatment means for pruning weight and grape yield/pruning weight ratio. Values in Table 6.14 can be compared with industry standards for vigour level and grapevine balance, as defined by Smart and Robinson (1991) (Table 1.5).

Table 6.14. Mean grape yield, pruning weight, mean cane weight and grape yield to pruning weight ratio for grapevines from each treatment for season 1997/98

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Wetting rate</th>
<th>Vine-line cover</th>
<th>Grape yield B (kg/vine)</th>
<th>Pwt A,C (kg/vine)</th>
<th>Mean cane wt D (g)</th>
<th>Ratio Grape yield/Pwt E</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>slow</td>
<td>rye +gyp</td>
<td>10.3</td>
<td>0.9</td>
<td>4.1</td>
<td>12.0</td>
</tr>
<tr>
<td>2</td>
<td>slow</td>
<td>ws +gyp</td>
<td>8.3</td>
<td>0.8</td>
<td>4.0</td>
<td>10.4</td>
</tr>
<tr>
<td>3</td>
<td>slow</td>
<td>ws –gyp</td>
<td>10.2</td>
<td>0.8</td>
<td>4.0</td>
<td>12.8</td>
</tr>
<tr>
<td>4</td>
<td>slow</td>
<td>rye –gyp</td>
<td>8.4</td>
<td>0.7</td>
<td>3.6</td>
<td>12.3</td>
</tr>
<tr>
<td>5</td>
<td>fast</td>
<td>rye +gyp</td>
<td>10.2</td>
<td>0.9</td>
<td>4.0</td>
<td>11.9</td>
</tr>
<tr>
<td>6</td>
<td>fast</td>
<td>ws +gyp</td>
<td>9.3</td>
<td>0.8</td>
<td>3.7</td>
<td>12.0</td>
</tr>
<tr>
<td>7</td>
<td>fast</td>
<td>ws –gyp</td>
<td>9.1</td>
<td>0.8</td>
<td>3.9</td>
<td>11.8</td>
</tr>
<tr>
<td>8</td>
<td>fast</td>
<td>rye –gyp</td>
<td>10.9</td>
<td>0.8</td>
<td>3.6</td>
<td>13.5</td>
</tr>
</tbody>
</table>

A Pwt = Pruning weight. B LSD5% = 2.7. C LSD5% = 0.2. D LSD5% = 1.0. E LSD5% = 4.2.
Mean cane weights show that vegetative growth in all treatments was low in season 1997/98 (Table 6.14), compared with industry standards (Table 1.5). Mean cane weight was typically 4 g, less than half the maximum for vigour to be classed as low. The mean grape yield in 1997/98 was 16.7 t/ha (9.6 kg/vine), which was high compared with the mean grape yield in Moira Shire West (7.5 t/ha) and Greater Victoria (7.9 t/ha) (Australian Bureau of Statistics 1999). The ratio of grape yield to pruning weight showed that grapevines were only just into the moderate level of vigour. Therefore, vegetative vigour (including mean cane weight) of these grapevines could have been increased to improve the balance between grape yield and pruning weight.

6.5.4 Vegetative growth and grapevine balance summary and conclusion

In season 1995/96, water stress between bud burst and flowering in rye treatments caused lower pruning weights compared with ws treatments. Grapevines from all treatments were balanced although generally low in vegetative growth and grape yield.

In season 1996/97, shoot growth per week and leaf number per shoot were the same for all treatments. Shoot growth peaked at 100 mm per week around October 21 1996. Butt circumference did not change from October 14 to November 29 1996. Pruning weight was marginally but significantly greater in rye than in ws treatments, however, commercial activities may have influenced results when the experiment was accidentally trimmed and sawed. The large increase in grape yield relative to pruning weight from season 1995/96 to 1996/97 resulted in unbalanced grapevines in all treatments.

In season 1997/98, shoot growth per week, leaf number per shoot and pruning weight per grapevine were the same for all treatments. Change in butt circumference was small and not different between treatments. Shoot growth peaked at approximately 140-160 mm per week around November 3 1997. Pruning weights were similar to season
1996/97 and there were no differences between treatments. As in season 1996/97, vegetative growth was again low for all treatments and as grape yield dropped from the previous season grapevines were in balance.

6.6 Root growth

6.6.1 Roots 1996

In January 1996, at 200-250 mm depth, rye treatments had greater root length per volume of soil than ws treatments (Table 6.15). At 450-500 mm, rye treatments had greater root length per volume of soil than did ws treatments (Table 6.15). Pradel and Pieri (2000) found that grapevines were more deeply rooted on grassed (rye grass/fescue (*Festuca* sp.)) than on ploughed soil, presumable due to competition with grass roots for soil resources.

Maximum root length per volume of soil was 4.48 cm/cm$^3$ at 100-150 mm depth in ws–gyp slow treatments. Concentrations of grapevine roots recorded at various locations, under a range of conditions and stages of grapevine growth varied from 0.4-0.5 cm/cm$^3$ (Stevens and Douglas 1994; Hunt 1994) to 1.2 cm/cm$^3$ (Freeman 1983).

The values found here are at least 3 times those that were previously reported. Therefore, the determination of root concentrations was needed in following seasons to quantify and qualify these initial results.
Table 6.15. Root length per volume of soil (RLD, cm/cm³) with depth below the vine-line (mean of 2 vines). The effects of vine-line cover (January 1996)

rye = ryegrass grown in vine-line April-September, ws = wheat straw cover of vine-line all year

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>rye</th>
<th>ws</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-50 A</td>
<td>1.67</td>
<td>2.26</td>
</tr>
<tr>
<td>50-100 B</td>
<td>3.06</td>
<td>2.96</td>
</tr>
<tr>
<td>100-150 C</td>
<td>2.68</td>
<td>2.83</td>
</tr>
<tr>
<td>150-200 D</td>
<td>2.35</td>
<td>1.99</td>
</tr>
<tr>
<td>200-250 E</td>
<td>1.71</td>
<td>1.22</td>
</tr>
<tr>
<td>250-300 F</td>
<td>1.24</td>
<td>1.11</td>
</tr>
<tr>
<td>300-350 G</td>
<td>0.95</td>
<td>0.83</td>
</tr>
<tr>
<td>350-400 H</td>
<td>0.96</td>
<td>0.98</td>
</tr>
<tr>
<td>400-450 I</td>
<td>0.90</td>
<td>0.89</td>
</tr>
<tr>
<td>450-500 J</td>
<td>0.84</td>
<td>0.57</td>
</tr>
</tbody>
</table>

A LSD₅% = 1.00. B LSD₅% = 0.68. C LSD₅% = 1.16. D LSD₅% = 0.61. E LSD₅% = 0.47. F LSD₅% = 0.43. G LSD₅% = 0.36. H LSD₅% = 0.51. I LSD₅% = 0.33. J LSD₅% = 0.26.

In July 1998, at 0-100 mm, rye treatments had greater root length per volume of soil than did ws treatments (Table 6.16). At 200-300 mm depth rye treatments showed a non-significant trend (P = 0.059) for greater root length per volume of soil than ws treatments (Table 6.16).

The concentration of roots in the top 100 mm increased substantially from 1996 to 1998 (mean of all treatments 1996 = 2.6 cm/cm³, and 1998 = 4.2 cm/cm³), indicating extensive exploration of the hilled vine-line soil. The actively growing ryegrass in the vine-line at the time of sampling soil for root determination (July 1998) may have...
influenced results because some ryegrass roots may have been included in the total. This was a result of the difficulty of separating ryegrass and grapevine roots. The root concentrations found in my experiment were higher than those previously reported for grapevines (Stevens and Douglas 1994) and similar to those found in fruit trees (Richards and Cockroft 1974; Olsson and Rose 1988).

Table 6.16. Root length per volume of soil (RLD, cm/cm³) with depth below the vine-line (mean of 2 vines). The effects of vine-line cover (July 1998)

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>rye</th>
<th>ws</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-100 A</td>
<td>5.05</td>
<td>3.35</td>
</tr>
<tr>
<td>200-300 B</td>
<td>2.21</td>
<td>1.47</td>
</tr>
<tr>
<td>400-500 C</td>
<td>0.57</td>
<td>0.87</td>
</tr>
</tbody>
</table>

A LSD5% = 1.08. B LSD5% = 0.76. C LSD5% = 0.45.

6.6.3 Root growth summary and conclusion

In January 1996 and July 1998, rye treatments had greater root length per volume of surface soil at 200-250 mm and 0-100 mm depth respectively, than did ws treatments. In January 1996, rye treatments also had greater root length per volume of subsoil (450-500 mm) than did ws treatments. Root growth in rye treatments was probably more explorative early (season 1995/96) in the experiment when grapevines experienced water stress than root growth in ws treatments.

The concentrations of roots in the surface soil in my experiment are at least 3 times those previously reported. This was probably a result of the ideal growing conditions provided by the treatments. For example, penetrometer resistance less than 2 MPa for a
depth of at least 130 mm, bulk density less than 1.28 g/cm$^3$ in the surface 114 mm of soil, and macroporosity greater than 0.27 in the surface 114 mm of soil.

For all treatments, the concentration of roots in the surface 0-100 mm increased from January 1996 to July 1998, indicating exploration of the hilled vine-line soil, however, ryegrass roots may have been counted as those of grapevine.

6.7 Summary and conclusions
In March 1996, grape yield as bunches per vine, bunch weight and berries per bunch was decreased by water stress in rye compared with ws treatments. The addition of +gyp to rye treatments increased grape yields probably from improved soil conditions and greater hydraulic conductivity in these treatments. The greater estimated volume of soil wet in fast treatments probably increased grape yield and bunch weight at harvest 1997, compared with those of slow treatments. Conservation of water by ws increased berry weight compared with rye treatments and ws –gyp treatments had the greatest number of berries per bunch. Treatments had no impact on grape yield or its components at harvest 1998. Grape yields at harvest 1996, 1997 and 1998 were 5.3, 19.5 and 9.6 kg fruit/vine. The rise in grape yield in 1997 was attributed to improved conditions for root growth, water and nutrient uptake and shoot fruitfulness, while the fall in 1998 was probably from depleted carbohydrate reserves in grapevines.

Consistent with water stress pre-veraison, rye treatments at harvest 1996 had greater concentration of soluble solids in berry juice than did ws treatments. At harvest 1997, as indicated by soluble solids and pH of berry juice, and irrespective of the heavy crop load, grapes in rye treatments were at a more advanced stage of ripeness than were grapes in ws treatment. This was probably a result of smaller and fewer berries per bunch in rye than those in ws treatments. Berry composition at harvest 1998 was beyond optimum as a
result of early ripening compared with the commercial Chardonnay crop, and hence for commercial reasons the experiment was harvested later than was desirable.

Fruitfulness of grapevine shoots was low at the beginning of the experiment (October 1995) compared with other varieties elsewhere. Shoot fruitfulness improved markedly in all treatments in October 1996, probably from improved bud selection at pruning and more efficient irrigation. Shoot fruitfulness dropped in October 1997 after the heavy crop in the previous season, however, shoot fruitfulness increased to the highest level in the 4 years in October 1998. The number of bunches from MBC’s always correlated well with the number of bunches at harvest. The CV between treatments for the number of bunches per grapevine decreased each year of the experiment, suggesting management of the experiment decreased variation between treatments to a greater degree than treatments impacted on bunches per grapevine.

Shoot growth per week was the same for all treatments in seasons 1996/97 and 1997/98, with peak growth per week occurring around October 21 1996 and November 3 1997, respectively. Butt circumference did not change significantly; therefore, no differences between treatments were apparent. Pruning weights per grapevine were low at the beginning of the experiment (July 1996) compared with industry standards. The symptoms of water stress in season 1995/96 were again apparent in rye treatments as lower pruning weights than in ws treatments. Pruning weights increased marginally in the following seasons (1996/97 and 1997/98), though still low compared with industry standards. Grapevines were balanced at the beginning of the experiment, high yields lead to unbalanced grapevines in season 1996/97 and a drop in yield in 1997/98 produced balanced grapevines.

Explorative root growth as a result of water stress in season 1995/96, may explain greater concentrations of roots at 200-250 mm and 450-500 mm depths in rye than in ws treatments. Root concentrations in the surface soil were found to be 3 times those previously reported, indicating extensive exploration of the hilled vine-line soil.
Improved soil physical and hydraulic properties of hard-setting and crusting soil with the growth of ryegrass for stable aggregates and coagulated clay by the application of gypsum can improve grape yield. Two seasons of ryegrass growth in the vine-line soil can result in advanced ripening of smaller berries and fewer berries per bunch compared with those with vine-line soil under mulch. Improved shoot fruitfulness and uniformity in yield between grapevines can be achieved by improving management such as: hilling soil in the vine-line when the surface soil is shallow (< 300 mm), pruning grapevines to 15-20 buds per m of cordon, and applying the same volume of water to each grapevine.
Chapter 7

General discussion and conclusion
Many of the grapegrowing regions in south-eastern and Western Australia have HRDS as the major soil type (Northcote 1988). Tilled HRDS slake and disperse when wet and set hard if not protected by organic matter and supplied with a calcium rich electrolyte. Because the production of winegrapes is a long term (> 20 years) investment, managing HRDS to decrease the rate of crusting and/or hard-setting will benefit viticulture.

The most common management of HRDS in vineyards includes growing a covercrop or permanent sward in the inter-row, while maintaining the vine-line bare and weed free with herbicide. If organic matter and gypsum are not applied to the surface soil a crust forms and the soil sets hard. It is difficult to manage irrigation and plant nutrition on such soils because initially irrigation water runs off. Once rain or irrigation does wet the soil, it can remain wet for long periods, with the potential of waterlogging the rootzone. The vine-line soil described in chapters 2-6 had slaked and dispersed before my experiment was set up and so was typical of a HRDS.

My experiment was set up to modify the soil to overcome the limitations of hardsetting and crusting, to improve infiltration of water and aeration and increase root growth and grapevine performance. The experiment was established at Rosbercon Vineyard, Picola, Victoria in May 1995 and concluded in October 1998. The null hypotheses, a) transient waterlogging decreases root growth and grapevine performance, and b) hardening of soil decreases root growth and grapevine performance, were disproved.

The results of the experiment showed that waterlogging of the surface soil 24 h after 40 mm of irrigation can be avoided and root growth and grapevine performance increased (hypothesis a). Hardening of tilled soil can be overcome, at least in the medium term (3 years), and root growth and grapevine performance can be increased (hypothesis b). The flow chart (Fig. 7.1) at the rear of this thesis shows how the results discussed in this chapter are linked to root growth and grapevine performance.

Soil properties that were improved and may have contributed to improved growth of grapevines are now discussed. A greater depth of soil < 2 MPa penetrometer resistance
was achieved where rye was grown and +gyp applied compared with ws and –gyp. There was a greater proportion (0.35 cm³/cm³) of surface soil (20-114 mm depth) containing macropores where rye was grown than where ws was applied (0.31 cm³/cm³). As a result of hilling up soil macroporosities in all treatments were markedly greater than the critical volume for root growth (0.10 cm³/cm³). There was also a decrease in spontaneous and remoulded aggregate dispersion to 500 mm depth where +gyp was applied. For example, remoulded aggregate dispersion decreased from 3.8 (–gyp) to 1.1 (+gyp) at 200-300 mm depth (where 0 = none, 6 = strong dispersion) (chapter 3), probably resulting in the greater penetration of water to 250 mm depth described in chapter 5 (Fig. 7.1).

EC increased to a depth of at least 500 mm where +gyp was applied. For example, the EC increased from 0.04 (–gyp) to 0.15 dS/m (+gyp) at 200-300 mm depth but was still well below concentrations that are harmful to roots (0.80 dS/m). The SAR of the surface soil decreased where +gyp was applied (from 1.05 to 0.44), as did ESP of the surface and subsoil (chapter 4). The subsoil was transformed from sodic (ESP > 6) to non-sodic (ESP = 2.9) (Fig. 7.1).

Air-filled porosity was increased (> 0.10 cm³/cm³) in the surface soil (250-344 mm depth) 16-17 and 35.5 h after the beginning of irrigation where +gyp was applied. There was an increase in the ∆volumetric water content/h of the surface soil where +gyp was applied (chapter 5) (Fig. 7.1).

The response of Chardonnay grapevines that was in part due to the improved soil properties could be considered beneficial or detrimental depending on the use and management of the grapes. The grapevine responses to the treatments (chapter 6) are now discussed. Where rye was grown and +gyp applied, grape yield increased to levels more economic than the commercial Chardonnay yields in Rosberson Vineyard. The quality and quantity of grapes from these higher yielding grapevines could be controlled with irrigation scheduling techniques such as PRD and RDI, which should be more easily managed because soil hydraulic properties and uniformity in block have improved
(chapter 5) or by canopy management (Fig. 7.1). Where water was conserved by applied ws larger (1.17 g) berries resulted. Large berries may be unfavourable for disease control and may be difficult to ripen. Berries were smaller (1.10 g) and there were fewer berries per bunch (80.4) that ripened earlier where rye was grown compared with where ws was applied (chapter 6). This effect of rye on berry size and number may also be relevant to red varieties, because the skin to juice ratio is increased, thus improving colour and associated flavour and aroma compounds in the resultant must and wine.

In the experiment, shoot fruitfulness and uniformity in yield across all treatments were each increased (where soil was hilled in the vine-line, grapevines were pruned to 15-20 buds per m of cordon, and the same volume of water applied to each grapevine), suggesting management improved the uniformity of growing conditions (chapter 6) (Fig. 7.1). Shoot fruitfulness increased from 1.2 bunches per fruitful shoot in October 1996 to 1.6 in October 1998. The CV for the number of bunches per grapevine between treatments decreased from 24.8 in October 1995 to 13.5 in October 1998. Uniform soil in vineyards is beneficial for irrigation scheduling because measurements of soil water are likely to represent the soil across the vineyard. Crop forecasting is also likely to be accurate, and with few samples needed, in a uniform vineyard.

Roots were at a greater depth and at a greater concentration with rye than without, probably as a result of competition (chapter 6). Deep roots can increase the grapevines tolerance to drought, but may also decrease the impact that irrigation has on inducing stress. In the experiment, maximum root concentrations in the hilled vine-line soil (4.2 cm/cm²) were 3 times that reported previously.

Research is needed to understand further the mechanisms changing particular soil properties. These mechanisms include the loss of macroporosity under ws compared with that under rye, and what sizes of pores are increased (eg. pores that supply or hold plant available water). The relationship between macroporosity and penetrometer resistance should be further explored so that we can predict the magnitude of one parameter from
measurement of the other (chapter 3). Also, the critical penetrometer resistance that limits growth of grapevine roots (taken in this thesis as 2 MPa) should be identified, and how this critical penetrometer resistance varies for different rootstocks and varieties (Fig. 7.1).

The effect that rye has on the dissolution of gypsum and distribution within the soil matrix needs further investigation. The economical rates and frequencies of gypsum applications that efficiently maintain EC (to 0.5 dS/m) and decrease ESP (< 6) need to be identified (Fig. 7.1). A maximum, sustainable rate of wetting should be identified for soil supporting either active or dead rye, before which soil structure deteriorates (eg. penetrometer resistance > 2 MPa or macroporosity < 10 cm³/cm³ or bulk density > 1.5 g/cm³) and restricts root growth (Fig. 7.1).

A micro-irrigation system is needed to apply less than the maximum rate of wetting identified above, to the vine-line (spray diameter < 1.5 m), to avoid excessive periods and volumes of saturated soil. The adoption by winegrape growers of PRD and RDI as irrigation scheduling techniques suggests that a better understanding is needed of the interaction between PRD and RDI and different soil types and management. The effect of rye and +gyp on the vine-line soil to provide greater penetration of water to depth (chapter 5) may create a wetting pattern that is elongated, and thus assist the separation of wetting patterns either side of the grapevine and ensure that PRD is successful.

Research is needed to identify the optimum properties of soil for optimum quality of berries. The optimum properties of soil are possibly know for establishment of grapevines and yield of grapevines.

Modifications to the treatments I imposed, methods or analyses I used that could have improved the experiment are now discussed. Before the experiment started, I should have measured the variability of grapevine characteristics and soil properties across the experimental site. This would have determined the optimum number of replications
needed in the experiment and allowed a determination of whether variability was decreased by soil management.

In the experiment, I should have included a treatment identical to the rest of the commercial Chardonnay crop at Rosbercon Vineyard as a control, even though this would have been difficult because of the overhead sprinkler irrigation. Further investigation of wine made from the grapes picked from the experiment may have shown differences and provided the ultimate analysis, even though wine tasting is not quantitative.

Management strategies for HRDS in vineyards as identified from my research are now described. To maintain soil in a state appropriate for root growth, freshly tilled aggregates of soil in the vine-line should be stabilised by a fine rooted species of grass and clay should be coagulated by the application of Ca$^{2+}$ in a form such as gypsum (chapter 3) (Fig. 7.1). HRDS that have had wheat straw or gypsum applied should be monitored for pH and amended with lime if soil pH drops to critical levels (chapter 4). My experiment showed (chapter 4) that EC increased and ESP decreased to depths of at least 500 mm within 3 years of the application of 12 t/ha gypsum (Fig. 7.1). Soil EC can increase faster when Ca$^{2+}$ is applied to soil supporting ryegrass than soil covered by wheat straw (chapter 4).

Gypsum applied to the vine-line of a HRDS can improve air-filled porosity and hydraulic conductivity of the surface soil, thus decrease run-off of water into the inter-row and improve vehicle access throughout the vineyard (chapter 5) (Fig. 7.1). Grape yield can be increased when the growth of ryegrass for stable aggregates and the application of gypsum to coagulate clay improve the physical and hydraulic properties of hard-setting and crusting soil (chapter 3 and 6) (Fig. 7.1).

When ryegrass is grown in the vine-line soil for at least 2 seasons, smaller berries with fewer berries per bunch can mature earlier than those grown in vine-line soil under wheat straw (chapter 6). Improved shoot fruitfulness and uniformity in yield between grapevines can be achieved by improving management such as: hilling soil in the
vine-line when the surface soil is shallow (< 300 mm), pruning grapevines to 15-20 buds per m of cordon, and applying the same volume of water to each grapevine (chapter 6).

In summary, in vineyards with hard-setting and crusting surface soil, soil physical (maintain a low strength, increase macroporosity and increase infiltration) and chemical properties (increase electrolyte and decrease ESP/SAR) will improve if gypsum and a covercrop such as ryegrass are included in the management of vine-line soil. These improved growing conditions should enable grapevines to reach their potential in grape yield, vegetative growth and possibly quality.

A method of producing a soft and porous surface soil in the vine-line of an established vineyard planted on a HRDS in south-eastern Australia is shown in Fig. 7.1 (included in an envelope in the back cover of the thesis). This flow chart shows the factors that limit root growth and performance of grapevines grown in HRDS, showing results of my research and that done previously and suggestions where research is needed to improve further the soil management of HRDS in vineyards.
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Appendix

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