Sustainable Viticultural Production

Optimising Soil Resources

Project CRS 95/1

Compiled by Alfred Cass





Final Report
to
Grape
and
Wine
Research
and
Development
Corporation

Alfred Cass & Associates
VITICULTURAL SOIL & WATER TECHNOLOGIES

January 2002

Executive Summary

Sustainable Viticultural Production: Optimising Soil Resources (CRS 95/1)

The aims of Project CRS 95/1 were, briefly, to:

1. Develop and test a set of soil sustainability criteria relating to vine performance.
2. Describe soil constraints to vine performance for Australian soils.
3. Analyse appropriate soil data and evaluate against soil indicators of sustainability.
4. Group soil types with similar constraints and develop management systems for each.
5. Disseminate information via field days, seminars, technical articles and scientific papers.
6. Produce a comprehensive field manual on soil types and soil management.

Soil and viticultural scientific and industry literature was reviewed to develop a comprehensive overview of the role of soil in grape production. The review focuses on how soil physical and chemical properties affect vine root growth. The mechanics of root growth are discussed in detail. Soil sustainability indexes are defined as an aid to guide to selecting, developing and managing viticultural soils. The soil properties and management factors included in these indexes are: soil profile texture forms, available water, soil aeration, internal drainage status, soil strength, soil salinity and sodicity, soil chemical status, soil nutrient status, irrigation water chemistry, gypsum indicators, lime indicators and compost quality criteria.

Field trials were established in South Australia on new and established vineyards on several important soils with the aim of monitoring the adverse effects of some soil properties on vine performance. These trials were also used to test a range of soil development techniques and soil management methods targeted to improve the adverse properties. The ultimate aim of this work was to refine development and management packages for the viticultural industry. The soils that were included in this research are:

- Rendzina soils at Coonawarra,
- Non-sodic duplex soils at McLaren Vale and Padthaway,
- Yellow, sodic duplex soil in the Barossa Valley and McLaren Vale,
- Dark cracking clay soils at Coonawarra and McLaren Vale.

In addition to these trials many other un-replicated, informal trials were established in South Australia in commercial vineyards where soil treatments were tested and monitored with the assistance of industry collaborators. The aim of these trials was to develop concepts further and extend research findings and soil management packages in commercial settings to industry leaders.

Soils on 140 Australian rootstock trials were assessed and documented with the aim of refining selection of rootstocks and developing a national overview of a cross-section of viticultural soils. A Microsoft Access database, the Australian Rootstock Soils Database on compact disk, was established as a reference of soil data to aid research workers in interpreting results from the trials. The aim of this work was to refine matching of rootstocks to different soils. This aim has not yet been fully realised because more work needs to be done in coordinating soil and vine performance data. A small national workshop needs to be convened to achieve this objective. The aid of overseas experts in the field of soil and rootstock compatibility should be sought to enhance outcomes from the workshop.

Data from field trials on the formal as well as the informal trials and the comprehensive soil information in the Australian Rootstock Soils Database provided a broad national framework of soils used for grape production. These data enabled development of a system for categorising soils in terms that have relevance for selection, development and management of viticultural soils. This system, the Australian Viticultural Soil Key, is correlated with major soil classification systems and vineyard soils can be identified with a range of local and international systems used in viticulture. This enhances acquisition of overseas information about vine performance in relation to soil properties. The Key also provides a powerful framework for conveying information about selecting, developing and managing Australian viticultural soils.

Soil selection, development and management information, including diagrams, photographs and slides derived from a comprehensive review of soil and viticultural scientific literature, from results of experimentation and monitoring numerous research experiments and from an assessment of rootstock trials, were delivered to the viticultural industry in the form of draft chapters in the Grape Production Series No. 2 publication and the Manual that underpinned the Research to Practice™ Water Management Seminar series. Although Grape Production Series No. 2 has yet to be published, the Research to Practice™ Seminars proved to be very successful in delivering information to industry and in facilitating adoption of the technology.

All members of the research group actively participated in delivery of research material to the industry in the form of a series of workshops, seminars, field days and industry publications over the period 1994 to 1999. Some of these activities were conducted under the auspices of the Barossa Valley Rotary Club Foundation Fellowship, awarded to Philip Myburgh (some 30 field days, seminars and workshops were held in 1996), the Research to Practice™ seminar series (some 34 workshops between 1997 and 1999) and many other seminars and field days held under the banner of the CRC for Soil and Land Management or industry sponsors (some 20-30 field days and seminars). These events reached many hundreds, possibly thousands of grape growers, industry planners and researchers.

Information gathered during the course of this project has been organised into a set of “Best Practice” soil selection, development and management packages that have been extensively tested in Australia and California. This information served as the basis for contributions to the proposed Grape Production Series No. 2 publication and the Research to Practice™ Water Management Manual. However, the project matured considerably after this period and these packages need updating at this stage. They should be published in the form of an industry

Manual after integration with the information derived from the Australian Rootstock Soils Database and the Australian Viticultural Soil Key. Additional work will be required to reconfigure the information against the new perceptions that have become apparent with finalisation of the Australian Viticultural Soil Key.

Publications and extension events produced (or scheduled for production, in parentheses) that flowed from this project during the period 1996 to 2000 include the following:

- Manual(s) or Book Chapters: 4 (2)
- Papers or Conference Proceedings: 19 (12)
- Industry Journal Articles: 11 (10)
- Dissertations: (2)
- Data on Compact Disk: 1
- Review Article, available on the Internet: (1)
- Seminars, workshops and field days: more than 75.

Final Report

Sustainable Viticultural Production: Optimising Soil Resources (CRS 95/1)

CONTENTS

1. Introduction…… 1

2. Summary Literature Review: Grapevine Performance and Soil Conditions……. 5

3. Research on Soil Management and Vine Performance…….. 16

3.1 Soil Mounding and Mulching Trials at Nuriootpa……. 16
3.2 Soil Amelioration Trials at Lyndoch……. 18
3.3 Improving Soil Structure in a Seasonally Waterlogged, Duplex Soil at McLaren Vale…… 25
3.4 Improving Soil Structure in a Cracking Clay at McLaren Vale.…… 29

4. Soil Waterlogging and Vine Performance Research…….. 34

4.1 Sodic, Duplex Soil at Nuriootpa…… 34
4.2 Non-Sodic, Duplex Soil at McLaren Vale……. 40
4.3 Poorly Structured Cracking Clay at McLaren Vale……... 44
4.4 Black Earth Cracking Clay at Coonawarra…… 49
4.5 Drained Groundwater Rendzina at Coonawarra…… 52
4.6 Vine Response to Early Season Waterlogging……... 55

5. Soil Water Management Research: Outcomes from Research at Nuriootpa…….. 59

6. Development of Research Tools……. 62

7. Rootstock Trial Soil Properties…… 67

8. Australian Viticultural Soil Key…….. 77

9. Delivery of Outcomes to Industry…… 88

9.1 Barossa Rotary Club Foundation Fellowship…… 88
9.2 Grape Production Series No. 2…….. 93
9.3 Water Management for Grape Production Research to Practice™ Manual and Workshops……. 94
9.4 Industry Manual: Selection, Development and Management of Viticultural Soils…… 97

10. Optimal Soil Management of Australia Vineyards – Appropriate Earthworms…… 102

11. Conclusions…… 109

12. Appendix: Organisations, Staff and Collaborators…… 111

Bibliography: Grapevine Performance and Soil Conditions…… 115

Sustainable Viticultural Production

Optimising Soil Resources

1. Introduction

In the early 1990's Australian wine production was in the midst of an unprecedented development of a greatly increased foreign market and consequent expansion of production. Large new plantings of grapes was in progress to keep pace with the demand for wine. Expansion of plantings was in progress in all the traditional viticultural areas and new viticultural areas were being established. There was a strong feeling in many quarters that new opportunities were being presented to the industry and new initiatives would be needed to capitalise on these opportunities.

At that time, a new Federal Government venture, the Cooperative Research Centre (CRC) program was being established in Australia. One such centre was the CRC for Soil and Land Management, established at the Waite Research Campus, Glen Osmond, South Australia, in partnership with the CSIRO Division of Soils, the University of Adelaide and The South Australian Government. This facility attracted the attention of far-sighted individuals in the Australian Wine Industry and resulted in negotiations with CRC management and senior staff for soils research directed at wine grape production.

In part, the perceived need for soil research in the industry was driven by the historical lack of such research input into the industry and the feeling that productivity in many Australian vineyards was limited by a lack of soil information for making development and management decisions. Several factors were important in strengthening the need for additional soil research input:

- Many criteria for selecting and managing viticultural soils in Australia had been inherited from the more mature viticultural industries of Europe and California.

- Generally, Australian soils are of lesser resilience than their counterparts in California and Europe and there was evidence to show that some of these inherited practices might not be ideal for optimum productivity and sustainability in Australia.

- Criteria for the ideal soil requirements of wine grapes in the Australian context were not clear at all and many conflicting ideas about soil suitability and management abounded.

- Shortage of soil resources in Australia seemed to have caused exploitation of some marginal soils or soils that had been removed from grape production in earlier times because of productivity or sustainability limitations.

- Generally, Australian irrigation water quality and availability was in a state of decline and the consequences of continued use of certain sources of water, especially on newly established vineyards, was causing concern at that time.

- More intensive competition on world markets had precipitated more intensive mechanical and chemical inputs into vineyards, sometimes with negative side effects.

- A rational system for classifying Australian soil suitability for vineyard development was not available to guide developers in selecting the best available soils.

- Technology was available to improve soil management in many vineyards, to make vineyard soils more uniform, to monitor soil water use more effectively and control vine vigour to predetermined levels, but this technology had not been placed within management systems suitable for adoption by the viticultural industry.

Accordingly a project submission was made to the Grape and Wine Research and Development Corporation with the following aims:

- Define, develop and test a set of soil criteria that will function as indicators of soil quality sustainability for optimum root growth, vine establishment and performance.

- Identify and describe soil physical and chemical constraints to vine performance by field examination of soils on selected vine experimental and rootstock sites, analysing soil samples from these sites and evaluating these soil and viticultural data against soil indicators of sustainability.

- Group soil types with similar constraints and develop for each grouping and for both new and established vineyards, management systems to create and maintain soil conditions and operating strategies that conform to the soil indicators of sustainability.

- Disseminate information on the indicators of sustainability, soil descriptions, vine performance data and the management systems to the industry via industry involvement in the work, demonstration sites, field days, a series of structured seminars, technical articles in industry journals and scientific papers.

- Produce a comprehensive field manual on soil types and soil management suitable for grape production, directed at grape growers and published in accordance with industry standards.

The application was approved and in July 1995 Project CRS 95/1 commenced, largely within the ambit of the Irrigated Trees and Vines program of the CRC for Soil and Land Management. Completion date for the project was originally set at June 1998. However, because several components were added during its first three years of operation, it was extended to 1999 with a final report being due during 2000. The project that evolved during 1995 was an amalgam of various soil-related projects scattered through several research institutions: CRC Soil and Land Management, CSIRO Land and Water, University of Adelaide and the South Australian Research and Development Institute. Alfred Cass & Associates funded the final stages of the project, including some fieldwork, some data analysis, co-ordination and production of this report. The original proposal for this project called for collaboration with the staff of the Institute for Sustainable Irrigated Agriculture at Tatura, Victoria. However, distance and staff changes on that campus made continued collaboration difficult and it was not sustained at a level that produced worthwhile results.

The broad strategies that were adopted by the participants for execution of this project were:

- Reviewed existing literature on soil quality and soil management in relation to vine performance and grape quality and defined a set of "ideal" soil characteristics for vines.

- Tested methods of soil manipulation and surface management designed to improve soil quality in both new and established vineyards, using laboratory and field experiments on commercial properties.

- Surveyed soils on selected existing viticultural experiments, rootstock trials and commercial properties to add a soil component to the experiments and commercial enterprises which provided information on current soil conditions in relation to known vine performance, water management, cover cropping and canopy management.

- Refined "ideal" soil characteristics in relation to vine performance and grape quality using information derived from the literature and laboratory, glasshouse and field experiments and surveys.

- Formulated "best practice" packages that were aimed at creating and maintaining optimal soil conditions in vineyards and encapsulated these packages in a draft manual and lecture series on vine performance relative to soil properties, classification and management in Australian vineyards.

- Deliver "best practice" technology to the industry via Landcare groups, consultants, wineries, individual growers, industry service organisations (eg ICMS), commercial suppliers (vineyard machinery manufacturers) and stakeholders (GWRDC, etc). Feedback and "validation" will allow final publication of manuals.

The Federal Government, unexpectedly, failed to renew the mandate of the CRC for Soil and Land Management and in June 1998 it terminated, before this project could be completed. At that time, not all participants had completed their research work. However, most continued to

work towards completion, aiming to end by 2000. Management of funding via the CRC for Soil and Land Management ceased in 1998 but some components were transferred to CSIRO Land and Water for 1999. At about the same time some of the associated research activity was prematurely terminated in collaborating outside agencies. Because of these changes, those of the original research team who remained working on this project were forced to finish their work largely outside of the formal funding sphere. It is to their credit, and a mark of their dedication, that they completed much of their commitments, albeit later than originally projected. These events dictated that this report was not completed until 2001.

This report summarises and reports outcomes from Project CRS 95/1, Sustainable Viticultural Production – Optimising Soil Resources, covering the following components:

- Review of the literature and bibliography on soil issues related to viticulture.
- Indicators of soil health and sustainability relevant to Australian viticulture.
- Field and laboratory research on soil properties, soil biology and vine responses.
- Soil management packages derived by formal research and commercial testing.
- A key for classifying Australian viticultural soils.
- Soil database of Australian rootstock and other viticultural experiments.
- Delivery of the research findings via manuals and seminar series.

2. Summary of Literature Review

Grapevine Performance and Soil Conditions

Alfred Cass, David Hansen and Andrew Dowley

A review of scientific and industry literature was done to meet the basic aim of Project CRS 95/1 which was to "*Define, develop and test a set of soil criteria that will function as indicators of soil quality sustainability for optimum root growth, vine establishment and performance*". The purpose of the review was to bring together information on soil limitations to optimum vine performance and reveal opportunities that might exist to improve vine growth by improving soil conditions. The review was seen as the basic pathway to developing a set of critical parameters to form a framework for quantitative, soil-based criteria for judging the health and sustainability of vineyard soils in Australia and for designing soil specific development and management tools for new and existing vineyards. The topics covered in the review are listed in Table 2.1.

Table 2.1: Contents of the literature review "Grapevine Performance and Soil Conditions"

2.1 Soil Properties and Vine Performance

2.1.1 Limitations to Grapevine Root Development
2.1.2 Soil Structure
1.2.1 Pore Size Distribution
1.2.2 Soil Structural Stability
2.1.3 Soil Properties That Limit Grapevine Root Growth
2.1.3.1 Soil Strength
2.1.3.2 Bulk Density
2.1.3.3 Penetration Resistance
2.1.3.4 Soil Water
2.1.3.5 Aeration
2.1.3.6 Soil Salinity
2.1.3.7 Soil Sodicity
2.1.3.8 Soil Temperature
2.1.4 Soils Conditions That Limit Grapevine Root Growth
2.1.4.1 Ideal Soils for Grape Production
2.1.4.2 Cracking clays
2.1.4.3 Compact and Sodic Subsoil Clays
2.1.4.4 Calcareous Soils
2.1.4.5 Dense Sandy Soils and Subsurface Sandy Layers
2.1.4.6.Hardsetting and Crusting
2.1.4.7 Wheel and Tillage Compaction
2.1.5 Soil Structure Management
2.1.5.1 Deep Tillage
2.1.5.2 Mounding Topsoil to Create Raised Soil Beds
2.1.5.3 Conventional Tillage, Mulch, Permanent Swards and Cover Crops
2.1.5.4 Gypsum Application
2.1.5.5 Organic Matter Application . . . continued overleaf

Table 2.1 (continued)

2.2. Vine Root Growth, Morphology and Function

2.2.1 Anatomy and Development of Roots
2.2.2 Periodicity of Root growth
2.2.3 Water and Nutrient Uptake
2.2.4 Grapevine Root Distribution
2.2.5 Soil Factors Affecting Grapevine Root Growth
2.2.5.1 Mechanical Resistance
2.2.5.2 Irrigation and Soil Water
2.2.5.3 Chemical and Nutrient Imbalances
2.2.5.4 Soil Temperature
2.2.5.5 Soil Aeration
2.2.6 Grapevine Root Density – Measurement
2.2.7 Grapevine Performance in Poorly Aerated Soils
2.2.8 Determining Oxygen Status in the Rootzone
2.2.8.1 Soil Morphology
2.2.8.2 Oxygen Electrode
2.2.8.3 Oxygen Diffusion Rate
2.2.8.4 Air-filled Porosity
2.2.8.5 Redox Potential

2.3 Critical Soil Parameters for Vine Root Growth

2.3.1 Critical Limits for soil texture
2.3.2 Critical limits for available water in vineyards
2.3.3 Critical limits for root aeration and available water for moderate vigour vines
2.3.4 Critical limits for soil drainage classes
2.3.5 Soil Penetration Resistance Criteria
2.3.6 Soil Salinity Criteria
2.3.6.1 Factors for converting salinity units to dS/m
2.3.6.2 Criteria for Soil Salinity and Potential Yield Reductions for Vines
2.3.7 Critical limits for soil sodicity
2.3.8 Soil chemical assay criteria for sustainable grapevine performance
2.3.9 Soil Nutrient Assay Criteria for Optimum Grapevine Performance
2.3.10 Irrigation water chemistry limits for vines
2.3.11 Gypsum: criteria for optimum effect on soil amelioration of vineyards
2.3.12 Lime: criteria for optimum effect on soil amelioration in vineyards
2.3.13 Compost standards for young vines (AS4454, 1997)

The review was broken into three broad sections:

- Soil Properties and Vine Performance
- Vine Root Growth, Morphology and Function
- Critical Soil Parameters for Vine Root Growth

Soil Properties and Vine Performance

In this section, the soil factors that limit vine root growth are identified and links between vine performance and root growth are established and discussed. Soil types that are important in limiting vine root growth are listed and ideas relating to use of these features as a vehicle for selecting, developing and managing vines are introduced. In explaining why these soil types limit root growth, the role of soil structure and related properties, water availability, soil salinity and sodicity are discussed.

Properties of the best Australian soils for wine production are identified and used to contrast properties of soils that limit and restrict vine production. These soils are discussed in detail and their properties listed.

Management of soil structure from the vineyard development stage through to routine management issues are reviewed and discussed. Most of the information on this topic was obtained from reports on soil tillage in South African vineyards, although some of the theory of soil tillage was developed in England. Up to 1995, very little research on tillage and soil manipulation in viticulture had been done in Australia, although some work had been done in the cereal and horticultural industries.

Vine root restrictions arising from poor physical properties are identified as the main issue that has to be confronted to improve soil selection, development and management in the Australian viticultural industry. This does not mean that issues relating to salinity, sodicity and root diseases are unimportant. However, solutions to these issues lie, at least in part, within the scope of better soil structure management. In limiting vine performance, poor soil properties act on the vine roots that are then restricted in function to various degrees. Accordingly, an extensive review of vine root growth, morphology and function was undertaken.

Vine Root Growth, Morphology and Function

The anatomy and development of vine roots is discussed and the growth phases identified. The mechanism of nutrient and water uptake by vine roots is explained in relation to root morphology as an aid to understanding what part of the root system is most vital to vine performance. The relationship between vine root distribution and soil properties, including nutrient and moisture status, developed in the previous section, is further expanded.

Measurement of vine root density is an important problem in trying to understand the form and function of roots. A detailed examination of various techniques used for this purpose and results obtained reveal that there are remarkable inconsistencies in the literature. A very wide range of values for vine root densities is reported. This indicates that, if progress is to be made in understanding the role of soil properties in determining vine performance, more accurate methods for determining vine root densities need to be developed.

Soil aeration is identified as a limitation to vine root growth and vine performance. However, little quantitative information on its effect as far as impact on the vine and period of most sensitivity was available from the literature. Methods of measuring aeration limitations in soil are critically reviewed as a means to identifying the best method for use in vineyards to answer some of the many questions that exist regarding the role of aeration in limiting vine root growth.

The review provided an overview of the role of soil in limiting vine performance. As an aid to developing a set of soil sustainability index values for viticulture, a set of critical soil parameters that affect vine performance were tabulated. These parameters are reproduced in this summary.

Critical Soil Parameters for Vine Root Growth

Two aims of this project were to develop management packages (Best Practice Packages) that provide:

1. a specific description of a set of soil characteristics (sustainability indexes) that are related to the function and performance of vines,
2. soil quality criteria and soil and water management strategies to maintain sustainability and long term productivity of vineyard soils.

The information in this section, in part, addresses these aims. The data were derived, largely, from literature reviewed here. However, gaps in the information were filled by research findings and experience gained during the course of the project between 1995 and 1999.

The critical parameters presented here are intended to form a summary of a quantitative, soil-based, framework for judging the health and sustainability of vineyard soil in Australia. This data set should not be regarded as a final compilation, rather as a work in progress. These criteria will evolve as more information and experience become available.

Critical limits for soil texture

Texture plays a significant role in determining the suitability of soil for vines and influences vine performance quite decisively. However, texture as such, is not a root-limiting factor unless there are other, secondary factors present such as silica cementation. However, the distribution of different texture classes down the soil profile, as a function of depth, is a more significant factor in determining root growth.

The classical theory of soil genesis from parent material predicts an increase in clay content with depth in the soil profile. However, depending on the magnitude and relative importance of the soil-forming factors, the pattern of this increase, if indeed it is present, differs from soil to soil. Three distinct patterns of texture variation are recognised (Northcote, 1960): Duplex, Gradational and Uniform Profiles. A fourth has been added for completeness: Inverted Profile.

Duplex soils show large increases in clay content (texture) over small depths, generally starting with low to moderate clay in surface layers and rising to high clay in deeper layers (Figure 2.3.1). This rate of increase is generally referred to as “abrupt” or “sharp”. Gradational soils have a steady increase in clay from the surface to depth with no abrupt changes. Uniform soils have no significant change in clay but may be Sandy, Loamy or Clayey, depending on how much clay is present. Some soils on highly weatherable rock show reversal of the normal increase in clay with depth and are here referred to as Inverted Profiles.

The most limiting of these profile forms is the Duplex Profile. A large proportion of the Australian viticultural industry is founded on these soils and they form an important part of the Australian Viticultural Soil Key (Section 9). The other profile forms are less limiting and are collectively referred to as “Unigrad” soils in the Australian Viticultural Soil Key.

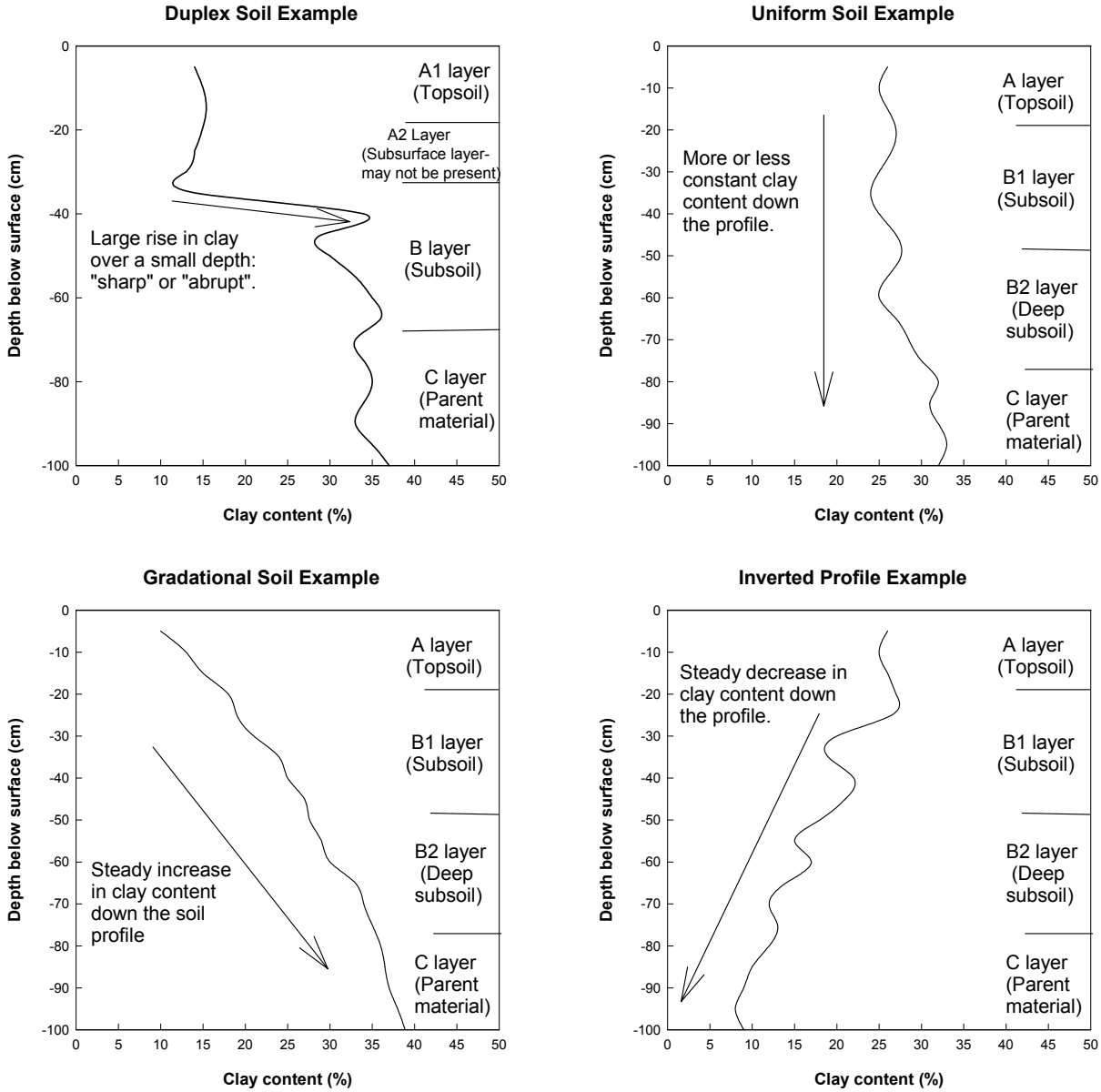


Figure 2.3.1: Hypothetical distribution of clay down three soil profiles to give three distinct classes of profile form: Duplex, Gradational and Uniform.

The distribution (amount and variation) of clay down a soil profile will influence drainage of water and penetration of roots. Duplex soils show poor drainage and root penetration through the “sharp” or “abrupt” interface between the A and B layers. Gradational clay distribution allows better drainage and root penetration. The amount of clay in Uniform soils determines the drainage status. In soils with low clay, water drainage and root penetration is usually good unless there are other factors influencing these properties. If the clay content is high then drainage is poorer but root penetration may not be restricted, depending on other factors such as soil structural type, ped size and ped hardness.

Critical limits for available water in vineyards

The current criteria for moderately vigorous vines on wide spacing (3 x 2 m) for total (plant) available water (TAW), stress available water (SAW), readily available water (RAW) in the effective root depth (mm of water) are as follows:

Criterion	Moderate vigour vines		
	TAW	SAW	RAW
	mm of water in the effective root depth		
Very high (excessive)	> 200	> 150	> 100
High (high)	150-200	113-150	75-100
Moderate (optimum)	100-150	75-110	50-75
Low (sub-optimum)	50-100	38-75	25-50
Very low (insufficient)	< 50	< 38	< 25

The estimated available water storage capacity of soils with and without deep ripping should be evaluated. Although no exact procedure to do this is available, there are reliable approximate methods available. The approximate values are of use in irrigation design and in formulating irrigation management strategies. The available water data are usually expressed as total plant available water, between field capacity and wilting point (TAW), water held between field capacity and a matric suction of 200 kPa (so-called "stress available water", SAW) and readily available water between field capacity and a matric suction of 60 kPa (RAW). The usefulness of these quantities is as follows:

- TAW: indicates total available storage and all current useful benchmarks are expressed as TAW values,
- SAW: is a useful "regulated deficit management" parameter, indicating the allowable depletion of water from field capacity to the soil matric tension (200 kPa) where it is thought vines switch their physiological processes from vegetative growth to solute storage in berries (at this time this point is thought to be the 200 kPa soil matric tension value),
- RAW: is a useful general irrigation management parameter, indicating the irrigation refill water content up to which no water stress will have been imposed on the vine.

In the Australian viticultural literature, an additional quantity is often referred to, the "deficit available water" or DAW. This is determined as SAW minus RAW. DAW is interpreted as the depth of irrigation water that must be applied at 200 kPa tension to return the soil to its lower RAW water content. At a practical, physical level, this is not possible. Soils will only wet to saturation (or close to) and it will then, if freely-draining, drain to between 5 to 30 kPa over a period of about 24 hours. So, in reality DAW, as a practical irrigation tool does not really do what it is said to do. The practical effect is to wet the soil to FC, but to a shallower depth than if one were irrigating to FC water content.

Water availability cannot be separated, as a physiologically limiting process, from soil aeration and both these important properties have to be considered together in judging soil physical quality.

Critical limits for root aeration and available water for moderate vigour vines

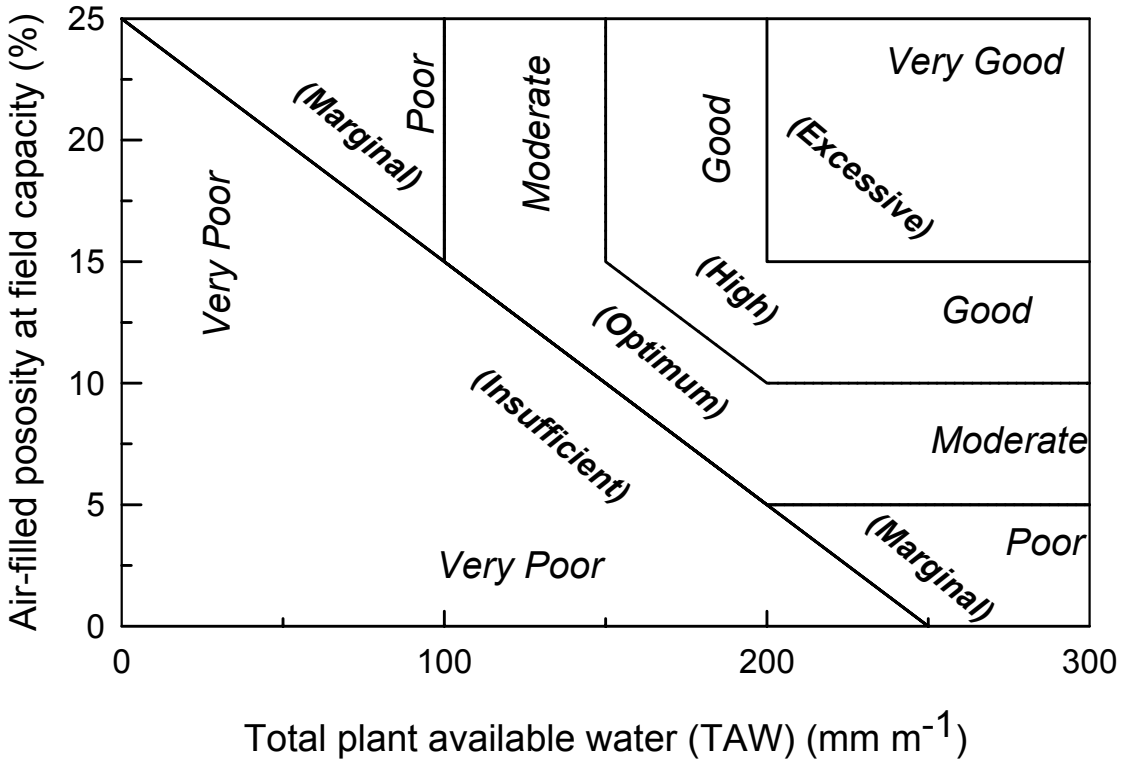


Figure 2.3.2: Suitability of soil aeration and drainage (air-filled porosity) and water storage for moderately vigorous vines on wide spacing (>3 x 2 m) (adapted from Hall et al., 1977).

Critical limits for soil internal drainage classes

The presence of water tables in the soil profile or the accumulative presence of the following properties determine the drainage status of a soil: nature of the change from the topsoil (A) layer to the subsoil (B) layer and the properties of the subsoil layers (B1 and/or B2) within the potential root depth (pers. com. Dr. R. Fitzpatrick, 1999).

Property	**Drainage status (rate of water drainage) and length of time saturated in any one year**			
	Poor/slow	**Moderate**	**Good/rapid**	**Freely drained**
	Months	***Weeks***	***Hours to days***	***Never***
Evidence of a groundwater table within *x* m of the surface	< 2 m	> 2 m	> 2 m	> 2 m
Evidence of a perched water table within *x* m of surface	< 0.5 m	0.5 to 1 m.	1 to 2 m	> 2 m

. . . continued overleaf

Critical limits for soil internal drainage classes (continued)

If no water tables are evident, the following properties determine drainage status:

Property	Drainage status (rate of water drainage) and length of time saturated in any one year			
	Poor/slow	**Moderate**	**Good/rapid**	**Freely drained**
	Months	***Weeks***	***Hours to days***	***Never***
Thickness of A/B interface change	Sharp (< 5 mm)	Abrupt (5-20 mm)	Clear/Gradual (20-100 mm)	Diffuse (> 100 mm)
Structure of B layers	Prismatic, massive	Blocky	Granular	Single grain, granular
Hardness of B layers	Hard, rigid	Firm	Friable	Loose, friable
Pores or cracks in B	Nil	Few	Many	Many
Texture of B layers	Heavy, med. clay	Med., light clay	Light clay	Clay loam, etc
Plasticity of B layers	Highly plastic	Medium plastic	Slightly plastic	Not plastic
Mottled colours in B	Prominent	Distinct	Feint	None
Mottle colours in B layers	Bleached, gray	Yellow, brown	Red, No mottles	No mottles
Root density in B	Nil	Nil, Few	Few, Many	Many

Soil penetration resistance criteria

Soil strength is strongly dependent on soil water content and bulk density. Soil is weakest when wet and uncompacted and usually strongest when dry and compacted. The critical factor in assessing soil strength is the penetration resistance value, which will limit root growth over the available water content range (i.e. from field capacity to the lower limit of available water). Grape vine roots do not grow in soil that has a penetration resistance of 2 MPa, or greater, at field capacity. Such a soil should be regarded as less than ideal for vines and amelioration by tillage is recommended. If above 3 MPa anywhere **over the available water content range**, the soil must be ameliorated by tillage if rapid early growth is to be achieved and later problems avoided.

Critical limits for soil sodicity

Sodicity hazard	ESP* (%)	SAR*$_{ec}$	SAR*$_{1:5}$	Soil structural stability
Non-sodic	0 to 6	0 to 6	0 to 3	Soil microstructure is generally stable
Sodic	6 to 15	6 to 15	3 to 10	Soil microstructure susceptible to damage by tillage and trafficking especially when wet
Very sodic	> 15	> 15	> 10	Soil microstructure may be damaged by tillage and trafficking and spontaneously by irrigation and rainfall (dispersion of clays)

*ESP, Exchangeable sodium percentage; SAR Sodium adsorption ratio of saturation (ec) or 1 to 5 soil to water extract.

Critical limits for soil salinity

Factors for converting salinity units to dS/m

Salinity Unit	x = dS/m	Salinity Unit	x = dS/m	Salinity Unit	x = dS/m
µS/cm	0.001	S/m	10	ppm	0.0016
mS/cm	1	µmho/cm	0.001	mg/L	0.0016
mS/m	0.01	mmho/cm	1	grains/gal	0.023

Criteria for soil salinity and potential yield reductions for vines

Salinity hazard	EC_{se} dS/m	Effects on grapevine growth	$EC_{1:5}$ (dS/m)				
			Loamy sand	Loam	Sandy clay loam	Light clay	Heavy clay
Non-saline	<2	Negligible effect on vines	<0.15	<0.17	<0.25	<0.30	<0.4
Slightly saline	2-4	Own-rooted vines start to be affected	0.16-0.30	0.18-0.35	0.26-0.45	0.31-0.60	0.41-0.80
Saline	4-8	Own rooted vines severely affected but some rootstocks are more tolerant	0.31-0.60	0.36-0.75	0.46-0.90	0.61-1.15	0.81-1.60
Very saline	8-16	Vines cannot be grown successfully	0.61-1.20	0.76-1.45	0.91-1.75	1.16-2.30	1.60-3.20
Highly saline	>16	All grapevines will die	>1.20	>1.45	>1.75	>2.30	>3.20

EC_{se} is saturated paste electrical conductivity, $EC_{1:5}$ is the corresponding approximate electrical conductivity of a 1:5 soil:water extract for various soil textures:

Soil chemical assay criteria for sustainable grapevine performance

pH_{CaCl2}	pH_{water}	Chloride Cl_{se} toxicity	Boron $B_{hotwater}$ toxicity	Exchangeable cation concentrations					
				Calcium Ca	Magnesium Mg	Sodium Na*	Potassium K	Ca:Mg	K:Mg
-	-	$mmol_{c+}/L$	mg/kg	Percentage of total exchangeable cation concentration				Molar ratios	
5.5 to 8	6 to 9	<10	< 3	> 40	< 60	< 6	> 5	2 - 10	0.1-0.4

*ESP, Exchangeable sodium percentage, Subscript "se" is saturation extract, Subscript "hotwater" is for a hot water extraction of soil Boron.

Soil nutrient assay criteria for optimum grapevine performance

Macro-elements				Micro-elements				
Nitrate NO3-N	Phosphorous P	Potassium K (AA)*	Potassium K (Acid)*	Boron B	Copper Cu	Zinc Zn	Manganese Mn	Iron Fe
mg/kg or ppm				mg/kg or ppm				
> 2 to 10	> 35	> 100	> 2000	0.2 to 1.0	> 0.2	> 1.0	> 1.0	> 4.5

*AA, Neutral ammonium acetate or similar extract; Acid, Sulphuric acid extract.
Phosphorous: Correct deficiencies at time of vineyard development. Nitrate, Potassium and micronutrients: Correct deficiencies by annual fertiliser program based on petiole analysis.

Irrigation water chemistry limits for vines

Total dissolved solids	Electrical conductivity	Reaction	Total cations Ca+Mg+Na	Total carbonate	Chloride	Boron	Total iron	Sodium adsorp-tion ratio
TDS	**EC_{iw}**	**pH_{iw}**	**TC**	**HCO_3^-**	**Cl^-**	**B**	**Fe**	**SAR**
mg/L	**dS/m**	**-**	**$mmol_{c+}/L$**			**mg/L**		**-**
< 1060	< 1.7	6.5-8.5	< 17	< 1.5	< 4	< 0.5	0.4-1	<6

Gypsum: criteria for optimum effect on soil amelioration of vineyards

- $CaSO_4$-$2H_2O$ - mined or by-product of phosphate manufacture
- Solubility in water (maximum): 2.41 g/L.
- Optimum fineness: 85 % less than 2 mm diameter (passes US 10 mesh screen).
- Maximum purity: 16 % sulphur (wet wt).
- Impurities: water, soil, limestone, salt, fluoride.

The following are **indicators** of a need to apply gypsum

1. sodic soils where soil analyses shows that ESP is above 6 %, or saturation extract sodium adsorption (SAR) greater than 6 or 1:5 soil: water extract SAR greater than 3,
2. soils that rank as Type 3 (Emerson, 1991) and particularly Type 1 in a dispersion test,
3. subsoils that have strong blocky, angular blocky, prismatic or columnar structure that has strong consistency,
4. surface soils that crust readily, causing rain or irrigation water to run off before the soil wets up properly,
5. cracking clays that have poor surface properties (lack of self-mulching, large widely-spaced cracks, very hard crusts) and remain excessively wet and un-trafficable for long periods after rain or irrigation
6. soils that have exchangeable aluminium levels approaching or exceeding 100 mg/kg.

Lime: criteria for optimum effect on soil amelioration in vineyards

- Calcium carbonate ($CaCO_3$): ground limestone, agricultural lime, shell lime (NP 60-98) (NP is the neutralizing power relative to that of pure $CaCO_3$ (100 % purity).
- Solubility in water (maximum): 0.014 g/L.
- Optimum fineness: 90 % less than 0.85 mm (passes US 20 mesh screen).
- Maximum purity: 38 % Calcium (dry weight basis).
- Other types: Dolomitic lime: mixture of $CaCO_3$ and $MgCO_3$ (must have more than 6 % Magnesium) (NP 60-98).
  Calcium hydroxide ($Ca(OH)_2$): slaked or hydrated lime (NP 105-120)
  Calcium oxide (CaO) : burnt lime or quicklime (NP 120-150)
  Mixtures : e.g. cement kiln dust, packing shed waste, sugar beet lime.

The only indicator for addition of lime to soil is pH less than 5.5

Compost standards for young vines (AS4454, 1997)

pH	Nitrogen		C:N	Organic matter	Boron	Sodium	Moisture	Plastic or rock > 5 mm
	Ratio Nitrate : Ammonia	Ammonium (NH_4)						
-	-	mg/L	-	% mass	mg/kg	% mass	% mass	% mass
5-7.5	>0.14	<300	<20	>25	< 100	< 1	> 25	< 5

Electrical conductivity (EC_{se}): Calculate the maximum compost application if incorporated as: tonne/ha = $94.6EC^{-0.7}$

Toxicity Index: > 60 % (AS4454, 1997, page 26).

See AS4454 (1997) for method for obtaining a saturation extract from compost.

Outcomes from the Research

Scientific Papers and Conference Presentations

Cass A., McKenzie N. and Cresswell H. 1996. Indicators of Physical Soil Health. In Walker J. and Reuter D. J. (editors). Indicators of catchment health. Pages 89-108.CSIRO Australia.

Cass A. 1999. Interpretation of some soil physical indicators for assessing soil physical fertility. In Peverill K.I., Sparrow L.A. and Reuter D.J. (editors). Soil Analysis, An Interpretation Manual. Pages 95-102. CSIRO Australia.

Cass A., Hansen D. and Dowley D. 2002. Literature Review: Grapevine Performance and Soil Conditions. To be submitted to a review journal and/or available from www.winesoil.com after April 2002.

Section 3

Research on Soil Management and Vine Performance

3.1 Soil Mounding and Mulching Trials at Nuriootpa

Judy Eastham and Alfred Cass

The work we undertook at the CRC can be broadly characterised under the two general topics, soil management and irrigation management. One major experiment was carried out at Primrose Villa, the vineyard of the Schulz family at Nuriootpa in the Barossa Valley, SA. The aims of the project were to investigate the influence of different soil and irrigation management treatments on soil physical properties, root development and early growth of young vines growing on a duplex soil. The soil treatments included mounded and un-mounded soil with three different surface cover treatments (mulched, bare soil and ryegrass). The influence of irrigation application rate was also studied as high (4 l/hr) and low (2 l/hr) application rate drippers were applied to sub-plots. The experiment was carried through to the first harvest on the chardonnay grapes, when yield and fruit quality parameters were recorded on grapes from the three year old vines.

The soil physical properties within the mounded soil were markedly different from those in un-mounded soil, with bulk density and penetration resistance being significantly less in mounded soil. However, mounding did not significantly increase the water holding capacity of the soils, as total and plant available water and readily available water were similar for both these treatments. Total porosity and air filled porosity at field capacity was greater for mounded than for un-mounded soil. This suggests that improved drainage conditions in mounded soils which may be significant in preventing the development of saturated zones of soil during application of drip irrigation, or in reducing the intensity of waterlogging occurring in winter months on the duplex soil. The greater depth of topsoil observed in mounded soil may also be instrumental in reducing any adverse effect of waterlogging on vines.

As a result of the more benign soil properties in mounded soil, root development in this treatment was enhanced compared with un-mounded soil. Root length measured in mounded soil was double that in measured in un-mounded soil. Greater access to soil resources benefited the early growth of young vines planted in mounded soil. Their canopy growth at one and two years after planting was significantly greater than on un-mounded soil through increased length of main shoots and increased number and length of lateral shoots. A surface cover of ryegrass had a detrimental effect on vine growth, as vine survival and growth of both main and lateral shoots was significantly reduced compared with treatments with bare and mulched soil. Thus the benefits of soil structure amelioration were negated by the densely rooted ryegrass for water and nutrients. Earlier control of ryegrass by herbicides may have reduced competition and enabled better vine growth and establishment. The results also suggest that establishing ryegrass along vine rows would be an effective means of controlling vine vigour in situations where water and/or nutrient resources are excessive to vine requirements. Irrigation application rate had no significant effect on either vine survival or

growth. However, spatial application of water may become increasingly important with time as vine canopies expand, increasing their demand for water, and soil water availability becomes more critical.

More advanced early growth of vines planted on mounded soils translated to greater yields at the first harvest compared with yields from the un-mounded treatments. The exception was the mounded soil with ryegrass where yields were similar to those from vines in un-mounded soil. Yields ranged from 14.7 to 12.6 t/ha for un-mounded soil treatments and was 13.5 t/ha for the mounded ryegrass treatment. Yields from the mounded treatments without ryegrass ranged from 18.2 to 19.3 t/ha. The greater yields were achieved from greater bunch numbers counted on mounded soil treatments. The greater yields achieved from mounded treatments were not detrimental to any of the measured grape quality parameters. The juice soluble solids and pH were not influenced by any treatment, which is consistent with a similar leaf area to fruit weight ratio measured in the different treatments. The results of the experiment are published in Eastham et al (1996). Further research on this experiment is warranted to investigate whether these early benefits of soil mounding on vine growth and yield persist to give long-term increases in productivity.

Outcomes from the Research

Scientific Papers and Conference Presentations

Eastham, J A. Cass, S. Gray and D. Hansen 1996. Influence of raised beds, ground cover and irrigation on growth and survival of young grapevines. Acta Horticulturae. 427:37-43.

Industry Journal Articles

Due, G; J. Eastham and A. Cass, 1999. Little weeds cost big money in new vineyards. Australian Grapegrower and Winemaker, 424, 18-19.

Seminars and Field Days

These trials were used regularly as demonstration sites during field days between 1994 and 1998.

3.2 Soil Amelioration Trials at Lyndoch

David Hansen and Alfred Cass

In 1995 a vineyard near Lyndoch, South Australia, was selected for a soil management trial. The vineyard had been established without deep ripping and no improved soil management practices had been implemented. The commercial yields were reported to have declined from 23.0 t/ha in 1990 to 5.5 t/ha in 1995.

The aim of the research conducted on this site was to investigate the possibility of improving grape production via rejuvenation of soil physical fertility.

Methods and Materials

The vineyard had a 'long-term' average annual rainfall of 650 mm and a limit of 100 mm of irrigation water per annum. The grapevines were cv. Semillon planted on own roots in 1946. The duplex soil consisted of 20 cm of sandy loam (A_1 soil horizon), overlying 15 cm of bleached sand (A_2 soil horizon), overlying blocky, medium to heavy clay (B soil horizon).

The experimental site consisted of 25 rows of established vines each 100 m in length. These rows were split into four 25 m plots consisting of 16 vines per plot. Within the 25 rows were 17 treatment rows which allowed three complete blocks consisting of four soil management methods, and a half a block consisting of a single, double and a non-ripped row, (3.5 blocks). Effectively two experiments were conducted within one trial design.

The first experiment was to determine the effect of different soil preparation methods on soil physical factors and grapevine performance. The four soil management methods were; (1) no deep ripping or mounding (control), (2) deep ripping on one side of the vine row, no mounding, (3) deep ripping on one side of the vine row, mounding of topsoil, (4) deep ripping on both sides of the vine row, no mounding.

The second experiment was to determine the effect of soil surface cover management on soil physical factors and grapevine performance. The surface cover treatments applied to the non-mounded (flat treatment) rows were: (1) no lime plus no surface cover (bare), (2) no lime plus cereal straw mulch (5 kg m^{-2}), (3) lime plus bare, (4) lime plus cereal straw mulch. The surface cover treatments applied to raised soil beds were: (1) cereal straw mulch (5 kg m^{-2}), (2) bare soil, (3) living ryegrass cover (Victorian perennial ryegrass, sown at a rate of 2.5 g m^{-2}) killed by herbicide during spring and summer, (4) lime (1% of total soil mass), (5) grape marc (40 t ha^{-1}), (6) polymer, (synthetic polymers AP173 - high stabilisation, low flocculation, PV 200 - low stabilisation, high flocculation, 400 mg kg^{-1} of soil, total of 18 kg.

Mounding of topsoil to create raised soil beds was undertaken using a "v-delver". Raised soil beds were approximately 0.4 m high from the natural soil surface, 0.6 m wide at the top and approximately 1.6 m wide at their base. Deep ripping was done using a small bulldozer pulling a single ripping tine located 0.8 m away from grapevine trunks; this was approximately the centre of the wheel track. Ripping was done prior to mounding of topsoil.

Soil surface covers were applied immediately after deep ripping and mounding operations and the following measurements were made from October 1995 to April 1996:

1. Soil: available soil water by measuring water content, soil matric suction and water retention characteristic, soil strength, bulk density and salinity,
2. Irrigation water: quantity applied and salinity.
3. Vine: berry number and weight, bunch weight, bunch number, berry juice quality (baume, and chloride concentration), pruning weight, root density.
4. Meteorological: rainfall, pan evaporation, maximum and minimum temperature.

The soil water retention function was determined by means of laboratory procedures on small undisturbed cores and by monitoring water content and matric potential *in situ*. Volumetric soil water content was monitored throughout the 1995/96 growing season using time domain refelectometers and tensiometers. Readily available water (RAW) and total available water (TAW) were compared between treatments and the fractional depletion of these quantities monitored every 10 days.

Penetration resistance was measured on undisturbed cores taken from soil horizons, A_{new}, A_1, A_2 and B in treatments at a matric suction of 10 kPa (field capacity). A Lloyd Universal Test Instrument was used to do the penetration resistance. A penetration resistance of 2 MPa at field capacity is regarded as the critical limit for vine root growth (Van Huyssteen, 1983 and Myburgh et al., 1996).

Soil samples for salinity determination were collected from area under the dripper for bare and mulch covered treatments. The electrical conductivity of 1:5 soil:distilled water solution ($EC_{1:5}$) was determined and the saturation paste electrical conductivity calculated (Cass et al., 1996). Soil samples were collected in July 1996, November 1996 and March 1997.

Root density was measured by sampling known soil volumes in December 1995 and July 1996. Treatments sampled in December 1995 were bare soil surface, raised beds and flat treatments only. This provided preliminary data and a more intense investigation was done in July 1996 when bare soil and mulch treatments on flats and raised soil beds were sampled for roots.

Vine performance was recorded for 1996 and 1997 seasons only. Five sample vines were chosen in each plot for collecting pruning weights and berry characteristics. Grapevines were hand pruned (spur pruned), and weighed. Forty berries were picked from each of the five sample grapevines in each plot. One to two berries were picked from the top, middle and bottom of each bunch of the sample vine. Exactly two hundred berries were picked from each plot and weighed, crushed and baume and chloride analysed. Following individual berry picking every bunch on the five sample vines in each plot was counted, picked and weighed and mean berry number per bunch, mean berry weight, bunch number, bunch weight determined.

Results

Water contents at any time in the various treatments and consequently available water status, varied through each season of measurement, depending on when the measurement was made and the preceding weather and irrigation regime. These results can be understood in relation to the effect of certain treatments on soil properties and processes:

1. Lime and to a lesser extent, polymer stabilised large pores at the surface, improving infiltration (influx of water) but also promoted evaporation and drainage (outflux of water).
2. Cereal straw mulch (but not grape marc) applied to the surface reduced evaporation, raised surface moisture content, cooled surface layers during the growing season and protected collapse of large pores at the surface (i.e. retarded sealing).
3. Bare soil treatments were subject to progressive crust formation (sealing at the surface) through the early part of the season and, although the crust may have retarded infiltration, reduced evaporation, appearing, on balance to conserve moisture.
4. Mounding soil increased the surface area exposed to the atmosphere and created large pores at the surface and throughout the mounded volume, so increasing evaporative loss of water.

Volumetric water content varied as follows:

1. Water content was greater for flat treatments compared with raised soil beds.
2. The exception was for the raised beds with lime and surface mulch that was wetter than flat, bare treatments after 8/12/95.
3. Generally volumetric soil water content was greatest with incorporation of lime and addition of a straw mulch surface cover.
4. Grape marc treatments recorded the lowest volumetric soil water contents.
5. All other soil surface cover treatments ranged between these two.
6. Bare treatments ranged in the middle of the other treatments but in January began to rise relative to other treatments.

Readily available water (RAW) varied as follows:

1. The fraction of available water was manipulated by irrigation consequently it varied considerably during the growing season, particularly in the upper layers.
2. Ranking of the various horizons was: $B < A_{new} < A_2 < A_1$ flats $< A_1$ beds.
3. B horizon value was extremely low (i.e. little water was released from the soil between 10 and 60 kPa, most was released from 60 to 1500 kPa and the total available water held in the B soil horizon was not significantly less than any other soil horizon.
4. Bare soil surface raised soil beds was significantly greater than all other raised bed soil surface cover treatments.
5. Ryegrass treatments were similar to bare treatments because growth was so poor that these treatments behaved as bare treatments.
6. Mulch and ryegrass plus lime covered raised soil beds had lower values.
7. Flat and mulched treatments had lowest values.

Total available water (TAW) and associated RAW for the treatments varied as follows:

1. The available water is used steadily through the growing season, being depleted layer by layer as the season advances.
2. For layers of equal depth, each held similar depths of total available water but layer depths varied and layer type varied, depending on treatment.
3. Flat treatments, because of the shallow depth of the A_2 soil horizon, contained the least absolute depth of total available water.
4. Raised soil beds had more total available water than in flat soil beds, particularly above the A_2 soil horizon.
5. Available water above the A_2 soil horizon is important since this horizon limited grapevine root growth into the B soil horizon below.
6. Above the A_2 soil horizon raised soil beds held 75.6 and 42.8 mm of total available and readily available water respectively.
7. Flat treatments held 47.3 and 25.0 mm of total and readily available water respectively. i.e., raised soil beds had 60 % more total available water and 71 % more readily available water above the A_2 soil horizon than flat soil beds.

Readily and total available water are soil properties while soil water relations of vines depend on the changes in these quantities through time, depending on processes adding or depleting water. For this reason, the depletion of readily available water and total available water was monitored through the growing seasons of 1995 and 1996 to determine how treatments affected water supply to the vines.

From the results obtained it was clear that, raised soil beds could have a negative or a positive effect on the fractional use of total available water depending on how soil water is managed. If irrigation is managed on raised soil beds so that volumetric soil water content is similar to flat soil beds, fractional use of total available water in raised soil beds may be greater than that of flat treatments. It is only when the volumetric soil water content of raised soil beds becomes lower than flats that depletion of total available water becomes significantly less in raised soil beds.

Any result in which raised soil beds contained a significantly smaller remaining fraction of readily or total available volume than flat treatments is due to a combination of 3 possible factors:

1. the higher air-filled pore space and consequently lower soil water content in raised soil beds,
2. the greater evaporation from raised soil beds because of their greater surface exposure and greater surface porosity,
3. denser, finer and more efficient root systems in raised soil beds resulting in greater uptake of water by grapevine roots.

Raised soil beds had greater readily and total available water above the A_2 soil horizon than flat soil beds. Furthermore, the extraction of readily and total available water in raised beds was almost twice that of flat soil beds, except for raised, bare treatments. This greater water

use was probably due to the greater root length density in raised soil beds causing increased water uptake and transpiration and greater evaporative losses from the surface.

Readily and total available water volumes were not generally significantly different between double and single ripped treatments compared with non-ripped treatments. However, on some occasions there was a difference in the remaining fraction of readily and total available water between these treatments. On these occasions, the water content in double and single ripped beds was greater than in un-ripped beds. The explanation probably lies in greater infiltration of water (rainfall and irrigation) into double and single deep ripped treatments because of large and continuous "water transport" soil pores created by ripping.

Raised, mulched treatments were seen to be conserving water better than raised bare treatments. At no time did raised bare soil beds contain a greater total available water volume than raised mulch soil beds, although at times they were similar. Thus mulching reduced water loss from raised soil beds.

Flat, bare treatments showed a significantly greater change in the remaining fraction of readily and total available water than flat mulched treatments. This was probably due to the decreased evaporation caused by the mulch. The difference in root length density between flat bare and flat mulch treatments was not significantly different, suggesting the water uptake rates were similar.

Raised bare treatments had a significantly smaller change in the remaining fraction of readily and total available water volumes compared with raised, mulch treatments. This may have been due to an increased water uptake by grapevines growing in mulch covered raised soil beds compared with bare soil beds. The higher water content environment combined with lower soil temperatures may have enhanced root growth in mulch covered raised soil beds compared with bare raised soil beds. Root length density was greater in raised mulch covered soil beds than raised bare soil beds but not significantly so. However, roots in mulched soils grew closer the surface than on flats because of the lower temperatures and moister conditions at the surface of the soil.

There were no significant differences in penetration resistance between any treatments at any depth. There were however significant differences in penetration resistance within treatments between depths. Generally the trend in penetration resistance was: newly mounded material (A_{new} soil horizon) < the original surface soil (A_1 soil horizon) < the A_2 soil horizon > the subsoil (B soil horizon). In this experiment the soil management treatments that provided the maximum depth of soil with the lowest penetration resistance were the raised, mulched treatments.

The soils were slightly saline to saline (Cass et al. 1996) in July 1996 but with a high degree of variability within treatments, ranging from about 1.5 dS m^{-1} to 3.3 dS m^{-1}. Because of the large variation between replicates there were no significant differences found between treatments or between depths. In 1996, soil salinity was least in November, ranging from about 1.5 dS m^{-1} in the top-soil to about 0.5 dS m^{-1} in the sub-soil. The salinity, generally remained static from November 1996 to March 1997. The only treatment to be greater than 2 dS m^{-1} in March was the flat soil bed with a bare soil surface.

Root density changed substantially during the course of the trial in all treatments, including the control. Initially significant differences were detected but by July 1997 these differences had disappeared. After establishing mounds, roots grew rapidly from the A_1 horizon into the raised soil beds. In December 1995, root length densities ranged from about 0.1 to 1.5 cm cm^{-1} with raised soil beds having greatest densities at all depths. At 200 mm below the soil surface (A_1 soil horizon) the mean root length density in raised soil beds was significantly greater than in flat treatments (0.85 and 0.25 cm cm^{-1} respectively). By July, 1996 this difference was still present but not significant. Root length density tended to be greater under straw mulch covered soil. Within the vine-strip root length density was greatest 400 mm from the dripper and least directly under the dripper in the A_2 soil horizon. Root length density tended to increase with depth except in the A2 soil horizon where root length density remained static. It appeared that once grapevine roots had penetrated through the A_2 soil horizon they began to develop more freely than in the A_2 soil horizon.

Due to the short period of time treatments had been in place there were no significant differences in pruning weight per vine between treatments, Table 3.9.

Significant differences in yield of fruit were obtained. Production was greatest from those treatments which had the greatest fraction readily available water throughout the season: Mulched treatments produced significantly greater yields than bare soil, 12.0 and 10.7 t/ha respectively in 1996 and 13.5 and 11.7 t/ha respectively in 1997. There were no significant differences in yield between other treatments.

There were no significant differences in bunch or berry number between treatments. So, yield differences were due to significant differences in berry weight. The heaviest berries were produced from grapevines grown under straw mulch. Grapes grown on both mulched flat treatments or mulched raised soil beds produced significantly heavier berries compared to treatments with bare soil surface. Mean berry weights were 1.18, 1.32, 1.16 and 1.33 grams for flat bare, flat mulch, raised bare and raised mulch treatments.

Two berry juice factors were considered in berry quality: baume and berry juice chloride concentration. There were no significant differences baume levels between the treatments, despite the large differences in yield. Vines grown on both flat and raised straw mulch treatments produced berries with significantly greater chloride ion concentration than berries from grapevines grown under bare soil surface cover. Chloride ion concentration from berries grown under flat bare, flat mulch, raised bare and raised mulch were 321.5, 331.1, 325.5 and 347.3 mg/kg respectively. Significantly higher berry chloride ion concentrations were found in berries from straw mulch treatments. There were no significant differences in soil salinity. Consequently the chloride ion concentration found in berries appeared not be dependant on soil salinity but on berry size.

The most economical soil management treatment was the flat soil beds, non-ripped with mulch. Since apart from no soil preparation this treatment cost the least while providing an economic yield. Straw mulch increased yield by 1.3 t ha^{-1} in 1996 and 1.8 t ha^{-1} in 1997 compared with no straw mulch addition.

The major outcome of this research was an increased understanding of what soil management treatments should be applied to what soil types, (i.e. site specific soil management). The

major result suggests that the most economical soil management treatment (which could also be deemed the most appropriate) was the application of mulch. The A_2 soil horizon limited root development but once roots were through this horizon there were roots in the B horizon accessing soil moisture. If ripping had been undertaken appropriately (to a depth of approximately 0.7 m and on the wheel track) on this site that may have produced a greater response in combination with the mulch treatment.
In moderate to warm climates where irrigation water is limited, due to increased loss of water from mounded soil, mounding soil should be a last resort. Increasing soil volume through deep ripping and application of mulch should be the first options. Where root development is limited vertically, in most cases deep ripping should be applied. Where root development is limited horizontally, deep ripping may be appropriate or no treatment may be necessary if the root limitations are only shallow. Where root development is limited both vertically and horizontally then mounds **may** be appropriate. Where root development is limited, in most cases the application of mulch is economically appropriate.

Consequently, in a subsequent experiment established at Padthaway (not funded by the GWRDC) mulch and ripping treatments were applied to a deep sandy topsoil with a compacted A_2 horizon and compacted wheel traffic areas. Others soils which had soil constraints to root development both vertically and horizontally were mounded and mulch applied to the mounds. These treatments were all effective because of the experience gained at Lyndoch.

Outcomes From the Research

Scientific Papers and Conference Presentations

Lanyon D M, Cass A, Cockroft B, Olsson K A. 1996. Coalescence: a long term decrease of soil physical fertility in irrigated no-till raised beds. Australia and New Zealand National Soils Conference, Melbourne, July 1996.

Hansen D., Kyloh S. and Cass A. 2002. An investigation into the effect of soil management on grapevine performance at Lyndoch, South Australia. Paper to be submitted to the Australian Journal of Viticulture and Enology.

Industry Journal Articles

David Hansen, Syd Kyloh and Alfred Cass A. 2002.Vine response to mounding and mulching at Lyndoch. Article to be submitted to the Grapegrower & Winemaker.

Dissertation

David Hansen. 2002. The effect of soil and irrigation management on grapevine performance. M.Sc. Thesis, University of Adelaide, South Australia. To be submitted in 2002.

Seminars and Field Days

The trial served as a demonstration site on about six occasions for various groups of grape growers, viticulturists and TAFE and university students from 1995 to 1998.

3.3 Improving Soil Structure in a Seasonally Waterlogged, Duplex Soil at McLaren Vale

Andrew Dowley, Alfred Cass and Robert Fitzpatrick

Seasonally waterlogged duplex soils present serious problems for early root growth in vines. Depending on spring rainfall, perched water tables develop at shallow depths and the deeper subsoil may be saturated for long periods into summer. The shallow perched water tables may not drain rapidly and the vine root zone may remain waterlogged well beyond bud burst, compromising early root growth and canopy development. Although the soil may drain before the season is greatly advanced, it is likely that early damage to the physiological development of the vine may translate into fruit yield and quality reductions. Certainly, impairment of root growth at this stage of the annual cycle will limit the size and density of the root system. The generally poor root systems associated with vines growing in these soils is probably attributable to restricted opportunity for full spring growth.

Results reported in Section 4.2, obtained from monitoring conditions on this duplex McLaren Vale soil showed that seasonal root survival and water extraction efficiency were severely inhibited by the properties of the clay sub-soil. This section summarises results obtained from an experiment designed to determine the effectiveness of a number of soil physical amendments applied to improve rootzone soil conditions.

These methods were tested in replicated, small scale plots under field conditions. The aims of the experiment were to:

1. determine what soil altering processes effectively ameliorate the adverse rootzone conditions here,
2. define what sort of performance outcomes are required of machinery in order to effectively ameliorate these identified rootzone restrictions,
3. provide recommendations to agricultural equipment design teams on performance requirements for effective soil amelioration technology.

Materials and Methods

Seven root zone amelioration processes (Treatments) were tested:

1. Uniformly mixing the A1, A2e and Bt1 horizons to a depth of 800 mm, 4 t/ha equivalent of gypsum was mixed into the soil and a further 4 t/ha equivalent was spread on the surface.
2. Uniformly mixing the A2e and Bt1 horizons to a depth of 800 mm with 4 t/ha equivalent of gypsum, replacing the A1 horizon as an unmixed soil layer on top and spreading 4 t/ha equivalent of gypsum on the surface.
3. Uniformly mixing the A1 and A2e horizons with 4 t/ha equivalent of gypsum, creating a 400 mm high, bell shaped mound on top of the mixed A1 and A2e soil with A1 horizon soil from the inter-row, spreading 4 t/ha equivalent of gypsum on the surface.
4. As for Treatment 3 but with straw mulch (5 kg/m^3) covering the mound surface.
5. As for Treatment 4 but with 6 % (dry mass) compost uniformly mixed throughout.

6. Uniformly mixing the A1 and A2e horizons with 4 t/ha equivalent of gypsum. Spreading 4 t/ha equivalent of gypsum on the surface.
7. As for Treatment 6 but with 6 % (dry mass), equivalent to 60-100 t/ha, compost uniformly mixed throughout.
8. An undisturbed site was taken as the control.

Treatments were tailored with a view to overcoming the root zone restrictions evident in the unaltered soil. The A2e and Bt1 horizons were seen as key root restricting layers. Consequently Treatments were designed to alter the physical properties of these horizons. An area of vineyard was selected in which the depths and properties of the A1, A2e, Bt1 and Bt2 horizons were found to be relatively uniform. Treatments were installed in early October, 1997, about 4 weeks after bud burst in three adjacent rows of 7 panels in a randomised block arrangement where each row was a separate block and one Treatment plot was installed per panel.

Individual plots were excavated to the required depth by a mini excavator and extended from the butt of the first vine to the butt of the middle vine in each 3-vine panel, a distance of 1.8 meters. Each of these plots was 500 mm wide, the width of the excavator bucket. The close proximity of the Treatments to the vine row ensured that treated soil was not subject to wheel track compaction.

Treatments were sampled for root length density in May, 1998 after one full growing season. Soil samples were collected using an 80 mm diameter hand augur from the top 100 mm, at 100 to 200 mm depth, and then at 200 mm intervals to a depth of 1 meter (or to the bottom of the Treatment for shallow Treatments). Samples were collected at this time. Sampling holes were augured in the equivalent position relative to the dripper in the unaltered soil as for Treatments 1, 2, 6 and 7. Root length density in each sample was determined using a soil dispersion technique (Section 6).

The Eh monitoring equipment described in Section 6 was installed in the middle row of the experiment in May, 1998. Five of the eight channels were connected to Pt electrodes installed in undisturbed soil horizons. Three channels were connected to Pt electrodes installed in plots of treated soil. Electrodes were installed at 400 mm and 700 mm in Treatment 1 and a single electrode was installed at 700 mm in Treatment 2. Penetration resistance was determined for all Treatments in August, 1998. At this stage the A1 and A2e horizons (and most probably all treated soil) was at field capacity. The Bt1 and Bt2 horizons of the undisturbed soil were still saturated.

In late October, 1998, all Treatments and the undisturbed soil were sampled for a second time. Late October corresponded with the cessation of anaerobic conditions in the undisturbed clay subsoil after the winter-spring period of seasonal waterlogging. Samples were collected adjacent to the same drippers as occurred in May, at different locations but equivalent distances to the drippers. Root length density was again determined using the soil dispersion technique (see Section 6).

A backhoe was used to excavate pits alongside all soil Treatments in a single row in May, 1999 to examine and sample soil Treatments for bulk density and water retention properties.

Results

Alterations to the soil profile had a large effect on root length density in this soil. Clear differences in root length density were detected between flat and mounded treatments and between mulched and bare mounds with highest root length density in mulched mounds. Results indicate that insufficient soil moisture was the main root limiting factor in bare mound. The data suggest that bare mounds on duplex soils are of little benefit in dryland vineyards and are probably only of marginal benefit in vineyards with drip irrigation systems. However, retaining the straw mulch on the mound was found to be extremely difficult at this site and at other sites against wind. Other potential mulches need to be investigated that are less prone to wind loss.

The benefit of mixing the A1 and A2e horizons is questionable. The cementing properties of the A2e horizon appear to have severely limited root development in the mixed A1/A2e horizon soil. While root length density was significantly higher in the mixed soil than in the unaltered A2e horizon, root length density was much lower than in the unaltered A1 horizon. However, the efficiency of the root system was higher in the mixed soil than in the unaltered A2e horizon.

Root length density was highly variable throughout much of Treatment 2 because the A2e and Bt1 horizons were incompletely mixed. Fragments of the loosened Bt1 clay developed high root length density while the patches of A2e soil re-cemented and had low root length density. This probably meant that the root system of Treatment 2 was less efficient than that of Treatment 1.

The root length density of Treatments 5 and 7 were significantly higher than all other Treatments and all other study sites with the exception of a friable *Terra Rossa* soil in the Coonawarra. This high root length density can be attributed to the large amounts of macro organic matter added to the soil that decreased bulk density and increased soil friability. Comparison of conditions with Treatments 3, 4 and 6 suggests that the root limiting factor in the latter is probably physical despite the low penetration resistance observed. Further research is required to determine effective lesser, more commercially acceptable rates of macro organic matter addition.

Redox potential in the 400 mm to 800 mm depth zone in Treatments 1 and 2, equivalent to the Bt1 horizon in the unaltered soil, indicated anaerobic conditions existed for shorter periods of time than in the unaltered soil. Eh results showed that the lower parts of Treatment 2 were less well drained than Treatment 1, but still considerably better drained than the unaltered soil. The data suggests that deep ripping (as opposed to horizon mixing) may improve drainage and aeration in seasonally waterlogged duplex soils such as this, but will be less effective than if the A and B horizons are actually mixed.

In soil horizons that become seasonally or periodically adverse to root function, due to factors such as sustained waterlogging or excessive desiccation, most of the absorbing root system will perish. This was evidenced by the large reduction in total root length density in the Bt1 and Bt2 horizons of the unaltered soil between May and October.

Root growth, distribution and survival in this soil were most improved by uniform mixing of the A1, A2e and Bt1 horizons. Machinery that could effectively mix these soil horizons, within the limitations of an established vineyard, would be of great benefit to large areas of vineyards in South Eastern Australia. Machinery that could effectively rip the soil to the bottom of the Bt1 horizon (at least 800 mm), and incorporate gypsum to depth, would be the second best option. If these two options prove to be impractical, the incorporation of large quantities of macro organic matter into the A1 and A2e horizons should be investigated. Soil mounds with closely spaced drippers or, preferably, micro sprinklers, would also be of benefit to vine growth and yield.

Scientific Papers and Conference Presentations

Dowley A., Cass A. and Fitzpatrick R. W. 2002. Improving Soil Conditions for Vine Root Growth in a Vertic Palexeralf (Seasonally Waterlogged, Non-sodic, Texture Contrast Soil). Paper to be submitted to Australian Journal of Grape and Wine Research.

Industry Journal Articles

Andrew Dowley, Alfred Cass and Rob Fitzpatrick. 2002. Managing waterlogging and poor structure in a vineyard on a Duplex soil in South Australia. Article to be submitted to the Australian Grapegrower & Winemaker.

Dissertations

Dowley A. Grapevine Performance On Seasonally Waterlogged and Poorly Aerated Soils in South Australia, PhD Thesis, University of Adelaide, South Australia. To be submitted in 2002.

Seminars and Field Days

The trial was used regularly for informal field days and Research to Practice™ Seminars between 1996 and 1999.

3.4 Improving Soil Structure in a Cracking Clay Soil at McLaren Vale

Andrew Dowley, Alfred Cass and Robert Fitzpatrick

Major differences in grapevine performance and growth properties have been observed on vertisol soils (dark cracking clays) in different viticultural regions of South Australia. In the report on seasonal soil conditions in this cracking clay soil, in Section 4.3, grapevine root growth was inhibited in the surface soil by excessive temperature during the summer period, in the sub-soil by excessive penetration resistance and poor aeration and in the inter-row by excessive desiccation. Severe iron chlorosis, evident in the young vines, could also be related to the high pH, high free lime content, poor aeration and low EDTA extractable trace elements in the main part of the root zone at a depth of 200 to 400 mm (B1 horizon).

A mounding trial was established on this site in 1997 to address these physical impediments to root growth. The site was selected for the trial because of the exceptionally poor growth of vines planted in the preceding year. The objectives of the trial were to determine soil management techniques that could improve the growth of young vines on this soil type. It was hypothesized, at the time of the trials establishment, that poor vine growth and symptoms of iron deficiency were related to waterlogged, or at least poorly aerated conditions in the main part of the root zone. Numerous researchers have shown that deep tillage, with a view to improving sub-soil aeration, is inconsequential in Vertic soils due to the swelling properties and structural instability of the clay. Treatments in the trial, therefore, were selected with a view to lifting a substantial part of the grapevine root system above the zone of poor aeration and inadequate macro-porosity. Mounding was considered the best option for achieving this aim. This chapter presents and discusses the methods and results of the vineyard establishment trial.

Materials and Methods

The vineyard was first planted in September and October 1996 with non-grafted callused cuttings. However, a large proportion of the vines died in the first season. The trial itself was established from callused cuttings in October 1997 to coincide with extensive re-planting of the rest of the vineyard. Treatments were:

1) Not mounded, no gypsum.
2) Not mounded, gypsum spread on surface at 5 t/ha equivalent.
3) Mounded, 400 mm high, no gypsum.
4) Mounded, 400 mm high, 5 t/ha gypsum, incorporated to 400 mm.
5) Mounded, 400 mm high, 5 t/ha gypsum, incorporated to 400 mm, straw surface mulch at 5 kg/m.
6) Mounded, 400 mm high, 5 t/ha gypsum, incorporated to 400 mm and 6 % (by mass, equivalent to 60-100 t/ha) macro-organic matter, incorporated to 400 mm, straw mulch at 5 kg/m.

Chemical analyses indicated that the soil was nor sodic in the top 800 mm depth. Flat surface mulch was not used as a treatment because of the adverse early season temperature effects of

surface mulches (Hillel, 1980; etc). Low early season soil temperatures in hydromorphic soils have been shown to significantly delay bud-burst and early season root growth (Hillel, 1980).

The experiment was installed in four adjacent rows of 12 panels in a semi-randomised block arrangement where each row was a separate treatment block. Treatment plots incorporated individual panels of 4 vines (vines spaced at 1.5 m intervals), separated by buffer panels. Treatments extended one vine out into the buffer panel on each side thus ensuring no edge effects within the four vine treatment panel. With this arrangement each treatment was replicated sixteen times. All measured vine growth parameters were analysed by ANOVA.

The top 60 to 70 mm (A1 and part of A2 horizon) of inter-row soil, that was just below the plastic limit water content, was pushed up into mounds by repeated passes with a disc plough. All organic matter and gypsum amendments were evenly spread across the inter-row space on either side of the treatment zone prior to mound formation. The amendments were then incorporated into the mounded soil by the disc plough.

The experimental vines were not trained in the first season. All vines were pruned to a two bud spur after the first season to allow measurement of pruning weight and butt diameter. As vines were trained to the trellis in the second season, meaningful pruning weights could not be collected. Pruning weights, butt diameters and, where applicable, yield and bunch numbers, were collected from the treatment vines in 2000, the third season after planting.

An 80 mm diameter hand auger was used to collect soil samples for root analyses in May, 1999, at depth intervals of 0-100, 100-200, 200-400, 400-600, 600–800 and 800-1000 mm mid-way between the second and third vines in each treatment plot. Samples were also collected at equivalent depths from a position one meter directly out into the inter-row space from the vine-row sampling points. Root length density was determined for each sample using a soil dispersion technique (Section 6).

Soil temperature was monitored at a depth of 300 mm in a mulched and un-mulched mound between early February and early June 1999. Measurements were made using electronic sensors that were connected to the datalogger also used for the measurement of Eh and matric suction (see Section 6).

Petiole sampling could not be done during flowering due to the extremely poor growth of vines on un-mounded treatment. Instead, leaf blade mineral analysis was undertaken for all treatments in January 1999 and 2000. Bulk leaf samples from each treatment were rinsed in demineralised water and dried at 60^{o}C before being ground and analysed by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP).

Results

Soil mounds substantially improved the rate of vine growth that appeared to be a function of two things: 1) improved micro-nutrient uptake in the case of the un-mounded treatments and, 2) greatly improved root development in the mounds of the two mulched treatments. The different growth properties of the various mounded treatments and control vines could largely be explained by the root systems observed in each treatment. The root systems, in turn, were

largely determined by the physical properties of the soil, soil water content and, in surface layers, soil temperature.

From the surface to a depth of about 50 mm, the mounded soil had 'self-mulching' properties (loose, friable structure) with a low bulk density, low penetration resistance at field capacity, high macro-porosity and optimal aeration. All of these physical properties are ideal for root growth. Accordingly, where temperature or soil moisture were not limiting, dense root systems were able to develop in the surface layer of the mounded soil.

At greater depth the mounded soil coalesced and became compact due to its relatively poor macro-aggregate stability. The pressure exerted by overburden weight compressed the soil on drying forming a dense, massive structure of very low macro-porosity within just two seasons. This is a process that has been extensively studied (e.g. Lanyon et al. 1996). The physical properties of the soil beneath the mound also appeared to decline in accordance with its increased depth in the new mounded profile. This layer, formerly loose and friable, had become hard, dense and massive.

Incorporation of composted macro-organic matter had a significant positive effect on the structure and stability of the mounded soil in Treatment 6. Bulk density within the mounds remained low throughout the trial period with only relatively minor compaction (increased bulk density) evident in the lower part of the mound. Despite the virtual disappearance of any visible macro-organic matter by the end of the second season, the mounded soil remained friable throughout.

Soil temperature and moisture were also found to strongly influence root development. Grapevine root growth decreases rapidly when soil temperature rises above 32^{o}C. The temperature regularly approached 30^{o}C at a depth of 300mm in the bare (non-mulched) mounds during the summer period. Soil temperature at 100 mm depth in the non-mounded soil was found to regularly exceed 32^{o}C during the summer period and reached as high as 40^{o}C during an extended heatwave in January 2000. Consequently, soil temperature in the top 200 mm of the bare (non-mulched) mounds was too high for root growth and survival during the summer months. Despite the favourable physical properties of the soil, roots were unable to establish themselves in this part of the potential root zone.

Inherent structural instability meant that the un-mulched treatments quickly developed a soil profile, although raised by the height of the mound, which was very similar to that of the control treatments. Consequently the root system was similar to that observed in the non-mounded (control) treatments in terms of root zone volume, RLD and total root length per vine.

Despite the similarity of their root systems, mounded vines exhibited much better growth over the first three growing seasons than non-mounded vines. Severely chlorotic leaves in the non-mounded treatment vines indicated a serious iron, and possibly also zinc and manganese deficiency. Chlorosis was most severe during spring and early summer. No such chlorosis was evident in the un-mounded treatments.

Although not limited by micro-nutritional deficiencies, vines on un-mounded treatments demonstrated significantly lower growth and vigour than the two mulched treatments. Vines on un-mounded treatments also demonstrated symptoms of severe water stress such as early

cessation of growth and basal leaf defoliation in the latter parts of the second and third season. Soil moisture extraction by the small and sparse root system was clearly limiting in this treatment.

The physical properties of Treatment 5 mounded soil were very similar to those of the un-mounded treatments. However, unlike the un-mounded treatments, a significant grapevine root system was present in the top 200 mm of the mounded soil. While the average RLD in the 0-100 mm depth interval was only moderate (0.6 cm/cm^3), the variability was high. Root variability reflected the variable soil temperature effects in the surface soil due to an irregular cover of straw mulch. Straw mulch is difficult to retain on soil mounds. Root development below 200 mm in the Treatment 5 profile was very similar to that in the un-mounded treatments.

Grapevine growth in Treatment 5 was significantly stronger in each of the first three seasons than either the control or un-mounded treatments. As with the un-mounded vines, no signs of iron chlorosis were evident in the early part of the growing season. The vines also provided a substantial yield of 3.1 kg/vine in the third season with no obvious signs of severe water stress. Improved growth rates, higher yield and a lack of severe water stress can largely be attributed to the greatly improved root development in the top 200 mm of the soil profile. This extra root development greatly increased the total root length per vine and thus allowed for a substantially increased rate of soil water extraction than was achievable in either the un-mounded or control vines.

Root development in Treatment 6 plots reflected the excellent physical properties of the mounded soil. The average RLD in the 0-100 mm layer was approximately 0.9 cm/cm^3. At 100-200 mm RLD was relatively high (2 cm/cm^3) and uniform. Here root development was controlled principally by the physical properties of the soil: low bulk density and favourable soil structure. An average RLD of 1.1 cm/cm^3 was recorded in the lower part of the mound (200-400 mm depth interval), which is still relatively high, but significantly lower than that recorded at 100-200 mm. This lower RLD value reflects the marginally higher bulk density and coarser structure.

No significant differences in grapevine growth (pruning weight and butt diameter) were detected between Treatments 5 and 6 in either of the first two seasons. In the third season, pruning weight and yield were both significantly higher in Treatment 6 than Treatment 5. However, no significant differences were detected for butt diameter or bunch number. In common with of all other mounded treatments, no symptoms of iron deficiency were detected in Treatment 6 vines.

The similar growth properties of Treatment 5 and 6 vines in the first two seasons can be explained by two factors: the relatively small canopy size of the young vines, and the near optimal condition of the root zone in the top 200 mm of both treatment mounds. The small canopy size of the vines meant that vine water requirement in the first two seasons was substantially less than in the third (or subsequent) seasons. Thus the relatively restricted root zone of Treatment 5 mounds was still adequate to satisfy the water requirements of the small and developing vines in the first two seasons.

Outcomes from the Research

Scientific Papers and Conference Presentations

Dowley A., Cass A. and Fitzpatrick R. W. 2002. Improving Soil Conditions for Vine Root Growth in Ento Calciaquerts (Cracking grey and black clays). Paper to be submitted to Australian Journal of Grape and Wine Research.

Industry Journal Articles

Andrew Dowley, Alfred Cass and Rob Fitzpatrick. 2002. Managing cracking clay soils for grape production. Article to be submitted to the Australian Grapegrower & Winemaker.

Dissertation

Dowley A. Grapevine Performance On Seasonally Waterlogged and Poorly Aerated Soils in South Australia, PhD Thesis, University of Adelaide, South Australia. To be submitted in 2002.

Seminars and Field Days

The trial was used regularly for informal field days and Research to Practice™ Seminars between 1996 and 1999.

Section 4

Soil Waterlogging and Vine Performance Research

4.1 Sodic, Duplex Soil at Nuuriootpa

Andrew Dowley, Alfred Cass and Robert Fitzpatrick

Seasonally waterlogged duplex soils present serious problems for early season root growth in vines. Depending on spring rainfall, perched water tables develop at shallow depths and the deeper subsoil may be saturated for long periods into summer. The shallow perched water tables may not drain rapidly and the vine root zone may remain waterlogged well beyond bud burst, compromising early root growth and canopy development. Although the soil may drain before the season is greatly advanced, it is likely that early damage to the physiological development of the vine may translate into fruit yield and quality reductions. Certainly, impairment of root growth at this stage of the annual cycle will limit the size and density of the root system. The generally poor root systems associated with vines growing in these soils is probably attributable to restricted opportunity for full spring growth.

Up to the present, definitive data on the severity and duration of anaerobic conditions in vineyards has not been available. With the development of the monitoring system described in Section 6, these data can be obtained, allowing an assessment of the impact of these conditions on vine performance. In pursuit of this objective, soil of this type was studied at Nuuriootpa in the Barossa (this section) and McLaren Vale (Section 4.2). Morphological, physical and chemical characteristics of the soils and the redox potential over the winter/spring period of 1996 and 1997, as well as the relationship between Redox potential, matric suction (Ψ), perched water tables, soil physical and chemical parameters and "redoximorphic" morphological soil features were investigated. Grapevine root growth, survival and length density distribution and fruit yield and quality were measured and related to soil properties.

There is some evidence in the literature to suggest that Ramsey is better able than most rootstocks to develop shallow root systems in coarse textured soil. Nagarajah (1987), comparing the root systems of own rooted Thompson Seedless to Thompson Seedless on Ramsey rootstock, found a significantly higher density of Ramsey roots in the top 400 mm of a coarse textured soil. Similarly, Southey & Archer (1988) found that Chenin Blanc grafted to Ramsey had the highest actual root length density and the second highest fraction of total roots in the top 250 mm of a sandy soil in a study involving 8 separate rootstocks.

The experimental site is at Nuuriootpa had previously been planted to own-rooted vines but poor production resulted in removal in 1975. Between 1975 and 1984 the area was grazed by stock. In 1984 the vineyard was ripped with a wingless tine to a depth of approximately 700 mm and planted to Shiraz at 2.7 x 2.1 m. In November 1984 a fully replicated and randomized rootstock experiment was established at the site in with shiraz vines (scion SA 1654) grafted to 7 different rootstocks as well as ungrafted vines. The site is drip irrigated

(one 4 L/hr dripper per vine) using winter run-off water stored in a nearby dam. All plots were drip irrigated in the first three seasons after establishment. Prior to bud-burst in 1988 the drip irrigation system was redesigned such that half of the plots would receive no further irrigation.

McCarthy (1997b) investigated vine water relations at this site in 1988. The effects of water stress in this vineyard are evident in his vine performance data. Bunch weight, berry weight and yield were significantly lower for all rootstocks in the non-irrigated treatment. Pruning weight and bunch number were also significantly lower for all but the most drought tolerant rootstocks. Yield was, on average across all rootstocks, more than doubled when between 100 mm and 160 mm of irrigation water was applied but only increased by 40% in one season where just 40 mm of water was applied.

Methods and Materials

The soil at the Nuriootpa waterlogging research site is classified as a Yellow Duplex (Typic Natraqualf). The A1 horizon (0-250 mm) had loamy sand texture, single grain structure and weak consistence. However texture varied over short distances in the vineyard ranging from loose sand to sandy loam, structure from single grain to massive and consistence from weak to very strong. The bulk density of the A1 horizon ranged from 1.65 to 1.7 Mg/m^3.

The A2e horizon (250-400 mm) is loamy sand with massive structure that was very strong. The bulk density was more variable. Sandy A2e horizons usually had bulk densities between 1.65 and 1.7 Mg/m^3but sandy loam A2e horizons had a bulk densities up to 2 Mg/m^3.

The Bt1 horizon (400-700 mm) had a relatively thin layer of very firm, massive, heavy clay with a coarse (> 200 mm diameter) domed surface. The clay was mottled light grey, yellowish brown and red and was covered by light bluish grey siliceous cement. Saturated hydraulic conductivity could not be adequately determined using a Guelph Permeameter because of the thin and irregular depth of this heavy clay layer. However, saturated hydraulic conductivity would be expected to be extremely low.

The Bt2 horizon (700-1000 mm) had a medium clay texture and a strong, very coarse (> 100 mm) angular blocky structure. Linear shrinkage was low and slickensides (pressure surfaces) were virtually absent. Occasional vertically orientated structural cracks extended to the clay surface and had rough, sandy surfaces indicating that they probably did not fully close in winter or spring and instead acted as conduits for water and oxygen to the lower horizons. Like the Bt1 horizon, the consistence of the Bt2 was firm when moist and very strong when dry. The horizon was also highly sodic (ESP >15) and aggregates slaked and dispersed rapidly in distilled water (Emerson, 1991). Saturated hydraulic conductivity was low (< 1 mm/day). Organic matter content was also very low (0.3%). Gleyed colours occurred on ped surfaces while variously coloured red and orange mottles occurred in ped interiors.

The Bt3 horizon had a sandy light clay texture and strong, coarse but extremely tight prismatic structure. Consistence was very firm when moist and almost rigid when dry. Very few roots were able to penetrate between the tight, unmoving structural units. Organic matter was low (< 0.1%) but boron was high. Gleyed colours were rarely observed despite the extremely low (< 1 mm/day) saturated hydraulic conductivity.

Two wells were installed along the vine-row in September 1997 to monitor perched water tables, one on top of the clay sub-soil (350mm depth) and one in the undisturbed Bt3 horizon at 1m depth. The well at 1 m depth was sealed with bentonite below the surface of the clay subsoil. A soil observation pit was excavated next to the 1 meter well in November 1997. Consequently a second 1 meter well was installed in an adjacent vine panel in order to monitor perched water tables in the winter and spring of 1998. Rainfall data for Site 2 was obtained from the Australian Bureau of Meteorology database using data from the rainfall gauge at the Nuriootpa Post Office, about 3 kilometers away.

The redox potential and matric suction monitoring equipment was first installed in mid September 1997. The system used is described in Section 6. Duplicate platinum electrodes were installed in the A2e horizon (300 mm depth), in the upper Bt2 horizon (500 mm depth) and in the Bt3 horizon (750 mm depth). Matric suction was recorded in the A2e and Bt2 horizons at equivalent depths to the Pt electrodes. Electronic data was down loaded and batteries changed at 2 to 3 week intervals. The system was re-installed in May 1998 with duplicate Pt electrodes in the A1 horizon (200 mm depth), lower A2e horizon (400 mm depth), Bt2 horizon (600 mm depth) and Bt3 horizon (800mm depth).

A neutron moisture meter was used to determine soil moisture content to a depth of 1 meter at irregular intervals during each growing season. Access tubes for the neutron moisture meter were installed adjacent to own rooted vines and vines on Ramsey in both irrigated and non-irrigated plots.

Grapevine root distribution and density within the soil profile was determined in late April 1998. Four vines of the highest vigour rootstock (Ramsey) and lowest vigour rootstock (110 Richter) were selected from both the irrigated and non-irrigated treatments in the central or western portions of the experimental plot. The A1 and A2e horizons in the central and Western parts of the experimental plot were soft, loamy sands rather than the hard sandy loam that occurred in the eastern portion of the plot. An 80 mm diameter hand auger was used to collect soil samples to a depth of 1 meter in 200 mm increments directly under the 4 L/hr drippers, located mid way between the vines, and at the equivalent position for non-irrigated vines and also 1 meter directly out into the inter row. Root density for all samples was determined using a soil dispersion method. In all horizons, however, the majority of roots were in the very fine (0.2-0.5 mm diameter) category.

Results

The A1 and A2e horizons are freely draining loamy sands or sandy loams. Consequently saturation of these horizons only occurred after heavy rainfall events when perched water tables formed on top of the impermeable Bt1 and Bt2 horizons. These perched water tables first appeared in late June 1998 after the Bt1 and Bt2 horizons were already saturated and typically remained for between 1 and 3 days after the rainfall event. When multiple rainfall events occurred on consecutive day, perched water was detected for continuous periods of up to 10 days. The extremely low saturated hydraulic conductivity of the Bt2 horizon suggests that these perched water tables subsided principally due to horizontal flow into a nearby drain. However, occasional sand filled cracks in the Bt1 and Bt2 horizons may have allowed some of the perched water to flow into the deeper clay horizons. Only very small decreases in

redox potential were detected in the A1 horizon in 1998. These decreases corresponded with perched water tables that extended into the A1 horizon. The low organic matter content of the A1 horizon (0.3%) (and thus low rate of biological respiration), and the limited duration of perched water within the horizon, precluded any significant change in redox potential.

Redox potential was similarly unresponsive in the A2e horizon. Several slight decreases in redox potential were recorded in 1997 and 1998 that, again, corresponded with perched water tables. The most significant decrease in redox potential was recorded in 1998 when it decreased from +680 mV to +380 mV over a period of 3 weeks from mid August to early September.

Redox potential in the Bt2 horizon was highly variable with no two platinum electrodes installed in the horizon in 1997 or 1998 recording comparable redox responses. The redox potentials recorded were also generally considerably higher (less reducing) than those recorded in the Btg1 horizon at Site 1 with potentials rarely decreasing much below 0 mV. The variability of the redox environment in the Bt2 horizon is indicative of the low average organic matter content of the horizon (0.3%) and heterogeneous distribution of organic matter. Roots (the main source of soil organic matter) were only able to penetrate the horizon through cracks (planar voids) in the coarse angular blocky structure. Consequently organic matter distribution and redox potential were also structurally defined. The variability of the redox environment was confirmed by visual observation of colour distribution in the horizon. Gleyed colours, indicative of iron reduction, occurred almost exclusively on the surfaces of peds while red and orange mottles, indicative of iron oxidation, tended to occur in ped interiors.

Although the redox environment was highly variable, in most of the horizon it also appeared to be quite stable. Other electrodes were observed to decrease very slowly and steadily over the course of three to four weeks after installation into soil that was already saturated. This indicates that a very low rate of biological respiration was occurring in the vicinity of these two electrodes. At redox potentials greater than +50 mV the concentration of reduced (Fe^{2+}) iron in solution is in the order of 10^{-5} M (Jeffries, 1961). Consequently the 'poise' of such a system is very low and the input of only minute amounts of oxygen will generate aerobic conditions. The fact that such a slow and steady decrease in redox potential was able to occur indicates that virtually no oxygen was entering the horizon in the vicinity of these two electrodes from external sources. This, in turn, is indicative of the extremely low saturated hydraulic conductivity and thus poor drainage of most of the horizon. Some heterogeneity in saturated hydraulic conductivity was detected along the vine row. Electrode Bt2-1 in 1998 demonstrated relatively rapid changes in redox potential and an apparent responsiveness to heavy rain or perched water tables. This electrode may have been inserted in a slightly better drained part of the horizon.

The physical properties of the A1 and A2e horizons were conducive to root growth. However, virtually no roots of 110 Richter were detected in the non-irrigated parts of the A1 horizon and only a very low (approximately 0.1 cm/cm^3) root length density was detected in the A2e horizon. By comparison, the root length density of Ramsey detected in the non-irrigated parts of the A1 horizon varied between 0.2 cm/cm^3 and 0.4 cm/cm^3, and between 0.3 cm/cm^3 and 0.7 cm/cm^3 in the A2e horizon. The A1 and to a lesser extent the A2e horizons were characterised by high temperatures and extreme desiccation during the late spring and

summer months (Table 7.4). This strongly suggests that 110 Richter has a lower tolerance to high temperatures and/or desiccation than Ramsey rootstocks. The root length density of both rootstocks was also significantly higher under the drippers than in other parts of the A1 or A2e horizons. However, the density of Ramsey roots under the drippers was still significantly higher than 110 R. This was particularly true in the rapidly desiccated A1 horizon.

Root length density in the clay sub-soil was low compared to the McLaren Vale study site (Section 4.2). Root length density also appeared to decrease steadily between the clay surface and a depth of 1 meter (approximately the lower boundary of the Bt3 horizon) where root length density approached zero. Root distribution in the Bt1 and Bt2 horizons was highly variable. No significant differences in root length density were detected between rootstocks, irrigation treatment or between vine rows and inter row in the clay sub-soil. There was, however, a significant difference in root length density between the top 300 mm of clay (Bt1 and Bt2 horizons) and the Bt3 horizon. Roots were only able to penetrate the clay Bt1 and Bt2 horizons through planar voids (structural cracks) that opened up between the coarse, sub-angular blocky structural units.

No quantifiable differences in soil water uptake were detected between own rooted vines and vines on Ramsey rootstock.

Plant available water within the top 1 meter of the profile was approximately 70 mm. This very low figure reflects the low water holding capacity of the loamy sand A1 and A2e horizon, and the high bulk density of the sub-soil clay. The high bulk density of the sub-soil clay can largely be attributed to its highly sodic and structurally unstable nature. By mid to late November, 1998 the A1 and A2e horizons were at the permanent wilting point The clay sub-soil (Bt2 horizon), by comparison, was still between saturation and field capacity. A similar situation was observed in 1988 (McCarthy, 1997b). This suggests that the root system in the clay sub-soil was ineffective prior to December 1 and that all soil moisture extraction in spring occurred in the sandy A1 and A2e horizons. The lack of soil moisture extraction from the clay sub-soil probably reflects a ‘die-back’ of fine, absorbing roots due to anaerobic conditions in winter and spring in a manner similar to that observed at McLaren Vale (Section 4.2).

Soil moisture extraction occurred very slowly in the Bt1, Bt2 and Bt3 horizons between December, 1988 and March, 1989 and was so slow in the Bt3 horizon that only around half of the available water had been extracted by March, 1989. This slow rate of soil water extraction can be explained by the extremely low density and heterogeneous distribution of roots in the Bt3 horizon. Soil water extraction was probably also slowed by poor root soil contact due to the near rigid consistence of soil peds.

Volumetric water contents of the A1 and A2e horizons from January 1 indicate the extreme desiccation of these sandy surface horizons during summer. Approximately 60 mm/m of water remains in loamy sand at the permanent wilting point (1500 KPa suction). The water content of these horizons decreased to 30 mm/m in January, 1989 with just 10 mm/m remaining in February. The top 100 to 200 mm of sub-soil clay also appeared to dry beyond the permanent wilting point in late summer.

Vine performance was poor. Although small amounts of irrigation water are applied annually, the average yield of the vineyard over the last decade is just 3.1 t/ha (Vineyard Manager – Pers. Comm.) and fruit quality is also regarded as being highly variable. Symptoms of severe drought stress were clearly evident in the vineyard in the summers of 1998 and 1999. The poor performance of this vineyard can clearly be attributed to the inadequacies of the root zone.

Only 70 mm of plant available water is held within the root zone. However, not all of this water is utilized by the vines. The extremely slow rate of water extraction from the Bt3 horizon means that plant available water probably remains in this horizon at the end of the growing season. Similarly, poor root development in the A1 horizon means that most water held in this horizon is probably lost to surface evaporation.

Outcomes from the Research

Scientific Papers and Conference Presentations

Dowley A.C., R.W. Fitzpatrick and A. Cass. 2000. Redox Potential (Eh) and Root Damage in Periodically Waterlogged Viticultural Soils (2000). In New Horizons for a New Century. Australian and New Zealand Second Joint Soils Conference Volume 3: Poster Papers. (Eds. J.A. Adams and A.K Metherell). 3-8 December 2000, Lincoln University, New Zealand Society of Soil Science. pp. 55-56.

Dowley A., Cass A. and Fitzpatrick R. W. 2002. Redox Potential Regimes and Vine Performance on Sodic, Seasonally Waterlogged Duplex Soils (Aquic Natrixeralf and Vertic Palexeralf) (combined with paper in next section). Paper to be submitted to Australian Journal of Grape and Wine Research.

Industry Journal Articles

Andrew Dowley, Alfred Cass and Rob Fitzpatrick. 2002. Vines performance suffers from early season waterlogging in Duplex soils in South Australia (combined with article in next section). Article to be submitted to the Australian Grapegrower & Winemaker.

Dissertation

Dowley A. Grapevine Performance On Seasonally Waterlogged and Poorly Aerated Soils in South Australia, PhD Thesis, University of Adelaide, South Australia. To be submitted in 2002.

Seminars and Field Days

The trial was used regularly for informal field days and Research to Practice^{TM} Seminars between 1996 and 1999.

4.2 Non-Sodic, Duplex Soil at McLaren Vale

Andrew Dowley, Robert Fitzpatrick and Alfred Cass

A study was described in Section 4.1, where the severity and duration of anaerobic conditions in a vineyard on a sodic Yellow Duplex soil at Nuuriootpa was described. A similar study was conducted at McLaren Vale to extend those findings to another grape-growing region, using a similar soil. As before, morphological, physical and chemical characteristics of the soils and the redox potential over the winter/spring period of 1998 and 1999, as well as the relationship between Redox potential, matric suction, perched water tables, soil physical and chemical parameters and "redoximorphic" morphological soil features were investigated. Grapevine root growth, survival and length density distribution and fruit yield and quality were measured and related to soil properties.

Methods and Materials

The soil profile consisted of a topsoil (A1 horizon) at 0 to 200 mm depth, a bleached subsurface layer (A2e horizon) at 200 to 400 mm depth, an upper subsoil layer (Btg1 horizon) at 400 to 700 mm depth and a lower subsoil layer (Btk2 horizon), deeper than 700 mm. This profile was classified as a non-sodic Yellow Duplex (Vertic Palexeralf). Both the A1 and A2e horizons had a clayey sand texture. The A1 horizon is relatively soft and penetrable to roots, with a penetration resistance at field capacity of around 2 MPa. The A2e horizon, by contrast, was very firm, dense and had a penetration resistance greater than 8 MPa.

The Btg1 horizon had a medium to heavy clay texture and a strong, coarse (50 to 100 mm) polyhedral structure breaking to moderate, medium (20 to 50 mm) angular blocky. The horizon also demonstrated moderate to high linear shrinkage characteristics and strongly developed pressure surfaces (slickensides) on the ped surfaces. Organic matter content was 0.7 %, pH was neutral and gleyed colours were extensively developed throughout the horizon, particularly on the ped surfaces. Saturated hydraulic conductivity was extremely low (< 1 mm/day).

The Btk2 horizon had a medium clay texture, moderate coarse sub-angular blocky structure and lesser linear shrinkage characteristics than the Btg1 horizon. Organic matter content was low (0.3 %), pH was moderately high (8.3 in water) due to the high lime content (calcareous). Only very weakly developed slickensides were detected on ped surfaces. Saturated hydraulic conductivity, although low, was significantly higher than in the Btg1 horizon.

Redox potential and matric suction monitoring equipment described in Sections 6 and 4.1 was installed in May 1998, before winter rain saturated the soil. Two wells were installed to monitor perched water table depths within the soil profile. The wells were constructed from 50 mm PVC drain pipe that had horizontal slots cut at 20 mm intervals in the lower 200 mm of the pipe. The first well was installed to the depth of the top of the clay Btg1 horizon (430 mm) to monitor the depth of any perched water tables that formed within the A2e horizon

(water perched on top of the impermeable clay Btg1 horizon). As the sandy loam A1 horizon was assumed to drain freely, no attempt was made to seal the well from the A1 horizon. The second well was installed at a depth of 1 meter to determine the periods when the clay Bt1 and/or Bt2 horizons were saturated. The depth of water within the wells was recorded using single channel Dataflow data loggers attached to Dataflow capacitance type water sensors.

Rainfall data was obtained from the Australian Bureau of Meteorology database and was recorded by a rain gauge situated at McLaren Vale Post Office, approximately 2 km from the research site.

Grapevine root distribution and density was determined in order to better understand the interaction between soil and vine performance. Root distribution was first determined in early May, 1998. This period was chosen to correspond with the end of the growing season and was approximately 1 month before anaerobic soil conditions developed during the winter/spring period. Root distribution was again determined in late October, 1998, early in the new growing season and shortly after anaerobic soil conditions had ceased. This was done in order to determine the effect of anaerobic soil conditions on grapevine root growth and survival through the winter and early spring period.

Soil samples were collected for root analysis at 200 mm intervals to depth of 1 m using an 80 mm diameter hand augur. Four holes were hand augured under vines growing within 18 meters (3 panels) of the permanently installed redox monitoring equipment. Holes were augured approximately 300 mm from the 4 L/hr dripper that was located mid way between the vines. Root length density (root length density) was determined using a soil dispersion method.

Results

Measurements commenced on May 20, 1998 before winter rains saturated the soil and redox potentials in all horizons was between +500 mV and +630 mV indicating aerobic conditions. The A1 and A2e horizons are freely draining clayey sands and saturation of these horizons only occurred after heavy rainfall when perched water tables formed on top of the impermeable Bt1 horizon. These water tables were monitored in the shallow (430 mm deep) well. The duration of perched water tables in these layers was always short because of a moderate land slope (5 to 7 degrees) causing water perched in the freely draining A1 and A2e horizons to rapidly drain down the slope.

Small decreases in redox potential were recorded in the A1 horizon during the brief periods in which the perched water table extended into the A1 horizon. No corresponding decrease in redox potential was recorded in the A2e because of the difference in organic matter content of the two horizons. Biological respiration can proceed much more rapidly in the A1 than the A2e due to the greater concentrations of readily oxidisable organic matter. Dissolved O_2 was not depleted fast enough in the A2e to influence redox potential in the 4 or 5 hour period that it was saturated.

Heavier falls of rain (>25 mm) caused perched water tables that formed on top of the Bt1 horizon which remained for many (4 to 10) days. The saturated hydraulic conductivity of the

clay Bt1 horizon is extremely low (less than 1 mm/day). However, initial wetting of the Btg1 horizon was rapid due to water flow down between the coarse, sub-angular blocky structures The redox potential of the Btg1 horizon decreased rapidly to around +50 mV, indicating that the horizon was saturated and that all structural cracks had swelled shut. This resulted in a stable, anoxic, redox environment that lasted from June until October. Complete seasonal closure of structural cracks occurs in this horizon is indicated by presence of polished pressure surfaces (slickenslides) on the faces of the clay peds, reflecting the high swelling pressure that arise between opposing ped surfaces during swelling. Gleyed colours in this horizon are derived from the reduction and depletion of oxidised iron and manganese and correlate with the recorded redox environment.

Despite the extremely low saturated hydraulic conductivity of the Btg1 horizon, a considerable depth of water was recorded in the 1 m well after major falls of rain. Water infiltrated fairly rapidly into the well, probably through occasional structural cracks and old root channels that had opened slightly due to very slow drainage of the horizon, but drained out of the well and into the Btk2 horizon only relatively slowly.

Redox potential in the Bt2 horizon declined slowly and steadily between August 22 and September 11 to a minimum of +83mV. The slow decline in redox potential may reflect the low organic matter content (0.3 %) in this horizon and relatively cool soil temperatures in August (< 13^{o}C), resulting in a very low rate of biological respiration. Redox potential did fluctuate in response to rain to mid October then rose again. In calcareous soils like these, only minute amounts of Fe^{2+} exist in solution when redox potential is positive (Gotoh & Patrick, 1974). Consequently, only minute amounts of oxygen are required to satisfy the resperative demand of the soil and generate aerobic conditions. The higher saturated hydraulic conductivity of this horizon also indicates better drainage than the Btg1 horizon. This suggests that oxygenated air is able to enter and permeate relatively rapidly through the Btk2 horizon via occasional structural cracks in the generally anaerobic Btg1.

These results show that the drainage properties at this site are at their worst in the Btg1 horizon. This horizon also had the longest period of anaerobic conditions in the winter and spring of 1998. Drainage in the calcareous Btk2 horizon is slightly better than in the Btg1. Redox conditions are also less stable or intense in the Btk2 than in the Btg1. This is probably a reflection on the lower organic matter content, and therefore lower rate of soil respiration, as well as the higher pH of this calcareous horizon. However, redox conditions in the Btk2 horizon are still controlled to some extent by conditions in the Btg1 horizon as oxygen has to pass through that horizon before it enters the Btk2. The most rapidly drained horizons are the A1 and A2e. Generally, these horizons only become anaerobic for short periods after heavy rainfall.

Vine root length density in the A1 horizon was high (about 2 cm/cm^3) but low (0.5 cm/cm^3) in the A2e horizon in both May and October. Visual *in-situ* observation of root distribution in the A2e indicated that, while root density was low, it was also unevenly distributed and largely confined to clumps of roots formed in occasional cracks within the horizon. The effectiveness of the root system in the A2e is thus probably even lower than that suggested by the root length density estimates.

Root length density in the clay B horizons was quite high in May and highest in the top 200 mm of the Bt1 horizon (approximately 2 cm/cm^3), and gradually declined to a density of approximately 1 cm/cm^3 at 1 meter depth. Visual, *in-situ* observation of the root system indicated that, as with the A2e horizon, roots were primarily confined to the structural cracks between individual peds. At least two orders of structural cracks were evident. The largest cracks occurred between large, polyhedral units approximately 50 to 100 mm in diameter. These units were divided by second order structural cracks with the smallest structural units just 20 mm to 30 mm in diameter. Most roots existed in clumps of first and second order roots in the largest structural cracks. No roots could penetrate the dense clay peds themselves. Occasional woody framework roots (> 2 mm diameter) were also observed.

The root system in the Bt1 and Bt2 horizons changed substantially over the winter-spring period. The density of living roots in October was much less than in May (< 0.5 cm/cm^3 as opposed to 1 to 2 cm/cm^3). A large number of dead, black root fragments were also observed. Most roots were considerably darker than those observed in May which led to considerable difficulty in distinguishing between living and dead root fragments in the < 0.5 mm size fraction. All woody 'framework' roots observed in samples collected in October were alive.

Very little effective root system remained in the clay sub-soil at the end of the period of winter-spring saturation. The sub-soil root system was found to be almost totally ineffective for at least the first three months of the growing season. During this period vine growth depended almost exclusively on the A1 and, to a lesser extent, the A2e horizons. These horizons are shallow and can only store very limited quantities of readily available water that could be depleted from the A1 horizon in just 3 or 4 days in late October. This suggests that these vines are at risk of water stress during flowering and fruit set if close attention is not paid to irrigation scheduling.

Outcomes from the Research

Scientific Papers and Conference Presentations

Dowley A., Cass A. and Fitzpatrick R. W. 2002. Redox Potential Regimes and Vine Performance on Sodic, Seasonally Waterlogged Duplex Soils (Aquic Natrixeralf and Vertic Palexeralf) (combined with paper in previous section). Paper to be submitted to Australian Journal of Grape and Wine Research.

Industry Journal Articles

Andrew Dowley, Alfred Cass and Rob Fitzpatrick. 2002. Vines performance suffers from early season waterlogging in Duplex soils in South Australia (combined with article in previous section). Article to be submitted to the Australian Grapegrower & Winemaker.

Dissertation

Dowley A. Grapevine Performance On Seasonally Waterlogged and Poorly Aerated Soils in South Australia, PhD Thesis, University of Adelaide, South Australia. To be submitted in 2002.

Seminars and Field Days

The trial was used regularly for informal field days and Research to Practice™ Seminars between 1996 and 1999.

4.3 Poorly Structured Cracking Clay at McLaren Vale

Andrew Dowley, Robert Fitzpatrick and Alfred Cass

Research was described in Sections 4.1 and 4.2, describing the severity and duration of anaerobic conditions in vineyards on Yellow Duplex soil at Nuriootpa and McLaren Vale. This section describes a similar study, at McLaren Vale on a Black Earth (Cracking Clay), which extended those findings to a different soil.

Cracking clay soils have been used for grape production in Australia but often with mixed success. With the recent industry expansion, larger areas have been developed and problems have been encountered in establishing young vines on these soils.

Cracking clays are dark, gray or reddish clays (>50 % clay) that tend to swell when wetted and crack when dry. Plant growth and hydrological properties of these soils are dominated by the dynamic structural changes that these soils undergo on wetting and drying. Cracking, particularly if it occurs in a fine, closely spaced pattern is of great importance to adequate water intake and thus available water storage. Excessive tillage and trafficking can damage soil structure, causing the cracking pattern to become less fine and more widely spaced. The hydrological effect of this is to limit water intake, perturb even distribution of water and reduce storage of available water.

Young vines are often slow to establish on these soils, but after an initial period of slow growth (5 to 7 years) they often become excessively vigorous. The growth of young vines is restricted by waterlogging (lack of aeration) of the shallow root system and/or severe cracking around the young root system. However, as the root system deepens, this restriction diminishes and the growing root system has access to a larger and larger reservoir of total available water held by these soils that promotes vigorous growth.

As before, morphological, physical and chemical characteristics of the soils and the redox potential over the winter/spring period of 1997 to 2000, as well as the relationship between Redox potential, matric suction, perched water tables, soil physical and chemical parameters and "redoximorphic" morphological soil features were investigated. Grapevine root growth, survival and length density distribution and fruit yield and quality were measured and related to soil properties.

Methods and Materials

The vineyard on a cracking clay at McLaren Vale was first planted to vines in September and October 1996. Initial vine growth was poor and extensive re-planting was done in October 1997. Planting material was non-grafted, callused cuttings from an unidentified clone of Shiraz. Subsequently, growth in the first four years was poor with most vines still well short of being established along the lower trellis wire (and many barely reaching the trellis wire) by the end of the 1999/2000 growing season. Most of the vines were chlorotic, which reached severe levels in the spring (September to November) of each growing season and during summer in the first and second seasons.

The vineyard was ripped prior to establishment to a depth of approximately 800 mm. Vines were spaced 3 x 1.5 m and trained onto two cordon wires with 2 L/h drippers placed at 0.5 m intervals. The vineyard was initially irrigated for 2 hours a night between November and April. This was reduced to every second night in the 1998/1999 and 1999/2000 growing seasons. The inter-row space was tilled irregularly with a rotary hoe to control weed growth in the inter-row and herbicide was applied before bud-burst each season to control weed growth along the vine row.

A soil management trial was established at the site in early October 1997 with callused cuttings used for the major vineyard replant. Results from the soil management trial are presented in Section 3.4. All soil and vine measurements reported here were made within the treatment plots of the management trial.

The soil has two surface layers, a self-mulching layer (A1 horizon) at 0 to 100 mm depth, and a topsoil layer (A2 horizon) at 100 to 200 mm depth, and a series of subsoil layers: B1 200 to 500, B2 500 to 800, B3k 800 to 1000 and a B4k horizon deeper than 1000 mm. The self-mulching A1 horizon is a clay loam, with friable, fine (2-5 mm) sub-angular blocky structure, low bulk density and high air filled porosity at field capacity (16 %). Aggregates slaked moderately fast but did not disperse. The A2 horizon is light clay, has firm (moist) to strong (dry) massive structure with higher bulk density than the A1 horizon but air filled porosity was adequate (9 %). On drying, the soil shrinks to large coarse hard peds surrounded by large cracks. The air filled porosity of these peds is commonly less than 2% over a wide range of soil moisture contents (Daniells, 1989, Chan, 1982).

The four subsoil layers are all medium to heavy clay but structure varied. The upper subsoil layer (B1ss horizon) was firm (when moist) sub-angular blocky structure (5-10 mm) with weakly defined pressure surfaces (slickensides indicated by “ss”) that tended to form large, very hard, dense peds as it dried. Internal (pedal) shrinkage occurred within the peds as they dried thus generating some structural macropore space. The second subsoil layer (B2ss) had strong, sub-angular blocky structure (20-50 mm diameter) with prominent slickensides. As it dried, individual peds tended to shrink away from each other thus forming a network of fine structural cracks. Peds from these two layers slaked rapidly but did not disperse, reflecting the relatively low ESP values. Air-filled porosity at field capacity was 6 % in the B1 and 3 % in the B2 horizon. The B3kss and B4kss horizons had similar texture but were both alkaline and sodic and consequently dispersive.

Redox potential, temperature and matric suction were monitored at this research site between July 1999 and March 2000 using the equipment described in Section 6. Duplicate platinum electrodes were installed at 300 mm depth (B1 horizon), 600 mm depth (B2 horizon), and at 900 mm depth (B3k or B4k horizons). Duplicate tensiometers were installed at the same depths. Data was downloaded and systems checked approximately once a month. Platinum electrodes were also installed within soil mounds for an experiment described in Section 3.4. A single well was installed to a depth of 1 m in June 1999. Water depth was logged between June and November 1999. Rainfall data was acquired from the Bureau of Meteorology’s rain gauge at McLaren Vale, a distance of approximately 2 km.

Grapevine root distribution and density was determined in early May 1999, after two full seasons of growth. Soil samples were collected mid-way between the second and third vine in each of the 4 panels using an 80 mm diameter hand augur in increments of 100 mm to 200 mm depth then in 200 mm increments to 1 m. Paired samples were also collected 1 meter directly out into the inter-row from the vine row samples. Root length density (RLD) was determined using a soil dispersion method and observations of the root systems were also made in the soil pit excavated in June 1999.

Results

Drainage properties of the B1 and B2 horizons were similar: Matric suction typically remained below field capacity (10 KPa) for a period of 5 to 7 days after major rainfall events during the winter-spring period but rarely decreased below 5 KPa. The lack of absolute saturation (0 KPa) confirmed the observation of an absence of a perched water table in the 1 m well. The B2 horizon remained at or below field capacity for the entire period up until the start of December. No apparent water extraction occurred within this horizon during the winter-spring period. The rapid drying of the soil in December coincided with the formation of large (up to 80 mm wide) vertical cracks parallel to the vine-rows on either side of the wetted zone. Drainage in the B3k horizon was poor: Matric suction remained below field capacity throughout the winter-spring period but rarely reached the point of absolute saturation (0 KPa) and began to increase in December, approximately 10 to 12 days after the B2 horizon.

Redox potential remained relatively stable in the B1 horizon (300 mm depth) at +600 to +650 mV throughout the monitoring period. Eh in the B2 horizon was generally lower than in the B1 horizon and decreased sufficiently after major rainfall events to indicate the onset of anaerobic conditions (Eh < +300 mV) that correlated with matric suction values below field capacity (10 KPa). In the B3k horizon, Eh remained relatively stable at –160 to –210 mV (anaerobic) between June and late November then increased to approximately +200 mV in a period of just 2 days. This increase in Eh corresponded to the onset of rapid drying of the sub-soil in early December. Eh continued to increase slowly to reach + 400 mV by early January.

The B2 horizon became anaerobic after major rainfall events probably due to two factors: (1) the low air-filled porosity of the B2 horizon at field capacity (3 %), and (2) the length of the diffusion path between the horizon and the atmosphere above the soil. These conclusions are supported by the findings of Wesseling (1974) and Hodgson & MacLeod (1989a) who showed that oxygen diffusion could not occur at air-filled porosity values less than 10 to 15 %. The fact that O_2 diffused through this soil at all (at or near field capacity) suggests very good macro-pore continuity (Blackwell *et al.*, 1991; Hodgson & MacLeod, 1989b) and probably reflects the strong sub-angular blocky structure evident in the B2 horizon. The second factor influencing the periodically anaerobic B2 horizon was that O_2 was depleted rapidly as it diffused from the surface down towards the deeper horizons. In such an environment of highly restricted gaseous diffusion, much of the O_2 in the soil atmosphere was probably depleted in the A and B1 horizons. The B3k horizon remained strongly reducing throughout the winter-spring period because of the saturated condition.

Maximum daytime soil temperature at 100 mm and 300 mm depth generally followed the pattern described for a non-irrigated vineyard in South Africa by Myburgh & Moolman (1993). Vine root growth can be expected to decline sharply below 11^{o}C and above 32^{o}C (Hanks & Ashcroft, 1980, Jooste 1983). Daytime maximum soil temperatures were never recorded below 11^{o}C in the post bud-burst period. However, daytime maximum soil temperatures at 100 mm depth regularly exceeded 32^{o}C from late November, reaching 40^{o}C during an extended heat wave in January 1998. Atmospheric temperatures in February and March 2000 suggest soil temperatures were probably also excessive for root growth during this period. During periods of high incident radiation, the temperature of the top 100 mm of bare soil would have to be excessive for root growth and function.

No vine roots were present in the A1 horizon under the vines. Root length density was very low in the A2 horizon (0.02 cm/cm^3) and low in the B1 horizon (0.08 cm/cm^3). No grapevine roots were observed in the B2, B3k or B4k horizons along the vine row or at any depth in the inter-row.
Mechanical and chemical properties of the A1 horizon were ideal for root development. Desiccation along the vine-row was also not a problem due to regular irrigation scheduling. The lack of grapevine roots in the A1 horizon along the vine-row, therefore, could only be attributed to excessive soil temperatures in late spring and summer. Limited grapevine root development in the A2 horizon was probably also largely due to excessive soil temperature, but the physical properties of this horizon also played a role. Temperature did not limit root length density in the subsoil layers. Poor aeration on the wet end and high strength on the dry end provided only a narrow window for root growth to occur, effectively limiting root length density throughout these layers. The absence of root growth in the inter-row can be attributed to the large shrink-swell capacity of the soil that physically sheared fine roots during drying. Development of cracks accelerated the soil drying process by exposing subsoil layers and desiccated roots within the cracks

Severe micro-nutrient deficiency was evident in the vines in each of the first three growing seasons after planting: Leaves were chlorotic, developing a diffuse yellow to golden yellow colour soon after bud-burst, shoot development was restricted and leaf and stem die-back occurred. These are all ‘classic’ symptoms of severe iron deficiency (Grundon et al., 1997; Robinson, 1992; Wallihan, 1977). Iron chlorosis has also been reported in crops grown on black or grey vertisols in Victoria (Millikan, 1951), New South Wales (Hodgson, *et. al*., 1992) and Western Australia (Chapman & Boundy, 1977). Iron chlorosis is strongly associated with poor soil aeration, high ‘active lime’ content and high soil pH (Kolesch *et al.*, 1987; Fregoni & Bavaresco, 1985; Scholl, 1983). Active lime was determined for each horizon following the method of Drouineau, (1942). The B1 horizon, being the only horizon with significant grapevine root development, had a high ‘active lime’ content, high pH and sub-optimal aeration.

A decrease in chlorotic symptoms was observed in the latter part of the 1998/1999 and 1999/2000 seasons. This corresponded with a decrease in irrigation frequency from once every day (in the 1996/1997 and 1997/1998 seasons) to once every two or three days in the 1998/1999 and 1999/2000 seasons. Although the site was irrigated for only 2 hours a day (less than 4 L/dripper/day), this clearly led to inadequate aeration in the main part of the root zone, the B1 horizon. Better aeration in the B1 horizon in the last two seasons was probably

responsible for the decrease in visible chlorotic symptoms. Vine growth improved in these last two seasons (Figures 12.4 and 12.5), but was still far from adequate.

Vineyard establishment is typically extremely slow on this soil type. This appears to be due to a number of soil properties hostile to root growth and plant nutrition: excessive temperature in the surface horizons, high pH, insufficient macro-porosity and poor aeration when wet and excessive hardness when dry. The inter-row is also sharply divided from the vine-row by massive vertical cracks that form on either side of the wetted zone. Developing irrigation practices to optimize vine growth on this soil type is difficult. Daily irrigation, designed to maintain the soil at or near field capacity, resulted in symptoms of iron chlorosis. A reduction in irrigation frequency to every two or three days led to some improvement in the rate of vine growth. However, even after two seasons of this modified irrigation regime, most vines still had not reached the lower trellis wire. Vine growth in an adjacent vineyard that was irrigated once a week with 4 L/hr drippers was also extremely poor. The reasons for the low rate of vine growth under almost any irrigation regime were explained by the soil properties that restrict root growth at almost any soil moisture content.

Outcomes from the Research

Scientific Papers and Conference Presentations

Dowley A., Fitzpatrick R. W. and Cass A. 2002. Redox Potential Regimes and Vine Performance on a poorly structured cracking clay and a well structured Black Earth (Calciaquert and Endo-Calciaquert) (combined with paper in next section). Paper to be submitted to Australian Journal of Grape and Wine Research.

Industry Journal Articles

Andrew Dowley, Rob Fitzpatrick and Alfred Cass. 2002. Vines performance can suffer from early season waterlogging in cracking clays (combined with article in next section). Article to be submitted to the Australian Grapegrower & Winemaker.

Dissertation

Dowley A. Grapevine Performance On Seasonally Waterlogged and Poorly Aerated Soils in South Australia, PhD Thesis, University of Adelaide, South Australia. To be submitted in 2002.

Seminars and Field Days

The trial was used regularly for informal field days and Research to Practice^{TM} Seminars between 1996 and 1999.

4.4 Black Earth Cracking Clay at Coonawarra

Andrew Dowley, Alfred Cass and Robert Fitzpatrick

Major differences in grapevine performance and growth properties have been observed on vertisol soils (cracking clays) in different viticultural regions of South Australia. This section characterises soil properties and seasonal redox regimes of a Black Earth at Coonawarra, South Australia. Detailed morphological, physical and chemical characteristics, redox potential (Eh) over the winter-spring period and the relationship between Eh, matric suction and perched water tables are presented and discussed in relation to soil physical and chemical properties. Grapevine root growth, survival and length density distribution is presented in relation to soil conditions.

The vineyard was established in 1987 and contains a rootstock trial to determine the performance of Pinot noir on 10 vigour- reducing rootstocks: Schwarzmann, 140 Rugeri, 110 Richter, SO4, 5BB Kober, 1103 Paulsen, SA Teleki, 99 Richter, 101-14 and 5C Teleki. The remainder of the vineyard is ungrafted Pinot noir at a spacing of 3 x 2 m on a single wire trellis positioned at a height of 2 m. The high trellis system and wide inter-row space are designed to minimise frost damage and to allow for high vine vigour. Between 50 mm and 75 mm of irrigation water is applied in a normal season. The midrow space is non-cultivated and herbicide is occasionally used to control weed growth.

The soil is classified as a Black Earth (Stace et al., 1972) (Endo Calciaquert, Soil Taxonomy, 2000) and is associated with excessive vine vigour and poor fruit quality. An average soil profile is presented in Plate (8.1). The soil profile has a shallow topsoil (A1 horizon) at 0 to 50 mm depth, overlying a series of subsoil layers: B1ss horizon at 50 to 220 mm, B2ss horizon at 220 to 400 mm, B3k horizon at 400 to 500 mm depth and a B4k horizon 500 t0 1300 mm depth. Across the rootstock trial, the base of the B2ss horizon varied from 300 mm to 600 mm in depth and the B3k horizon varied in thickness from 50 to 200 mm across the vineyard.

The self-mulching, medium clay A1 horizon had firm polyhedral structure (2-5 mm diameter). The heavy clay B1ss and B2ss horizons also had firm polyhedral structure (2-5 mm diameter) with pressure surfaces (slickensides - ss). Dull, gleyed mottles covered 20-30 % of the profile and air-filled porosity at field capacity was low (< 7 %) All layers down to B2 horizons were largely free of calcrete nodules. The light clay B3k horizons and firm polyhedral structure (5-10 mm diameter) with 25 to 30 % calcrete concretions stained with yellow Goethite minerals. The staining arises when Fe(III) is reduced in the B2 horizon, translocated in solution to the top of the B3k horizon and re-oxidised as Goethite. Air-filled porosity at field capacity was greater than 11 % in the calcareous B3k horizon. The B4k horizon had similar properties to the B3k horizon but with a much higher content of rubble calcrete with Goethite precipitates.

Redox potential and matric suction were monitored between August and November 1997 and 1998. Redox potential and matric suction were also monitored in January 1999 in order to determine water extraction from the soil profile in the latter stages of the growing season. Duplicate platinum electrodes and tensiometers were installed at 200 mm (B1 horizon), 350

mm (B2 horizon) and 600 mm depth (B4k horizon). In 1998 the 600 mm sensors were removed and a set at 500 mm (B3k horizon) and 800 mm (B4k horizon) were installed. A single well was installed top a depth of 1 m in August, 1997 to monitor water table depths but no free water was ever detected in it. Rainfall data was from the Bureau of Meteorology's rain gauge at Coonawarra, a distance of approximately 100 m.

Vine root distribution and density were determined in early October 1997 (early season) and again in late March 1998 (late season). Root samples were collected mid-way between vines along the vine row to a depth of 1 meter. Samples were collected at 100 mm increments to 200 mm depth then at 200 mm intervals to 1000 mm using an 80 mm diameter hand augur. Paired samples were also collected 1 meter directly out into the inter-row from the vine row samples. Root length density was determined using a soil dispersion method. Observations of root systems were also made in soil pits excavated in 1997.

Results

Eh was stable throughout winter and spring in the B1 and B3k horizons in 1997. A slight decrease, however, was recorded in the gleyed B2 horizon. While Eh in the B3k horizon remained stable, values recorded were approximately 100 mV less than in the B1 horizon despite the greater air-filled porosity at field capacity and better drainage of the light clay in the B3k and B4k horizons relative to the B1 and B2 horizons. Anaerobic soil conditions (Eh < 300 mV) were not detected in any horizon in 1997. The relatively aerobic properties of the Btk2 horizon relative to the Btg1 horizons can be explained by the low organic matter content of Btk2 horizons, and associated extremely low respiration rates and O_2 demand.

Drainage properties of all three horizon were found to be fairly similar. The soil became saturated after major rainfall events during the winter and spring but usually drained to field capacity (10 kPa) within a period of 3 or 4 days. Matric suction only increased slowly after bud-burst (early September) and by the end of November did not exceeded 20 kPa at any depth. Similar results were detected in the late winter and spring of 1998.

The reducing conditions in the B4k horizon are indicative of a high soil respiration rate and, therefore, a high O_2 demand. This horizon has the potential to become anaerobic, despite a relatively high air-filled porosity, if O_2 diffusion into the horizon is limited by the B1 and B2 horizons. The B1 horizon has an air-filled porosity of < 7 % at field capacity. Hodgson & McLeod (1989) concluded that gas diffusion will not occur within a vertisol when the air-filled porosity is < 15%. Consequently, O_2 diffusion into the B3k and B4k horizons in this soil is clearly restricted during winter & spring by the poor physical properties of the B1 and B2 horizons and, on occasions, is unable to satisfy the O_2 demand. Slightly anaerobic conditions result.

Vine root length density was found to be relatively low in all horizons (0.3 to 0.6 cm/cm^3) probably due to the adverse structural properties of the soil. Small, polyhedral peds in these horizons are strongly accommodating, limiting root penetration between peds. Root length density in the soil fraction of the B4k horizon was significantly higher than the upper layers, probably due to better physical properties, although total root length density was less due to the very high proportion of calcareous gravel. Accommodation between structural units in the

B4k horizon clay is less than in the B1 and B2 horizons and air-filled porosity at field capacity is higher so roots are able to penetrate better.

No significant difference in root length density was detected between October and March. This accords with the generally aerobic soil conditions detected throughout the winter-spring period. The marginally aerobic conditions in the vicinity of the roots, however, may impede new root growth. Numerous authors have demonstrated that the roots of woody plant species grow most rapidly in an optimal soil oxygen environment, usually above 10%, but will often survive at much lower O2 concentrations (Huck, 1970; Iwasaki et al., 1966; Geisler, 1965; Iwasaki & Sato, 1963, Cannon, 1925).

Matric suction data indicated a gradual but fairly uniform moisture extraction pattern between bud-burst (early September) and late November in both 1997 and 1998. The root system appeared to be equally functional in all soil horizons. Matric suction data acquired between January and March 1999 indicates that matric suction in all horizons did not exceed 20 to 25 kPa. No significant drying of the soil profile occurs beyond this point. This suggest that root penetration may be even deeper than these observations suggest, drawing on water reserves down to the regional water table at a depth of 2 to 3 meters.

Outcomes from the Research

Scientific Papers and Conference Presentations

Dowley A., Fitzpatrick R. W. and Cass A. 2002. Redox Potential Regimes and Vine Performance on a poorly structured cracking clay and a well structured Black Earth (Calciaquert and Endo-Calciaquert) (combined with paper in previous section). Paper to be submitted to Australian Journal of Grape and Wine Research.

Industry Journal Articles

Andrew Dowley, Rob Fitzpatrick and Alfred Cass. 2002. Vines performance can suffer from early season waterlogging in cracking clays (combined with article in previous section). Article to be submitted to the Australian Grapegrower & Winemaker.

Dissertation

Dowley A. Grapevine Performance On Seasonally Waterlogged and Poorly Aerated Soils in South Australia, PhD Thesis, University of Adelaide, South Australia. To be submitted in 2002.

Seminars and Field Days

The trial was used regularly for informal field days and Research to Practice™ Seminars between 1996 and 1999.

4.5 Drained Groundwater Rendzina at Coonawarra

Andrew Dowley, Robert Fitzpatrick and Alfred Cass

Coonawarra has been subjected to seasonal flooding over a long period of time and this has influenced soil development in this area. Construction of a regional drainage system between 1912 and 1925 and consequent lowering of the water table and prevention of flooding has subsequently changed the character of many of the soils. The area had large areas of shallow, dark, formerly seasonally waterlogged soils described by Blackburn (1964) as Ground Water Rendzinas. Since drainage, these soils have evolved into soils that closely resemble the Terra Rossa, except for colour, that are seldom saturated for any length of time. As such they soils constitute a special case of waterlogged soil which merit further study in the continuum from waterlogged to well drained soil. A site was selected to investigate the seasonal degree of waterlogging suffered by these soils. Detailed morphological, physical and chemical characteristics of the soil were investigated and related to vine performance. Soil redox potential (Eh) was monitored and the relationship between Eh, matric suction and perched water tables developed and related to soil physical and chemical properties, redoximorphic morphological features, vine root growth, survival and density, vine growth, yield and fruit quality.

Methods and Materials

The soil was identified as a Ground-water Rendzina by Stace et al. (1968), (Aquic Mollisols, Soil Survey Staff, 2000) but, we believe, is now minimally affected by waterlogging. The vineyard was established in 1988 and at the same time, a rootstock trial was established to determine the performance of cabernet sauvignon (Langhorne Creek Clone 10) on SO4, Kober 125AA, Teleki 5C, Teleki 5B, Riparia Gloire, 101-14, 34EM, 420 A and 1616 rootstocks. Vines are planted on a spacing of 3 x 2 meters, spur pruned with vertical shoot positioning on a single wire trellis and irrigated by overhead sprinklers which are also used for frost control. The inter-row space is maintained with a permanent, closely mown sward.

The soil on the research area varied between 200 mm and 500 mm in depth, down to an undulating layer of hard, dense, sheet calcrete (Cm horizon). The typical research site profile consisted of a topsoil (A1 horizon) at 0 to 50 mm, a subsurface bleached layer (A2 horizon) from 50 to 180 mm and a subsoil (Bg horizon) from 180 to 400 mm depth with a sharp boundary between the Bg horizon and the sheet calcrete pan. The A1, A2 and Bg horizons were devoid of lime nodules or limestone fragments. Dark red mottles occupied approximately 10 to 20 % of the A2 horizon. The dominant colour of the Bg horizon was olive brown. This colour is indicative of Fe(III) depletion (gleying) due to waterlogging. All upper layers were silty clay loams with friable sub-angular blocky structure (5 to 10 mm diameter). Penetration resistance at field capacity was less than 2 MPa at field capacity, indicating easy root penetration. Air filled porosity at field capacity (matric suction = 1 m) was a low 7 %. Plant available water (water stored at matric suction between 1 m and 150 m), however, was relatively high at approximately 170 mm/m.

Duplicate platinum electrodes and tensiometers were installed at 200 mm (A2 horizon), 400 mm (Bg horizon), and in the fractured limestone near the bottom of the rip line (600 mm

depth) in September 1997 where they remained until summer 1998. Tensiometers could not be installed effectively in the ripped limestone bedrock. A single well was installed at a depth of 600 mm. Rainfall data was from the Bureau of Meteorology's rain gauge at Penola Post Office approximately 1.5 km away.

Grapevine root distribution and density was determined in March (late in the growing season) and October (early in the growing season) in 1998. Four vines were selected for root analyses from a moderate to high yielding treatment (5C Teleki), and the lowest yielding treatment (Own rooted) in the rootstock trial. Samples were collected, mid-way between vines along the vine row, in 100 mm increments down to 400 mm and 1 meter directly out into the inter-row from the vine row samples. Root length density was determined using a soil dispersion method. Observations of root systems were also made in the soil pits excavated in 1997.

Results

A water table was not detected up to November 1997 nor between May and November 1998, nor were anaerobic soil conditions (Eh < 300 mV) recorded. Eh remained relatively stable at approximately + 600 mV to +680 mV. However, small peaks in Eh were detected in association with rainfall events after the data logger was installed on September 7. These peaks in Eh could be explained by the high dissolved O_2 content of rainwater, contributing an electrochemical couple due to oxygen and hydrogen (Rowell, 1981; Tisdall et al., 1984 and Evangelou, 1999). Air filled porosity at field capacity, was found to be only 7 % in the A2 horizon along the vine-row, indicating that O_2 exchange during winter and spring is marginal.

No significant difference ($P<0.05$) was detected in RLD at any depth in the soil profile between March and October, 1998. On both sampling dates, root length density was moderate to high in all soil horizons along the vine-row with the highest occurred in the top 100 mm depth interval (A1 and A2 horizons). This was the most friable and finely structured part of the soil profile and penetration resistance was between 0.5 and 1 MPa in the A1 horizon. Root length density was significantly lower in the 100 to 200 mm depth interval (A2 horizon) because this layer was significantly less friable and had a significantly higher penetration resistance (1 to 1.5 MPa). Penetration resistance in the Bg horizon, with even lower root length density, was higher than that of the A2 horizon (1.5 to 2 MPa). Few grapevine roots were detected 1 meter into the inter-row space but, a dense mat of grapevine roots existed at the calcrete-soil interface. This mat of fine grapevine roots is present because of the drainage impediment at this interface but they may also be absorbing moisture from the limestone bedrock as observed by Duteau (1987).

Neither competition with the cover crop, nor wheel track compaction is likely to be a factor restricting grapevine root development in the inter-row space. Wheel compression rapidly degrades macropore structure, but has very little impact on water storage pores (Hamblin, 1985; Cass et al., 1993). The poor grapevine root development in inter-row soil profile, therefore, can be mainly attributed to the lack of macroporosity.

The rootstock with the lowest yield and vigour (own rooted vines) had a significantly higher overall root length density along the vine-row than the rootstock with the higher yield and vigour (5C Teleki). This concurred with results from many other rootstock experiments. Many observations support the notion that high vigour rootstocks have a significantly higher

mass and density of large, woody 'framework' roots (roots > 2 mm diameter) than low vigour rootstocks (Southey, 1992; Southey & Archer, 1988; Nagarajah, 1987).

Matric suction was low (< 5 to 10 kPa) throughout the winter but anaerobic soil conditions were not detected in any soil horizon during the winter or spring of 1997 or 1998. Matric suction steadily increased above 5 kPa in both the A2 and Bg horizons from mid-September, soon after bud-burst, indicating that the grapevine root system functioned effectively in all soil horizons from the very start of the growing season. The rate of water extraction (rate of increase in matric suction) was higher in the A2 horizon than the Bg horizon. This is consistent with the lower root length density values detected in the Bg horizon relative to the A2 horizon.

These results support the assertion that the character of these soils has changed from a "Ground Water Rendzina" to a soil with upland hydrologic features. Waterlogging, either from seasonally perched water or from high groundwater tables, is not a significant problem at this site. However, several soil morphological features still reflect the historical seasonal waterlogged regime: marginally gleyed colour of the Bg horizon (olive brown); red mottles in the A2 horizon; poor macro-aggregate stability of the A2 and Bg horizons.

Outcomes from the Research

Scientific Papers and Conference Presentations

Dowley A., Fitzpatrick R. W. and Cass A. 2002. Redox Potential Regimes and Vine Performance on a drained Rendzina (Acquic Mollisol). Paper to be submitted to Australian Journal of Grape and Wine Research.

Industry Journal Articles

Andrew Dowley, Rob Fitzpatrick and Alfred Cass. 2002. Drainage of Groundwater Rendzinas creates Black "Terra Rossa". Article to be submitted to the Australian Grapegrower & Winemaker.

Dissertation

Dowley A. Grapevine Performance On Seasonally Waterlogged and Poorly Aerated Soils in South Australia, PhD Thesis, University of Adelaide, South Australia. To be submitted in 2002.

Seminars and Field Days

The trial was used regularly for informal field days and Research to Practice™ Seminars between 1996 and 1999.

4.6 Vine Response to Early Season Waterlogging

Andrew Dowley, Robert Fitzpatrick and Alfred Cass

The response of woody plant species to rootzone waterlogging is well documented in the scientific literature. Symptoms of waterlogging stress include reduction or cessation of shoot and root growth, injury, epinasty, senescence and abscission of leaves, root death, specialised adventitious root formation near the soil or water surface, shoot die-back and, eventually, death. Physiological effects such as reduction in photosynthesis, transpiration, stomatal conductance and stem or leaf water potential have also been observed. In contrast, information on the relative tolerance of grapevine rootstocks to waterlogging is limited. Most information is subjective in that it is based on non-experimental field observation and accumulated industry experience.

The redox and drainage characteristics of a number of seasonally waterlogged but viticulturally important soil types have been discussed in Section 4. In all cases, waterlogged and anaerobic conditions were first detected in winter when the vines were still dormant. At a number of sites, however, anaerobic soil conditions in at least part of the rootzone continued into spring when the vines were actively growing. Given these soil conditions and the uncertainty surrounding the waterlogging tolerance of a number of commercially important grapevine rootstocks, the aims of this experiment were to determine vine response to rootzone waterlogging for the following:

1. rootzone waterlogging in the pre- and post-bud burst period,
2. effect of entire rootzone and partial rootzone waterlogging on vine growth,
3. relative waterlogging tolerance of a number of commercial rootstocks,
4. effect of the rooting medium (high organic matter potting mix and sand).

Materials and Methods

Callused cuttings of eight commercially important rootstocks grafted to Semillon and non-grafted Semillon cuttings were obtained from a commercial nursery in early October, 1997. Rootstocks selected for trial were Ramsey, 99R, 5C Teleki, SO_4, 1103P, 140 Ru, 110R, and 101-14. The callused cuttings were transferred to 4.7 L green plastic pots filled with a commercial grapevine nursery potting mix containing a 6:1 ratio of hammer milled pine bark and coarse river sand fertilized with nutricote orange, dolomite, $FeSO_4$, NH_4NO_3, complete nutrient mix and single super. Ten non-grafted Semillon cuttings were also potted in steam sterilized coarse washed sand. Irrigation four times a day with 0.2 L of water, ensured drainage after each irrigation. The glasshouse was air-conditioned with temperature set between 15 and 30^{o}C.

After dormancy from July to 20 August 1998, the vines were trimmed to a 2-bud spur. The top 10 mm of potting mix or sand was removed from each pot in order to remove all granules of slow release fertilizer. The non-control vines were placed in a double layer of heavy-duty plastic bags and then inserted in a second 4.7L pot for support. The sealed pots were then filled with tap water until overflowing. For the 'half rootzone waterlogging' treatment, small

drainage holes were punched through the side of the double layer of pots at points half way down the side of the pots. Several Pt electrodes were inserted into selected waterlogged and control pots. These Pt electrodes were used to periodically monitor redox potential (Eh) through the dormant and growing phases of the waterlogging period. The vines were then placed in a dark room with the temperature maintained at 10^{o}C for a period of one month. On removal from the dark room, the vines were sprayed with a solution of 10.4 mg/L hydrogen cyanamide (DORMEX) to ensure an even bud burst, which occurred 6 days later.

The pots were placed outside on polystyrene blocks (to ensure that there was no contact between the plant and soil) in a randomised block arrangement, replicated 6 times and irrigated four times a day with about 0.2 L of water. Treatments were:

T1: Full rootzone waterlogging until 4 weeks after bud burst.
T2: Full rootzone waterlogging until 2 weeks after bud burst
T3: Full rootzone waterlogging until bud burst
T4: ½ rootzone waterlogging until 4 weeks after bud burst.
T5: Control. No waterlogging.
T6: As for Treatment 1 but vines rooted in coarse sand.
T7: As for Treatment 5 but vines rooted in coarse sand.

Shoot length was measured periodically after bud-burst for 10 weeks and leaf water potential was measured with a Scholander Bomb using basal leaves of non-grafted vines at the 4 week and 12 week stages. After 10 weeks the stems and leaves of all surviving vines were harvested, dried at 60^{o}C and weighed. Dense root systems formed in the near ideal rooting environment of the potting mix but most roots died in the waterlogged treatments Under these circumstances, the most convenient method of measuring root density was to section the root systems into 10 mm fragments, sub-sample five random fractions onto a clear plastic tray with a 20 mm grid on the base. Root fragments were counted and divided into three categories: 1 year old living roots (brown), 1 year old dead roots (black) and recently formed, actively growing roots (white).

Results

Redox potential measurements taken two days after waterlogging commenced indicated anaerobic conditions (Eh < 300 mV) at all depths in the pots of waterlogged treatments, which remained stable throughout the period of waterlogging. In the coarse sand waterlogged treatments, after bud-burst Eh decrease to less than 300 mV in the first week, but remained aerobic (Eh>300 mV) in the top few centimeters. Eh was highly variable at 100 mm depth.

Differences in shoot elongation rates between Treatments 1, 2 and 6 and the others were detected in the second week after budburst. No differences were seen between Treatments 3, 4, 5 and 7 vines over the coarse of the trial. Treatment 6 vines planted in coarse sand had a significantly lower shoot length than Treatment 7 vines from 23 days after budburst, but a significantly higher shoot length than Treatment 1 vines (waterlogged for the same period of time) from 14 days after budburst. Treatment 1 vines had a significantly lower shoot length than Treatment 2 vines from 23 days after budburst, and a significantly lower shoot length than all other treatments from 14 days after budburst.

At the end of the experiment (67 days after budburst), average leaf dry weights of Treatment 1 to 4 vines (potting mix) and Treatment 6 vines (coarse sand) were, respectively, 50%, 76%, 100%, 110% and 89% that of the control vines. Stem dry weights were 25%, 53%, 105%, 112% and 70% that of control vines.

The ratio of new living roots (white) to old living roots (brown) was highest in the fully waterlogged Treatment 1 and 2 pots at the end of the experiment (67 days after bud burst) and lowest in Treatments 3, 5, 6 and 7 (Table 13.3). The ratio in Treatment 4 was equivalent to that of Treatments 3, 5, 6 and 7 in the upper half of the rootzone and to Treatment 1 in the lower half of the rootzone.

Treatment 1 (waterlogged) vines had significantly higher leaf water potentials than Treatment 5 (control) vines when waterlogging ceased four weeks after budburst. Treatment 1 and 2 vines still had significantly higher leaf water potential than Treatment 5 vines at the end of the experiment (67 days after budburst) although the difference between Treatments 1 and 5 was less than after 4 weeks. No significant difference in leaf water potential was detected between Treatment 3, 4, 5, 6 or 7 vines.

Shoot elongation rates of Treatment 1 and 2 vines from different rootstock/scion combinations diverged markedly from the second week after budburst. Treatment 1 and 2 vines planted on 99R, 5C Teleki, SO4, and 1103P rootstocks stopped growing in the second week and subsequently died. Waterlogged 140Ru and 110R rootstock shoots grew at intermediate rates while 101-14 and non-grafted Semillon vines grew at high rates.

Rootzone waterlogging prior to budburst did not affect early season vine growth that concurs with results for apple trees (Olien, 1987), numerous *Prunus* species (Rom and Brown, 1979) and various other species of nut tree (Kozlowski, 1984). Waterlogging after budburst did have a major impact on early season vine growth. Treatment 1 and 2 vines showed significant retardation of growth but considerable variation in waterlogging tolerance was observed between rootstocks: 99R, 5C Teleki, SO4 and 1103P were most sensitive, 110R and 140Ru were moderately sensitive while 101-14 and non-grafted Semillon vines were least sensitive.

Growth effects due to waterlogging continued after drainage of treatments had ceased. Shoot growth reduction was correlated with the rate of recovery of shoot growth after waterlogging had ceased. Although all rootstocks survived waterlogging in Treatments 1 and 2 but the most sensitive (99R, 5C Teleki, SO4 and 1103P) continued to decline after the cessation of waterlogging and either died or did not grow for the remainder of the experiment. Moderately sensitive rootstocks (110R and 140Ru) ceased growing about 14 days after budburst for up to a month after waterlogging and then grew at a slower rate than the control vines. The least sensitive vines (101-14 rootstocks and non-grafted Semillon) continued growing throughout the trial and growth rates recovered soon after cessation of waterlogging.

The growth patterns of the rootstocks were mirrored by the state of their root systems at the end of the experiment. The fine roots of dead or barely surviving 99R, 5C Teleki, SO4 and 1103P rootstocks were in an advanced state of decay with only a ‘skeleton’ of major root conduits remaining. The root systems of moderately sensitive 110R and 140Ru rootstocks were also in a state of decay, although to a lesser extent than those of the highly sensitive rootstocks. A large number of new white root tips were observed to be emerging from the

surviving framework of the original root system. The relatively low survival rate of established (brown) roots in 140 Ru rootstock resulted in a high ratio of white to brown roots in the subsequent root analyses. Relatively little decay was evident in the root systems of Treatment 2 vines of non-grafted Semillon and 101-14 rootstock. However, waterlogged Semillon vines had a significantly higher proportion of both fine, black roots and new, actively growing white roots than control vines. The black roots were interpreted to be roots that had survived the period of waterlogging but had then died prior to the end of the experiment. These root observations suggest that the ability of roots to survive protracted periods of waterlogging varies between rootstocks and that shoot growth rates decline in proportion to the damage done to the root system by waterlogging. The evidence also suggests that more severely damaged root systems take longer to recover after waterlogging has ceased.

In vineyards, soil conditions are rarely ideal for root development. This is particularly true of seasonally waterlogged soils where waterlogging and poor root development are both symptoms of poor soil structure. Consequently anaerobic conditions in part of the rootzone may have a direct effect on early season vine growth by restricting the active part of the root system to a sub-optimal volume of soil. Of even more importance to early season vine growth is the restriction that partial rootzone waterlogging places on plant available water. If roots die in the waterlogged part of the soil profile, access to water is confined to the non-waterlogged (aerobic) part of the rootzone. Consequently soil water available to the vines is also restricted, and irrigation is often needed earlier in the season than what would otherwise occur in a well drained and aerated soil of equivalent water holding capacity.

Leaf water potential was found to differ significantly from the control in the fully waterlogged Treatment 1 and 2 vines. This contrasts with the findings of Stevens and Prior (1994) who found no significant difference in leaf water potential between fully waterlogged and control vines. Olien (1989) found various responses in apples and suggested that an absence of change in leaf water potential was due to an effective adjustment of transpiration rate by stomata and the presence of change due to an over or under adjustment by stomata. Our results suggest that differences in root system efficiency between fully waterlogged (Treatment 1 and 2) vines and control (Treatment 5) vines were too great for effective stomatal adjustment to occur.

Outcomes from the Research

Scientific Papers and Conference Presentations

Dowley A., Fitzpatrick R. W. and Cass A. 2002. Grapevine and rootstock performance under early season waterlogging conditions. Paper to be submitted to Aus. J. of Grape and Wine Res.

Industry Journal Articles

Andrew Dowley, Rob Fitzpatrick and Alfred Cass. 2002. Vines suffer during early season waterlogging. Article to be submitted to the Australian Grapegrower & Winemaker.

Dissertation

Dowley A. Grapevine Performance On Seasonally Waterlogged and Poorly Aerated Soils in South Australia, PhD Thesis, University of Adelaide, South Australia. To be submitted in 2002.

Section 5

Soil Water Management Research

Outcomes from Research at Nuriootpa, South Australia

Judy Eastham and Concha Ginestar

The irrigation management research we undertook covered a series of experiments investigating the interaction between irrigation, yield and fruit quality; and developing and evaluating methods of scheduling irrigation to influence grape quality. In particular, the project focused on the development and evaluation of sap flow sensors as tools for scheduling irrigation to influence yield and fruit quality. The assumption was that plant-based measurements are likely to be more useful in controlling the degree of water stress experienced in vineyards than soil based measurements, because of the complicating factors of differing canopy size, soil type, and climatic conditions in different vineyards and regions. Much of the work was conducted in collaboration with Patrick Iland of the Department of Viticulture and Enology, University of Adelaide, and with Southcorp wines.

The preliminary work focused on evaluating the suitability of sap flow for measuring water use in grapevines. It was important to show that the devices were responsive to differing canopy size and climatic conditions, and that effects of water stress could be measured. This preliminary work was carried out in a Southcorp vineyard (Koonunga Hill) in the Barossa Valley, and at the Waite vineyard, and the results published in Eastham and Gray (1998). The next stage involved using the sensors for scheduling post-veraison irrigation applications for Marcus Schulz's Shiraz vineyard in the Barossa Valley. Three irrigation treatments were applied, with the irrigation amounts based on the vine water use measured by sap-flow sensor. Canopy growth, yield and grape composition of the different irrigation treatments were measured, and related to plant water status.

The plant water use measured by the sensors was directly related to the intensity and duration of water stress, as indicated by pre-dawn leaf water potentials. Canopy size and grape yield decreased with increasing degree of water stress. The concentration of total soluble solids and titratable acidity of the grape juice were unaffected by irrigation treatment, but the concentration of anthocyanins and phenolics expressed on a unit weight basis increased with increase in the degree of water stress due to decreased berry weights. The direct relationship between water stress and post-veraison water use of vines suggests that vine water use measurements from sap-flow sensors can be used as a basis for applying either excessive, sufficient or deficit amounts of irrigation to influence the degree of water stress and hence berry weight and composition. The results of this experiment are reported in Ginestar *et al.* 1998a and 1998b.

The final phase of the work involved an experiment in the Barossa Valley in which the performance of the sap flow sensors in scheduling irrigation in Chardonnay grapevines from

flowering until harvest was compared with other quantitative scheduling methods. The quantitative scheduling methods investigated were gypsum blocks, the neutron probe, crop coefficients and sap flow. These were compared with the normal irrigation practice of the grower that was based on qualitative considerations. The responses were quantified in terms of water status, growth, yield, fruit composition and water use efficiency.

The different methods of scheduling irrigation influenced both the timing and total amount of irrigation applied, with the crop coefficient treatment receiving the most water and exceeding the regional limit (100mm) for irrigation application. Soil water contents were generally greater and leaf water potentials consistently higher in the crop coefficient compared with other treatments, but were similar in the four other irrigation treatments. Vine growth was similar for all treatments, except for a greater number of lateral shoots produced in the crop coefficient treatment. Yield was greatest for the crop coefficient treatment, but there was no significant difference in yield between the other scheduling methods that received less than 100 mm of water. Berry composition at harvest was largely unaffected by the scheduling method. Of the quantitative scheduling methods, water use efficiencies were similar for the two soil water monitoring and the sap flow treatments, but significantly lower for the crop coefficient treatment. It was concluded that adoption of quantitative methods for irrigation scheduling is warranted in regions such as the Barossa Valley where water supplies are limited, and that sap flow and soil water monitoring methods were equally effective in ensuring efficient use of irrigation without detriment to yield or grape quality. The results of this experiment will be published in Ginestar et al.

Outcomes from the Research

Scientific Papers and Conference Presentations

Eastham, J and S. Gray 1998. A preliminary evaluation of suitability of sap flow sensors for use in scheduling vineyard irrigation. American Journal of Enology and Viticulture 49:1-6.

Ginestar, G. J. Eastham S. Gray & P. Iland, 1998a. Use of sap flow sensors to schedule vineyard irrigation: I Effects of post-veraison water deficits on water relations, vine growth and yield of Shiraz grapevines. American Journal of Enology and Viticulture 49: 413-420.

Ginestar, G. J. Eastham S. Gray & P. Iland, 1998b. Use of sap flow sensors to schedule vineyard irrigation: II Effects of post-veraison water deficits on composition of Shiraz grapes. American Journal of Enology and Viticulture 49: 421-428.

Ginestar, G. J. Eastham S. Gray & P. Iland (2002). A comparison of different methods for scheduling irrigation, and their influence on the water relations, vine growth and grape composition of Chardonnay vines. Submitted to the American Journal of Enology and Viticulture

Gray S, Eastham J and Cass A. 1995. Sap flow sensors - tools for scheduling irrigation. Ninth Australian Wine Industry Technical Conference : Information and Abstracts. Adelaide, Australia. Poster.

Cass A, Eastham J, Chapman J, Hansen D. 1995. Improved water use efficiency and vineyard productivity. Seminar: Water for Viticulture - Optimising the Resource. Adelaide 14 December, 1995. Grape and wine Research and Development Corporation.

Industry Journal Articles

Eastham, J; S.Gray and C. Ginestar, 1996. Sap flow sensors - a new approach to scheduling vineyard irrigation. Australian Grapegrower and Winemaker. 395, 26-28.

Seminars and Field Days

"Irrigation and soils". Water Management for Grape Production Research to Practice workshops at Albany and Margaret River in WA, 1998, 1999 and 2000.

"A water balance approach to sustainable winery effluent disposal". South Australian Interwinery Environment Committee. 1997.

"Quantitative Methods for Irrigation Management in Vineyards". Barossa Landcare Group. 1996.

"The use of sap-flow sensors for scheduling irrigation in vineyards" to Southcorp Grower Groups in the Barossa Valley and McLaren Vale. 1996.

"Interactions between irrigation and Grape Quality". Southcorp Technical Personnel and Winemakers. Nuriootpa, Barossa Valley. 1996.

"Interactions between irrigation and Grape Quality" to Hardy's Technical Personnel and Winemakers, Berri, South Australia. 1996.

Section 6

Development of Research Tools

Andrew Dowley, Alfred Cass and William Besz

This project had national scope in that it involved all rootstock trials on mainland Australia and the products of the research, particularly via Research to Practice seminars, were expected to be delivered to all grape-producing areas in Australia. Furthermore, the project involved monitoring aspects of mechanistic soil processes that would require considerable labour to accomplish effectively. For a small group of researchers (see Appendix), this was a daunting task. A solution to this problem lay in acquiring and developing sensors for the processes of interest and in automating data acquisition from these sensors. An electronic engineering facility was created to service this requirement and William Besz was appointed to run this facility. The campus-wide needs for this type of facility were such that it grew beyond the confines of this project.

The aims of the electronic facility was to build whatever automated devices were required to meet the vine and soil monitoring needs requirements of the project. In addition, other innovative devices were constructed that did not necessarily monitor processes and new methodologies were developed to improve measurements of soil properties and vine growth.

Materials and Methods

The more noteworthy devices developed were:

1. Low cost, highly adaptable data loggers that accessed a wide range of environmental sensors, providing a stand-alone complete soil and atmosphere monitoring system, including:

    - weather station sensors (wind speed, tipping bucket rain gauge, air temperature, solar radiation)
    - soil temperature sensors (transistorized electronic types),
    - water content sensors (time domain reflectometer devices),
    - soil matric suction devices (tensiometers with differential pressure transducers, gypsum blocks),
    - vine sap flow sensors (heat pulse type),
    - soil aeration sensors (platinum and calomel electrode couples),
    - well water depth sensors (capacitance type).

2. Strength measuring devices to characterise soil mechanical properties, including:

    - penetration resistance of field soils (manually driven, automated force and depth measurement macropenetrometer)
    - penetration resistance of soil beds (stepper-motor and manual driven, automated force measurement micropenetrometer),
    - penetration resistance of small undisturbed soil cores (automated force measurement micropenetrometers),
    - tensile strength of small undisturbed soil cores.

3. Automated water content and matric suction measuring device for manual measurements of soil water status.

4. Mechanised devise for measuring soil aggregate stability.

Results

All research, monitoring and extension activities benefited from these devices. Two examples are discussed here, others are mentioned at appropriate places elsewhere in this report.

Oxidation-reduction monitoring system

Platinum electrodes were constructed from platinum wire and silver plated copper wire. The copper wire was insulated with PTFE (Teflon) and the whole was encased in neutral-cure epoxy resin inserted into rigid plastic tubing (Figure 7.1). The plastic tubing with pointed resin tip encasing the platinum wire allowed installation in to the soil. The contact surface between soil and electrode was sealed with bentonite. This system required minimal soil disturbance and allowed for easy retrieval of the electrode. A salt bridge is necessary for the completion of the soil couple (Dowley et al, 2002). This was constructed from PVC tubing, with 6 mm holes sealed with filter paper to retain the salt bridge solution (saturated potassium chloride solution and 3 % agar plus phenol to prevent microbial growth). A clear, flexible plastic tubing filled with salt bridge solution connected the salt bridge to a calomel electrode (see Figure 7.1). The Salt Bridge was installed in the soil at the monitoring site by back filling with a soil-kaolinite slurry.

The custom-built datalogger was capable of simultaneously monitoring 8 platinum electrodes as well as 8 tensiometers, 8 gypsum blocks, 2 temperature sensors and a tipping bucket rainfall gauge. Differential pressure sensors were used to record the matric suction within the tensiometers while soil and reference electrode temperature were monitored with electronic precision centigrade temperature sensors. The complete assembly is shown in Figure 7.1. This system allowed acquisition of information discussed in Sections 3.3, 3.4 and 4.

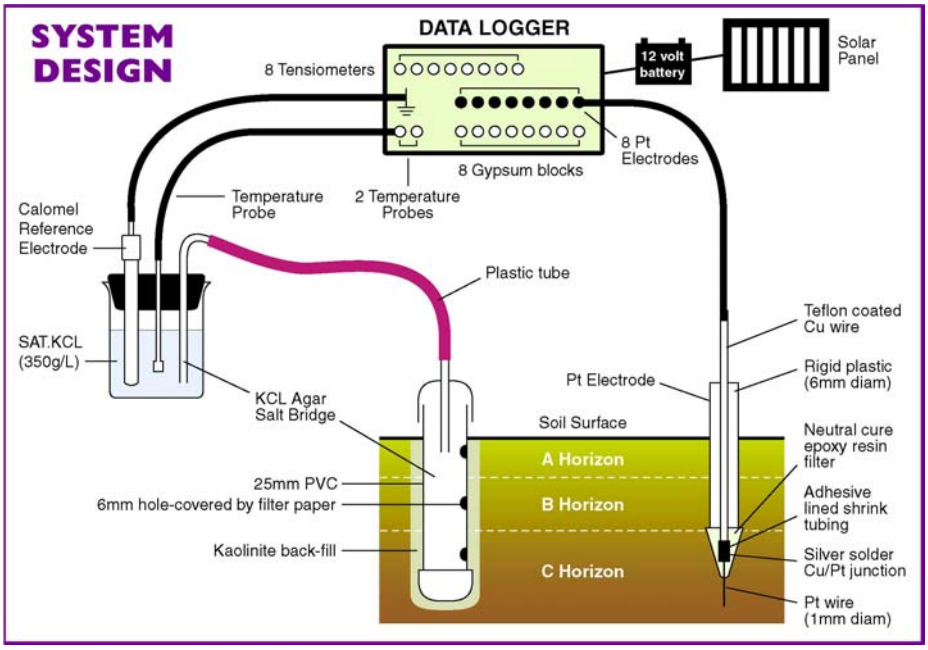


Figure 7.1: Schematic diagram of automated system for long term, *in situ* measurement of soil redox potential.

Improved vine root length measurement method

Reported root length results have used one of three methods to separate soil and roots:

1. Manual separation: tweezers or similar tools used to manually detach roots.
2. Water dispersion: dispersed by water pressure and washed through sieve.
3. Chemical dispersion: chemical dispersant added and the resulting slurry sieved.

Researchers who used manual separation methods reported grapevine root length densities of between 0.01 and 0.1 cm/cm^3 (Nagarajah, 1987; Randall and Coombe, 1978), and led to the notion that grapevines typically have a lower root length density than other woody plant species (Richards, 1983; Smart and Coombe, 1983). More recent research using the water dispersion method has reported root length density values of between 0.3 and 0.8 cm/cm^3 (Stevens and Douglas, 1994; Stevens et al., 1995). These results are similar to those obtained for pine trees (Milthorpe and Moorby, 1974) and peach and plum trees (Atkinson, 1980) using similar water dispersion methods. The third method was initially developed for cereal crops (Hignett, 1976) but later modified and used to quantify the root length density of peach trees (Tisdall et al. 1984), which gave an average root length density of over 3 cm/cm^3 in the upper soil layers and an average of 1.86 cm/cm^3 for 600 mm depth. These values were several times larger than values previously reported for peaches.

This information shows that flaws were present in current methods of root density determination, especially in vines. Since the project sought to characterise the relationship between soil properties and root growth, an improved method for determining root density was necessary. The new method modified after Hignett (1976) and Tisdall et al. (1984), is briefly described below.

The following laboratory equipment is required for this method: Brass sieve, 80 mm diameter with 250 μm mesh size; Clear plastic containers (1 L) with watertight, screw on lid; Plastic beakers (1 L); Sodium metaphosphate dispersant (Calgon).

Soil cores or bulk soil samples are obtained at appropriate locations in the vineyard and allowed to air dry on metal trays. When dry the samples are, where necessary, gently broken up with a hammer until all soil fragments are fractured to less than 20 mm diameter. The sample is then thoroughly mixed in the tray and sub-sampled at 6 different points using a metal tablespoon. Each sub-sample should weigh approximately 100 g.

Place each sub-sample in a 1 L plastic container and add approximately 3 g of sodium metaphosphate (Calgon) to each container followed by 750 ml demineralised water. Seal the containers and rotate on an end-over-end shaker for 2 hours then remove and stand until sand particles have all settled (about 10 to 60 seconds). Decant the dispersed clay and suspended silt and root fragments through a 250 μm sieves. Re-fill the container with tap water, agitate thoroughly, stand to allow sand to settle and decant for a second time. Wash material remaining in the 1 L container (sand with occluded root material) into a 1 L plastic beaker and extract any root material remaining in the sample manually and pass through sieve. Determine the length of root material extracted by standard methods. Calculate the length density (cm/cm3) by dividing the total root length by the volume of the sub-sample. Sub-sample volume is calculated from the mass of the air-dry soil and an independent determination of field bulk density.

A comparative trial involving 4 soils, this method and the others discussed above as well as a range of sieve sizes was done. The largest vine root length recovered was from the modified dispersion method with a 250 μm sieve (Dowley method). The highest root length density recovered with the 250 um sieve was 4.86 cm/cm^3 from a friable clay and 3.03 cm/cm^3 from a friable granular clay. Relative recovery rates for all methods are shown in Table 6.1.

Table 6.1: Relative recovery rates (%) of vine roots from 4 soils using 3 dispersion methods.

Soil	Chemical dispersion		Water dispersion		Manual dispersion
	250 um sieve	1000 um sieve	1000 um sieve	2000 um sieve	1000 um sieve
Friable Clay Loam	100	62	32	22	16
Friable Clay	100	41	22	10	7
Hard Blocky Clay	100	NA	<15	<15	6
Friable Clay Sand	100	56	61	39	26

Table 6.1 shows that the dispersion method is superior to the other two methods, but the degree of superiority was not uniform for different soils. For example, the manual separation method recovered 26 % of the root length recovered by the dispersion method from the soft, single grain clayey sand but only 6 % from the hard, coarsely structured, heavy clay. The proportion of the total root length recovered by the different methods was largely determined by the physical properties of the soil. However, even in weak and finely structured soils, the dispersion method was superior at extracting grapevine roots than the other two methods. The

method was applied to determining root density in the research reported in Sections 3.3, 3.4 and 4.

Other research tools developed during this project gave excellent results. The sapflow sensors used by Eastham, Gray and Ginestar (1996) were highly innovative and ahead of their time. Failure to capitalise on this advancement was due entirely to the short duration of this project. The field penetrometer too was ahead of its time in that no commercially available penetrometer nor any know research device at that time, could automatically sense depth of insertion into the soil without any additional external devices on the penetrometer. An additional, innovative feature was a small computer screen that plotted the pressure-depth relationship measured by the penetrometer. This feature was invaluable in demonstrating to grape growers the adverse effects of traffic and tillage compaction.

Outcomes from the Research

Scientific Papers and Conference Presentations

Dowley A., R.W., Fitzpatrick, A. Cass and W. Besz. 1998. Measurement of redox potential (Eh) in waterlogged viticultural soils. Paper delivered at the 10th Australian Wine Industry Technical Conference, Sydney, 3-6 August, 1998. Book of Abstracts.

Dowley A., R.W., Fitzpatrick, A. Cass and W. Besz. 1998. Measurement of redox potential (Eh) in periodically waterlogged viticultural soils. Proceedings of the International Soil Science Society Congress, Montpellier, France. 20-26 August, 1998. Symposium No. 35; pp.10. CD-ROM.

Dowley A., Fitzpatrick R.W. and Cass A. 2002a. Redox measurement in soils: A review. Submitted to Australian Journal of Soil Research.

Dowley A., Cass A. and Fitzpatrick R.W. 2002b. Improved method for measuring vine rroot density. To be submitted to Australian Journal of Soil Research.

Dowley A., Fitzpatrick R.W., Besz W. and Cass A. 2002. Development and validation of system for automated measurement of in situ redox potential (Eh) in soil. Submitted to Australian Journal of Soil Research.

Industry Journal Articles

Dowley A., Fitzpatrick R. W., and Cass A. 2002. Redox measurements in soils: A Review. To be submitted to the Australian Journal of Soil Research.

Dowley A., Fitzpatrick R. W., Besz W. and Cass A. 2002**.** Development and Validation of a System for Automated Measurement of *in situ* Redox Potential (Eh) in soils. To be submitted to the Australian Journal of Soil Research

Eastham, J; S. Gray and C. Ginestar, 1996. Sap flow sensors - a new approach to scheduling vineyard irrigation. Australian Grapegrower and Winemaker. 395, 26-28.

Dissertation

Dowley A. Grapevine Performance On Seasonally Waterlogged and Poorly Aerated Soils in South Australia, PhD Thesis, University of Adelaide, South Australia. To be submitted in 2002.

Section 7

Rootstock Trial Soil Properties

Alfred Cass, Robert Fitzpatrick, Karin Thompson, Andrew Dowley and Susan Van Goor

Research and development in matching vine requirements with soil attributes to optimize grape production was limited in Australia prior to 1995. This was particularly true for selection of soil for rootstock trials. Most of the Australian rootstock trials seem to have been developed with little attention to selecting soil as an experimental variate. Consequently, extracting soil-rootstock information from these trials has been difficult. Although soil survey and classification information for most grape growing areas is available (e.g. Taylor and Hooper, 1938; Blackburn 1964; Ward, 1966, etc), this information is not readily used by viticultural developers for soil selection, vineyard soil management and rootstock choice in Australia.

The most recent text on viticulture in Australia (Coombe and Dry, 1988) summarises results of previous research in the area of soil requirements for rootstocks and grapes in general. In this text, Hardie and Cirami (1988) provide characteristics for 26 rootstocks, including adaptation to some soil conditions. This appears to be the best available information on soil requirements at the present time. This information, however, is of limited use, as May (1994) pointed out, since these data cannot be related with any degree of effectiveness to soil information elsewhere in the book (e.g. Northcote 1988).

In defense of Hardie and Cerami (1988), there did not exist a soil classification system that was practical and useful to viticulturists, around which to organise their rootstock data at that time. Soil classification is the first and most fundamental step in organizing information relating to soil. This is as true of rootstock soil-related properties as any other attributes. Unfortunately, all soil classification systems in use in Australia are too complex for most viticulturists to use for soil identification and matching to viticultural attributes of rootstocks. As a result, even recent rootstock-soil information is couched in blunt appellations such as “sandy”, “acid”, “saline”, “waterlogged”, etc (Nicholas, 1997; Ludvigsen, 1999).

Furthermore, viticultural information published by overseas workers, based on soils classified using international schemes, cannot be applied correctly to Australian conditions, because there is no ready means to link their soil information to local soils. The effect of this is that much of the detailed, local, knowledge of rootstocks in, say, California, is not effectively available to the Australian grower.

May (1994) recognized these deficiencies and urged authorities to promote work on development of a user-friendly soil key that could be used by viticulturists to help select and match grapevine rootstocks to appropriate Australian soils. Other uses for the key were foreseen, for example, as a tool to correlate grower knowledge about their soils with other soils classified using these more technical systems and as a vehicle for delivering soil-specific land development and soil management packages to growers.

As an essential step to addressing these needs, one of the aims of Project CRS 95/1 was to:

"identify and describe soil physical and chemical constraints to vine performance by field examination of soils on selected vine experimental and rootstock sites, analysing soil samples from these sites and evaluating the soil and viticultural data against soil indicators of sustainability to add a soil component to these experiments which will provide information on current soil conditions in relation to documented vine performance, water management, cover cropping and canopy management".

In addition the researchers proposed to:

"test these data against the criteria for soil quality, correlate with vine performance data, establish a data base of soil information, integrate this information with the management packages and produce a draft field guide to selection and management of vineyard soils".

Materials and Methods

A survey of existing field experimental sites and rootstock trials was undertaken and attempts made to link these data with existing vine performance data. In South Australia the fieldwork was done with the assistance of Messrs. D. Maschmedt, P. Nicholas and M. McCarthy of PIRSA. In Victorian, New South Wales and Western Australia the soil survey work was done by members of the Irrigated Trees and Vines Program of the CRC for and Land Management with assistance from State Department staff: Mr. John Whiting (Victoria); Mr. T. Somers (New South Wales); and Mr. J. Campbell-Clause (Western Australia). Other experimental sites were included in these surveys, notably those of Dr. R. Walker in South Australia and Victoria and Mr. P. Sinclair in New South Wales. These collaborators provided valuable information about the rootstock trials including location, contact information, experimental design, rootstocks, management, etc.

All existing information on soil distribution and properties in the major grape growing areas of Australia were examined and collated. This information was used to guide field evaluation of soil properties relevant to the indicators of sustainability on the rootstock trials and other important vine experimental sites. Existing rootstock performance data were obtained from Mr. Nicholas for South Australia (Nicholas et al., 1996), Mr. Whiting for Victoria (Whiting, 1998) and from Dr. Walker (Walker et al., 1995; Walker et al., 1998). These data were largely annual fruit yields although Dr. Walker's data included a variety of other information on vine performance and fruit composition and quality.

A soil scientist visited each of the known rootstock trials at least once during the life of the project. Using site information provided by the State Department collaborators, soil pits and auger sampling sites were established and the soils described (see Table 7.1) using standard pedological methods (McDonald et al., 1990). Soil samples, including, in many cases, undisturbed soil cores, were extracted from the soil genetic layers and transported to Adelaide for analysis in the laboratories of CSIRO Land and Water. All samples from sites outside South Australia were transported under license from the South Australian Government after sterilisation by gamma radiation at Steritech, Dandenong, Victoria. All sample residues are presently stored at the CSIRO laboratories at Glen Osmond, South Australia.

Samples were analysed for chemical properties using standard methods employed by the analytical laboratories of CSIRO Land and Water. Physical properties were determined on a selection of samples using methods described by Klute (1986). Wherever possible, the important soil indicators of sustainability described in Section 2, including chemical, physical and water storage and transmission properties were measured and documented (Table 7.1). These data allowed identification of the soils in terms of several different classification schemes, notably the Australian Viticultural Soil Key (described in Section 8), The Australian Soil Classification (Isbell, 1996) and USDA Soil Taxonomy (Soil Survey Staff, 1996). Correlation tables have been developed to allow identification of Great Soil Group Names (Stace et al., 1968), The South African System (Soil Classification Working Group, 1991) and the European System (World Reference Base for Soil Resources, 1998).

Table 7.1: Properties of rootstock sites and soils listed in the Rootstock Soil Database. Bold italic typeface indicates basic information and the minimum soil data set required for classification purposes.

Site Data	Soil Morphology	Chemical Properties	Physical Properties
Australian Viticultural region	Australian Viticultural Soil Key Name	***Horizon depth intervals (mm)***	Horizon depth intervals (mm)
Vineyard name	Australian Soil Classification Name	***Slaking***	Clay %
Contact name and address	USDA Soil Taxonomy Name	***Dispersion***	Silt %
Geographical (GPS) coordinates	***Genetic horizon type***	***$pH_{1:5}$***	Fine sand %
Experiment code	***Horizon depth intervals (mm)***	***Salinity, $EC_{1:5}$ (dS/m)***	Coarse sand %
Grape variety	***Moist soil colour***	***Sodicity, $SAR_{1:5}$***	Retention Curve: Water content at 1, 2, 5, 10, 30, 60, 200, 1500 kPa (m/m)
Rootstocks	***Munsell colour code***	Total carbon (%)	
Year planted	***Texture***	Organic carbon (%)	
Experimental design	***Structure shape, grade and size***	Boron[1] (mg/kg)	Bulk density (BD, Mg/m^3)
Row and vine spacing	***Hardness***	Phosphorous[2] (mg/kg)	Air-filled porosity (m/m)
Soil treatment	***Visible pores***	Potassium[3] (mg/kg)	Total available water (TAW, mm/m)
Weed control	***Mottle abundance and contrast***	Sulphur[4] (mg/kg)	Stress available water (SAW, mm/m)
Surface management	***Cutan type and abundance***	Carbonate as $CaCO_3$ (mg/kg)	Readily available water (RAW, mm/m)
Irrigation type, spacing, schedule	***Gravel content***	Exchangeable cations: Ca, Mg, Na (cmol+/kg)	Calculated TAW, SAW, RAW at high BD (1.5 Mg/m^3)
Irrigation water source	***Root density***	Cation exchange capacity (cmol+/kg)	Calculated TAW, SAW, RAW at low BD (1.0 Mg/m^3)
Irrigation water salinity (dS/m), sodicity (SAR)	***Acid reaction***	Heavy metals[5]: Cu, Fe, Mn, Zn (mg/kg)	Penetration resistance at field capacity water content (MPa)

Extractants: [1]$CaCl_2$; [2,3]HCO_3; [4]$Ca(H_2PO_4)_2$; [5]DTPA

However, because of resource limitations, not all rootstock sites enjoyed the same level of analytical examination. Three levels of analytical intensity were applied:

1. basic data set (bold italic typeface in Table 7.1) that allowed sufficient characterisation for soil classification to be done,
2. complete physical and chemical data set that allowed full development of the important soil indicators of sustainability described in Section 2 (all data listed in Table 7.1),
3. some rootstock sites were selected for more detailed study by establishing research trials on them as described in Sections 3 and 4 of this report.

All available information on the rootstock soils were assembled into a Microsoft Access database (Rootstock Soil Database) that is available to any with an interest in the trials. Eventually this database should be published (Cass et al., 2002).

Results

The data contained in the Australian rootstock trials soil database is only one step towards realizing the ultimate goal of defining rootstock characteristics in terms of Australian soil properties. It is, however, the first and most essential of the steps in this direction. Despite the fact that the subsequent steps have not been completed, the database has already provide the following:

1. useful data regarding the soil properties on particular rootstock trials and will continue to provide such a resource in the future,
2. essential characteristics of a wide selection of Australian viticultural soils that are suitable for delivering a set of soil selection, development and management technologies to the Australian industry,
3. a framework to develop the Australian Viticultural Soil Key (Section 8) for describing viticultural soils in terms meaningful to Australian grape growers and cross referencing these soils to other soil classification systems,
4. applying the Soil Key (Table 8.1) to the Rootstock Soil Database allows description and classification of the rootstock experiment soils (Table 7.3) and using the correlation table (Table 8.2) allows naming rootstock soils in European, Californian and South African terms.

In the light of these outcomes the database stands as a complete work. The next step in the process is to devise and execute suitable means to disseminate the information more widely than hitherto. This has not yet been done. However, even when this is accomplished the outcomes of this part of the project fall short of the vision expressed by May (1998) for improved soil-rootstock information.

The creation of the Australian Rootstock Soil Database marks a significant step towards the optimum goals for rootstock technology stated by May (1994 on pages 33 and 34). He foresaw the creation of an “Atlas of Australian Vineyard Soils” as an ultimate objective. This goal has not been achieved yet, although the Rootstock Soil Database and the Australian Viticultural Soil Key (Section 8) are essential components of such an atlas.

Furthermore, the kind of rootstock-soil information tabulation that May (1998, page 34) described has not been done. This is partly due to insufficient communication between

rootstock scientists and the soil scientists involved in the project, because of lack of time and opportunity. A further difficulty is the limitations of the rootstock trials themselves. One of these is the wide diversity of soils on these trials. Table 7.2 shows that a total of 21distinctly different viticultural soils occur on the 140 rootstock trials investigated. Of these 6 viticultural soils have sufficient replication to form a reliable basis to formulate more precise rootstock – soil interactions. This work is yet to be done.

Table 7.3: Frequency of soil occurrence on the Australian rootstock trials (extracted from the Rootstock Soil Database)

Australian Viticultural Soil Key Name		Great Soil Group (Stace et al., 1968)	Number of rootstock trials	Proportion of total (%)
4.2	Shallow loamy soil over calc-rock	Terra Rossa	4	2.9
4.4	Shallow clayey over calc-rock	Rendzina, Groundwater Rendzina	3	2.2
5.1	Poorly structured cracking clay	Black Earth	1	0.7
5.2	Well structured over restrictive cracking clay	Weisenboden	4	2.9
5.3	Well Structured throughout cracking clay	Black Earth	1	0.7
6.1	Restrictive duplex thin well structured topsoil	Solonetz, Red-brown Earth or Gleyed Podzolic	4	2.9
6.2	Restrictive duplex thick well structured topsoil	Solonetz, Red-brown Earth or Gleyed Podzolic	12	8.7
6.3	Restrictive duplex with thin hard topsoil	Solonetz, Red-brown Earth or Gleyed Podzolic	6	4.3
6.4	Restrictive duplex subsoil, thick hard topsoil	Solonetz, Red-brown Earth or Gleyed Podzolic	3	2.2
7.2	Non-restrictive duplex thick well structured topsoil	Podzolic or Red-brown Earth	11	8.0
7.3	Non-restrictive duplex thin hard topsoil	Podzolic or Red-brown Earth	5	3.6
7.4	Non-restrictive duplex thick hard topsoil	Podzolic or Red-brown Earth	4	2.9
8.3	Shallow calcareous non-restrictive	Calcareous Sand or Calcareous Red Earth	3	2.2
8.4	Rubbly calcareous soil	Calcareous Sand or Calcareous Red Earth	4	2.9
8.5	Clayey calcareous soil	Red Calcareous Soils or Terra Rossa	3	2.2
8.6	Loamy calcareous soil	Terra Rossa or Desert Loam	18	13.0
9.1	Deep uniform sandy soil	Red Earthy or Siliceous Sand or Podzol	11	7.9
9.2	Sandy gradational soil	Red Earthy or Siliceous Sand or Podzol	1	0.7
9.3	Deep loamy unigrad calcareous soil	Red Earth	14	10.0
9.4	Deep clayey unigrad calcareous soil	Red Earth	8	5.8
9.5	Deep hard loamy unigrad soil	Krasnozem or Euchrozem	20	14.5
		Total	140	100.0

Further effort is required to capitalise on the achievements of this part of the project and those described in Section 8 (Viticultural Soil Key). These outcomes need to be more closely linked, analysed more fully and integrated with rootstock performance data more effectively than has been achieved in this project. The latter goal can only be accomplished with more assistance from the respective viticultural experts involved in the rootstock trials. Furthermore, there is a great deal of practical knowledge in California, on how rootstock performance is influenced by soil properties. Much of this information is poorly documented but is part of the commercial technology underlying their industry. Efforts should be made to tap into this technology.

We propose that the following steps be taken, in conjunction with an effort to rectify and capitalise on the investment in the rootstock experiments as so eloquently described by May (1998):

1. identify a group of qualified Australian experts (Working group) to conclude this project,
2. invited participation by a small group of Californian, European and/or South African viticulturists with clear expertise in rootstock-soil issues,
3. provided the Working group with the Rootstock Soil Database, the Australian Viticultural Soil Key, rootstock performance data and other available resources,
4. develop a clear set of outcomes and products for this venture with appropriate funding to ensure completion,
5. convene a workshop to correct and discuss the outcomes of this project and develop a process to complete the objectives and produce the required products.

Such a workshop was foreshadowed in a memorandum from Mr. H Armstrong to Mr. P. Hayes (copied to Dr. A. Cass) on 18 February 1998. This workshop has not yet occurred, due to delayed completion of the project. However, at this stage, sufficient finality has been reached for benefit to be gained from such a meeting.

Outcomes from the Research

Scientific Publications

Walker R. R., Blackmore D. H., Cass A. and Clingeleffer P. R. 1995. Use of rootstocks to reduce the levels of chloride and sodium in wine. Ninth Australian Wine Industry Technical Conference : Information and Abstracts. Adelaide, Australia. Abstract, p 34.

Cass A., Fitzpatrick R. W., Thompson K., Dowley A., and Van Goor S. 2002. Australian Rootstock Soil Database. Version 1.0. Microsoft Access database on compact disk. Grape and Wine Research and Development Corporation.

Cass A., Fitzpatrick R. W., Thompson K., Dowley A., and Van Goor S. 2002. Soil properties of the Australian rootstock trials. To be submitted to the Australian Journal of Grape and Wine Research.

Industry Journal Articles

Alfred Cass, Rob Fitzpatrick, Karin Thompson, Andrew Dowley and Susan Van Goor. 2002. Soils of the Australian rootstock trials. Article to be submitted to The Australian Grapegrower & Winemaker.

Table 7.2: The rootstock trials included in the Australian Rootstock Soil Properties Database with soil names (modified from Cass et al., 2002).

Region	Vineyard Name	ID Code		Australian Viticultural Soil Key (Section 8 this report)		Australian Soil Classification (Isbell 1996)	USDA Soil Taxonomy (Soil Survey Staff 1996)
New South Wales:							
Cowra	Cowra Estates	1		**9.3**	Deep loamy unigrad calcareous soil	Brown Kandosol	Kandiustult
		2		**9.5**	Deep hard loamy unigrad soil	Red Kandosol	Kandiustult
	Richmond Grove- Cowra Vyd			**9.5**	Deep hard loamy unigrad soil	Red Dermosol	Typic Calcixerept/Rhodoxeralf
Dareton	Agricultural Research and Advisory Station	1		**9.1**	Deep uniform sandy soil	Mesotrophic Red Chromosol	Typic Palexeralf
		2		**9.3**	Deep loamy unigrad calcareous soil	Eutrophic Red Dermosol	Petrocalcic Calcixerept/Rhodoxeralf
Hunter Valley	Spring Mountain			**9.2**	Sandy gradational soil	Orthic Tenosol	Dystric Xeropsamment
	Wyndahm-Orlando Pokolbin Vyd						Alfisol ? Insuffient data
Mudgee	Gleneske Estate	1		**9.3**	Deep loamy unigrad calcareous soil	Eutrophic Brown Kandosol	Typic Paleustult
		2		**6.4**	Restrictive duplex subsoil thick hard topsoil	Eutrophic Brown Chromosol	Typic Paleustalf
		3		**6.1**	Restrictive duplex subsoil thin well structured topsoil	Eutrophic Brown Chromosol	Typic Paleustalf
		4		**9.3**	Deep loamy unigrad calcareous soil	Eutrophic Brown Dermosol	Typic Paleustult
	Orlando-Wyndham: Montrose Wines			**9.5**	Deep hard loamy unigrad soil	Eutrophic Black Dermosol	Typic Calcixerept/Rhodoxeralf
	Orlando-Wyndham: Stoney Creek			**9.3**	Deep loamy unigrad calcareous soil	Eutrophic Red Dermosol	Aquic Calcixerept
Griffith	DeBortoli Vineyards			**6.1**	Restrictive subsoil thin well structured topsoil	Mottled-Subnatic Red Sodosol	Typic Natrixeralf/ TypicNatrustalf
	Viticulture Research Station			**7.2**	Non-restrictive duplex thick well stuctured topsoil	Eutrophic Red Chromosol	Sodic Palexeralf
South Australia:							
Adelaide Hills	G Gramp & Sons						Alfisol ? Insuffient data
	Petaluma						Alfisol ? Insuffient data
	Wark	1		**9.5**	Deep hard loamy unigrad soil	Eutrophic Brown Dermosol	Typic Rhodoxeralf
	Wark	2		**9.3**	Deep loamy unigrad calcareous soil	Eutrophic Brown Dermosol	Typic Rhodoxeralf
	Wilson			**9.5**	Deep hard loamy unigrad soil	Mesotrophic Brown Dermosol	Typic Rhodoxeralf
	Waite Institute			**9.3**	Deep hard loamy unigrad soil	Eutrophic Red Dermosol	Typic Rhodoxeralf
	Partalunga Vyd	1		**6.4**	Restrictive subsoil thick hard topsoil	Black Kurosol	Typic Palexeralf
		2		**9.3**	Deep hard loamy unigrad soil	Eutrophic Brown Kandosol	Aquic Palexeralf
Adelaide Plains	Katsarelias						Alfisol ? Insuffient data
Barossa	Beer		RSBV-08	**6.2**	Restrictive duplex thick well stuctured topsoil	Mottled-Subnatric Sodosol	Typic Natrixeralf
	Harris (Hample)	1	RSBV-03/1	**6.3**	Restrictive duplex with thin hard topsoil		Typic (Calcic) Natrixeralf
		2	RSBV-03/1	**6.3**	Restrictive duplex with thin hard topsoil	Subnatric Red Sodosol	Typic (Calcic) Natrixeralf
	Kraft		RSBV-07/1	**9.1**	Deep uniform sandy soil	Eutrophic Grey Chromosol	Natric Palexeralf
	Pech		RSBV-06/1	**9.1**	Deep uniform sandy soil	Regolithic Orthic Tenosol	Dystric Xeropsamment
	PISA (Research Centre) Cab			**6.2**	Restrictive duplex thick well stuctured topsoil	Red Sodosol	Typic Natrixeralf
	PISA (Research Centre) MB			**6.3**	Restrictive duplex thin hard topsoil	Red Sodosol	Typic (Calcic) Natrixeralf
	Riebke		RSBV-01/1	**6.1**	Restrictive duplex thin well stuctured topsoil	Mottled-Mesonatric Brown Sodosol	Typic (Calcic) Natrixeralf
	Rob Walker - Nuriootpa			**6.1**	Restrictive duplex thin well stuctured topsoil	Eutrophic Mottled-Subnatric Grey Sodosol	Aquic Palexeralf
	Rob Walker - Rowland Flat			**6.2**	Restrictive duplex thick well stuctured topsoil	Eutrophic Mesonatric Red Sodosol	Typic Natrixeralf
	Semmler		RSBV-09/1	**9.5**	Deep hard loamy unigrad soil	Eutrophic Black Dermosol	Aquic Calcixeroll
	Southcorp (Kalimna)	1		**6.2**	Restrictive duplex thick well stuctured topsoil		
		2		**6.2**	Restrictive duplex thick well stuctured topsoil		
		3		**6.2**	Restrictive duplex thick well stuctured topsoil	Mottled-Mesonatric Brown Sodosol	Typic Natrixeralf

Continued overleaf

Table 7.2: The rootstock trials included in the Australian Rootstock Soil Properties Database with soil names (modified from Cass et al., 2002).

Region	Vineyard Name	ID Code		Australian Viticultural Soil Key (Section 8 this report)		Australian Soil Classification (Isbell 1996)	USDA Soil Taxonomy (Soil Survey Staff 1996)
Clare	Hardy's (White Hut)	1	RSCV-01/1	**6.3**	Restrictive duplex with thin hard topsoil	Red Sodosol	Typic (Calcic) Natrixeralf
		2	RSCV-01/5	**7.3**	Non-restrictive duplex thin hard topsoil	Eutrophic Red Chromosol	Typic Palexeralf
		3	RSCV-01/1	**7.3**	Non-restrictive duplex thin hard topsoil	Petrocalcic Red Chromosol	Petrocalcic Palexeralf
	Koerner (Leasingham)	1	RSCV-04.1	**4.2**	Shallow loamy soil over calc-rock	Petrocalcic Red Dermosol	Petrocalcic Calcixerept
		2	RSCV-04.2	**6.3**	Restrictive duplex with thin hard topsoil	Brown Sodosol	Typic (Calcic) Natrixeralf
		3	RSCV-04.3	**7.3**	Non-restrictive duplex thin hard topsoil	Eutrophic Red Chromosol	Calcic (Natric) Palexeralf
		4	RSCV-04.4	**5.2**	Well structured over restrictive cracking clay	Self-Mulching Brown Vertosol	Typic Calcixerert
	Penfold's		RSCV-03	**6.4**	Restrictive duplex subsoil thick hard topsoil	Brown Sodosol	Natric Palexeralf
	Pulford		RSCV-02	**7.3**	Non-restrictive duplex thin hard topsoil	Hypercalcic Red Chromosol	Natric Palexeralf
Koppamurra	Mildara Blass	1		**9.3**	Deep loamy unigrad calcareous soil	Eutrophic Red Dermosol	Petrocalcic Calcixerept/Rhodoxeralf
		2		**6.2**	Restrictive duplex thick well stuctured topsoil	Eutrophic Brown Chromosol	Calcic (Natric) Palexeralf
		3		**6.2**	Restrictive duplex thick well stuctured topsoil	Chromosol	Typic Paleustalf
Langhorne Creek	Case		RSLC-03/1	**9.5**	Deep hard loamy unigrad soil	Eutrophic Brown Dermosol	Typic Haploxeralf
	Cleggett		RSLC-01/1	**9.5**	Deep hard loamy soil	Eutrophic Black Dermosol	Typic Haploxeralf
	Elliot	1	RSLC-02/1	**7.4**	Non-restrictive duplex thick hard topsoil	Eutrophic Brown Chromosol	Natric Palexeralf
		2	RSLC-02/5	**7.4**	Non-restrictive duplex thick hard topsoil	Eutrophic Red Chromosol	Natric Palexeralf
		3	RSLC-02/8	**7.4**	Non-restrictive duplex thick hard topsoil	Eutrophic Red Chromosol	Natric Palexeralf
Riverland	Arnold		RSRL-03/1	**9.4**	Deep clayey unigrad calcareous soil	Calcic Red Kandosol	Typic Paleustult
	Biggins		RSRL-23/1	**8.6**	Loamy calcareous soil	Regolithic Supracalcic Calcarosol	Sodic Calcixerept
	Brooke		RSRL-17/1	**8.6**	Loamy calcareous soil	Regolithic Calcic Calcarosol	Sodic Calcixerept
	Chabrel			**8.6**	Loamy calcareous soil	Regolithic Hypercalcic Calcarosol	Sodic Calcixerept
	Dawe		RSRL-04/4	**6.3**	Restrictive duplex thin hard topsoil	Mottled-Hypernatic Brown Sodosol	Typic Natrixeralf
	Duggan		RSRL-26/1	**9.4**	Deep clayey unigrad calcareous soil	Calcic Red Kandosol	Typic Natrixeralf/Natrustalf
	Feher	1	RSRL-15/1	**8.3**	Shallow calcareous non-restrictive	Petrocalcic Hypocalcic Calcarosol	Petrocalcic Calcixerept
		2	RSRL-15	**8.3**	Shallow calcareous non-restrictive	Petrocalcic Calcic Calcarosol	Petrocalcic Calcixerept
	Gilles	1	RSRL-14/1	**8.4**	Rubbly calcareous soil	Regolithic Supracalcic Calcarosol	Sodic Calcixerept
	Halupka	1	RSRL-12/1	**8.6**	Loamy calcareous soil	Regolithic Hypercalcic Calcarosol	Sodic Calcixerept
		1	RSRL-13/1	**8.6**	Loamy calcareous soil	Regolithic Hypercalcic Calcarosol	Sodic Calcixerept
	Hentschke	1	RSRL-10/1	**8.6**	Loamy calcareous soil	Regolithic Supracalcic Calcarosol	Sodic Calcixerept
		2	RSRL-10/9	**8.6**	Loamy calcareous soil	Regolithic Hypercalcic Calcarosol	Sodic Calcixerept
	Jericho	1	RSRL-06/1	**8.6**	Loamy calcareous soil	Regolithic Hypercalcic Calcarosol	Sodic Calcixerept
		2	RSRL-06	**8.4**	Rubbly calcareous soil	Regolithic Lithocalcic Calcarosol	Sodic Calcixerept
		3	RSRL-06/5	**8.4**	Rubbly calcareous soil	Regolithic Supracalcic Calcarosol	Sodic Calcixerept
	Kimber		RSRL-11/1	**8.6**	Loamy calcareous soil	Regolithic Hypercalcic Calcarosol	Sodic Calcixerept
	Kregar		RSRL-21/1	**8.6**	Loamy calcareous soil	Regolithic Supracalcic Calcarosol	Sodic Calcixerept
	Ludas		RSRL-25/1	**9.4**	Deep clayey unigrad calcareous soil	Calcic Brown Kandosol	Natric Palexeralf
	McFarlene		RSRL-02/1	**8.5**	Clayey calcareous soil	Regolithic Hypercalcic Calcarosol	Sodic Calcixerept

Continued overleaf

Table 7.2: The rootstock trials included in the Australian Rootstock Soil Properties Database with soil names (modified from Cass et al., 2002).

Region	Vineyard Name	ID Code		Australian Viticultural Soil Key (Section 8 this report)		Australian Soil Classification (Isbell 1996)	USDA Soil Taxonomy (Soil Survey Staff 1996)
Riverland	Nitschke		RSRL-05/1	**8.5**	Clayey calcareous soil	Regolithic Calcic Calcarosol	Sodic Calcixerept
	Page		RSRL-18/1	**8.6**	Loamy calcareous soil	Pedal Supracalcic Calcarosol	Sodic Calcixerept
	PISA (Loxton Centre)		RSRL-07/1	**8.4**	Rubbly calcareous soil	Regolithic Supracalcic Calcarosol	Sodic Calcixerept
	PISA (Loxton Centre) Reisling			**8.6**	Loamy calcareous soil	Regolithic Supracalcic Calcarosol	Sodic Calcixerept
	Proud		RSRL-22/1	**8.6**	Loamy calcareous soil	Regolithic Supracalcic Calcarosol	Sodic Calcixerept
	Roberts (Loxton)		RSRL-28	**8.6**	Loamy calcareous soil	Petrocalcic Hypercalcic Calcarosol	Sodic Calcixerept
	Roberts	1	RSRL-19/1	**8.5**	Clayey calcareous soil	Regolithic Supracalcic Calcarosol	Sodic Calcixerept
		2	RSRL-20/1	**8.6**	Loamy calcareous soil	Regolithic Hypercalcic Calcarosol	Petrocalcic Calcixerept
	Roy		RSRL-24/1	**5.1**	Poorly structured cracking clay	Epipedal Grey Vertosol	Typic (Sodic) Calcixerert
	Tonkin		RSRL-09/1	**8.6**	Loamy calcareous soil	Regolithic Supracalcic Calcarosol	Sodic Calcixerept
	Welby		RSRL-16/1	**9.4**	Deep clayey unigrad calcareous soil	Regolithic Supracalcic Calcarosol	Sodic Palexeralf
	Wishart	1	RSRL-27	**7.2**	Non-restrictive duplex thick well stuctured topsoil	Pedrocalcic Red Chromosol	Petrocalcic Palexeralf
South East	Hollick	2		**4.4**	Shallow clayey over calc-rock	Self-Mulching Black Vertosol	Petrocalcic Calcixerert
		1	RSSE-02/1	**9.4**	Deep clayey unigrad calcareous soil	Hypercalcic Dermosol	Petrocalcic Calcixerert
	Mildara - Chardonnay Lodge	2		**4.2**	Shallow loamy over calc-rock	Petrocalcic Red Dermosol	Petrocalcic Calcixerept/Rhodoxeralf
			RSSE-03/1	**9.4**	Deep clayey unigrad calcareous soil	Hypercalcic Dermosol	Petrocalcic Calcixerept/Rhodoxeralf
	Penfold's Padthaway-Keppoch		RSSE-05/1	**9.1**	Deep uniform sandy soil	Argic Bleached-Orthic Tenosol	Dystric Xeropsamment
	Rob Walker - Padthaway Lawsons			**8.3**	Shallow calcareous non-restrictive	Hypervescent Petrocalcic Lithocalcic Calcarosol	Petrocalcic Calcixerept
	Rob Walker - Padthaway G Block			**4.4**	Shallow clayey over calc-rock	Epibasic Petrocalcic Lithocalcic Calcarosol	Petrocalcic Calcixerept
	Southcorp-Padthaway Vyd			**9.1**	Deep uniform sandy soil	Arenic Orthic Tenosol	Dystic Xeropsamment
	Wynn's Cellar Block		RSSE-01/1	**4.4**	Shallow clayey over calc-rock	Self-Mulching Black Vertosol	Petrocalcic Calcixerert
	Wynn's Gartner Block 160-175	1					Alfisol ? Insuffient data
		2	RSSE-04/1	**4.2**	Shallow loamy soil over calc-rock	Petrocalcic Red Dermosol	Typic Rhodoxeralf
Southern Vales	Branson Rd Vyd			**5.3**	Well Structured throughout cracking clay	Epipedal Black Vertosol	Typic Calcixerept
	Johnston	1	RSMV-01.2	**9.4**	Deep clayey unigrad calcareous soil	Hypercalcic Black Chromosol	Aquic Calcixeroll
		2	RSMV-01.2	**7.3**	Non-restrictive duplex thin hard topsoil	Hypercalcic Red Chromosol	Petrocalcic Palexeralf
		3	RSMV-01.3	**6.1**	Restrictive subsoil thin well structured topsoil	Brown Sodosol	Typic Natrixeralf
	Kyloh		RSMV-04	**9.1**	Deep uniform sandy soil	Eutrophic Brown Chromosol	Typic Palexeralf
	Oakley	1	RSMV-02/1	**6.2**	Restrictive duplex thick well structured topsoil	Eutrophic Grey Chromosol	Aquic Palexeralf
		2	RSMV-02/2	**7.4**	Non-restrictive duplex thick hard topsoil	Subnatric Red Sodosol	Natric Palexeralf
	Pridmore	1	RSMV-05/1	**7.2**	Non-restrictive duplex thick well stuctured topsoil	Eutrophic Yellow Chromosol	Aquic Palexeralf
	Scarpantoni	1	RSMV-03/1	**9.1**	Deep uniform sandy soil	Mesotrophic Red Chromosol	Typic Palexeralf
		2	RSMV-03/1	**7.2**	Non-restrictive duplex thick well stuctured topsoil	Mesotrophic Red Chromosol	Typic Palexeralf
		3	RSMV-03/1	**9.1**	Deep uniform sandy soil	Mesotrophic Red Chromosol	Typic Palexeralf
	Wits End	1		**5.2**	Well stuctured over restrictive cracking clay	Mesotrophic Red Chromosol	Petrocalcic Calcixerert
		2		**5.2**	Well stuctured over restrictive cracking clay	Self-Mulching Black Vertosol	Petrocalcic Calcixerert

Continued overleaf

Table 7.2: The rootstock trials included in the Australian Rootstock Soil Properties Database with soil names (modified from Cass et al., 2002).

Region	Vineyard Name	ID Code		Australian Viticultural Soil Key (Section 8 this report)	Australian Soil Classification (Isbell 1996)		USDA Soil Taxonomy (Soil Survey Staff 1996)
Victoria:							
Sunraysia	Herath's (Gordo)	1					Alfisol?Insuffient data
	Herath's (Carina)	2					Alfisol?Insuffient data
Glenrowan	Auldstone			**9.3**	Deep loamy unigrad calcareous soil	Dystrophic Red Kandosol	Typic Paleustult
Goulburn Valley	Chateau Tahbilk			**9.5**	Deep hard loamy unigrad soil	Eutrophic Red Dermosol	Typic Haploxeralf
Grampians	Bests Wine	1		**7.2**	Non-restrictive duplex thick well stuctured topsoil	Eutrophic Brown Chromosol	Natric Palexeralf
		2		**7.2**	Non-restrictive duplex thick well stuctured topsoil	Eutrophic Yellow Kurosol	Aquic Palexeralf
		3		**7.2**	Non-restrictive duplex thick well stuctured topsoil	Red Kurosol	Vertic Palexeralf
Knoxfield	Noarlunga Knoxfield			**9.3**	Deep loamy unigrad calcareous soil	Eutrophic Brown Dermosol	Sodic Calcixerept/Rhodoxeralfs
Mornington Peninsula	King Creek Vyd			**6.2**	Restrictive duplex thick well structured topsoil	Mesotrophic Brown Kurosol	Ultic Palexeralf
	Moorooduc Estate			**7.2**	Non-restrictive duplex thick well stuctured topsoil	Dystrophic Brown Kurosol	Aquic Palexeralf
Murray Valley / Sunraysia	Rob Walker - Merbein			**9.4**	Deep clayey unigrad calcareous soil	Hypervescent Pedal Calcic Calcarosol	Typic Calcixerept
	Rob Walker - Koorlong			**9.3**	Restrictive duplex thin well structured topsoil	Calcareous Arenic Orthic Tenosol	Typic Calcixerept
Ovens / King Valley	Brown Bros.	1		**9.5**	Deep hard loamy unigrad soil	Mesotrophic Red Dermosol	Typic Haploxeralf
		2		**9.5**	Deep hard loamy unigrad soil	Red Dermosol	Typic Haploxeralf
	Myrrhee Hills			**9.5**	Deep hard loamy unigrad soil	Red Dermosol	Petrocalcic Calcixerept
Rutherglen	All Saints Vyd			**9.5**	Deep hard loamy unigrad soil	Eutrophic Red Kandosol	Kandiustult
Rutherglen	Stanton & Killeen			**9.3**	Deep loamy unigrad calcareous soil	Red Dermosol	Calcixerall
Ballarat	Eastern Peak Vyd			**9.5**	Deep hard loamy unigrad soil	Eutrophic Brown Dermosol	Typic Natrixeralf/Natrustalf
Far South West	Southcorp-Seppelts Vyd			**9.3**	Deep loamy unigrad calcareous soil	Eutrophic Red Dermosol	Aquic Calcixeroll
Yarra Valley	Warramate			**9.3**	Deep loamy unigrad calcareous soil	Dystrophic Brown Dermosol	Typic Rhodoxeralf
Western Australia:							
	Amberly			**7.2**	Non-restrictive duplex thick well stuctured topsoil	Dystrophic Yellow Kurosol	Ultic Palexeralf
	Evans&Tate - Lionels			**9.5**	Deep hard loamy soil	Regolithic Orthic Tenosol	Typic Haploxerept
	Neil Delroys			**9.5**	Deep hard loamy soil	Eutrophic Yellow Kandosol	Kandiustult
	Old Manjimup Research Station			**6.2**	Restrictive duplex thick well structured topsoil	Eutrophic Red Kurosol	Typic Palexeralf
	Paul Conti			**9.1**	Deep uniform sandy soil	Tenosol	Xeropsamment
	Petaluma - Smithbrook	1		**6.2**	Restrictive duplex thick well structured topsoil	Mesotrophic Yellow Chromosol	Typic Palexeralf
		2		**9.3**	Deep loamy unigrad calcareous soil	Mesotrophic Brown Kandosol	Typic Palexeralf
	Sandalford Estate			**9.1**	Deep uniform sandy soil	Arenic Orthic Tenosol	Dystric Xeropsamment
	Steve Illich			**9.1**	Deep uniform sandy soil	Arenic Orthic Tenosol	Dystric Xeropsamment
	Swan Research Station			**7.2**	Non-restrictive duplex thick well stuctured topsoil	Mottled-Mesonatric Brown Sodosol	Typic Natrixeralf

Section 8

Australian Viticultural Soil Key

Rob Fitzpatrick, David Maschmedt and Alfred Cass

The soil identification key was developed to provide the viticulture industry with a language to facilitate communication about soils used for wine grape production. The key uses, as far as is possible, non-technical terms to categorise soils in terms of attributes that are important for vine growth. The basic philosophy of the key is strongly linked to issues of viticultural soil management. However, as a tool for understanding wine production historically within Australia and in competitor countries, the key needs also to correlate with previous and current Australian and international soil classification schemes. Several different soil classification systems have been or are used in Australia (Stace et al. 1968; Northcote 1979; Isbell 1996) and in overseas countries that produce wine (Soil Survey Staff 1999; USDA Soil Taxonomy and Soil Classification Working Group 1991; Soil Classification: A Taxonomic System for South Africa, 1991; FAO World Reference Base for Soil Resources 1998).

All these classification systems lack user-friendly keys for identifying soil profiles by people who are not experts in soil classification. It was clear from their lack of use in Australia, that the existing technical systems were not suitable because they are too complex. Viticultural information in Australian and overseas literature, based on soils classified using these schemes, could often not be applied correctly to Australian conditions, because there was no means to link these identifiers to local understanding of the nature and properties of soils. Consequently, the project reported here called for the development of a user-friendly soil key, which could be used by viticulturists to help select and match grapevine rootstocks to appropriate Australian soils (May 1993). In this paper, May states " … the choice of the most suitable rootstock may not be possible until we know more about the way in which rootstocks intact with the soil environment on the one hand and with their scion on the other hand". Other uses for the key were foreseen, for example, as a tool to correlate grower knowledge about their soils with other soils classified using these more technical systems.

The primary aim of this soil key is to identify categories of vineyard soils, using soil features, that are associated with the main soil types occurring in viticultural regions of Australia. The soil features used in the key are easily recognised in the field by people with limited soil classification experience. The key layout is bifurcating, based on the presence or absence of the particular keying property, which is usually a diagnostic property. The concept is similar to the key compiled by Schoknecht (1997) for soils in Western Australia, and by Fitzpatrick et al. (2001) to solve practical, soil related, problems. In the published versions of the soil key (Maschmedt et al., 2002; Fitzpatrick et al., 2002 and Cass et al., 2002, see "Outcomes from the Research", below), more comprehensive definitions of the properties used to classify the soils, limitations to use and coloured photographs for each sub-category will be provided. However, the essential features of the key are summarised here for the purpose of reporting on the final outcome of the project.

Characteristics of the Soil Key

In the system described here, we have developed a simple soil key to assist viticulturists to categorise visual soil properties into a system for naming soils used for wine growing in Australia. In developing the Soil Key we used soil descriptions and soil chemical data contained in the Rootstock Soil Properties Database (see Section 7 in this report), which consists of 132 characterised viticulture soils from rootstock trials across Australia. We focussed on the following viticulturally important and mostly visual diagnostic features: wetness, depth, calcareousness, cracking and texture contrast (Duplex character). The key is tabulated in Table 8.1. Between 1997 and 2001, the key has been successfully tested on many viticultural soils throughout Australia.

The terminology used is a combination of that used by McDonald *et al*., (1990), Stace et al. (1968), Northcote (1979), Isbell (1996) and recently summarised in Fitzpatrick et al. (1998). This reflects common usage in Australia where soil might be referred to as either "texture contrast" (duplex, with abrupt change from a sandy to a clayey layer, "uniform" (little change in texture down the profile) or "gradational" (gradual increase in texture down the profile), “cracking clay”, and/or “calcareous”. These terms have been found to be useful in the field. In particular, in the key we have paid particular attention to identifying "potential soil constraints", such as easily identifiable restrictive soil layers that might limit effective root depth. We also use observations of depth to certain characteristic changes in waterlogging, consistency, colour, texture and structure in different restrictive layers. Each soil category is provided with a listing of possible qualifiers in a priority sequence.

The Soil Key and Other Soil Classification Systems

One of the main objectives in developing practical attributes was to build the key in such way that it uses knowledge and experience of many soil scientists in Australia and from all over the world. In Table 8.2 we have correlated each sub-category identification in the key for vineyard soils with the following systems: The Australian Soil Classification System (Isbell 1996), Great Soil Group Classification (Stace et al. 1968), United States Soil Taxonomy (Soil Survey Staff 1999), A Taxonomic System for South Africa (Soil Classification Working Group, 1991), World Reference Base for Soil Resources (FAO, 1998).

Brief Definitions of Morphological Descriptors

Morphological descriptors are used for assessing soil conditions. These are observations of depth changes in the different soil layers are:

1. Consistence: see definitions and tables in
2. Texture: relative proportions of sand, silt and clay in the soil
3. Texture Groups (according to Northcote, 1979):
   The Sands = sand (S), loamy sand (LS), clayey sand (CS).
   The Sandy Loams = sandy loam (SL).
   The Loams = Loam (L); sandy clay loam (SCL); Silty loam (ZL).
   The Clay Loams = Clay loam (CL).
   The Light Clays = light clay (LC).
   The Medium-Heavy Clays = Medium clay (MC), Heavy clay (HC).
4. Structure: distinctness, size and shape of individual natural soil aggregates (peds).

5. Presence of a ground water table: free water at a particular depth in the soil.
6. Segregations: discrete accumulations of material by chemical or biological processes (e.g. carbonates and ironstone).
7. Coarse (rock) fragments: proportion and dominant size.
8. Colour: the dominant colour of the soil matrix.
9. Mottles: spots, blotches, or streaks of colour subdominant to the matrix colour.
10. Topsoil: the surface layer of the soil, generally but not always darkened by accumulation of organic matter.
11. Subsoil: the subsurface layer, lacking in organic matter and generally coloured by secondary accumulations of iron, clay, carbonate, etc.
12. "Duplex" texture: contrast in texture between the topsoil and subsoil that is greater than 1 ½ the Texture Groups defined under “texture” above, e.g.:
    Sand/clay
    Sand/sandy clay loam
    Loam/clay
    Loam/clay loam/medium or heavy clay.
13. Uniform texture: very little contrast in texture between layers in the profile, e.g.:
    Sand/sand/sand
    Clay loam/clay loam/clay loam
    Clay/clay/clay.
14. Gradational texture: steady increase in clay down the soil profile, e.g.:
    Sand/loamy sand/sandy loam
    Loam/clay loam/clay
    Clay loam/clay/medium clay.
15. Calcareous: reaction of the soil to a drop of hydrochloric or other acid (indicates the presence and possibly amount of free lime present).
16. Rippable vs. unrippable rock:
17. Calcrete: hard, rigid limestone or lime-rich soil material (calc rock).
18. Slickensides: Natural shiny surfaces found on soil aggregates formed by the parallel orientation of clay particles during swelling and shrinking cycles. Refers to polished or grooved surfaces within soils resulting from part of the mass sliding or moving against adjacent material along a plane that defines the extent of the slickensides. In soils, they only occur in clay rich materials with high swelling clay content.
19. Blocky, prismatic, columnar structure: distinct pedological character with clear planes of weakness between each ped and with equi-dimensional, sharp angled, accommodating sides (blocky) or vertical dimensions greater than horizontal but with rounded tops (columnar) or flat tops (prismatic).
20. Well structured: consistence that is firm or weaker in moderately moist condition and does not have columnar, prismatic or course blocky structure but rather more sperical, non-accommodating peds.

In addition to the above attributes a set of modifiers can be used to further refine soil classes. Modifiers are properties that cannot be determined in the field but require laboratory intervention. The modifiers are determined on samples taken from soil layers within the soil profile. They are used to designate any soil category as, say, “Saline” or “Sodic” or “Acid”, etc. Morphological descriptors combined with modifiers are useful in assessing soil conditions because they assist in diagnosing possible constraints to vine growth and they can be used in research to evaluate causes for variation in soil condition induced by land management, hydrology and weather conditions. The principle modifiers used in this key are:

- Soil reaction: the pH of a 1:5 soil to water extract.
- Salinity: the amount of salt in the soil as measured by electrical conductance of a 1:5 soil to water extract.
- Sodicity: the relative proportion of sodium to calcium and magnesium in a 1:5 soil to water extract.

Outcomes from the Research

Scientific Papers and Conference Presentations

Fitzpatrick R. W., Maschmedt D. and Cass A. 2002. The Australian Viticultural Soil Key. Paper to be submitted to Australian Journal of Viticulture and Enology.

Maschmedt D., Fitzpatrick R. W. and Cass A. 2002. Key for identifying categories of vineyard soils in Australia. CSIRO Land and Water Technical Report.

Industry Journal Articles

Alfred Cass, Rob Fitzpatrick and David Maschmedt. 2002. A key to understanding and identifying viticultural soil. To be submitted to The Australian Grapegrower & Winemaker.

Table 8.1 Key for identifying categories of vineyard soils in Australia

Does the soil have one of the following diagnostic features?	Soil Category	Sub-category	Code
a water table within 50 cm for three months of the year? **or** grey subsoil layers that may have yellow and/or reddish mottles? **YES? →→→→→→→→→→→→** **NO?↓**	**1: Wet Soil**	Can soil be drained? **NO? ↓** **Un-drainable wet soil** **YES? → Wet drainable - continue below↓**	**1**
is less than 15 cm deep (or <25 cm if sandy) over **non-rippable** rock. **YES?→→→→→→→→→→→→** **NO?↓**	**2: Very shallow non-rippable soil**	**Very shallow non-rippable soil**	**2**
is non calcareous and overlies loose stones, semi-hard rock or calcareous pan (**all rippable**) within **15 cm**? **YES? →→→→→→→→→→→→** **NO?↓**	**3: Very shallow or stony rippable soil**	**Deep stony soil** Soil has more than 75 % loose stones/ rocks in upper 100cm	**3.1**
		Very shallow soil over hard rock Hard fractured non-calcareous rock within 15 cm.	**3.2**
		Very shallow sandy soil over calc-rock Sands over calcareous rock or calcrete.	**3.3**
		Very shallow loamy/clayey soil over calc-rock Loams to clays over calcareous rock or calcrete.	**3.4**
is non calcareous and has a uniform clay content or gradual increase in clay content with depth over hard rock, hard pan or calcrete within **50 cm** of the surface? **YES? → → → → → → → → → →** **NO?↓**	**4: Shallow soil**	**Shallow sandy soil** Sandy over hard rock or hard pan between 25 and 50cm	**4.1**
		Shallow loamy soil over calc-rock Loamy to clay loamy over calcareous rock or calcrete between 15 and 50 cm.	**4.2**
		Shallow loamy soil over rock/pan Loamy to clay loamy over non- calcareous hard rock or hard pan between 15 and 50cm.	**4.3**
		Shallow clay over calc-rock Clayey, non-cracking over calcareous rock or calcrete between 15 and 50cm.	**4.4**
		Shallow cracking clay over calc-rock Clayey, cracking over calcareous rock or calcrete between 15 and 50cm.	**4.5**
is clayey to at least 50 cm, cracks on drying? **and** has slickensides within 50cm? **YES?- → → → → → → → → →** **NO? ↓**	**5: Cracking Clay**	**Poorly structured cracking clay** Hard setting coarse blocky or massive surface.	**5.1**
		Well structured over restrictive cracking clay Well structured within 80 cm of surface over restrictive layer (coarse blocky structure or wet/grey subsoil layers).	**5.2**
		Well structured thoughout cracking clay Well structured surface, no coarse blocky structure within 80cm of surface.	**5.3**

Table 8.1 (continued) Key for identifying "categories of vineyard soils" in Australia

Diagnostic features	Soil Category	Sub-category	Code
has a sandy, loamy or clay loamy topsoil hard more clayey subsoil <80cm thick abruptly overlying (with sharp abrupt or clear boundary) ,prismatic, columnar or coarse blocky structure and/or dull grey colours within the depth specified in the Sub-category. **YES?** →→→→→→→→→→→ **NO?** ↓	**6: Duplex soil with restrictive sub-soil**	**Restrictive duplex soil with thin well structured Topsoil.** Topsoil is not hard and thinner than 30cm.	**6.1**
		Restrictive duplex soil with thick well structured Topsoil. Topsoil is not hard and between 30 and 80 cm.	**6.2**
		Restrictive duplex soil with thin hard topsoil Topsoil is hard and thinner than 30cm.	**6.3**
		Restrictive duplex subsoil with thick hard topsoil Topsoil is hard and between 30 and 80 cm thick.	**6.4**
has an abrupt change from a sandy, loamy or clay loamy topsoil to a subsoil which does not have prismatic, columnar or coarse blocky structure and/or dull grey colours? **YES?** → → → → → → → → → **NO?** ↓	**7: Duplex soil with non-restrictive sub-soil**	**Non-restrictive duplex soil with thin well structured topsoil.** Topsoil is not hard and thinner than 30cm.	**7.1**
		Non-restrictive duplex soil with thick well structured topsoil. Topsoil is not hard and between 30 and 80 cm.	**7.2**
		Non-restrictive duplex soil with thin hard topsoil Topsoil is hard and thinner than 30cm.	**7.3**
		Non-restrictive duplex soil with thick hard topsoil Topsoil is hard and between 30 and 80 cm thick.	**7.4**
is calcareous throughout or at least below 10 cm **YES?** → → → → → → → → → **NO?** ↓	**8: Calcareous Soil**	**Sandy calcareous soil.** Sandy to at least 80 cm	**8.1**
		Shallow calcareous restrictive soil. Soil over non-rippable carbonate pan (calcrete) between 15 and 50 cm thick.	**8.2**
		Shallow calcareous non-restrictive soil. Soil over rippable carbonate-rich rock or pan between 15 and 50 cm thick.	**8.3**
		Rubbly calcareous soil. Soil has a layer with more than 30% carbonate rubble at least 20 cm thick	**8.4**
		Clayey calcareous soil Clayey (> light clay) over carbonate layer in 80cm	**8.5**
		Loamy calcareous soil. Loamy to clay loamy over carbonate layer within 80 cm.	**8.6**
has a uniform clay content or gradual increase in clay content. A hard restrictive layer may occur anywhere in the profile? **YES?-** → → → → → → → → →	**9: Uniform or gradational soil ("Unigrad")**	**Deep sandy uniform soil** Sandy to at least 50 cm.	**9.1**
		Sandy gradational soil Sandy topsoil over loam to clay within 50 cm	**9.2**
		Deep loamy unigrad, calcareous soil Sandy loam to loam surface, calcareous subsoil	**9.3**
		Deep clayey unigrad, calcareous soil Clay loam to clay surface soil, calcareous subsoil	**9.4**
		Deep hard loamy unigrad soil Firm to hard sandy loam to loam surface soil	**9.5**
		Deep well structured loamy unigrad soil Sandy loam to loam surface soil well structured to at least 50 cm	**9.6**
		Deep hard clayey unigrad soil Firm to hard clay loam to clay surface soil	**9.7**
		Deep well structured clayey unigrad soil Clay loam to clay surface soil well structured to at least cm	**9.8**

Table 8.2: Correlation between categories of vineyard soils in Australia and other soil classification systems

Key for identifying Australian vineyard soils	Australian Soil classification (Isbell, 1996)	Great Soil Group (Stace et al., 1998)	USDA Soil Taxonomy (Soil Survey Staff, 1996)	Taxonomic System for South Africa (SCWG 1991)	World Reference Soil Base for Soil Resources (WRB, 1998)
1: Un-drainable wet soil	Hydrosols	Grey clay Humic gley Neutral to alkaline peat Acid peat Lithosol	Aqualfs Salids Aquents Fibrists Saprists Hemists Aquepts Aquolls Aquox Aquod Auults Aquerts	Champagne Katspruit Pinedene Bloemdal Rensburg	EndogleyicHistosols Epigleyic Histosols Rheic Histosols Endogleyic Gleysols EpigleyicGleysols Plinthic Gleysols Sodic Gleysols Umbric Gleysols Mollic Gleysols Arenic Gleysols Calcic Gleysols Haplic Gleysols
2: Very shallow non rippable soil	**Lithic Rudosol (very shallow Lithic Tenosol (very shallow) Petrocalcic Rudosol / Tenosol (v shallow)**	**Lithosol**	**Entosols Salic aridisols**	**Mispah Knersvlakte Dresden Coega**	**Lithic Leptosols Lithic Calcisols**
3: Very shallow or stony rippable soil	**Rudosol Tenosol**	**Lithosol Alluvial soil**	**Entosols Salic aridisols Inceptisols**	**As above**	**Paralithic Leptosols Hyperskelectric Leptosols**
3.1 Deep stony soil	Clastic Rudosol Clastic Tenosol	Lithosol Terra rossa	Entosols Salic aridisols	Mispah	Lithic Leptosols Paralithic Leptosols
3.2 Very shallow soil over hard rock	Paralithic Leptic Rudosol (very shallow) Petroferric Tenosol (very shallow	Lithosol Terra rossa	Entosols Salic aridisols	Mispah Knersvlakte Dresden	Paralithic Leptosols Hyperskelectric Leptosols
3.3 Very shallow sandy soil over calc-rock	Petrocalcic Tenosol	Lithosol Terra rossa	Entosols Salic aridisols	Coega	Lithic Calcisols Epileptic Calcisols Arenic Durisols
3.4 Very shallow loamy/clayey soil over calc-rock	Petrocalcic Tenosol Petrocalcic Dermosol	Lithosol Terra rossa Rendzina	Inceptisols Entosols Lithic Calcixerepts	Coega	Lithic Calcisols Petrocalcic Calcisols Renzic Leptosols Rhodic Calcisols

Table 8.2: (continued) Correlation between categories of vineyard soils in Australia and other soil classification systems

Key for identifying Australian vineyard soils	Australian Soil classification (Isbell, 1996)	Great Soil Group (Stace et al., 1998)	USDA Soil Taxonomy (Soil Survey Staff, 1996)	Taxonomic System for South Africa (SCWG 1991)	World Reference Soil Base for Soil Resources (WRB, 1998)
4: Shallow soil	**Rudosol Tenosol Vertosol**	**Lithosol Shallow Black earths Cracking Clay**	**Entosols Inceptisols Verisols**	**Prieska Dundee Arcadia (shallow)**	**Leptosols**
4.1 Shallow sandy soil	Rudosol Tenosol	Lithosol Red siliceous sand	Inceptisols Xerepts, Udepts	Dundee	Arenosols Cambisols
4.2 Shallow loamy over calc-rock	Petrocalcic Red Dermosol / Kandosol Petrocalcic Tenosol	Terra rossa	Calcixerepts	Prieska	Calcaric Cambisols
4.3 Shallow loamy soil over calc-rock	Lithic / Petroferric / Silpanic Tenosol	Red and brown hardpan soil	Durixerepts	Prieska	Leptic Cambisols Regosols
4.4 Shallow clay over calc-rock	Petrocalcic, Black Dermosol	Rendzina Ground water Rendzina	Calcixerepts Calciaquolls	Prieska	Phaeozems Kastanozems
4.5 Shallow cracking clay over calc-rock	Petrocalcic, Black Dermosol	Rendzina Ground water Rendzina	Xerolls Calcixerolls Lithic Argixerolls Calcic Argixerolls	Immerpan Milkwood	Calcic Vertisol Duric Vertisol Kastanozems,Phaeozems
5: Cracking Clay	**Vertosol**	**Black earths, Cracking Clay**	**Vertisols**	**Arcadia, Rensburg**	**Vertisols**
5.1 Poorly structured cracking clay	Massive / Epihypersodic Vertsol		Sodic Haploxererts	Arcadia Rensburg	Mazic Vertisol Hyposodic Vertisol Natric Vertisol
5.2 Well structured over restrictive cracking clay	Endohypersodic Vertosol	Wiesenboden	Aquerts Xererts Calciaquerts Endoaquerts Aquic Haploxererts	Rensburg	Calcic Vertisol Pellic Vertisol Grumic Vertisol Gypsiric Vertisol Natric Vertisol
5.3 Well structured throughout cracking clay	Self-mulching / Epipedal Vertosol	Black earths	Calcixererts Chromic Haploxererts	Arcadia	Calcic Vertisol, Pellic Vertisol Grumic Vertisol, Haplic Vertisol Chromic Vertisol

Table 8.2: (continued) Correlation between categories of vineyard soils in Australia and other soil classification systems

Key for identifying Australian vineyard soils	Australian Soil classification (Isbell, 1996)	Great Soil Group (Stace et al., 1998)	USDA Soil Taxonomy (Soil Survey Staff, 1996)	Taxonomic System for South Africa (SCWG 1991)	World Reference Soil Base for Soil Resources (WRB, 1998)
6: Duplex soil with restrictive sub-soil	**Sodosol Sodic Chromosol Natric Kurosol**	**Solodized brown soil Solodized solontz, Solodic Soloth Red-brown earth Gleyed podzolic soil**	**Xeralfs Udalfs Natrixeralfs**	**Kroonstad Longlands Wasbank Estcourt Cartref Westleigh Klapmuts Glencoe Sterkspruit Sepane**	**Gleyic Solonetz Duric Solonetz Calcic Solonetz Magnesic Solonetz Albic Solonetz Stagnic Solonetz Gleyic Planosols Sodic Planosols Albic Planosols Petroferric Planosols Albic Plinthosols**
6.1 Restrictive duplex soil with thin well structured topsoil	See above	See above	See above	See above	
6.2 Restrictive duplex soil with thick well structured	See above	See above	See above	See above	
6.3 Restrictive duplex soil with thin hard topsoil	See above	See above	See above	See above	
6.4 Restrictive subsoil with thick hard topsoil	See above	See above	See above	See above	

Table 8.2: (continued) Correlation between categories of vineyard soils in Australia and other soil classification systems

Key for identifying Australian vineyard soils	Australian Soil classification (Isbell, 1996)	Great Soil Group (Stace et al., 1998)	USDA Soil Taxonomy (Soil Survey Staff, 1996)	Taxonomic System for South Africa (SCWG 1991)	World Reference Soil Base for Soil Resources (WRB, 1998)
7: Duplex soil with non-restrictive sub-soil	**Chromosol Kurosol**	**Red podzolic soil Yellow podzolic Brown podzolic Lateritic podzolic soil Red-brown earth**	**Plintoxeralfs Rhodoxeralfs Palexeralfs Haploxeralfs Rhodustalfs Plinthustalfs**	**Constantia Vilfontes Avalon Klinelbos, Swartland Valsrevier, Tukulu**	**Plinthic Planosols Mollic Planosols Calcic Planosols Alic Planosols Geric Planosols Albic Plinthosols**
7.1 Restrictive subsoil with thin friable topsoil	As above	As above	As above	See above	
7.2 Restrictive subsoil with thick friable topsoil	As above	As above	As above	See above	
7.3 Restrictive subsoil with thin hard topsoil	As above	As above	As above	See above	
7.4 Restrictive subsoil with thick hard topsoil	As above	As above	As above	See above	
8: Calcareous Soil		Calcareous sand, Grey-brown Calcareous soil Calcareous red earth			
8.1 Sandy calcareous soil	Calcic Calcarosol	Calcareous sand	Lithic Xerothens Calcixerepts		Calcaric Arenosol Arenic Regosol
8.2 Shallow calcareous restrictive soil	Petrocalcic Calcarosol	Calcareous sand	Petrocalcic Calcixere Calcixerepts	Etosha Gamoep, Trawal	Epipetric Calcisol
8.3 Shallow calcareous non restrictive soil	Petrocalcic / Paralithic Calcarosol		Lithic Calcixerepts	Brandvlei Addo	Calcic Calcisol Hypocalcic Calcisol
8.4 Rubbly calcareous soil	Supracalcic, Lithocalcic Calcarosol		Lithic Calcixerepts	Brandvlei, Addo	Skeletic Calcisol Hypocalcic Calcisol
8.5 Clayey calcareous	Hypercalcic Calcarosol	Red calcareous soils Terra Rossa	Typic Calcixerepts Petrocalcic Rhodoxra Calcic Rhodoxralfs	Molopo Oakleaf Montagu, Augrabies	Calcisol
8.6 Loamy calcareous soil	Calcic Calcarosol	Terra Rossa Desert loam	Typic Calcixerepts Petrocalcic Rhodoxra Calcic Rhodoxralfs	Oakleaf Montagu Augrabies	Endopetric Calcisol

Table 8.2: (continued) Correlation between categories of vineyard soils in Australia and other soil classification systems

Key for identifying Australian vineyard soils	Australian Soil classification (Isbell, 1996)	Great Soil Group (Stace et al., 1998)	USDA Soil Taxonomy (Soil Survey Staff, 1996)	Taxonomic System for South Africa (SCWG 1991)	World Reference Soil Base for Soil Resources (WRB, 1998)
9 Uniform or gradational soil	Wide range - see below	Wide range – see below	Wide range – see below		
9.1 Deep sandy soil	Arenic Tenosol	Red earthy sand Podzol Red siliceous sand	Psamments Spodosols	Fernwood Namib Lamotte Concordia	Arenosols Arenic Regosols Arenic Fluvisols Arenic Ferralsols
9.2 Sandy gradational soil	Kandosol		Alfisols Ultisols	Vilafontes Shortland	Arenic Ferralsols Plinthic Ferralsols
9.3 Deep loamy calcareous soil	Calcic Kandosol/Dermosol; loamy	Red earth	Alfisols Ultisols	Klinkelbos Hutton	Hypocalcic Calcisol Luvic Calcisol
9.4 Deep clayey calcareou soil	Calcic Dermosol; clayey		Alfisols Ultisols	Kimberley Shortlands Swartland	Luvic Calcisol Lixic Ferralsols
9.5 Deep hard loamy soil	Eutrophic Kandosol; loamy	Krasnozem Euchrozem	Alfisols Ultisols	Hutton Clovelly	Lixic Ferralsols
9.6 Deep well structured loamy soil	Eutrophic Dermosol; loamy		Alfisols Ultisols	Hutton Clovelly	Lixic Ferralsols Plinthosols
9.7 Deep hard clayey soil	Eutrophic Kandosol; clay loamy	Krasnozem Euchrozem	Alfisols Ultisols	Hutton Clovelly Griffin	Lixic Ferralsols Plinthosols
9.8 Deep well structured clayey soil	Eutrophic Dermosol; clayey loamy	Krasnozem Euchrozem	Alfisols Ultisols Oxisols	Hutton Kranskop Magwa Inanda	Alumic Nitosols Lixic Ferralsols Gibbsic Ferralsols

Section 9

9.1 Barossa Valley Rotary Club Foundation Fellowship Report

Alfred Cass

Early in 1996, following suggestions made by Dr. Rob Walker of CSIRO Division of Plant Industry, a meeting was arranged with Messrs Bryon Pearson, Colin Gramp and Terry Sachse of the Barossa Valley Rotary Club. They signified that the Barossa Valley Rotary Club Foundation wished to sponsor an international visitor to Australia who would highlight the significant features of the Barossa Valley. A small committee (see Appendix) was established from a core group of interested institutions to organise and underwrite such a visit:

- The Rotary Club of the Barossa Valley
- Grape and Wine Research and Development Corporation
- Cooperative Research Centre for Viticulture
- Cooperative Research Centre for Soil & Land Management
- CSIRO Division of Horticulture (now Plant Industry).

The directors of these institutions charged the committee with the task of planning, organizing and finding financial resources to underwrite the visit. The Fellowship, although underwritten by these institutions, was to be self-funding. The visitor was to have expertise in viticulture (the main industry of the Barossa Valley) and soil science (the main interest of the CRC for Soil and Land Management). The format and aims of the Fellowship were formalized as follows:

- Study, with the help of local researchers, soil and water management problems in vineyards in selected areas of South Australia, Victoria and New South Wales and Western Australia with particular emphasis on the Barossa Valley.
- Participate in instructional seminars, field days and workshops with the aim of defining improved soil and water management strategies for the benefit of the viticultural industry in these areas.
- Examine current soil and water management research in these areas.
- Discuss with responsible researchers and report on the quality, relevance and effectiveness of this research.
- Report back to the industry at the conclusion of the visit, to in an open meeting in the Barossa Valley.
- Prepare a written report of the outcomes of the Fellowship.

Examination of the scientific literature in the areas of viticultural soil research revealed a short list of outstanding candidates with suitable qualifications for the Fellowship as defined by the broad objective and the specific aims. Most of these candidates were resident in South Africa. Opinions of industry leaders, with personal knowledge of international viticulture, were canvassed. After considering of this information, the committee selected Mr. Philip Myburgh of Nietvoorbij Institute for Viticulture and Oenology, Stellenbosch, South Africa, for award of the 1996 Fellowship. The committee on behalf of the sponsoring institutions issued an invitation. The director of the Nietvoorbij Institute accepted the invitation and Philip Myburgh arrived in

Australia on Saturday 3 August 1996.

The program of events that was followed during tenure of the Fellowship is shown in Table 9.1.1.

The interest and participation of all sections of the viticultural industry in southeastern Australia in execution of the Fellowship was outstanding. In all regions visited, local viticultural grower and wine producing associations, educational and research institutions, land care groups and private individuals assisted in organizing and financing local events. Private individuals in the Barossa Valley provided lodging (Mr. and Mrs. de Haan) for Philip Myburgh at no cost and a local motor business provided a vehicle for his use in the Barossa Valley. Additional in-kind and financial support for the Fellowship was provided by:

- The Rotary Club of the Barossa Valley Foundation
- Grape and Wine Research and Development Corporation
- Murray Valley Winegrape Industry Development Committee
- Cooperative Research Centre for Viticulture
- Cooperative Research Centre for Soil & Land Management
- CSIRO Division of Horticulture (now Plant Industry)
- Dried Fruits Research and Development Council
- Department of Agriculture Western Australia
- Department of Agriculture Extension, Faculty of Agriculture, University of Western Australia
- Orlando Wyndam Wines
- Southcorp Wines
- Mildara Blass Wines
- Numerous individual grape growers.

Two broad outcomes that the Fellowship achieved were to (1) highlight the importance of the Barossa Valley as a grape-producing area and (2) draw the attention of a wide range of the viticultural industry to the importance of soil management technology to winegrape production. A total of some thirty field days, seminars and workshops were held across southeastern and Western Australia (Table 9.1.1), attended by many hundreds of people. The format of most of the presentations was hands-on with participation by Philip Myburgh and associates at soil pits in vineyards where practical pertinent issues were discussed in an open, informal manner. Several formal seminars and workshops were also arranged and were well attended. The outcomes of the Fellowship were described in a report prepared by Myburgh, Cass and Clingeleffer (1996).

Highlights from this report are:

1. Soil physical problems or limitations exist in many vineyard and orchard soils.
2. A general lack of knowledge of how soil conditions affected root development and distribution was detected.
3. Irrigation water quantity and quality was a limitation in many areas, primarily due to salinization of aquifers
4. Soil salinity as well as sodicity in some cases is increasing.
5. Poor soil conditions result in slow production of sugars and cause undesirably low total titratable acidity, reducing berry and must quality and eventual wine quality,
6. Reduction in saline irrigation water applications reduce the load of salt and sodium in

soil

7. Extractable soil water can be increased if grapevine root systems are allowed optimal use of the available soil volume.
8. Criteria for optimum grape vine root systems:
   - penetrate and develop to soil depths of at least 0.8 m to 1.0 m
   - develop in soil between grapevine rows.
   - have large numbers of fine roots, allowing efficient water and nutrient uptake.
9. Favourable physical and chemical conditions allow optimal root growth and functioning.
10. Susceptibility to root diseases can be reduced by improved soil structure.
11. Root diseases are often secondary effects where waterlogging and poor soil aeration exists.
12. Variations in soil depth cause variation of grapevine response.
13. Well-developed root systems reduce risk of low yields, ensuring stable income and profit.
14. Grapevine roots cannot readily explore soil if penetration resistance exceeds 2 MPa
15. Vine root depth can be estimated with a penetrometer with a standard error of 82 mm.
16. Depth of grapevine root systems in SE Australia varied between 200 mm and 900 mm.
17. Soil texture had no effect the relationship between root depth and penetration resistance.
18. Shallower root systems occur on sandy soils (sands, loamy sands, sandy loams).
19. Deepest root systems were found in soils with clay loam and clay textures.
20. Penetration resistance could also serve as a means to assess:
    - deep tillage effects,
    - problems such as too shallow ripping,
    - compact soil in the midrow,
    - soil physical limitations in existing vineyards.
21. Ramsey rootstock produces stronger, better developed root systems in calcareous subsoils.
22. Sandy soils often compact to readily and limit root penetration and development.
23. Wheel compaction can restrict root development in the inter row space and consequently prevent optimal utilization of water and nutrients.
24. Severity of wheel compaction depends on topsoil texture:
    - sandy and sandy loam soils tend to compact more readily,
    - heavier textured soils such as loams or clays less compactable.
25. Wheel compaction was encountered in most vineyards visited.
26. Adverse effect of wheel traffic compaction increased where roots are confined to shallow topsoil.
27. Deep ripping is the only form of soil preparation that is currently done.
28. Ripping generally limited to a single rip on the vine row.
29. Wingless tined rippers had a limited loosening effect in most soils.
30. Wingless tines are not able to alleviate the physical problems or to ensure optimal utilization of the total available soil volume.

Philip Myburgh's recommendations for future research (Myburgh et al., 1996, page 26) are summarised below:

1. Develop implements for the effective management of specific soil physical problems.
2. Implements should include better ripping tines that can mix coarse subsurface soil layers

with topsoil.

3. Support tillage research with proper evaluation and demonstration using rigorous field trials.
4. Land Care groups can play a role via their "demonstration vineyard" approach.
5. Develop and evaluate suitable implements for deep tillage in existing vineyards.
6. Management of cracking clays needs special attention:
   a. investigate soil based technology,
   b. develop appropriate viticultural practices to manage vigour,
   c. investigate feasibility of dryland viticulture on well prepared soils,
   d. investigate low producing grapevines on small trellises.
7. Establish a team of soil scientists that can focus the their attention primarily to research and development of soil management practices for viticulture as well as horticulture.
8. Industry needs multi-disciplinary research to a larger extent to ensure a balance between soil management and viticultural practices.
9. Industry support for post graduate scholarship for research and development of deep tillage techniques is needed.
10. Soil preparation and management for viticulture or horticulture should form an integral part of university and college courses
11. Courses presented by the institutes of TAFE address these subjects in theoretical as well as practical training.
12. Techniques for estimation of potential root depth needs refinement (quantification of natural soil compaction).
13. Value of soil pits to evaluate soil conditions and root system development should not be underestimated
14. Growers, technical advisors and consultants should be encouraged to qualify root systems in existing vineyards and orchards to enable them to adapt irrigation management to the depth or volume of soil actually used.

Outcomes from the Research

All the suggestions for future research made by Philip Myburgh, that fell within the ambit of Project CRS 95/1, were adopted and incorporated into the research and extension program. Of note are items 1, 2, 3, 4, 5, 6, 7, 12, 13 and 14. Each of these topics of research is addressed in this report. Some of these suggestions were dealt with in research projects, others in seminars such as the Research to Practice series.

Scientific Papers and Conference Presentations

Cass A., Maschmedt D. and Myburgh P. 1998. Soil Structure - are there best practices? Proceedings of the Australian Society for Viticulture and Oenology, Viticultural Best Practices Seminar, Mildura, August 1997.

Myburgh P., Cass A. and Clingeleffer P. 1996. Root systems and soils in Australian vineyards and orchards – an assessment. Barossa Valley Rotary Foundation Fellowship Report. CRC for Soil and Land Management, Adelaide, Australia

Seminars and Field Days

A total of some thirty field days, seminars and workshops were held across southeastern and Western Australia attended by many hundreds of growers and industry leaders.

Table 9.1.1: Program of activities for Philip Myburgh, recipient of the 1966 Barossa Rotary Foundation Fellowship.

"Soil and Water Management in Vineyards"

FAMILIARISATION TOUR

Discussion with research providers, Landcare organisers, industry leaders

Wed 7 August : ***Adelaide: Grape and Wine R&D Corporation, CRC Soil and Land Management, CSIRO Division of Soils, Dept. of Soil Science***
Thurs 8 August : ***Barossa Rotary Club***
Fri 9 August : ***Adelaide: CRC Viticulture, CSIRO Division of Horticulture, Dept. of Horticulture, Viticulture & Oenology***
Mon 12 August : ***Barossa Valley: PISA, Nuriootpa Research Station***
Tues 13 August : ***Barossa Valley: CRC S&LM and Landcare Research Sites***
Wed 14 August : ***McLaren Vale and Willunga Basin***
Thurs 15 August : ***Langhorne Creek***
Fri 16 August : ***Padthaway, Coonawarra***
Mon 19 August : ***Clare Valley Landcare, PISA***
Tues 20 August : ***Riverland; Riverlink Group***
Wed 21 to Fri 23 August : ***Sunraysia: CSIRO Division of Horticulture, Riverlink Group, Dried Fruits R&D Council, Murray Valley Wine Grape Industry Development Com.***

Sat 24 and Sun 25 August : ***Barossa Rotary Club Social Events***

CONSULTATION : MAJOR WINERIES

In-house discussions with staff of major South Australian wineries, Barossa Valley

Mon 26 August : ***Southcorp***

Thurs 29 August: ***Mildara Blass***

Wed 4 September: ***Orlando Wyndham***

PUBLIC EVENTS

Field days and seminars organised locally by industry bodies and Landcare groups

Tues 27 August: ***Barossa Landcare Field Day***

Wed 28 August : ***Fellowship Opening Ceremony, Barossa Valley***

Fri 30 August: ***Barossa Valley Floor Field Visits***
Mon 2 September: ***McLaren Vale Field Day***
Tues 3 September: ***TAFE CFP Students***
Thurs September 5: ***Eden Valley Field Day***
Fri 6 September : ***CRC Viticulture Symposium***
Tues 10 September : ***Clare Valley Field Day***
Thurs 12, Fri 13 Sept.: ***Riverland Field Days***
Mon 16 to Fri 27 Sept.: ***Sunraysia Field Days***
Fri 20, Sat 21 September : ***MIA Field Day***
Mon 30 Sept. : ***Langhorne Creek Field Day***
Wed 2 Oct.: ***Willunga AGA Landcare Field Day***
Thurs 3 October : ***Barossa Field Day Soil and Water Management***
Fri 4 October : ***Adelaide Hills Field Day***
Thurs 10 October : ***Padthaway and Coonawarra Field Day and Annual General Meeting SE Viticultural Council***

CONSULTATION : MAJOR WINERIES
Padthaway and Coonawarra:

Mon 7 October: ***Orlando Wyndham***
Tues 8 October : ***Southcorp***
Wed 9 October : ***Southcorp***
Fri 11 October : ***Mildara Blass***

Thur 17 October: ***Barossa Rotary Club Farewell***

Fri 18 October : ***Report Back: Barossa Winegrape Industry Advisory Com.***

Mon 21 to Fri 25 October: ***Western Australia***

9.2 Grape Production Series No. 2

Alfred Cass and Philip Myburgh

During 1997, Philip Nicholas of Primary Industries South Australia approached members of the Irrigated Trees and Vines Program of the CRC for Soil and Land Management and Philip Myburgh (Borossa Rotary Club Foundation Fellow), requesting contributions to a forthcoming publication: "Grape Production Series Number 2: Soil, Irrigation and Nutrition Management".

The response to this request was to edit and expanded draft chapters of the industry manual described in Section 9.4. These materials and photographs and slides illustrating the text material, were provided to the editor of the series between August and September 1997 for inclusion in that publication. The text material included topics that fell within the following titles:

1. Deep Ripping: New Vineyards
2. Gypsum Application
3. Carbon in Soil
4. Vineyard Floor Management
    - *Routine Soil Cultivation*
    - *Remedial Tillage*
5. Soil Salinity
6. Soil Sodicity
7. Salinity Management and Leaching
8. Management of Saline and Sodic Soils
9. Soil Preparation
    - *Mixing*
    - *Ridging*
    - *Mulching*
    - *Tillage*
10. Pre-planting Soil Treatments

Outcomes from the Research

Nicholas P. (Editor). 2002. Grape Production Series Number 2: Soil, Irrigation and Nutrition. Winetitels, Adelaide, South Australia.

9.3 Water Management for Grape Production Research to Practice™ Manual and Workshops

Alfred Cass, Judy Eastham and Andrew Dowley

The Water Management for Grape Production Research to Practice™ training workshop series has been described by Grieger (2001) in a final report on Project CRV 97/1, submitted to the Grape and Wine Research and Development Corporation. This workshop series was implemented by the CRC for Viticulture in 1997 and ran through to 1999.

The aims (Grieger, 2001) of the Research to Practice™ workshop series were to:

1. Provide Australian wine grape growers with a training framework to enable greater uptake of best practice in soil and water management for the production of wine grapes to specification.
2. Establish an avenue for improved and broader access to the outcomes of viticultural soil and water research and development in a consolidated, practical training format with a network of quality, commercially supported trainers.
3. Integrate the management of the soil resource with irrigation practice.
4. Enhance the management capacity and confidence of wine grape growers in initiating improved soil and water management practices.
5. Improve water use efficiency, product specification and enterprise performance through the adoption of "best practice" soil and water management.

Staff of the Irrigated Trees and Vines research program of the CRC for Soil and Land Management contributed substantially to this seminar series through provision of:

- chapters to the workshop manual (CRCV, 1997),
- photographic slides and prints to illustrate seminar presentations,
- PowerPoint seminar presentations,
- case study materials,
- participation in the majority of the workshop presentations,
- development of the presentation format and style.

The Research to Practice seminar organisers produced a manual for use by workshop participants (CRCV, 1997) as an information source of audio-visual material covered in the workshop. The manual contains 11 major sections encompassing vine physiology, vine water relations, soil information and management, irrigation water scheduling, management and quality information and monitoring and record keeping hints. The contribution to these sections from the Irrigated Trees and Vines research program encompassed material in draft form for the Industry Manual foreshadowed in the aims of Project CRS 95/1 (see Section 9.4). This material was edited and merged with other material by the series organisers to produce the workshop manual in its current form. As part of this report, Dr. Gayle Grieger has lodged a copy of the manual with the Grape and Wine Research and Development Corporation.

Staff of the Irrigated Trees and Vines program supplied a substantial proportion of the illustrative visual aids used in the workshop relating to soil and soil management. This material took the form of photographic slides and prints for seminar presentations and PowerPoint seminar summaries of the workshop manual. Eighteen case studies of specific soil problems in relation to viticultural issues were developed and given to the organisers for use in the workshop sessions. The case study materials were drawn from field investigation of rootstock, viticultural experimental trials and monitoring sites described in various parts of this report.

Several members of the Irrigated Trees and Vines program were involved in delivering part of the material during workshops the across the country. The workshops covered 14 general viticultural topics of which 7 involved soil or soil management (Grieger, 2001, page 8). Members of the Irrigated Trees and Vines program largely dealt with the soil topics. A total of 38 workshops were presented by the CRC for Viticulture (Grieger 2001) of which 34 involved staff from this project. Table 10.3.1 lists those formal workshops that were documented. This level of involvement allowed considerable scope for assisting the organisers in refining and polishing the presentation format and style of the workshop sessions.

The Research to Practice workshops reached a total of 763 participants in the period from 1997 to 1999. During the course of the series, demand for workshops by industry leaders in all regions of southeastern and Western Australia was high. Evaluation of the impact of the workshop, conducted in March 2001 was positive. Feedback during the workshop sessions showed that participants gained a great deal from the presentations. A clearly stated benefit from the workshops voiced by participants was increased realization of the importance of soil properties to applying scientific irrigation principles to produce high quality fruit. Apart from the many benefits that have been documented by Grieger (2001) concerning improved attitudes to and practices of irrigation and water management, there is no doubt that the workshops raised the perception of the need and possibilities for improved soil structure management as an integral part of best-practice viticulture.

The success of the workshops can be attributed to the quality and relevance of the material as well as the positive format and style used in the individual sessions. Participants were interested and eager to learn. To a great extent this positive climate was created by the knowledge, organizational ability, teaching skills and empathy of the principle organiser, Dr. Gayle Grieger.

Outcomes from the Research

Publications

CRCV. 1997. Water Management for Grape Production: Research to Practice™ Training Workshop Manual. CRC for Viticulture, Adelaide, South Australia.

Workshops

See Table 10.3.1 overleaf.

Table 9.3.1: CRC for Soil and Land Management project participants in the Research to Practice™ Workshops between 1997 and 1999 (data provided by Dr. Gayle Grieger).

Seminar	Seminar Location/Company	*Presenter*
1997		
1	Adelaide Hills	Alfred Cass
2	Coonawarra	Alfred Cass
3	Griffith	Alfred Cass
4	King Valley	Alfred Cass
5	McLaren Vale	Alfred Cass, Andrew Dowley
6	Yarra Valley	Alfred Cass
1998		
7	Albany	Alfred Cass, Judy Eastham
8	Clare	Alfred Cass
9	Cowra	Alfred Cass
10	Hunter Valley	Alfred Cass
11	Langhorne Creek	Alfred Cass
12	Manjimup	Alfred Cass
13	Margaret River	Alfred Cass, Judy Eastham
14	Griffith	Alfred Cass
15	Mildura No. 1	Alfred Cass
16	Mildura No. 2	Alfred Cass
17	Mt Benson	Alfred Cass
18	Mudgee	Alfred Cass
19	Nuriootpa	Alfred Cass
20	Riverland	Alfred Cass
1999		
21	Adelaide Hills	Alfred Cass, Andrew Dowley
22	Barossa Valley	Alfred Cass
23	BRL Hardy – McLaren Vale	Alfred Cass
24	BRL Hardy – South East	Alfred Cass
25	Canberra	Alfred Cass
26	Griffith	Alfred Cass
27	Margaret River	Judy Eastham
28	Orange	Alfred Cass
29	Southcorp No. 1	Alfred Cass
30	Southcorp No. 2	Alfred Cass
31	Wangaratta	Alfred Cass
32	McLaren Vale No. 1	Alfred Cass
33	McLaren Vale No. 2	Alfred Cass
34	McLaren Vale No. 3	Alfred Cass

9.4 Industry Manual: Selection, Development and Management of Viticultural Soils

Alfred Cass

Productivity and management problems exist in many vineyards on marginal soils (Davidson 1992). These problems relate largely to selection of inappropriate soils for new vineyards, poor soil preparation at establishment and inappropriate soil management during the life of the vineyard. Optimum soil conditions for plant growth are often not created at vineyard establishment, and many current management systems tend to degrade soil quality causing a decline in productivity (yield and quality) with time. Fitzpatrick et al. (1993) showed that there is a lack of definitive description of soil properties in relation to vineyard requirements and performance, especially in relation to soil and water management. This is a major obstacle to improved productivity and a basic reason for any failure of resource and production sustainability in the industry. The largest potential increase in vineyard productivity lies in defining standards for evaluating soils for viticulture which will lead to improved soil selection for new vineyards and better appreciation of the soil factors that need to be addressed in designing and establishment of new vineyards and management in existing vineyards, that assure long term production sustainability.

Improved soil management technology, recently developed in other intensive horticultural industries (Cass et al., 1993), has assisted those industries to increase productivity and ensure better sustainability of production. The technology is based on (1) understanding optimum properties of soils in relation to plant requirements ("benchmarking" soils) (Aumann, Ashcroft and Cass, 1998 and 1999), (2) establishing optimum soil physical quality relative to benchmark properties (soil sensitive land preparation) and (3) maintaining this quality by use of cover crops, management of tillage and traffic and controlling the manner, timing and application rate of inputs such as fertilizers, amendments and irrigation water. These procedures ensure that soil properties conform to certain minimum physical requirements and that these properties remain stable during the life of the enterprise. However, neither the optimal soil physical requirements of vines nor the particular mix of technologies ideally suited to systems of soil management for vineyards has been fully developed nor completely documented. The research described here was focused on these outcomes and achieved these objective in some measure.

The research focused on productivity and sustainability of vineyards in relation to soil quality. A major component of the research was to establish procedures for creating and maintaining soil conditions that conform to a set of soil quality indicators of sustainability, to link these procedures to the general distribution of soils and vine performance in the major grape growing areas, and to formulate "Best Practice" management packages aimed at improving grape production, managing vine vigour and increasing vineyard uniformity and sustainability.

Methods and Materials

The work was initiated by defining what soil properties have relevance to degradation of vineyard soils (Section 2) and how some of these properties impact on productivity and sustainability (Section 4). A review of viticultural scientific and industry literature (Section 2) provided the framework for the management packages. A set of key soil indicators of

sustainability for vineyard development and management were established (Section 2) which were used to guide development of soil selection criteria (Section 8) and management systems (Sections 9.2 and 9.3). A wide range of vineyard soils were investigated and documented during the tenure of the Barossa Valley Rotary Club Foundation Fellowship (Section 9.1) and during investigation of the rootstock experiments (Section 7). Personal experience gained by the researchers in other industries was used to expand the knowledge base of the project: Cass, Lanyon, Cockroft & Olsson (1997), Aumann, Ashcroft & Cass (1998, 1999) and Lanyon, Cass, Cockroft & Olsson (1999). During this project, information derived from characterisation of existing vine experimental soils, rootstock trials (Section 7) and results from soil management experiments (Sections 3, 5, 7 and 8) were used to refine the indicators of sustainability.

The scope and extent of this work could not only be achieved by conventional replicated field trials. A great deal of testing and refining was done in commercial vineyards. A network of industry collaborators assisted in this task. Information was derived from informal, partially replicated and un-replicated, observational and monitored field experiments in commercial vineyards throughout South Australia and in Victoria. These collaborators are listed in the Appendix to this report. The main issues that were addresses in these trials were:

- deep ripping technology,
- ridging shallow, saline and waterlogged soils onto mounds,
- mulching mounds using cereal straw,
- management of wheel track compaction,
- management of soil salinity.

Results

This component of the project developed management packages ("Best Practice" Packages) which encompassed:

- a specific description of a set of soil characteristics (sustainability indexes) that are related, in a practical manner, to the function and performance of vines,
- a mechanism to predict, within the environmental and management context of a vineyard site, the potential of native and specifically modified soil, to deliver particular vigour, fruit composition and quality,
- technology and soil manipulation criteria designed to achieve optimal amelioration and amendment of soils for both new and existing vineyards.
- soil quality criteria and soil and water management strategies to maintain sustainability and long term productivity of vineyard soils.

The benefits from this project to the industry has been refinement of soil management technology that optimises productivity, permits practical management of cultural practices to manipulate fruit composition and quality, attains greater uniformity, predictability and reliability of production (between blocks and seasons), better accessibility to vineyards at all times and ensures long term sustainability of vineyard productivity.

The results of this component of the project have been delivered to the industry as contributions

to the Research to Practice™ Manual and Seminar Series (Section 9.3) and to the Grape Production Series No. 2 Manual (Section 9.2). Many informal seminars, workshops and field days have also been directed to this end as well as the field days, seminars and workshops organised under the banner of the Barossa Valley Rotary Club Foundation Fellowship (Section 9.1). All grape production areas of Australia have been covered except Queensland and Tasmania. The focus of these seminars was on soil quality criteria, effects of local soil characteristics and distribution on soil selection for vineyards, soil preparation in new vineyards, soil manipulation to rejuvenate older vineyards and improved soil and water management.

The Australian Rootstock Soil Database and the Australian Viticultural Soil Key are now close to being finalised and made available to the industry. This opens the way to revising previously published material on the selection, development and management of soil for viticulture (Sections 9.2 and 9.3). The draft version of this manuscript has been developed as the Research to Practice™ Manual (CRCV, 1997), but a considerable amount of new material is now available for inclusion. Furthermore, the Australian Viticultural Soil Key provides an entirely new framework for developing soil-specific development and management perspectives compared to previous ideas. A tentative list of topics for such a revised manuscript is shown in Table 9.4.1.

Outcomes from the Research

Books and Manuals

Cass et al. 2003. Selection, Development and Management of Viticultural Soils in Australia. Manuscript to be revised and amplified for commercial publication as an industry manual.

Cockroft B, Cass A. 1995. Soils and land management in horticulture. In Coombs B. Horticulture Australia - the Complete Reference on the Horticulture Industry. Morescope Publishing, Canberra, Australia. Pages 79- 90.

CRCV. 1997. Water Management for Grape Production: Research to Practice™ Training Workshop Manual. CRC for Viticulture, Adelaide, South Australia.

Nicholas P. (Editor). 2002. Grape Production Series Number 2: Soil, Irrigation and Nutrition. Winetitels, Adelaide, South Australia.

Scientific Papers and Conference Proceedings

Cass A. 1999 Assessment of Vineyard Soils. Proceedings of the Tenth Australian Wine Industry Technical Conference.Winetitles, Adelaide Australia.

Cass A, Cockroft, B, Tisdall J M. 1993. New approaches to vineyard and orchard soil preparation and management. pp 18-24. In Hayes P (ed*.) Vineyard Development and Redevelopment*. Australian Society for Viticulture and Oenology, Adelaide, Australia.

Cass A, Maschmedt D and Myburgh P. 1998. Soil Structure - are there best practices? Proceedings of the Australian Society for Viticulture and Oenology, Viticultural Best Practices Seminar, Mildura, August 1997.

Cass A, Walker R and Fitzpatrick R W. 1995. Vineyard soil degradation by salt accumulation and the effect on vine performance. Proceedings of the Ninth Australian Wine Industry Technical Conference, pp 153-160.Winetitles, Adelaide Australia.

Chapman J, Cass A, Walker R R. 1995. Use of winery waste. Ninth Australian Wine Industry Technical Conference : Information and Abstracts. Adelaide, Australia. Poster.

Eastham J, Cass A, Gray, S and Hansen D. 1995. Improved soil management for Australian vineyards. Ninth Australian Wine Industry Technical Conference : Information and Abstracts. Adelaide, Australia. Poster

Eastham J, Cass A, Gray, S and Hansen D. 1995. Optimal soil management for Australian vineyards. International Society of Horticultural Science. Workshop on Stratagies to Optimise Wine Grape Quality. Conegliano Veneto, Italy. Abstract.

Industry Journal Articles

Cass A. and Maschmedt D. 1998a. Vineyard soils: Understanding soils for optimum yields. The Australian Grapegrower & Winemaker, March 1998, pages 13-16.

Cass A. and Maschmedt D. 1998b. Vineyard soils: Recognising structural problems. The Australian Grapegrower & Winemaker, April 1998, pages 23-26.

Cass A., Maschmedt D. and Chapman J. 1998c. Vineyard soils: Soil assessment - sampling and testing. The Australian Grapegrower & Winemaker, May 1998, pages 13-16.

Cass A., Maschmedt D. and Chapman J. 1998d. Vineyard soils: Managing physical impediments to root growth. The Australian Grapegrower & Winemaker, June 1998, pages 13-17.

Cass A. 1998e. Vineyard soils: Measuring and managing chemical impediments to growth. The Australian Grapegrower & Winemaker, July 1998, pages 13-16.

Cass A., Walked R. and Chapman J. 1998f. Vineyard soils: Soil degradation by salt accumulation. The Australian Grapegrower & Winemaker, September 1998, pages 95-97.

Cass A. 1999. What soil factors really determine water availability to vines. The Australian Grapegrower & Winemaker, 27th Annual Technical Issue, No. 426a.

Table 9.4.1: Proposed table of contents for the Industry Manual: Selection, Development and Management of Viticultural Soils.

1. Introduction
2. Soil Factors Affecting Plant Growth
3. Indicators of Vineyard Sustainability
4. Physical Limitations to Vine Root Growth
5. Chemical Limitations to Vine Root Growth
6. Nutritional Limitations to Vine productivity
7. Australian Vineyard Soils
8. Selecting Soil for Wine Grape Production
9. Land Preparation for New Vineyards:
    - *Control of Vine Vigor*
    - *Pre-planting Soil Treatments*
    - *Deep Ripping*
    - *Horizon Mixing*
    - *Ridging*
    - *Mulching*
    - *Tillage*
10. Soil Amelioration for Existing Vineyards
11. Structural Stability and Gypsum Application
12. Soil Acidity and Lime Application
13. Soluble Exchangeable Aluminium and Gypsum Application
14. Soil Organic Carbon and Compost Application
15. Vineyard Floor Management:
    - *Traffic Control*
    - *Routine Soil Cultivation*
    - *Remedial Tillage*
    - *Permanent Cover Crops*
16. Irrigation Water Quality
17. Management of Soil Water
18. Soil Salinity Management and Leaching
19. Soil Sodicity Management and Gypsum

Section 10

Optimal soil management of Australia vineyards – appropriate earthworms

Alfred Cass

In 1996, a grant was awarded to CSIRO Land and Water for research on management of earthworms for improved grape production. The project was under the supervision of Mr. John Buckerfield of CSIRO. For administrative convenience to GWRDC, the project was placed under the umbrella of Project CRS 95/1. The project was coordinated with existing field trials reported in Sections 3 and 4 and Mr. Buckerfield established additional trials. The present status of the project is unknown but repeated requests to Mr. Buckerfield to provide a final report on his work yielded only the following article which had been published in The Australian Grapegrower & Winemaker in 2001. No diagrams or illustrations accompanied the article.

Managing earthworms in vineyards – improve incorporation of lime and gypsum

John Buckerfield & Katie Webster

EcoResearch, 92 Angas Road, Westbourne Park, South Australia 5041

Lime and gypsum are used to remedy low pH and improve structure in acidic and sodic soils - movement into the soil is relatively slow, when these amendments are applied to the surface.
We have demonstrated the use of organic 'wastes' to stimulate earthworm activity – and more rapid incorporation of lime and gypsum into the rootzone.

Earthworms for vineyards

Survey - A survey of fifty southern Australian vineyards[1] confirmed that the present earthworm fauna is predominantly exotic, with many of the same species reported from vineyards in Europe, North America and New Zealand. Other earthworms collected appear to have originated in South America, and some are common in similar climatic regions where grapes are grown in South Africa. These species have voluntarily colonized crops and pastures and have established in orchards (Table 1); there has been no deliberate effort to select and redistribute species suited to vineyards.

Native earthworm species appear to have been largely displaced by vineyard developments. But our surveys indicate that some indigenous earthworms have persisted with the changes in vegetation and have adapted to soil disturbance and increased levels of nutrients associated with grapegrowing.

Earthworms - the 'composters' and vermicompost

The *'composters'* are a few specialist earthworm species which thrive in organic-rich materials and are effective in processing plant and animal wastes (Table 1). They are not well-suited to survive in the soil, and are maintained in 'captivity' in beds where temperature and moisture are controlled.

[1] Earthworm sampling by TAFE Viticulture students, Nuriootpa and Naracoorte, South Australia.

Large-scale processing of organic wastes with '*composter*' earthworms is now producing commercial quantities of worm-compost which have been marketed by wormgrowers as 'vermicompost' or 'vermicast'. This has been promoted as an enhanced form of organic matter; glasshouse- and vineyard-trials suggest that the worm-worked wastes have properties which stimulate plant-growth and yields and can be used to improve soil structure (Buckerfield et al 1999, Buckerfield & Webster 1998a, 2000a).

Earthworms – the 'earthworkers' and soil improvement

But it is the '*earthworker*' earthworms, common in many soils under vines (Buckerfield 1996), which are closely linked with improved soil structure and increases in infiltration and water-storage (Buckerfield & Webster 2000b). Earthworms are now considered an important component of vineyard management; recent studies by have established methods for encouraging earthworm activity with straw and compost mulch (Buckerfield & Webster 1996, 1999b).

Soil Acidity - The continued use of ammonium-based nitrogen fertilizers and nitrogen-fixing legumes has contributed to soil acidification. Lime is applied to the soil surface to remedy acidity, but is generally slow to move into the root-zone. It is not appropriate to incorporate lime mechanically in established vineyards, but earthworms may be used to redistribute lime and raise pH at depth in the soil.

Soil Sodicity – Gypsum provides a source of calcium as a remedy for sodic soils and is used widely to improve the soil structure. When spread on the surface, gypsum is most effective in improving infiltration, but as the calcium sulphate is only slightly soluble, it is not readily transported into subterranean soil. Earthworms which ingest soil can provide intimate mixing with gypsum, and assist in developing crumb structure below the surface. The combined effect of the earthworms and gypsum can be expected to significantly improve aeration and water-movement in clay soils.

Earthworms to bury lime and gypsum

In New Zealand Dr Jo Springett in New Zealand had shown that some species of earthworms can assist in the burial of lime; her studies in pastures demonstrated that with the earthworms and increased lime burial, pasture growth also increased (Springett 1983, 1985). Subsequently, Dr Geoff Baker used similar earthworm species in trials under pastures and cereals in Australia[2]; where lime was added, an increase in soil pH was recorded at 15cm, after four months (Baker et al 1993, 1995, 1996). It was obvious that, with differing habits, earthworm species varied in their effect on soils (Fig. 1).

Studies by John Buckerfield had identified opportunities for promoting earthworm activity in soils used for cropping and grazing; populations were commonly increased at least five times with reduced cultivation and conservation of crop residues (Buckerfield et al 1992, 1997). Earthworm activity was further enhanced with lime and manures and the addition of organic mulches in horticultural soils (Buckerfield 1995). Intensive sampling of vineyard soils by Katie Webster, showed that these mulches were not only invaluable in conserving water[3], but straw undervine could at least double earthworm populations, within a single season (Buckerfield & Webster 1966).

In a glasshouse study with Dr Trish Fraser[4], we selected species common to Australia and New Zealand to determine the most appropriate earthworms to bury lime ($CaCO_3$) and gypsum ($CaSO_4$) in repacked soil-cores. Movement of lime was measured by change in pH to 15cm. With dung to provide an abundance of food on the surface, the 'composter' species which do not work in the soil, had little effect; the 'earthworkers' provided effective mixing and, within four weeks there was little difference between pH at the surface and at depth (Fig. 2a). Similarly, when calcium concentration was used to measure

[2] Studies funded by Grains and Wool R & D Corporations.
[3] Project initiated by Barossa Viticultural Landcare Group.
[4] Australian & New Zealand Foundation – ANZAC Fellowship, in Lincoln & Palmerston North, 1996.

gypsum movement, differences between species reflected activity of these earthworms in the soil (Fig. 2b).

Vineyard trials - Support from GWRDC[5] provided opportunities to extend these studies and demonstrate methods for managing earthworms under vines. To determine how this could assist in lime and gypsum burial, vineyard sites were chosen with a low background population of earthworms. Selected species, either *Aporrectodea trapezoides* or *Aporrectodea longa,* were introduced to mesh-covered cylinders set into the soil. Lime or gypsum, in combination with alternative organic food supplements (straw, manure, or pellets of shredded cereal straw and lucerne), was applied to the surface.

Movement of lime and gypsum was recorded within six months, with an increase of pH and higher levels of Ca down the soil profile; with the earthworm treatments, soil pH at 25cm had increased an additional 1.5 units (Fig. 3). The species *A. longa* and *A. trapezoides* which were 'introduced' to the soil were most effective, with indications of deeper burial by *A. longa* (Fig. 4). On vineyards with where earthworms were present, the 'resident' species *Aporrectodea caliginosa* had lesser influence on movement from surface, and the effects of *Aporrectodea rosea* and *Octolasion cyaneum* were negligible.

Earthworm populations were significantly higher in the treatments with additional organic matter; numbers increased with straw and dung and were highest with the pellets (Buckerfield & Webster 1999b). The rapid disappearance of the amendments from the surface correlated closely with increased earthworm activity; the surface covering of cast soil brought from depth, assisted in the burial of lime and gypsum.

Higher earthworm numbers were also linked with higher water-infiltration from the surface (Fig. 5) and a reduction in soil strength at depth (Fig. 6). This could be expected to assist in water movement and the passive dispersal of surface-applied amendments around the roots.

Encouraging earthworm activity in vineyards

Practices which are being promoted for optimal soil management in vineyards may often rely on an active earthworm population for success. While most Australian vineyards appear to have 'resident' earthworms we would not advocate further 'introductions'. But there are clearly opportunities to encourage earthworm activity (Buckerfield & Garnsey 1995).

The effects of a number of management options trialled on a Barossa vineyard were assessed with earthworm sampling after a year (Fig. 7). There was a response to lime on this acid soil; with a straw mulch over the lime, the combined effect on the earthworms was greater than either of the treatments alone. The ryegrass cover-crop, slashed and thrown undervine and the grape marc had little effect on earthworm biomass, suggesting that these may have little immediate food value[6]. Further studies may now be required to assess the suitability of grape marc for stimulating biological activity, and whether additional processing provides longer-term benefits to vine-growth.

Mulches – Surface mulches can encourage earthworm activity by reducing fluctuations in temperature and moisture in the upper soil (Buckerfield & Webster 1999a, 1998b).
. We have shown significant increases in earthworms with a straw mulch; a more rapid response can be expected from processed organic wastes such as composts and manures which provide a readily-available food source (Buckerfield & Webster 1996, 2000b).

Cover crops - An undisturbed pasture phase encourages earthworms - frequent tillage leads to rapid decomposition of plant residues and reduces earthworm abundance (Buckerfield 1992, 1995). Earthworm activity is likely to be higher in a permanent pasture sward, than in soil which is cultivated and cropped

[5] Grape & Wine Research & Development Corporation, Project CRS 95/1 "Optimal soil management of Australia vineyards – appropriate earthworms".
[6] We have subsequently maintained earthworms in culture for four years on composted grape marc.

regularly (Buckerfield 1993b). There is evidence that earthworm numbers may be reduced in vineyards where a cover-crop was incorporated by discing (Buckerfield & Webster 1996).

But soil disturbance may not be the major factor limiting earthworms – soil pH or low levels of organic matter may be more important. High earthworm populations are often associated with high-input management, with frequent cropping and regular use of fertilizers and other soil amendments (e.g. Buckerfield & Auhl 1994, Buckerfield & Wiseman 1997).

Management of soils for optimal growth of cover-crops in vineyards can be expected to encourage earthworm activity too.

Superphosphate - The abundance of earthworms is closely linked with the available food; soils deficient in phosphorus, supported poor plant growth, but the addition of superphosphate can increase both the growth of pasture production and earthworm abundance (Fraser et al 1994, Buckerfield et al 1995).

There may be a reduction in earthworm activity immediately following high applications of both organic and inorganic soil amendments; we know of no evidence of longer-term detrimental effects of inorganic fertilizers directly on earthworms. Soil management which improves conditions and increases plant biomass will also influence earthworm abundance.

Soil pH - Liming acid soils can increase earthworm numbers - this will provide a suitable pH for earthworm activity and improve soil conditions for the growth of cereals and pasture grasses. Studies in Australia and New Zealand suggest that earthworms respond to the effect of lime on pH (Springett & Syers 1984); there was no effect on earthworm populations when an equivalent amount of calcium was added as gypsum rather than lime (Buckerfield & Doube 1993).

Cultivation and compaction - In studies of vineyard management, earthworm activity undervine was significantly lower than in the mid-row (Buckerfield & Webster 1996); reduced earthworm numbers may be associated with tillage and compaction of soil by traffic between the rows.

Pesticides - While there is no evidence of direct effects on earthworms of the herbicides commonly used in vineyards, it is likely that repeated applications will affect the food-supply and reduce earthworm populations undervine. Some fungicides, in contact with the soil are known to be toxic to earthworms; earthworms dependent on soil microflora as food may be affected by fungicides in common use in vineyards (Buckerfield 1993a).

Our studies suggest that many earthworms survive the frequent use of pesticides and herbicides; however, there is evidence that some chemicals common in vineyard management may affect earthworms and can significantly influence the abundance of some species. We have established strategies for sampling, and will continue monitoring the longer-term effects.

Acknowledgements

The research has been conducted by CSIRO Land & Water and EcoResearch with support from Grape & Wine Research & Development Corporation (GWRDC) and the Australian and New Zealand Foundation (ANZAC Fellowship). Field trials were established in Australian pastures and vineyards by Dr Geoff Baker (CSIRO Australia) and Dr Alfred Cass (Cooperative Research Centre for Soil & Land Management) respectively. Field and glasshouse studies have involved collaboration with researchers Dr Trish Fraser(Crop & Food Research), Dr Jo Springett (Grasslands Research) in New Zealand.

We have recently reported on the use of mulching to increase earthworm activity in soils and improve water infiltration, storage and aeration. These studies have been linked with GWRDC and Landcare projects to promote more efficient use of water and to ameliorate waterlogging in Australian viticultural soils.

References

Baker, G.H., Barrett, V.J., Carter, P.J., Buckerfield, J.C., Williams, P.M.L. & Kilpin, G.P. (1995). Abundance of earthworms in soils used for cereal production in south-eastern Australia and their role in reducing soil acidity. In: "Plant-Soil Interactions at Low pH: Principles and Management", (R.A. Date, N.J. Grundon, G.E. Rayment & M.E. Probert, eds), pp. 213-218. Kluwer Academic Publishers, Dordrecht.

Baker, G.H., Barrett, V.J., Carter, P.J. & Woods, J.P. (1996). Method for caging earthworms for use in field experiments *Soil Biol. Biochem*. 28(3): 331-339.

Baker, G.H., Barrett, V.J., Williams, P.M.L., Carter, P.J. & Buckerfield, J.C. (1993). Distribution and abundance of earthworms in south-eastern Australia and their influence on the burial of lime. In: "Pest Control and Sustainable Agriculture", (S.A. Corey, D.J. Dall & W.M. Milne, eds), pp. 345-348. CSIRO Publications, Melbourne.

Blakemore, R.J. (1997). Agronomic potential of earthworms in brigalow soils of south-east Queensalnd. *Soil Biol. Biochem*. 29(3/4): 603-608.

Blakemore, R.J. (1999). Diversity of exotic earthworms in Australia – a status report. *Trans. Roy. Zool. Soc. NSW* 1999, pp. 182-187.

Buckerfield, J.C. (1992). Earthworm populations in dryland cropping soils under conservation-tillage in South Australia. *Soil Biol. Biochem*. 24(12): 1667-1672.

Buckerfield, J.C. (1993a). Long-term responses of native and introduced earthworms to pasture soil applications of fungicides. *Proc. 6th Australasian Grassl. Invert. Ecol. Conf.* (R.A. Prestidge, ed.), pp. 92-99. AgResearch, Hamilton, New Zealand.

Buckerfield, J.C. (1993b). Pastures in crop rotations enhance earthworm populations in southern Australia. *Proc. XVII Int. Grassl. Congr.*, Palmerston North, New Zealand. pp. 942-944.

Buckerfield, J.C. (1995). Earthworms as indicators of sustainable production. *Proceedings Inaugural Ecological Economics Conference*, pp. 333-339. Coffs Harbour, NSW. November 19-23, 1995.

Buckerfield, J.C. (1996). Management of appropriate earthworms in vineyards. In: "Maintaining the Competitive Edge". *Proceedings Ninth Australian Wine Technical Industry Conference* (C.S. Stockley, A.N. Sas, R.S. Johnstone & T.H. Lee, eds), pp. 199-200. Adelaide, South Australia.

Buckerfield, J.C. & Auhl, L.H. (1994). Earthworms as indicators of sustainable production in intensive cereal cropping. In: "Soil Biota. Management in Sustainable Farming Systems. Poster Papers" (C.E. Pankhurst, ed.), pp. 169-172. CSIRO Australia, Melbourne.

Buckerfield, J.C. & Doube, B.M. (1993). Responses of native and introduced earthworm species to limed soil. In: "Workshop on Tillage Systems, Rotations, Nutrition and Associated Root Diseases" (R.G. Fawcett, ed.), *South. Aust. Dept. Agric. Tech. Publ.* pp. 68-69.

Buckerfield, J.C., Fawcett, R.G., Herrmann, T.N. and Malinda, D.K. (1992). Effects of tillage, stubble and crop rotations on earthworm populations. In: "Workshop on Tillage Systems, Rotations, Nutrition and Associated Root Diseases" (R.G. Fawcett, ed.), *South. Aust. Dept. Agric. Tech. Publ.* pp. 45-46.

Buckerfield, J.C., Flavel, T.C., Lee, K.E. & Webster, K. A. (1999). Vermicompost applications in solid and liquid form as a plant-growth promoter. *Pedobiologia* 43:753-759.

Buckerfield, J.C. & Garnsey, R.B. (1995). Management of Earthworms in Agriculture. In: "The Role of Earthworms in Agriculture and Land Management". *Department of Primary Industries and Fisheries, Tasmania. Tech. Rep*. 1/96 pp. 99-107.

Buckerfield, J.C., Lee, K.E., Davoren, C.W. & Hannay, J.N. (1997). Earthworms as indicators of sustainable production in dryland cropping in southern Australia. *Soil Biol. Biochem.* 29(3/4): 547-554.

Buckerfield, J.C., Marvanek, S.P. & Fleming, N.K. (1995). Are earthworms reduced by higher rates of superphosphate?? In: "Workshop on Tillage Systems, Rotations, Nutrition and Associated Root Diseases" (J.E. Schultz, ed.), *C.R.C. Soil and Land Management Tech. Publ.* pp. 74-75.

Buckerfield, J.C. & Webster, K.A. (1996). Earthworms, Mulching, Soil Moisture and Grape Yields. *The Australian and New Zealand Wine Industry Journal* 11(1): 47-53.

Buckerfield, J.C. & Webster, K.A. (1998a). Worm-worked waste boosts grape yields - prospects for vermicompost use in vineyards. *The Australian and New Zealand Wine Industry Journal* 13(1): 73-76.

Buckerfield, J.C. & Webster, K.A. (1998b). Compost as mulch for managing young vines. *The Australian Grapegrower and Winemaker*, No. 418, pp. 75-78 (October 1998).

Buckerfield, J.C. & Webster, K.A. (1999a). Compost as mulch for vineyards. *The Australian Grapegrower and Winemaker*, 27th Annual Technical Issue 1999, No. 426a, pp. 112-118.

Buckerfield, J.C. & Webster, K.A. (1999b). Pellets for soil improvement at planting. *The Australian Grapegrower and Winemaker* No 430, pp. 31-33 (October 1999).

Buckerfield, J.C. & Webster, K.A. (2000a). Vermicompost – more than a mulch. Vineyard trials to evaluate worm-worked wastes. *The Australian Grapegrower and Winemaker*, 28th Annual Technical Issue 2000, No. 438a, pp. 160-166.

Buckerfield, J.C. & Webster, K.A. (2000b). Vineyard trials show value of mulches. Organic matter for better water management. *The Australian Grapegrower and Winemaker*, No. 441, pp. 33-39 (October 2000).

Buckerfield, J.C. & Wiseman, D.M. (1997). Earthworm populations recover after potato cropping. *Soil Biol. Biochem.* 29(3/4): 609-612.

Fraser, P.M. Haynes, R.J. & Williams, P.H. (1994). Effects of pasture improvement and intensive cultivation on microbial biomass, enzyme activities, and composition and size of earthworm populations. *Biol. Fertil. Soils* 17: 185-190.

Martin, N.A. (1977). Guide to the lumbricid earthworms of New Zealand pastures. *N.Z. J. Exp. Agric*. 5: 301-309.

Martin, N.A. (1978). Aspects of the biology of some lumbricid earthworms in New Zealand pastures. *N.Z. J. Ecol*. 1: 175-176.

Springett, J.A. (1983). Effect of five species of earthworm on some soil properties . *J. Appl. Ecol*. 20: 865-872.

Springett, J.A. (1985). Effect of introducing *Allolobophora longa* Ude on root distribution and some soil properties in New Zealand pastures. In: "Ecological Interactions in Soil" (A.H. Fitter, ed.), pp. 330-405. Blackwell, Oxford.

Springett, J.A. (1992). Distribution of lumbricid earthworms in New Zealand. *Soil Biol. Biochem*. 24 (12): 1377-1381.

Springett, J.A. & Syers, J.K. (1984). Effect of pH and calcium content of soil on earthworm cast production in the laboratory. *Soil Biol. Biochem*. 16: 185-189.

Captions for Figures

1. Earthworms increase soil pH with lime in Australian pasture/cover-crops.
2. Earthworms mix (a) lime & (b) gypsum in soil in glasshouse trials, New Zealand.
   0 = no worms, 1 = *Eisenia fetida*, 2 = *Lumbricus rubellus*, 3 = *Octolasion cyaneum*, 4 = *Aporrectodea caliginosa*, 5 = *Aporrectodea rosea*.
3. Earthworms, mulch and lime increase soil pH in Australian vineyards.
4. Earthworm species differ in effects on pH with depth of soil, under vines.
5. Mulch provides food for earthworms – increased infiltration.
6. Mulch provides food for earthworms – reduced soil strength.
7. Soil management in vineyards influences earthworm activity.

Tables

	EARTHWORM SPECIES	**Vineyard**	**Cover-Crop**		**Orchard,**	**Compost,**
		Undervine	**Pasture**	**Cereal**	**Garden**	**Dung**
*	*Allolobophora chlorotica*	**?**	+	+	+	-
	Amynthas corticis	**?**	+	**?**	+	**?**
*	*Aporrectodea caliginosa*	+	+	+	+	-
*	*Aporrectodea longa*	**?**	+	-	**?**	-
**	*Aporrectodea rosea*	+	+	+	+	-
**	*Aporrectodea trapezoides*	+	+	+	+	-
**	*Aporrectodea tuberculata*	**?**	+	+	**?**	-
	Dendrobaena veneta	**?**	**?**	-	**?**	+
***	*Eisenia andrei ('red' tiger worm)*	**?**	**?**	-	**?**	+
***	*Eisenia fetida (tiger worm)*	**?**	**?**	-	**?**	+
***	*Eisenia hortensis ('tiny' tiger worm)*	**?**	**?**	**?**	**?**	+
****	*Eiseniella tetraedra*	**?**	+	**?**	**?**	-
***	*Lumbricus castaneus('small' red)*	+	+	**?**	+	+
***	*Lumbricus rubellus ('true' red)*	+	+	**?**	+	+
**	*Microscolex dubius*	+	+	+	+	+
**	*Microscolex phosphoreus*	+	+	+	+	-
*	*Octolasion cyaneum*	+	+	**?**	+	-
***	*Perionyx excavatus (Indian 'blue')*	**?**	**?**	**?**	**?**	+
****	Native earthworms – 200+ species	**?**	**?**	**?**	**?**	**?**

* found *only* in higher-rainfall, pastures or irrigated crops
** found *also* in pastures and lower-rainfall cropping soils
*** found *mainly* in damp organic wastes, compost
**** found *mainly* in native, undisturbed soils
? suitable habitat, *occasionally* present

Table 1 – Earthworms recorded from southern Australian vineyards – similar species are known in crops and pastures, and can be expected in vineyards in New Zealand.

Source: Buckerfield (1995, 1996), Blakemore (1997, 1999), Martin (1977, 1978); Springett (1983, 1992).

11. Conclusions

1. A review of the soil and viticultural scientific and industry literature was used to develop a comprehensive overview of the role of soil in grape production. A set of soil sustainability indexes was developed to aid in selection, development and management of viticultural soils. This review will be made available from www.winesoil.com after April 2002.

2. Field trials were established in South Australia in new and established vineyards on several important soils with the aim of monitoring adverse effects of some soil properties on vine performance. The trials were used to test a range of amelioration and development techniques to refine development and management packages for the viticultural industry. The soils were:
   - Rendzina soils at Coonawarra,
   - Non-sodic duplex soils at McLaren Vale and Padthaway,
   - Yellow, sodic duplex soil in the Barossa Valley and McLaren Vale,
   - Dark cracking clay soils at Coonawarra and McLaren Vale.

3. In addition, soil treatments were tested and monitored with the assistance of industry collaborators at many vineyards in South Australia with the aim of testing research findings in commercial settings and as a means of extending soil management packages to industry leaders.

4. Soils on 140 Australian rootstock trials were assessed and documented with the aim of refining selection of rootstocks and developing a national overview of a cross-section of viticultural soils. A database, the Australian Rootstock Soils Database was established to aid research workers in interpreting data from the trials. The former aim has not yet been realised because more work needs to be done in coordinating soil and vine performance data. A small national workshop needs to be convened to achieve this objective.

5. Data from research and the Australian Rootstock Soils Database provided broad national coverage of Australian soils and enabled development of a soil categorisation system that describes soils in terms that have relevance for viticultural management. This system, the Australian Viticultural Soil Key, is correlated with major soil classification systems and vineyard soils can be identified with a range of local and international systems used in viticulture. The Key also provides a framework for conveying technology for selecting, developing and managing Australian viticultural soils.

6. Soil selection, development and management technology, including diagrams, photographs and slides derived from a comprehensive review of soil and viticultural scientific literature, from results of experimentation and monitoring numerous research experiments and from an assessment of rootstock trials, were delivered to the viticultural industry in the form of draft chapters in the Grape Production Series No. 2 publication

and the Manual that underpinned the Research to Practice™ Water Management Seminar series.

7. All members of the research group actively participated in delivery of research material to the industry in the form of a comprehensive series of workshops, seminars, field days and industry publications over the period 1994 to 1999. Some of these activities were conducted under the auspices of the Barossa Valley Rotary Club Foundation Fellowship, awarded to Philip Myburgh (some 30 field days, seminars and workshops), the Research to Practice™ seminar series (some 34 workshops) and many other seminars and field days held under the banner of the CRC for Soil and Land Management or industry sponsors (some 10-20 field days and seminars). These events reached many hundreds, possibly thousands of grape growers, industry planners and researchers.

8. Information gathered during the course of this project has been organised into a set of "Best Practice" soil selection, development and management packages that have been extensively tested in Australia and California and have served as the basis for contributions to Grape Production Series No. 2 publication and the Research to Practice™ Water Management Manual. These packages should be published in the form of an industry Manual after updating and integration with the information derived from the Australian Rootstock Soils Database and the Australian Viticultural Soil Key.

9. Publications from this project either produced or planned are listed in each section of the report. The numbers of publications (excluding those of John Buckerfield) are tabulated below:

Type of publication	Published or submitted	Planned for publication
Manuals or Book Chapters	4	2
Papers or Conference Proceedings	19	12
Industry Journals	11	10
Dissertations	-	2
Data on Compact Disk	-	1
Information on the Internet	-	1

Section 12

Appendix: Organisations, Staff and Collaborators

Research was conducted by staff of the Irrigated Trees and Vines Program of the Cooperative Research Center (CRC) for Soil & Land Management, CSIRO Land and Water and University of Adelaide, Glen Osmond, South Australia.

Research and Extension Staff

Dr. A. Cass, CRC for Soil and Land Management
Dr. R. Fitzpatrick, CSIRO Land and Water
Mr. D. Maschmedt, Department of Primary Industries, South Australia
Dr. J. Eastham, CRC Soil and Land Management
Dr. C. Ginestar, Visiting scientist, CRC Soil and Land Management
Mr. W. Besz, CRC Soil and Land Management
Mr. D. Hansen, CRC Soil and Land Management
Ms. S. Gray, CRC Soil and Land Management
Ms. K. Thompson, CRC Soil and Land Management
Ms. S. van Goor, Visiting scientist, CRC Soil and Land Management
Mr. J. Buckerfield, CSIRO Land and Water
Ms. K. Webster, CSIRO Land and Water
(all based on the Waite Campus, Glen Osmond, Adelaide, South Australia)

We express their sincere thanks to the following persons for their enthusiastic help, cooperation, generosity, and time and especially for provision of information in execution of this project:

Research Collaborators

Mr. M. Alexander, Southcorp Wines, Nuriootpa, South Australia
Mr. H. Armstrong, CRC for Viticulture, Adelaide
Mr. K. Ayliff, Southcorp Wines, Padthaway, South Australia
Mr. E. Buski, McLaren Vale, South Australia
Mr. J. Campbell-Clause, WA Department of Agriculture, Perth, Western Australia
Mr. P. Clingeleffer, CSIRO Plant Industries, Merbien, Victoria
Mr. R. Gibson, Southcorp Wines, Nuriootpa
Dr. G. Grieger, Department of Primary Industries, Nuriootpa, South Australia
Mr. J. Harvey, Slate Creek Vineyard, Willunga, South Australia
Mr. C. Hignett, CSIRO Land and Water, Adelaide
Mr. B. Hill, Southcorp Wines, McLaren Vale, South Australia
Mr. L. Hunt, Willunga Almond Growers Association, Willunga, South Australia
Mr. S. Kyloh, Mildara Blass Wines, Lyndoch, South Australia
Dr. P. Myburgh, Nietvoorbij Institute for Viticulture and Oenology, Stellenbosch, South Africa.
Mr. P. Nicholas, Department of Primary Industries, Loxton, South Australia

Mr. G. Oakley, McLaren Vale, South Australia
Mr. R. Porter, South Australian Seed Company (SeedCo), Adelaide
Mr. and Mrs. M. Schulz and family, Nuriootpa, South Australia
Mr. P. Sinclair, NSW Department of Agriculture, Dareton, New South Wales
Mr. J. Sobels, South Australian Seed Company (SeedCo), Adelaide
Mr. T. Sommers, NSW Department of Agriculture, Maitland, New South Wales
Dr. J. Tisdall, La Trobe University, Bundoora, Victoria
Dr. R. Walker, CSIRO Plant Industries, Merbien, Victoria
Mr. A. Wheaton, Victorian Department of Agriculture, Tatura, Victoria
Mr. J. Whiting, Victorian Department of Agriculture, Bendigo, Victoria

Barossa Valley Rotary Club Foundation Fellowship Organising Committee

Mr. H. Armstrong, CRC for Viticulture, Adelaide
Dr. A. Cass, CRC for Soil & Land Management, Adelaide
Mr. P. Clingeleffer, CSIRO Plant Industries, Merbien, Victoria
Mr. C. Gramp, Barossa Valley Rotary Club, Tanunda, South Australia
Mr. B. Pearson, Barossa Valley Rotary Club, Angaston, South Australia
Mr. T. Sachse, Barossa Valley Rotary Club, Tanunda, South Australia
Dr. R. Walker, CSIRO Plant Industries, Merbien, Victoria

Rootstock Experiment Collaborators

Region	Contact Name	Vineyard
New South Wales		
Cowra	Ian Johnston	Cowra Estates
Dareton	Phil Sinclair	Ag. Research & Advisory Station
Hunter Valley	Ian Perry	Spring Mountain
Mudgee	Jamie Hudson	Gleneske Estate
	Frank Hellwig	Orlando-Wyndham/Montrose Wines
		Orlando-Wyndham/Stony Creek
South Australia		
Adelaide Hills	Brian Lilliecrap	G Gramp & Sons
	Mike Harms	Petaluma
	Pat Wark	Wark
	Vineyard manager	Wilson
Adelaide Plains	Site manager	Waite Institute
Barossa	Colin Beer	Beer
	Keith Hample	Harris (Hample)
	Dennis Kraft	Kraft
	Leo Pech	Pech
	Leon Riebke	Riebke
	Rob Walker	Nuriootpa Trial
		Rowland Flats Trial
	Geoff Semmler	Semmler
	Matthew Alexander	Southcorp (Kalimna)

Continued overleaf

Rootstock Experiment Collaborators (continued)

Region	Contact Name	Vineyard
South Australia (continued)		
Clare	Ian Smith	Hardy's (White Hut)
	Anthony Koerner	Koerner (Leasingham)
	John Matz	Penfold's
	Darren Pulford	Pulford
Koppramurra	Ken Schultz	Mildara Blass
Langhorne Creek	L. G. Case	Case
	Mac Cleggett	Cleggett
	Dennis Elliot	Elliot
Riverland	John Arnold	Arnold
	Lindsay Biggins	Biggins
	R Brooke	Brooke
	Tim Dawe	Dawe
	Mark Duggan	Duggan
	J Feher	Feher
	E Gillies	Gilles
	Otto Halupka	Halupka
	P Hentschke	Hentschke
	Stan Jericho	Jericho
	David Kimber	Kimber
	John Kregar	Kregar
	David Ludas	Ludas
	J McFarlene	McFarlene
	David Nitschke	Nitschke
	Trevor Page	Page
	Primary Industries, SA	PISA (Loxton Centre)
	Steve Proud	Proud
	G B Roberts	Roberts (Loxton)
	D Roberts	Roberts1
	Vineyard manager	Roy
	Bruce Tonkin	Tonkin
	Graham Welby	Welby
	M Wishart	Wishart
South East	Ian Hollick	Hollick
	Vic Patrick	Mildara - Chardonnay Lodge
	Vineyard manager	Penfold's Padthaway-Keppoch
	Rob Walker	Padthaway Trial
	Max Arnie	Wynn's Cellar Block
		Wynn's Gartner Block 160-175

Continued overleaf

Rootstock Experiment Collaborators (continued)

Region	Contact Name	Vineyard
South Australia (continued)		
Southern Vales	Alex Johnston	Johnston
	Syd Kyloh	Kyloh
	Garry Oakley	Oakley
	David Pridmore	Pridmore
	Philip/Michael Scarpantoni	Scarpantoni
	John Harvey	Wits End
Victoria		
Sunraysia	Lindsay Herath	Herath's (Gordo)
Glenrowan	Michael Reid	Auldstone
Goulburn Valley	Ian Hendy	Chateau Tahbilk
Grampians	Viv Thompson	Bests Wine
Knoxfield	David Braybroock	Noarlunga, Knoxfield
Mornington Peninsula	Dr. Richard McIntyre	Moorooduc Estate
Murray Valley / Sunraysia	Rob Walker	Merbien and Koorlong Trials
Ovens/King Valley	Bruce Phillips	Brown Bros.
	Peter Read	Myrrhee Hills
Rutherglen	Lynton Enever	Stanton & Killeen
Western Australia		
	Steven James	Amberly
	Vineyard manager	Evans &Tate - Lionels
	Neil Delroy	Neil Delroys
	Vineyard manager	Old Manjimup Research Station
	Paul Conti	Paul Conti
	Phil May & Jane Williams	Petaluma - Smithbrook
	John Roe	Sandalford Estate
	Steve Illich	Steve Illich
	Vineyard manager	Swan Research Station

Bibliography: Grapevine Performance and Soil Conditions

Adem H. 1995. Vineyard soil management. The Australian Grapegrower and Winemaker, Journal of the Grape and Wine Industry, 71-73.

Adem H.H.& Tisdall J.M. 1984. Management of tillage and crop residues for double-cropping in fragile soils of south-eastern Australia. Soil and Tillage Research, 4, 577-589.

Adem H.H.& Tisdall J.M. 1983. Reconditioned soil : The key to better crops. The Australian Grapegrower and Winemaker, 238, 18-19.

Adem H.H., Tisdall J.M. & Willoughby P. 1984. Tillage management changes size-distribution of aggregates and macro-structure of soils used for irrigated row-crops. Soil and Tillage Research, 4:561-576.

Aljibury F.K.& Christensen L.P. 1972. Water penetration of vineyard soils as modified by cultural practices. Am. J. Enol. Vitic., 23, 35-38.

Allen, W. 1998. The practical implications of organic viticulture. Australian Viticulture, 49-59.

Anonymous 1995. Soil Survey Investigation, Willunga Almonds. Primary Industries South Australia, Irrigated Crop Management Service, Loxton, South Australia.

Anonymous 1984. Wingerdboukundige eienskappe van onderstokke. Wynboer Tegnies, 7, 18-19.

Antcliff A.J. 1979. Major Wine Grape Varieties of Australia. CSIRO Australia, Australia.

Antcliff A.J. 1983. Minor Wine Grape Varieties of Australia. CSIRO Australia, Australia.

Antcliff A.J. 1976. Some Wine Grape Varieties for Australia. CSIRO Australia, Australia.

Archer E. Effect of plant spacing on root distribution and some qualitative parameters of vines. T.H. Lee. Proceedings of Sixth Australian Wine Industry Technical Conference. 55-58. 1987. Adelaide, SA, Australian Industrial Publishers.

Archer E.& Strauss H.C. 1985. Effect of plant density on root distribution of three-year old grafted 99 Richter grapevines. S.Afr. J. Enol. Vitic., 6, 25-30.

AS4454. 1997. Australian Standard AS 4454: Composts, soil conditioners and mulches. Australian Standards.

Atkins P.W.& Beran J.A. 1992. General Chemistry. Scientific American Books, New York.

Atkinson, D. 1980. The distribution and effectiveness of the roots of tree crops. Hortic. Rev., 2, 424-490.

Atkinson D.& Wilson S.A. 1979. The root-soil interface and its significance for fruit tree roots of different ages. In: The soil-root interface (eds J.L. Harley & R. Scott Russell), pp. 259-271. Academic Press, London.

Atta S.K., Mohommed S.A., Van Cleemput O. & Zayed A. 1996. Transformations of iron and manganese under controlled Eh, Eh-pH conditions and addition of organic matter. Soil Technology, 9, 223-237.

Aumann C., Ashcroft W. & Cass A. 1998. Benchmarking soils for processing tomato production. Final Report to HRDC, Department of Natural Resources and Environment, Melbourne, Australia.

Aumann C., Ashcroft W. & Cass A. 1999. Soil Benchmarking for Australian processing Tomato Growers. Department of Natural Resources and Environment, Melbourne, Australia.

Ayers R. S. 1977. Quality of water for irrigation. Journal of the Irrigation and Drainage Division. ASAE , 103, 135-154.

Baas-Becking L.G., Kaplan I.R. & Moore D. 1960. Limits of the natural environment in terms of pH and oxidation reduction potential. J. Geol., 68, 243-284.

Bakker A.C., Cockroft B. & van den Ende B. 1979. Gypsum and ripping improve soil permeability. Agnote 120/1979, Victorian Depatrment of Agriculture and Rural Affairs, Melbourne, australia.

Baldock J.A., Aoyama M., Oades J.M., Susanto & Grant C.D. 1994. Structural amelioration of a South Australian Red-brown Earth using calcium and organic amendments. Aust. J. Soil Res., 32, 571-94.

Ballif J.L. and Vachier P. Methodes d'etude de l'espace poral de la craie et hypothese de son fonctionement hydrique. Communication aux journees scientifiques du G.F.H.N. 1981.

Bar-Yosef B.& Lambert J.R. 1981. Corn and cotton root growth in response to soil impedence and water potential. Soil Sci. Soc. Am. J., 45, 930-935.

Barley K.P. 1955. The determination of macroorganic matter in soils. Agron. J., 145-147.

Barley K.P. 1976. Mechanical resistance of soil in relation to the growth of roots and emerging shoots. Agrochimica, 171-181.

Barley K.P.& Greacen E.L. 1967. Mechanical resistance as a soil factor influencing the growth of roots and underground shoots. Advances in Agronomy, 19, 1-40.

Barnard, C. 1932. The root system of the sultana. Comm. Sci. Ind. Res. J., 5, 89-93.

Bartlett R.J. 1981. Oxidation-reduction status of aerobic soils. In: Chemistry in the soil environment - ASA special publication number 40 (ed M. Stelly), pp. 77-102. American Society of Agronomy & Soil Science Society of America, Madison, Wisconsin.

Ben-Hur M., Faris J., Malik M. & Letey J. 1989. Polymers as soil conditioners under consecutive irrigations and rainfall. Soil Sci. Soc. Am. J., 53, 1173-1177.

Ben-Hur M.& Letey J. 1989. Effect of polysaccharides, clay dispersion, and impact energy on water infiltration. Soil Sci. Soc. Am. J., 53, 233-238.

Bengough A.G.& Mullins C.E. 1990. Mechanical impedence to root growth: a review of experimental techniques and root growth responses. J. Soil Sci., 41, 341-358.

Bengough A.G.& Mullins C.E. 1990. The resistance experienced by roots growing in a pressurised cell. A reappraisal. Plant and Soil.

Bess V. Soil Biology-Why Monitor? November Educational meeting, "Applying Ecological Principles to Commercial Farms". 2001. Templeton, CA, Central Coast Vineyard Team.

Biddle D.L., Chittleborough D.J. & Fitzpatrick R. W. 1995. Field-based comparison of platinum and wax impregnated graphite redox electrodes. Aust. J. Soil Res., 33, 415-424.

Biggar J.W.& Nielsen D.R. 1972. Irrigating under adverse conditions. In: Physical Edaphology, The Physics of Irrigated and Nonirrigated Soils. S. A. Taylor and G. L. Ashcroft eds. Published by W. H. Freeman and Co. San Fransisco.

Blackburn G. 1959. Soils. In: Natural History of the South East (eds Tyler M. J. et al.), pp. 39-48. Royal Society of South Australia, Adelaide, Australia.

Blackburn G. 1964. The Soils of Counties Macdonnell and Robe, South Austrlia. Soils and Land Use Series No. 45, CSIRO, Melborne, Australia.

Blackwell P.S., Jayawardane N.S., Green T.W., Wood J.T., Blackwell J. & Beatty H.J. 1991. Subsoil macropore space of a transitional Red-brown Earth after either deep tillage, gypsum or both I. Physical effects and short term changes. Aust. J. Soil Res., 29, 141-154.

Blanchar R.W.& Marshall C.E. 1981. Eh and pH measurement in Menfro and Mexico soils. In: Chemistry in the soil environment - ASA Special Publication Number 40 (ed Stelly M), American Society of Agronomy & Soil Science Society of America, Madison, Wisconsin.

Bode H.R. 1939. Beitrage zur kenntnis der reisigkrankheit der rebe. Gartenbauwissenschaft, 12, 404-419.

Bodman G.B. and Colman E.A. 1943. Moisture and energy conditions during downward entry of water into soils. Soil Science Society of America Proceedings , 116-122.

Boehm W. 1995. The salt bogey in vineyard irrigating. The Australian Grapegrower and Winemaker, 380, 18-19.

Bohn H.L. 1968. Electromotive force of inert electrodes in soil suspensions. Soil Sci. Soc. Am. Proc., 32, 211-215.

Bohn H.L. 1971. Redox Potentials. Soil Science, 112, 39-45.

Bonner F.T.& Ralston C.W. 1968. Oxidation-reduction potential of saturated forest soils. Soil Sci. Soc. Am. Proc., 32, 111-112.

Bonython D.& Compton O.C. 1943. Effect of oxygen pressure in aerated nutrient solutions on production of new roots and growth of roots and top by fruit trees. Proc. Am. Soc. Hortic. Sci. , 42, 53-58.

Boynton D. 1940. Soil atmosphere and the production of new rootlets by apple tree root systems. Proc. Am. Soc. Hortic. Sci., 37, 19-26.

Boynton D., DeVilliers J. I. & Reuther W. 1938. are there different cortical oxygen levels for the different phases of root activity ? Science, 88, 569-570.

Bramley R.G.V., Pfoffitt A.P.B., Corner R.J., and Evans T.D. Varaition in grape yield and depth in two contrasting Australian vineyards. Proceedings of the 5th International Symposium on Cool Climate Viticulture and Oenology. 2000.

Brasher B.R., Franzmeier D.P., Valassis V. & Davidson S.E. 1966. Use of Saran resin to coat natural soil clods for bulk density and water retention measurements. Soil Sci., 101, 108.

Braunack M.V., H.J.S.a.D.A.R. 1979. Brittle fracture of soil aggregates and the compaction of aggregate beds. J. of Soil Science, 30, 653-667.

Bravdo B. and Hepner Y. Water management and effect on fruit quality in grapevines. T.H. Lee. Proceedings of Sixth Australian Wine Industry Technical Conference. 1987. Adelaide, SA, Australian Industrial Publishers.

Bravdo B., Hepner Y., Loinger C., Cohen S. & Tabacman, H. 1985. Effect of irrigation and crop level on growth, yield and wine quality of Cabernet Sauvignon. Am. J. Enol. Vitic., 36, 132-139.

Brennan E.W.& Lindsay W.L. 1998. Reduction and Oxidation Effect on the Solubility and Transformation of Iron Oxides. Soil Sci. Soc. Am. J. 62, 930-937.

Bristow K.L. 1986. SMAS Version 2 : A Basic Program for Simulating Heat and Moisture Transfer Through the Soil-Mulch-Atmosphere-System. CSIRO, Division of Soils, Townsville, Australia.

Bristow K. L., Cass A., Smettem K. & Ross P. 1995. Water entry in sealing, crusting and hardsetting soils: a review and illustrative simulation study. In: Sealing, Crusting and Hardsetting Soils: Productivity and Conservation (eds So H. B. et al.), pp. 183-203. Australian Society of Soil Scienc, Queensland, Australia.

Brown, D.A.& Upchurch, D.R. 1987. Minirhizotrons: A Summary of Methods and Instruments in Current Use. In: Minirhizotron Observation Tubes: Methods and Applications for Measuring Rhizosphere Dynamics (ed H. M. Taylor), American Society of Agronomy, Special Publication No. 50., Madison, Wisconsin, USA.

Buchanan G.A.& Amos T.G. 1992. Grape Pests . In: Viticulture Vol. 2 Practices (ed B. G. Coombe and P. R. Dry), Winetitles, Adelaide, Australia.

Buckerfield J. 1998. Mulch pellets show value in vineyards. Australian Viticulture, 41-42.

Calame F. 1993. Techniques culturales et microclimat de la vigne. Revue suisse Vitic. Arboric. Hortic. 25, 281-287.

Cannon W. A. 1925. Physiological features of roots with special reference to the relation of roots to aeration of the soil. Publ. No. 368, Carnegie Inst., Washington DC, USA.

Carmi A. and Heuer B. 1981. The role of roots in control of bean shoot growth. Ann. Bot., 48, 519-527.

Caspari H.& Trought M. 1994. Less water into better wine. Wine Industry Journal.

Cass A. Assessment of Vineyard Soils. Tenth Australian Wine Industry Technical Conference. 78-82. 1998. Adelaide, Australia, Winetitles.

Cass A. 1999. Interpretation of some soil physical indicators for assessing soil physical fertility. In: Soil Analysis, an Interpretation Manual (eds Peverill K.I. et al.), pp. 95-102. CSIRO, Melbourne, Australia.

Cass, A. 1998. Soil sampling methodology. Unpublished report, CRC for Soil and Land Management, Adelaide, Australia.

Cass A. 1980. Use of environmental data in assessing the quality of irrigation water. Soil Science, 129, 45-53.

Cass, A. 1998. Vineyard Soils: Measuring and managing chemical impediments to growth. The Australian Grapegrower and Winemaker, 13-16.

Cass A. 1999. What soil factors really determine water availability to vines. The Australian Grapegrower and Winemaker, Annual Technical Issue, 95-97.

Cass A., Campbell G. S. & Jones T. L. 1984. Enhancement of thermal water vapor diffusion in soil. Soil Science Society of America Journal, 48, 25-32.

Cass A., Cockroft B., Lanyon D. & Olsson K. 1997. Increasing the productivity and sustainability of orchard soils by improved soil management. Final Report of Project FR315, Australian Horticultural Research and Development Corporation.

Cass A., Cockroft B., Lanyon D., Olsson K. & Bourne J. 1995. Profitable soil management for orchards in the Goulburn Valley. Pamphlet, CRC for Soil and Land Management, Adelaide, South Australia.

Cass A., Cockroft B., and Tisdall J.M. New approaches to vineyard and orchard soil preparation and management. Vineyard Development and Redevelopment. 18-24 . 1993. Adelaide, Australian Society of Viticulture and Oenology.

Cass A., Eastham J., Chapman J., and Hansen D. Improved water use efficiency and vineyard efficiency. Water for Viticulture - Optimising the Resource. 1995. Adelaide, Australia, Grape and wine Research and Development Corporation.

Cass A., Fitzpartick R. W., Thompson K., Dowley A. & Van Goor S. 2002. Soil properties of the Australian rootstock trials, Version 1. Microsoft Access database on compact disk. Grape and Wine Research and Development Corporation, Adelaide, South Australia.

Cass A., Gusli S. & MacLeod D. A. 1994. Sustainability of soil structure quality in rice paddy-soya-bean cropping systems in South Sulawesi, Indonesia. Soil and Tillage Research, 31, 339-352.

Cass A., Hansen D. & Dowley A. 2002. Literature Review: Grapevine Performance ans Soil Conditions. www.winesoil.com, Calistoga, CA, USA.

Cass A., Letey J., Oster J. D. & Clark P. 2002. Polymer stabilization of infiltration during furrow irrigation. Soil Science Society of America Journal (to be submitted).

Cass A.& Maschmedt D. 1998. Vineyard Soils: Recognising Structural Problems. The Australian Grapegrower and Winemaker, 23-26.

Cass A.& Maschmedt D. 1998. Vineyard Soils: Understanding Soils - For Optimum Yield. The Australian Grapegrower and Winemaker, 13-16.

Cass A., Maschmedt D. & Chapman J. 1998. Vineyard Soils: Managing Physical Impediments to Root Growth. The Australian Grapegrower and Winemaker, 13-17.
Cass A., Maschmedt D. & Chapman J. 1998. Vineyard Soils: Soil Assessment - Sampling and Testing. The Australian Grapegrower and Winemaker, 13-16.
Cass A., Maschmedt D., and Myburgh P. Soil structure - are there best practices? Hayes P. Vineyard Development and Redevelopment. 1993. Adelaide, Australia, Australian Society of Viticulture and Oenology.
Cass A., McKenzie N. & Cresswell H. 1996. Physical Indicators of Soil Health. In: Indicators of Catchment Health: A Technical Perspective. (ed J. Walker and D. J. Reuter), pp. 89-108. CSIRO , Melbourne, Australia.
Cass A., Walker R.R., and Fitzpatrick R. Vineyard soil degradation by salt accumulation and the effect on vine performance. Ninth Australian Wine Industry Technical Conference. 153-160. 1996. Adelaide, Winetitles.
Cassel D. K.& Nielson D. R. 1986. Field Capacity and Available Water Capacity. In: Methods of Soil Analysis, Part 1: Physical and Minerlogical Methods, Second edn (ed A. Klute), pp. 901-926. American Society of Agronomy, Madison, Wisconsin USA.
Champion A. R.& Barley K. P. 1969. Penetration of clay by root hairs. Soil Science, 108, 402-407.
Chan K.Y. 1982. Shrinkage characteristics of soil clods from a grey clay under intensive cultivation. Aust. J. Soil Res., 20, 65-68.
Chan K.Y. and Hodgson A.S. 1981. Moisture regimes of a cracking clay soil under furrow irrigated cotton. Aust. J. Exp. Agric. Anim. Husb., 21, 538-542.
Chapman A.L.& Boundy C.A.P. 1977. Effects of zinc and iron fertilizers on a disorder in rice on the calcareous soils of the Ord Irrigation Area, Western Australia. Aust. J. Expt. Ag. Anim. Husb., 17, 290-295.
Chapman J., Cass A., and Walker R.R. Use of winery waste. Ninth Australian Wine Industry Technical Conference. 1996. Adelaide, Australia, Winetitles.
Chapman J. A., Correll R. L. & Ladd J. N. 1995. Removal of soluble organic carbon from winery and distillery wastewaters by application to soil. Australian Journal of Grape and Wine Research, 1, 39-47.
Charbaji T., Garcia M. & Fallot J. 1988. Effet du Chloure de Sodium sur la Croissance de la Vigne en Culture Hydroponique et sur la Repartition des deux Elements Constitutifs de ce Sel. Agrochimica, 418-429.
Christiansen J. E., Olsen E. C. & Willardson L. S. 1977. Irrigation Water Quality Evaluation. ASAE, 103, 155-168.
Chung H.H.& Kramer P.J. 1975. Abdorption of water and ^{32}P through suberized and unsuberized roots of loblolly pine. Can. J. For. Res., 5, 229-235.
Clarkson D.T., Robards A.W., Sanderson J. & Peterson C.A. 1978. Permiability studies on epidermal-hypodermal sleeves isolated from roots of Allium cepa (onion). Can. J. Bot., 56, 1526-1532.
Clingeleffer P.R. Vine response to modified pruning practices. R.M. Pool. Pruning mechanisation and crop control: Proceedings of the second Nelson J. Shaulis grape symposium. 20-30 . 1993. New York, Geneva.
Clingeleffer P.R. and Sommer K.J. Vine development and vigour control. P. Hayes. Canopy Management. 7-17. 1995. Adelaide, Australian Society of Viticulture and Oenology.
Cockroft, B. 1966. Soil management of peach trees in the Goulburn Valley, Victoria. Aust. J. Exp. Agric. Anim. Husb., 6, 62.
Cockroft B.& Cass A. 1995. Soils and land management in horticulture. In: Horticulture Australia - The Complete Reference on the Horticulure Industry (ed Coombs B.), pp. 70-90. Moorescope Publishing, Canberra, Australia.
Cockroft B.& Hughan D.A. 1964. Peach soil management trial, Tatura, 1948-1957. Station Report No. 2, Dept. Agric. Victoria, Australia.
Cockroft B.& Mason W. 1987. Irrigated Agriculture. In: Agriculture in Victoria., (ed D.J. Connor and D.F. Smith), Australian Institute of Agricultural Science, Victorian Branch, Parkville, Victoria.
Cockroft B.& Olsson K.A. 1972. The pattern of new root production in peach trees under irrigation. Aust. J. Agric. Res., 23, 1021-1025.
Cockroft B., Olsson K. A., Lanyon D. M., and Cass A. Soil quality for orchards in duplex soils. International Symposium: Advances in soil quality. 1996.
Cockroft B.& Tisdall J.M. 1974. Soil management of irrigated young peach trees in the Goulburn Valley, Victoria. Aust. J. Exp. Agric. Anim. Husb., 14, 269-272.
Cockroft B.& Tisdall J.M. 1978. Soil Management, Soil Structure and Root Activity. In: Modification of Soil Structure (eds Emerson W.W. et al.), pp. 387-391. Wiley, Chichester.
Cockroft B.& Wallbrink J.C. 1966a. Root distribution of orchard trees. Aust. J. Agric. Res., 17 , 49-54.
Cockroft B.& Wallbrink J. C. 1966b. Soil properties and tree vigour in the Goulburn Valley. Aust. J. Exp. Ag. Anim. Husb., 6, 204-208.

Cogger C.G., Kennedy P.E. & Carlson D. 1992. Seasonally Saturated Soils in the Puget Lowlands II. Measuring and Interpreting Redox Potentials. Soil Science, 154, 51-58.
Cogle A. L., Reddy M. V. R., Rao K. P. C., Smith G. D., McGarry D. & Yule D. F. 1995. The role of biological practices and soil biota in management of sealing, crusting and hardsetting soils. In: Sealing, Crusting and Hardsetting Soils: Productivity and Conservation (eds So H. B. et al.), pp. 305-324. Australian Society of Soil Scienc, Queensland, Australia.
Connell W.E.& Patrick W.H. J. 1968. Sulphate reduction in soil: Effects on redox potential. Science, 159, 86-87.
Conradie W.J. 1988. Effect of soil acidity on grapevine root growth and the role of the root as a source of nutrient reserves. In: The Grapevine Root and its Environment (ed J. W. Van Zyl), pp. 16-29. Technical communication No. 215, Department of Agriculture and Water Supply. Pretoria, South Africa.
Conradie W.J. 1983. Liming and choice of rootstocks as cultural techniques for vines in acid soils. S.Afr. J. Enol. Vitic., 4, 39-44.
Conradie W.J. 1980. Seasonal uptake of nutrients by Chenin blanc in sand culture: I. Nitrogen. S. Afr. J. Enol. Vitic., 1, 59-65.
Coombe B. G. 1995. Adoption of a system for identifying grapevine growth stages. Australian Journal of Grape and Wine Research, 100-110.
Coombe, B.G. 1992. Grape Phenology. In: Viticulture, 1 Resources (ed B.G. Coombe and P.R. Dry), pp. 139-153. Winetitles, Adelaide, Australia.
Coombe, B.G. 1998. Grapevine bunchstem necrosis in australia. Wine Industry Journal, August, 317-318.
Cornish P. S.& Pratley J. E. 1987. Tillage. New Directions in Australian Agriculture. Inkata Press, Melbourne and Sydney.
Coutts M.P. 1982. The tolerance of tree roots to waterlogging. V. Growth of woody roots of Sitka spruce and Lodgepole pine in waterlogged soil. New Phytol., 90, 467-476.
Cowan I.R. 1965. Transport of water in the soil-plant-atmosphere system. J. Appl. Ecol., 2, 221-239.
Crane J.H. and Davies F.S. 1989. Flooding responses of Vaccinium species. Hort. Science, 24, 203-209.
Crawford, J.W. 1994. The relationship between structure and the hydraulic conductivity of soil. European Journal of Soil Science, 45, 493-502.
CRCV 1997. Water Management for Grape Production : Research to Practice Training Workshop Manual. CRC for Viticulture, Adelaide, South Australia.
Currie J. A. 1984. Gas diffusion through soil crumbs: the effects of compaction and wetting. J. Soil Sci., 35, 1-10.
Currie J.A. 1975. Soil Respiration. In: Soil physical conditions and crop production (ed Currie J.A.), pp. 461-468. Tech. Bull. No. 29, Min. of Ag. Fish. and Food, London, UK.
Daniells I.G. 1989. Degradation and restoration of soil structure in a cracking grey clay used for cotton production. Aust. J. Soil Res., 27, 455-69.
Daulta B.S.& Chauhan K.S. 1980. Varietal variation in root growth of some grapevine cultivars. Proq. Hort. , 12, 37-39.
Davidson D. 1995. Challenges and consequences of a wet winter. The Australian Grapegrower and Winemaker, 380, 42-43.
Davidson D. 1994. A Guide to Growing Winegrapes in Australia. Dianne Davidson Consulting Services Pty Ltd, Adelaide, South Australia.
Davidson D. Natural resource management - a systems approach. Eighth Australian Wine Industry Technical Conference. 10-13. 1992. Adelaide, Australia, Winetitles.
Davidson D. 1995. Planting vines for maximum results. The Australian Grapegrower and Winemaker, 77.
Davidson D. 1991. Soil management and its effect on root growth. Wine Industry Journal.
Davidson E.A.& Swank W.T. 1986. Environmental parameters regulating gaseous nitrogen losses from two forested ecosystems via nitrification and denitrification. Appl. Environ. Microbiol., 52, 1287-1292.
de Jong R.& Bootsma A. 1996. Review of recent developments in soil water simulation models. Canadian Journal of Soil Science, 76, 263-273.
Degens, B.P., Sparling, G.P. & Abbott, L.K. 1994. The contribution from hyphae, roots and organic carbon constituents to the aggregation of a sandy loam under long-term clover-based and grass pastures. European Journal of Soil Science, 45, 459-468.
Delas J.J. Criteria used for rootstock selection in France. Tucker C. Rootstock Seminar: A Worldwide Perspective. 1992. UCLA, Davis, American Soc. Enol. Vitic.
Devitt, D. 1983. Comparison of methods used to estimate evapotranspiration for leaching control. Irrigation Science, 4.

Dexter A. R. 1988. Advances in characterisation of soil structure. Soil and Tillage Research, 11, 199-238.
Dexter A.R. 1988. Advances in characterization of soil structure. Soil and Tillage Res., 11 , 199-238.
Dexter A. R. 1987. Mechanics of root growth. Plant and Soil, 98, 301-312.
Dexter A.R., Kroesbergen B. & Kuipers H. 1984. Some mechanical properties of aggregates of top soils from the Ijsselmeer Polders. 1. Undisturbed soil aggregates. Netherlands J. of Agricultural Science, 32, 205-214.
Dowley A. 1995. The effect of irrigation on soil salinity, sodicity and quality of vineyard production. B.Sc.(Hons) Thesis, University of Adelaide.
Dowley A. 2002. Grapevine Performance On Seasonally Waterlogged and Poorly Aerated Soils in South Australia. PhD Thesis, University of Adelaide.
Dowley A., Fitzpatrick R.W., and Cass A. Redox potential (Eh) and root damage in periodically waterlogged viticultural soils. Adams J.A. and Metherall A.K. Australian and New Zealand Second Joint Soils Conference. 3, 55-56. 2000.
Dowley A., Fitzpatrick R.W., Cass A., and Besz W. Measurement of redox potential (Eh) in periodically waterlogged viticultural soils. Proceedings of the International Soil Science Society Congress. Symposium No. 35, pp.10. 1998.
Downey A 1995. Measure and monitor your way to consistent fruit quality in the vineyard. The Australian Grapegrower and Winemaker, 378a, 50-53.
Downton W.J.S. 1985. Growth and mineral composition of the sultana grapevine as influenced by salinity and rootstock. Aust. J. Agric. Res., 36, 425-34.
Downton W. J. S. 1977. Influence of rootstocks on the accumulation of chloride, sodium and potassium in grapevines. Aust. J. Agric. Res., 28, 879-889.
Downton W. J. S. 1977. Salinity effects on the ion composition of fruiting Cabernet Sauvignon vines. Australian Journal of Enology and Viticulture, 28, 201-214.
Drew M.C.& Saker L.R. 1975. Nutrient supply and the growth of the seminal root system in barley. II. Localized, compensatory increases in lateral root growth and rates of nutrient uptake when nutrate supply is restricted to only part of the root system. J. Expt. Bot., 26, 79-90.
Drouineau G. 1942. dosage rapide du calcaire actif des sols. Annales Agronomiques, 441-450.
Dry P. 1995. Root pruning as a potential method for vigour control - some preliminary results. The Australian Grapegrower and Winemaker, 378a, 15-16.
Dry P. R., Loveys B. R. & During H. 2000. Partial drying of the rootzone of grape. 1. Transient changes in shoot growth and gas exchange. Vitis, 39, 3-7.
Dry P. R., Loveys B. R. & During H. 2000. Partial drying of the rootzone of grape 2. Changes in the pattern of root development. Vitis, 39, 9-12.
Dry P. R., Loveys B. R., Iland P. G., Botting D. G., McCarthy M. G., and Stoll M. Vine manipulation to meet fruit specification. Tenth Australian Wine Industry Technical Conference. 1998.
Dry P. R., Loveys B. R., Stoll M., Stewart D. & McCarthy M. G. 2000. Partial rootzone drying - an update. The Australian Grapegrower and Winemaker, 28th Annual Technical Issue, 35-39.
Dry P. R.& Smart R. E. 1992. The Grapegrowing Regions of Australia. In: Viticulture, 1 Resources (ed B. G. Coombe and P. R. Dry), Winetitles, Adelaide, Australia.
Dry P. R.& Smart R. E. 1992. Vineyard Site Selection. In: Viticulture, 1 Resources (ed B. G. Coombe and P. R. Dry), Winetitles, Adelaide, Australia.
Due G. 1998. Root rots can stunt young vines. Page 16, Victoria Viticulture News, Melbourne, Australia.
Due G., Eastham J. & Cass A. 1999. Little weeds cost big money in new vineyards. The Australian Graegrower and Winemaker, April, 18-19.
Dugas W.A.& Bland, W.L. 1989. The accuracy of evaporation measurements from small lysimeters. Agricultural and Forest Meteorolgy, 46, 119-129.
Duncan W.G.& Ohlrogge A.J. 1958. Principles of nutrient uptake from fertilizer bands. II. Root development in the band. Agron., J., 50, 605-608.
Dutreau J. 1987. Contribution des reserves hydriques profondes du calcaire a Asteries compact a l'alimentation en eau de la vigne dans le Bordelais. Agronomie, 7, 859-865.
Eastham J. 1994. Improved Irrigation Scheduling for Vineyards to Produce High Quality Grapes Using Plant Indicators of Water Stress. Unpublished report, CRC for Soil and Land Management, Adeliade, Australia.
Eastham J., Cass A., Gray S., and Hansen D. Improved soil management for Australian vineyards. Ninth Australian Wine Industry Technical Conference. 1995.

Eastham J., Cass A., Gray S., and Hansen D. Optimum soil management for Australian vineyards. International Society of Horticultural Science. Workshop on Stratagies to Optimise Wine Grape Quality. 1995.

Eastham J.& Rose C. W. 1990. Tree/pasture interactions at a range of tree densities in an agroforestry experiment. 1 Rooting patterns. Aust. J. Agric. Res., 41, 683-695.

Eastham J., Rose C.W., Cameron D.M., Rance S.J., Talsma T. & Charles-Edwards D.A. 1990. Tree/pasture interactions at a range of tree densities in an agroforestry experiment. 2 Water uptake in relation to rooting patterns. Aust. J. Agric. Res., 41, 697-707.

Eastham J., Rose C.W., Cameron D.M., Rance S.J., Talsma T. & Charles-Edwards D.A. 1990. Tree/pasture interactions at a range of tree densities in an agroforestry experiment. 3 Water uptake in relation to soil hydraulic conductivity and rooting patterns. Aust. J. Agric. Res., 41, 697-707.

Eastham J., Rose C.W. & Charles-Edwards D.A. 1990. Planting density effects on water use efficiency of trees and pasture in an agroforestry experiment. New Zealand J. Forestry Science, 20, 39-53.

Eastham J and Gray S. A. 1998. A preliminary evaluation of the suitability of sap flow sensors for use in scheduling vineyard irrigation. Am. J. Enol. Vitic., 49.

Eck H.V.& Fanning C. 1961. Placement of fertilizer in relation to soil moisture supply. Agron. J., 53, 335-338.

Ehlers W., Kopke U., Hesse F. & Bohm W. 1983. Penetration resistance and root growth of oats in tilled and untilled loess soil. Soil Tillage Res., 3, 261-275.

Eibach R.& Alleweldt, G. 1985. Influence of water supply on growth, gas exchange and substance production of fruit-bearing grapevines. Vitis, 24, 183-198.

Emerson W. W. The dispersion of clay from soil aggregates. Ninth International Congress of Soil Science. 1, 617-624. 1968. Adelaide, Australia.

Emerson, W.W. 1964. The slaking of soil crumbs as influenced by clay mineral composition. Aust. J. Soil Res., 211-217.

Emerson, W.W. 1991. Structural decline of soils, assessment and prevention. Australian Journal of Soil Research, 29, 905-921.

Emmett R. W., Harris A. R., Taylor R. H. & McGechan J. K. 1992. Grape Diseases and Vineyard Protection. In: Viticulture, 2 Practices (ed B. G. Coombe and P R Dry), Winetitles, Adelaide, Australia.

Enz J.W., Brun J.B. & Larsen J.K. 1988. Evaporation and energy balance for bare and stubble covered soil. Agricultural and Forest Meteorolgy, 43, 59-70.

Evangelou V.P. 1999. Environmental soil and water chemistry. Wiley Inter-Science.

Eynard I. and Gay G. Yield and quality. C.S. Stockley, R. S. Johnstone P. A. Leske and T. H. Lee. Proceedings of the 8th Australian wine industry technical conference. 55-63. 1993. Adelaide, The Australian Wine Research Institute.

FAO 1974. Soil Map of the World 1:5 000 000. Volume 1. Legend. UNESCO, Paris.

FAO. World Reference Base for Soil Resources (WRB). 1998. Rome, Food and Agriculture Organisation for the United Nations (FAO). World Soil Resources Report No. 84.

Farouki O. T. 1986. Thermal Properties of Soils. Volume 11, Series on Rock and Soil Mechanics, Trans Tech Publications, Clausthal-Zellerfeld, Germany.

Faulkner S.P., Patrick W.H. & Gambrell R.P. 1989. Field techniques for measuring wetland soil parameters. Soil Sci. Soc. Am. J., 53, 883-890.

Ferguson L.B.& Clarkson D.T. 1976. Ion uptake in relation to the development of a root hypodermis. New Phytol., 77, 11-14.

Fitzpatrick R. W., Boucher S. C., Naidu R. & Fritch E. 1994. Environmental consequences of soil sodicity. Australian Journal of Soil Research, 22, 1069-1093.

Fitzpatrick R.W., McKenzie N.J. & Maschmedt D. 1999. Soil morphological indicators and their importance in soil fertility. In: Soil Analysis, an Interpretation Manual (eds Peverill K.I. et al.), pp. 55-69. CSIRO, Melbourne, Australia.

Fitzpatrick R.W., Slade P.M. & Hazelton P. 2001. Soil-related Engineering Problems: Identification and Remedial Measures. In: Gondwana to Greenhouse: Australian Environment Geoscience (ed Gostin V.A.), pp. 27-36. Special Publication 21, Geological Society of Australia, Adelaide, Australia.

Fitzpatrick R. W., Wright M. J., and Stevens R. M. Drainage, sodicity and related problems of vineyard soils. Eighth Australian Wine Industry Technical Conference. 45-59. 1992. Adelaide, Australia, Winetitles.

Freeman B.M. Grapevine development as influenced by water and oxygen supply. T.H. Lee. Proceedings of the Sixth Australian Wine Industry Technical Conference. 59-61. 1987. Adelaide, Australian Industrial Publishers.

Freeman B. M., Lee T. H. & Turkington C. R. 1980. Interaction of irrigation and pruning level on grape and wine quality of Shiraz vines. Am. J. Enol. Vitic., 31, 124-135.
Freeman B. M.& Smart R. E. 1976. Research note: A root observation laboratory for studies of grapevines. Am. J. Enol. Viticult., 27, 36-39.
Freeman B.M.& Smart R.E. 1976. Research note: A root observation laboratory for studies with grapevines. Am. J. Enol. Vitic., 27, 36-39.
Fregoni M. and Bavaresco L. 1984. Research on grapevine nutrition on acid soils in Italy. Progres Agricole et Viticole, 101, 64-72.
French R. J., Armstrong F.W., Hodge D., Rudd C.L., Till R.M., Moore S.D. & Cirami R.M. 1978. Vineyards of the Barossa. Soil Conservation Report S 17/78, Department of Agriculture, Adelaide, Australia.
Gee G.W.& Bauder L.W. 1986. Particle Size Analysis. In: Methods of Soil Analysis, Part 1, Physical and Mineralogical Methods, Second edn (ed A. Klute), pp. 383-411. American Society of Agronomy, Madison, Wisconsin, USA.
Geisler G. 1965. The morphogenetic effect of oxygen on roots. Plant Physiol., 40, 85-88.
Gelat P. 1996. Grape Diseases. Collection Avinir Oenologie, Oeno Plurimedia, Chaintre, France.
Ghavami M., Keller J. & Dunn I. 1974. Predicting soil density following irrigation. Transactions of the American Society of Agricultural Engineering, 17, 166-171Water retention, porosity and density of field soils.
Gill R.& Bolt G. H. 1955. Pfeffer's studies of the root growth pressures exerted by plants. Agronomy Journal, 47, 166-168.
Gladstones J. 1992. Viticulture and Environment. Winetitles, Adelaide.
Glenn D. et al. 1995. Trichogramma wasps successfully control lightbrown apple moth in vineyard trials. The Australian Grapegrower and Winemaker, 26-30.
Glenn D. M., Brown M.W. & Takeda F. 1987. Statistical Analysis of Root Count Data from Minirhizotrons. In: Minirhizotron Observation Tubes: Methods and Applications for Measuring Rhizosphere Dynamics (ed H.M. Taylor), American Society of Agronomy , Madison, Wisconsin, USA.
Goodwin I.& Jerie, P. 1989. Deficit irrigation of Chardonnay grapevines during flowering. Acta Horticulturae, 240, 275-278.
Goodwin I.& Macrae I. 1990. Regulated deficit irrigation of Cabernet Sauvignon grapevines. Australia and New Zealand Wine Industry Journal, May, 131-133.
Gornat B., Enoch H. & Goldberg D. 1971. The effect of sprinkling intensity and soil type on oxygen flux during irrigation and drainage. Soil Sci. Soc. Am. Proc., 35, 668-670.
Gotoh S.& Patrick W.H. 1974. Transformation of iron in a waterlogged soil as affected by redox potential and pH. Soil Sci. Soc. Am. Proc., 38, 66-71.
Gotoh S.& Patrick W.H.J. 1974. Transformation of iron in a waterlogged soil as influenced by redox potential and pH. Soil Sci. Soc. Am. Proc., 38, 66-71.
Grattan S.R., Bowers W., Dong A., Snyder R.L., Carroll J.J. & George W. 1998. New crop coefficients estimate water use of vegetables, row crops. California Agriculture, 52, 16-21.
Gray S., Eastham J., and Cass A. Sap flow sensors - tools for scheduling irrigations? Ninth Australian Wine Industry Technical Conference. 1995.
Greacen E.L. 1977. Mechanisms and models of water transfer. In: Soil factors in crop production in a semi-arid environment (eds J.S. Russell & E.L. Greacen), pp. 163-198. University of Queensland Press, St. Lucia, Qld.
Greacen E.L. Root response to soil mechanical properties. Proceedings of Hamburg Conference. 1977. Hamburg, Germany.
Greacen E.L., Barley K.P. & Farrell D.A. 1969. The mechanics of root growth in soils with particular reference to the implication for root distribution. In: Root growth (ed W.J. Whittington), pp. 256-269. Butterworths, London.
Greacen E.L., Walker G.R. & Cook P.G. 1989. Procedure for the filter paper method of measuring soil water suction. Divisional Report No. 108, CSIRO Division of Soils, Adelaide, Australia .
Green S.R.& Clothier B.E. 1995. Root water uptake by kiwifruit vines following partial wetting of the root zone. Plant and Soil, 173, 317-328.
Greenland D.J. 1981. Soil management and soil degradation. J. of Soil Science, 32, 301-322.
Greenwood D.J. 1968. In: Root Growth (ed W.J. Whittington), Butterworths, London.
Greenwood D.L. 1963. Nitrogen transformations and the distribution of oxygen in soil. Chem. & Ind., 799-802.
Gregory G. R. 1992. Development and Status of Australian Viticulture. In: Viticulture, 1 Resources (ed B. G. Coombe and P. R. Dry), Winetitles, Adelaide, Australia.

Grieger G. 2001. Water Management for Grape Production: Research to Pratice™. Final Report Project CRV 97/1, Grape and Wine Research and Development Corporation, Adelaide, South Australia.
Grierson I.T. 1978. Gypsum and Red-brown Earths. In: Modification of Soil Structure (eds Emerson W.W. et al.), Wiley, Chichester, UK.
Grimes D. W.& Williams L. E. 1990. Irrigation effects on plant water relations and productivity of Thompson Seedless grapevines. Crop Sci., 30, 255-260.
Gupta R.K., Bhumbla D.K. & Abrol I.P. 1984. Effect of sodicity, pH, organic matter, and calcium carbonate on the dispersion behavior of soils. Soil Science, 137, 245-251.
Gusli S., Cass A., MacLeod D.A. & Blackwell, P.S. 1994b. Structural collapse and strength of some Australian soils in relation to hardsetting. 2 Tensile strength of collapsed aggregates. European Journal of Soil Science, 45, 23-29.
Gusli S., Cass A., MacLeod D.A. & Blackwell P.S. 1994a. Stuctural collapse and strength of some Australian soils in relation to hardsetting. 1 Structural collapse on wetting and draining. European Journal of Soil Science, 45, 15-21.
Gusli S., Cass A., MacLeod D.A. & Hignett C.T. 1995. Processes that distinguish hardsetting from rain-induced crusting. In: Sealing, Crusting and Hardsetting Soils: Productivity and Conservation (eds H. B. So et al.), pp. 457-461. Australian Soil Scienc Society, Inc., Queensland Branch, Brisbane, Australia.
Hackett S. 1998. Sampling for a vine's nutritional needs. Australian Viticulture, September / October, 29-30.
Hall D. G., Reeve M. J., Thomasson A. J. & Wright V.F. 1977. Water retention, porosity and density of field soils. Soil Survey of Britain, Technical Monograph No. 9, Rothamsted Experimental Station, Harpenden, Herts, UK.
Hamblin A.P. 1985. The Influence of soil structure on water movement, crop root growth, and water uptake. Advances in Agronomy, 38, 95-197.
Hamilton R. Improved vine material - Its role in vineyard profitabilty. ASVO Seminar-Vineyard Development and Redevelopment. 44-45. 1994. Wine Industry Journal .
Hanks R.J.& Ashcroft G.L. 1980. Applied soil physics. Academic Press, New York.
Hansen D. W. 1995. Methods for use of the Atomic Absorption Spectrophotometer. Unpublished report, CRC for Soil and Land Management, Adelaide, Australia.
Hansen D.W 1995. Methods to analyse pH, EC, and SAR. Unpublished report, CRC for Soil and Land Management, Adelaide, Australia.
Hansen D.W. 1995. Particle Size Analysis - Pipette Method. Unpublished report, CRC for Soil and Land Management, Adelaide, Australia.
Hardie W.J.& Cirami W.J. 1988. Grapevine Rootstock. In: Viticulture Volume 1: Resources (eds Coombe B.G. & Dry P.R.), Australian Industrial Publishers, Adelaide, Australia.
Hardie W.J& Considine J.A. 1976. Response of grapes to water-deficit stress in particular stages of development. Am. J. Enol. Vitic., 27, 55-61.
Hardie W.J. and Martin S.R. A strategy for vine growth regulation by soil water management. P.J. Williams and D.M. Davidson. Seventh Australian Wine Industry Technical Conference. 51-57. 1990. Adelaide, Winetitles.
Hayes F.R., Reid B.L. & Cameron M.J. 1958. Lake water and sediment 2. Oxidation-reduction relations at the mud water interface. Limnol. Oceanogr., 3, 308-317.
Hayes P. 1998. Root zone wetting techniques can improve production efficiency. Australian Viticulture, September/October, 7-11.
Helalia A. M.& Letey J. 1988. Cationic polymer effects on infiltration rates with a rainfall simulator. Soil Sci. Soc. Am. J., 52, 247-250.
Helalia A. M.& Letey, J. 1989. Effects of different polymers on seedling emergence, aggregate stability, and crust hardness. Soil Science, 148, 199-202.
Helalia A. M.& Letey, J. 1988. Polymer type and water quality effects on soil dispersion. Soil Sci. Soc. Am. J., 52, 243-246.
Hepner Y., Bravdo B., Loinger C., Cohen S. & Tabacman, H. 1985. Effect of drip irrigation schedules on growth, yield, must composition and wine quality of Cabernet Sauvignon. Am. J. Enol. Vitic., 36, 77-85.
Hignett C.T. 1976. A method for sampling and measuring cereal roots. The Journal of the Australian Institute of Agricultural Science, 42, 127-129.
Hignett C. T., Gusli S., Cass A. & Besz W. 1995. An automated laboratory rainfall simulation system with controlled rainfall intensity, raindrop energy and soil drainage. Soil Technology , 8, 31-42.
Hillel D. 1980. Fundamentals of soil physics. Academic Press, New York.

Hilton R. J.& Khatamian H. 1973. Diurnal variation in elongation rates of roots of woody plants. Can. J. Plant Sci., 53.
Hodge D.& Staniford, A. 1989. Budding vine rootstocks. AGRISA.
Hodgson A.S. 1982. The effects of duration, timing and chemical amelioration of short term waterlogging during furrow irrigation of cotton in a cracking clay soil. Aust. J. agric. Res., 33, 1019-1028.
Hodgson A.S.& MacLeod D.A. 1989. Oxygen flux, air-filled porosity, and bulk density as indices of vertisol structure. Soil sci.Soc. Am. J., 53, 540-543.
Hodgson A.S.& McLeod D.A. 1989. Use of oxygen flux density to estimate critical air-filled porosity of a vertisol. Soil Sci. Soc. Am. J., 53, 355-361.
Hofäcker W. 1977. Investigations on the substance production of vines under the influence of changing water supply. Vitis, 16, 162-173.
Holmes J. W. 1971. Salinity and the Hydrological Cycle. In: Salinity and Water Use (ed T. Talsma and J. R. Philip), The Macmillan Press, London.
Huck M.G. 1970. Variation in taproot elongation rate as influenced by the composition of soil air. Agron. J., 62, 815-818.
Huck M.G., Hoogenboom G. & Peterson C.M. 1987. Soybean Root Senescence under Drought Stress. In: Minirhizotron Observation Tubes: Methods and Applications for Measuring Rhizosphere Dynamics (ed H.M. Taylor), American Society of Agronomy, Special Publication No. 50, Madison, Wisconsin, USA.
Hunter J. J., Ruffner H. P., Volscenk C. G. & Le Roux D. J. 1995. Partial defoliation of vitis vinifera L. cv. Cabernet Sauvignon/99 Richter: Effect on root growth, canopy efficiency, grape composition, and wine quality. Am. J. Enol. Vitic., 46.
Iland P.G., Botting D.G., Dry P.R., Giddings J., and Gawel R. Grapevine Canopy Performance. P. Hayes. Canopy Management. 18-21. 1995. Adelaide, Australian Society of Viticulture and Oenology .
Isbell R. S. 1996. Australian Soil Classification System. CSIRO Publishing, Melbourne, Australia.
Iwasaki K. 1972. Effects of soil aeration on vine growth and fruit development of grapes (English summary). Physiol. Plant, 35, 513.
Iwasaki K., Kadoya K. & Kuraoka T. 1966. Growth and nutrient absorption of Delaware grapes as affected by soil oxygen. IV. Comparison of the effect among different soil properties. J. Jap. Soc. Hort. Sci., 35, 15-22.
Jackson D. I.& Spurling, M.B. 1992. Climate and Viticulture in Australia. In: Viticulture, Volume 1 Resources (ed B. G. Coombe and P. R. Dry), Winetitles, Adelaide, Australia.
Jackson D.I. and Lombard P.B. 1993. Environmental and Management Practices Affecting Grape Composition and Wine Quality - A Review. Am. J. Enol. Vitic., 44, 409-30.
Jalota S.K.& Prihar S.S. Bare-soil evaporation in relation to tillage.
Jalota S.K., Prihar S.S. & Gill K.S. 1988. Modified square root of time relation to predict evaporation trends from bare soil. Aust. J. Soil Res., 26, 281-288.
James B.R.& Bartlett R.J. 2000. Redox Phenomena. In: Handbook of Soil Science (ed Sumner M.E.), pp. B169-B195. CRC Press LLC, USA.
Jeffery J.W.O. 1961. Defiining the state of reduction of a paddy soil. J. Soil Sci., 12, 172-179.
Johns G.G. 1982. Measurement and simulation of evaporation from a Red Earth. 1 Measurement in a glasshouse using a neutron moisture meter. Aust. J. Soil Res., 20, 165-178.
Jooste L.J. 1983. Invloed van grondtemperatuur op groei en sitokinienmatabolisme by wingerd (Vitis) . M.Sc. Thesis, Univ. Stellenbosch.
Jury W. A., Frenkel H., Fluhler H., Devitt D. & Stolzy L. H. 1978. Use of saline irrigation waters and minimal leaching for crop production. Hilgardia, 46, 5.
Kawai Y., Benz J. & Kliewer W.M. 1996. Effect of flooding on shoot and root growth of rooted cuttings of four grapevine rootstocks. J. Japan. Soc. Hort. Sci., 65, 455-461.
Kay B.D. 1990. Rates of change of soil structure under different cropping systems. Advances in Soil Science, 12, 1-52.
Keller J. 1970. Sprinkler intensity and soil tilth. Transactions of the American Society of Agricultural Engineering, 13, 118-125.
Kempton J.H., Lindberg R.D. & Runnells D.D. 1990. Numerical modelling of platinum Eh measurements by using heterogeneous electron-transfer kenetics. In: Chemical Modelling of Aqueous Systems II (ed D.C. Melchoir and R.L. Bassett), pp. 339-349. Am Chem. Soc., Washington D.C.
Khmelevskii K.K. 1971. Temperature conditions for life processes of vine roots (Russian). Meteorologiya Klimatologiya i Gidrologiya, 7, 128-131.

Kidd C.H. Canopy control. D.C. Lester and T.H. Lee. Coonawarra viticulture: proceedings of a seminar. 27-28. 1983. Adelaide, SA, Australian Society of Viticulture and Oenology.
Kirchhof G., Blackwell J. & Smart R. E. 1991. Growth of vineyard roots into segmentally ameliorated acidic subsoils. Plant and Soil, 134, 121-126.
Kirk J.T.O.& Hutchinson M.F. 1994. Mapping of grapevine growing season temperature summation. Wine Industry Journal, 9, 247-251.
Kliewer M. Improving wine quality by vineyard practices. Proceedings of the 1987 western regional conference. 181-191. 1987. Sacramento, CA, American Sociery for Quality Control.
Klute A. (editor) 1986. Methods of Soil Analysis. Part 1: Physical and Mineralogical Methods. American Society of Agronomy, Madison, Wisconsin, USA.
Kobayashi A., Iwasaki K. & Sato Y. 1963. Growth and nutrient absorption of grapes as affected by soil aeration. J. Jap. Soc. Hort. Sci., 32, 33-37.
Kolesch H., Hofner W. & Schaller K. 1987. Effect of Bicarbonate and Phosphate on Iron-Chlorosis of Grape-vines with Special Regard to the Susceptibility of the Rootstocks. I. Field Experiments. J. Plant Nutrition, 10, 207-230.
Kotze W.A.G. 1973. The influence of aluminium on plant growth. Decid. Fruit Grow., 23, 20-22.
Kozlowski T.T. 1984. Response of woody plants to flooding. In: Flooding and plant growth (ed T.T. Kozlowski), pp. 129-163. Academic Press, Orlando, Florida.
Kramer P.J.& Bullock H.C. 1966. Seasonal variations in the proportions of suberized and unsuberized roots of trees in relation to absorption of water. Amer. J. Bot., 53, 200-204.
Kristensen K.J. 1966. Factors affecting measurement of oxygen diffusion rate. Agron. J., 58, 351-354.
Kwaad F.& Mucher H.J. 1994. Degredation of soil structure by welding - a micromorphological study. Catena, 23, 253-268.
Laird D. A. Bonding Between Polyacrylamides and Clay Mineral Surfaces. R. E. Sojka and R. D. Lentz. Managing Irrigation-Induced Erosion and Infiltration with Polyacrylamide. 1996. Moscow, Idaho, USA, University of Idaho.
Laitinen H.A.& Encke C.G. 1960. The electrolytic formation and dissolution of oxide films on platinum. Journal of Electrochemical Society, 107, 773-781.
Lal R. 1978. Influence of Tillage Methods and Residue Mulches on Soil Structure and Infiltration Rate. In: Modification of Soil Structure (eds Emerson W.W. et al.), Wiley, Chichester.
Lal R. 1974. Soil temperature, soil moisture and maize yield from mulched and unmulched tropical soils. Plant and Soil, 40, 129-143.
Lambrechts J.J.N. Adjustment of soil limitations. Deciduous Fruit Grower, 30, 330-339.
Langmuir D. 1997. Aqueous Environmental Geochemistry. Prentice-Hall Inc., New Jersey.
Langmuir D. 1971. Eh-pH determinations. In: Procedures in sedimentary petrology (ed R.E. Carver), John Wiley & Sons, New York.
Lanyon D., Cass A., Cockroft B. & Olsson K. 1999. Improving soil structural quality to increase productivity in orchards. Final Report of Project HG96005, Australian Horticultural Research and Development Corporation.
Lanyon D. M., Cass A., Cockroft B., and Olsson K. A. Coalescence: a long term decrease of soil physical fertility in irrigated no-till raised beds. Australia and New Zealand National Soils Conference. 1996.
Lee K. E.& Foster R. C. 1991. Soil fauna and soil structure. Australian Journal of Soil Research, 29, 745-775.
Letey J. 1985. Relationship between soil physical properties and crop production. Advances In Soil Science , 1, 277-293.
Levan M.A., Yeas J.W. & Hummel J.W. 1987. Light Leak Effects on Near-Surface Soybean Rooting Observed with Minirhizotrons. In: Minirhizotron Observation Tubes Methods and Applications for Measuring Rhizosphere Dynamics (ed H.M. Taylor), American Soiciety of Agronomy, Special Publication No. 50, Madison, Wisconsin, USA.
Lilov D.& Andonova T. 1976. Cytokinins, growth, flower and fruit formation in Vitis vinifera. Vitis, 15, 160-170.
Linacre E. T. 1977. A simple formula for estimating evaporation rates in various climates using temperature data alone. Agricultural Meteorology, 18, 409-424.
Lindberg R.E.& Runnells D.D. 1984. Ground water redox reactions. Science, 225, 925-927.
Lipps R.C.& Fox R.L. 1964. Root activity of sub-irrigated alfalfa as related to soil moisture, temperature and oxygen supply. Soil Sci., 97, 4-12.
Loehle C. 1990. A guide to increased creativity in research-inspiration or perspiration? Bioscience, 40:123-129, 123-129.

Louw P.J.E. and Van Huysteen L. 1992. The effect of planting holes on the root distribution of grapevines. The Australian Grapegrower and Winemaker, 20th Annual Technical Issue, 7-15.
Loveys B., Stoll M., Dry P. & McCarthy M. 1998. Partial rootzone drying stimulates stress responses in grapevine to improve water use efficiency while maintaining crop yield and quality. The Australian Grapegrower and Winemaker, 26th Annual Technical Issue, 108-113.
Ludvigsen K. 1999. Rootstocks - a complex and difficult choice. The Australian Grapegrower & Winemaker, Annual Techннical Issue, 426a, 36-39.
Ludvigsen, K. 1995. Temperature of soil at three depths with straw mulch and bare soil treatments. The Australian Grapegrower and Winemaker, 378a, 103-109.
Lyr H.& Hoffman G. 1967. Growth rates and growth periodicity of tree roots. Int. Rev. Forest. Res., 2, 181-236.
Maas E. V.& Hoffman G. J. 1977. Crop salt tolerance - current assessment. Journal of the Irrigation and Drainage Division. ASAE, 103, 115-134.
Maertens C. 1987. Ways of Using Endoscopy to Determine Growth and Quality of Root Systems. In: Minirhizotron Observation Tubes Methods and Applications for Measuring Rhizosphere Dynamics (ed H.M. Taylor), American Society of Agronomy, Special Publication No. 50, Madison, Wisconsin, USA.
Magarey P.A., Nicholas P.R. & Wachtel M.F. 1994. Control of diseases of grapes in Australia and New Zealand. Wine Industry Journal, 9, 197-225.
Magarey R. 1995. Possible solutions for collecting vineyard weather data. The Australian Grapegrower and Winemaker, 50.
Mann L.D.& Stolzy L.H. 1972. An improved construction method for platinum electrodes. Soil Sci. Soc. Amer. Proc., 36, 853-854.
Marcelin H. 1974. La vigne dans le sols du Roussillon. Progres agric. vitic., 91, 548-555;570-576.
Marshall T.J.& Holmes J.W. 1979. Soil Physics. Cambridge University Press, London.
Marshall T.J. and Holmes J.W. 1979. Soil Physics. Cambridge University Press, London.
Masscheleyn P.H., Delaune R.D. & Patrick W.H.J. 1991. Effect of redox potential and pH on arsenic speciation and solubility in a contaminated soil. Environ. Sci. & Technology, 25, 1414-1419.
Matthews, M.A.A.M.M.a.S.H.R. 1987. Phenological and growth responses to early and late season water deficits in Cabernet franc. Vitis, 26.
May P. The grapevine as a perennial, plastic and productive plant. T.H. Lee. Proceedings of the Sixth Australian Wine Industry Technical Conference. 1987. Adelaide, SA, Australian Industrial Publishers.
May P. 1993. Grapevine rootstocks in Australia. Report commissioned by the Grape and Wine Research and Development Corporation, Adelaide, Australia.
May P. Review of Rootstocks in Australia. Vineyard development and redevelopment. Proceedings of a seminar organised by the Australian Society of Viticulture and Oenology. 1993.
May P. 1994. Using Grapevine Rootstocks - The Australian perspective. Grape and Wine Research and Development Corporation, Adelaide, Australia.
McBride M.B. 1994. Environmental Chemistry of Soils. Oxford University Press, New York.
McCarthy M. 1997. The effect of transient water deficit on berry development of cv. Shiraz (Vitis vinifera L.). Australian Journal of Grape and Wine Research, 102-108.
McCarthy M.G. 1994. Achieving optimal water use efficiency. ASVO Seminar-Vineyard Development and Redevelopment, 37-41.
McCarthy M. G. 1997. Effect of timing of water deficit on fruit development and composition of Vitis vinifera cv. Shiraz. PhD Thesis, University of Adelaide.
McCarthy M.G. 1997. The effect of transient water defecit on berry development of cv. Shiraz (Vitis vinifera L.). Aust. J. Grape & Wine Res., 3, 102-108.
McCarthy M.G., Cirami R.M. & Furkaliev D.G. 1997. Rootstock response of Shiraz (Vitis vinifera) grapevines to dry and drip-irrigated conditions. Aust. J. Grape Wine Res., 3, 95-98.
McCarthy M.G., Cirami R. M. and Furkaliev D. G. The effect of crop load and vegetative growth control on wine quality. Proceeding of Sixth Australin Wine Industry Technical Conference. 1988. Adelaide, The Australian Wine Research Institute.
McCarthy M. G., C.R.M.a.M.P. 1983. Vine and fruit responses to supplementary irrigation and canopy management. S. Afr. J. Enol. Vitic., 4.
McCarthy M. G., D.P.R.H.P.F.a.D.D.M. 1992. Soil management and frost control. In: Viticulture, Vol. 1 Resources (ed B.G. Coombe and P.R. Dry), Winetitles, Adelaide, Australia.

McCarthy M., J.L.D.a.D.G. 1994. Irrigation. In: Viticulture, Vol. 2 Practices (ed B.G. Coombe and P.R. Dry), Winetitles, Adelaide, Australia.
McDonald R. C., Isbell R. F., Speight J. G., Walker J. & Hopkins M.S. 1990. Australian Soil and Land Survey Field Handbook. Inkata Press, Melbourne, Australia.
McIntyre D. S. 1956. The effect of free ferric oxide on the structure of some Terra Rossa and Rendzina soils. Journal of Soil Science, 7, 302-306.
McIntyre D.S. 1970. The platinum microelectrode method for soil aeration measurement. Adv. Agron., 22, 235-283.
McIntyre D. S. 1976. Subplasticity in Australian soils I. Description, occurrence and some properties . Australian Journal of Soil Research, 14, 227-236.
McIntyre G.N., Lider L.A. & Ferrari N.L. 1982. The chronological classification of grapevine phenology. Am. J. Enol. Vitic., 33, 2.
McIntyre K. 1994. Quality planting material: Objectives for successful nursery operators. ASVO Seminar - Vineyard Development and Redevelopment, 9, 47-48.
McKenzie, B.M.& Dexter, A.R. 1988. Radial pressures generated by the earthworm Aporrectodea rosea. Biol. Fertil. Soils., 5, 328-332.
McLeod R., Somers T. & Gendy M. 1995. Covercrops and nematodes -Some field observations. The Australian Grapegrower and Winemaker, September, 53.
McMicheal B.L.& Taylor H.M. 1987. Applications and Limitations of Rhizotrons and Minirhizotrons. In: Minirhizotron Observation Tubes. Methods and Applications for Measuring Rhizosphere Dynamics (ed H. M. Taylor), American Society of Agronomy, Special Publication No. 50, Madison, Wisconsin, USA.
Meek B.D.& Grass L.B. 1975. Redox potential in irrigated desert soils as an indicator of aeration status. Soil Sci. Soc. Am. Proc., 39, 870-875.
Meek B.D., MacKenzie A.J. & Grass L.B. 1968. Effects of organic matter, flooding time and temperature on the dissolution of iron and manganese from soil in situ. Soil Sci. Soc. Am. Proc., 32, 634-638.
Millikan C.R. 1951. Diseases of flax and linseed. Technical Bulletin No. 9. Biological Branch, Department of Agriculture, Melbourne, Victoria.
Milthorpe F.L.& Moorby J. 1974. An Introduction to Crop Physiology. Cambridge Univ. Press, London.
Moore S. D. 1978. A method for determining supplementary irrigation requirements for vines. Soil Conservation Branch Report S18/78, Department of Agriculture and Fisheries, South Australia.
Morlat R.& Jacquet A. 1993. The Soil Effects on the Grapevine Root System in Several Vineyards of the Loire Valley (France). Vitis, 32, 35-42.
Morlat R., Remoue M. & Pinet P. 1984. Effects of planting density and soil cutlivation practices on the root sysytem of the vine. Agronomy, 4, 485-491.
Mosier A.R., Guenzi W.D. & Schweizer E.E. 1986. Soil losses of dinitrogen and nitrous oxide from irrigated crops in northeastern Colorado. Soil Sci. Soc. Am. J., 46, 937-942.
Mullins C.E. 1991. Matric Potential. In: Soil Analysis Physical Methods (ed K.A.S. C.E. Mullins). Notes: Published by Marcel Dekker, Inc., New York
Mullins C.E., Blackwell P.S. & Tisdall J.M. 1992. Strength development during drying of a cultivated, flood-irrigated hardsetting soil. I. Comparison with a structurally stable soil. Soil & Tillage Res., 25, 113-128.
Mullins C.E., MacLeod D.A., Northcote K.H., Tisdall J. M. & Young I. M. 1990. Hardsetting Soils: Behaviour, Occurrence, and Management. In: , Advances in Soil Structure, Volume 2, Soil Degredation Springer-Verlag, New York.
Munsell A.H. 1988. Munsell - A Color Notation. Macbeth, Div. of Kollmorgan, Baltimore, USA.
Myburgh P., Cass A. & Clingeleffer P. 1996. Root systems and soils in Australian vineyards and orchards - an assessment. Barossa Valley Rotary Club Foundation Fellowship Report, Cooperative Research Center for Soil and Land Management, Adelaide.
Myburgh P.A. 1994. Effect of Ridging on the Performance of Young Grapevines on a Waterlogged Soil. S. Afr. J. Enol. Vitic., 15, 3-8.
Myburgh P.A.& Moolman J.H. 1991. The effect of ridging on the soil water status of a waterlogged vineyards soil. S. Afr. J. Plant Soil, 8, 184-188.
Myburgh P.A.& Moolman J. H. 1993. Effect of ridging on the temperature regime of a waterlogged vineyard soil. S. Afr. J. Plant Soil, 10, 17-21.
Myburgh P.A.& Moolman J.H. 1991. Ridging - a soil preparation practice to improve aeration of vineyard soils. S. Afr. J. Plant Soil, 8, 189-193.

Myburgh P. A. and Moolman J. H. 1993. Effect of ridging on the temperature regime of a waterlogged vineyard soil. S. Afr. J. Plant Soil, 10, 17-21.
Nagarajah S. 1987. Effects of soil texture on the rootingpatterns of Thompson Seedless vines on own roots and on Ramsey rootstocks in irrigated vineyards. Am. J. Enol. Vitic., 38, 54-59.
Neja R.A., Wildman W.E., Ayers R.S. & Kasimatis A.N. 1977. Grapevine response to irrigation and trellis treatments in the Salinas Valley. Am. J. Enol. Vitic., 1, 16-26.
Newman E.I. 1966. A method of estimating the total length of root in a sample. Journal of Applied Ecology, 3, 139-145.
Newman E.I. 1969. Resistance to water flow in soil and plant. J. Appl. Ecol., 6, 1-12.
Nicholas P., Magarey P. & Wachtel M. 1994. Grape Production Series No. 1: Diseases and Pests. Winetitles, Adelaide, Australia.
Nicholas P. (Editor) 2002. Grape Production Series No. 2: Soil, irrigation and nutrition. Winetitles, Adelaide, Australia.
Nicholas P.R. 1997. Rootstock characteristics. The Australian Grapegrower and Winemaker, 400, 30.
Nicholas P. R., Cirami R. M. & McCarthy M. G. 1996. South Australian Vine Improvement Scheme Clonal and Rootstock Trials 1966-1996 (Draft Report). Primary Industries, South Australia, Adelaide.
Niimi Y.& Torikata H. 1978. Changes in endogenous plant hormones in the xylem sap of grapevines during development. J. Jap. Soc. Hort. Sci., 47, 181-187.
Nimmo J. R. 1997. Modelling structural influences on soil water retention. Soil Sci. Soc. Am. J., 61, 712-719.
Nordstrom D.K. 1977. Thermochemical redox equilibria of ZoBells solution. Geochimica et Cosmochimica Acta. , 41, 135-1841.
Nordstrom D.K.& Munoz J.L. 1994. Geochemical thermodynamics. Blackwell Scientific Publications, Melbourne.
Norrish K.& Rogers L. E. 1956. The mineralogy of some Terra Rossa and Rendzinas of South Australia. Journal of Soil Science, 7, 294-301.
Norrish K.& Tiller K. G. 1976. Subplasticity in Australian soils. V. Factors involved and techniques of dispersion. Australian Journal of Soil Research, 14, 273-290.
Northcote K. 1973. Preliminary study of soils and climate in relation to wine character. Aust. Grapegr., 112, 53-57.
Northcote K.H. 1960. A Factual Key for the Recognition of Australian Soils. Rellim Technical Publications, Adelaide, australia.
Northcote K. H. 1988. Soils and Australian Viticulture. In: Viticulture Volume 1. Resources (ed B. G. Coombe and P. R. Dry), Winetitles, Adelaide.
Northcote K.H., Russell J.S. & Wells C.B. 1953. Soils and Land Use in the Barossa District, South Australia.
Northcote K. H.& Skene J. K. M. 1972. Australian Soils with Saline and Sodic Properties. Soil Publication No. 27, CSIRO, Melbourne, Australia.
Novak M.D.& Black T.A. 1982. Test of an equation for evaporation from bare soil. Water Resources Research, 18, 1735-1737.
Oades J. M. 1978. Mucilages at the root surface. J.of Soil Science, 29, 1-16.
Oades J.M. 1993. The role of biology in the formation, stabilization and degredation of soil structure. Geoderma, 56, 377-400.
Oades J. M. 1984. Soil organic matter and structural stability. Plant and Soil, 76, 317-319.
Oades J.M. 1984. Soil organic matter and structural stability: mechanisms and implications for management. Plant and Soil, 76, 319-367.
Oden S. 1962. Electrometric methods for oxygen studies in water and soil IV. Fundamental problems involved with the design and use of oxygen diffusion electrodes. Grundforbattring, 3, 117-210.
Ogden C.B., Wagenett R.J., van Es H.M. & Hutson J.L. 1992. Quantification and modeling of macropore drainage. Geoderma, 55, 17-35.
Olien W.C. 1987. Effect of seasonal waterlogging on vegetative growth and fruiting of apple trees. J. Am. Soc. Hort. Sci., 112, 209-214.
Olsson K.A. 1977. Water relations of an irrigated peach orchard. Macquarie University.
Olsson K. A., C.B.a.R.P. Improving and Managing Subsoil Structure for High Productivity from Temperate Crops on Beds. Advances In Soil Science.
Osborne G.J., Rowell D.L. & Matthews P.G. 1978. Value and Measurement of Soil Structure Under Systems of Reduced and Conventional Cultivation. In: Modification of Soil Structure (eds Emerson W.W. et al.), Wiley, Chichester.

Osozawa S.& Kasubuchi T. 1987. Improved evaporimeter for measuring potential evaporation from field soils. Soil Sci. Plant Nutr., 33, 531-538.
Oster J. D. 1994. Irrigation with poor quality water. Agricultural Water Management, 25, 271-297.
Oster J. D. Sodic soil reclamation and management. Unpublished report, Department of Soil and Atmospheric Science, University of California, Riverside, California, USA.
Oster J.D.& Rhoades J.D. 1975. Calculated drainage compositions and salt burdens resulting from irrigation with river waters in the western United States. J. Environ. Quality, 4, 73-79.
Oster J.D., Shainberg I. & Abrol I.P. 1995. Reclamation of Salt-Affected Soils. ASA Drainage Monograph.
Papadimitriou J. 1994. Measuring and Monitoring of Improved Irrigation Methods for Vineyards. B.Sc(Hons.) Thesis, University of Adelaide, South Australia.
Passioura J.B. 1985. Roots and water economy of wheat. In: Wheat Growth and Modelling (eds W. Day & R.K. Atkinson), pp. 185-198. Plenum, New York.
Passioura J.B. 1991. Soil structure and plant growth. Aust. J. Soil Res., 29, 717-728.
Passioura J.B. 1988. Water transport in and to roots. Ann. Rev. Pl. Physiol. Pl. Mol. Biol., 39, 245-265.
Patrick W.H. 1977. Oxygen content of soil air by a field method. Soil Sci. Soc. Am. J. 41, 651-652.
Patrick W.H.J.& Jugsujinda A. 1992. Sequential reduction and oxidation of inorganic nitrogen, manganese and iron in flooded soil. Soil Sci. Soc. Am. J., 56, 1071-1073.
Patrick W.H.J.& Mahapatra I.C. 1968. Transformation and availability to rice of Nitrogen and Phosphorus in waterlogged soils. Advances in Agronomy, 20, 323-359.
Peck A.J. 1971. Transport of Salts in Unsaturated and Saturated Soils. In: In: Salinity and Water Use (ed Talsma T. and Philip J. R.), The Macmillan Press, London.
Penkov M., Nancheva D., Hristova D. & Etropolski H. 1979. The effect of bulk density on the position of the grapevine root system (in Bulgarian). Pochvoznanie i Agrokhimiya, 14, 23-27.
Penman F., Taylor J. K., Hooper R. D. & Marshall T. J. 1939. A Soil Survey of the Merbien Irrigation District, Victoria. Bulletin No. 123, CSIRO, Melbourne, Australia.
Penman P.& Creecy H. 1983. The Economics of Furrow Irrigation Alternatives for Dried Vine Friut Vineyards. New South Wales Department of Agriculture, Murray and Riverina Region, Australia.
Philip J.R. 1957. Evaporation and moisture and heat fields in the soil. J. of Meteorolgy, 14.
Pikul J. L. et al. 1996. Contour ripping: A tillage strategy to improve water infiltration into frozen soil. J. Soil and Water Cons. 51, 76-83.
Pinamonti F., Zorzi G., Gasperi F., Silvestri S. & Stringari, G. 1995. Growth and nutritional status of apple trees and grapevines in municipal solid-waste-amended soil. Acta Horticulturae, 383, 313-317.
Ponamtaranichagul M. 1995. Internal Drainage and Hydraulic Conductivity. Unpublished report, CRC for Soil and Land Management, Adelaide, Australia.
Ponamtaranichagul M. 1994. Use of Models to Predict Reference Crop Evapotranspiration and Crop Water Requirement. Unpublished report, CRC for Soil and Land Management, Adelaide, Australia.
Pongracz D.P. 1983. Rootstocks for grape-vines. David Phillip, Cape Town.
Poni S., Lakso A.N., Turner J.R. & Melious R.E. 1993. The effects of pre- and post-veraison water stress on growth and physiology of potted Pinot Noir grapevines at varying crop levels. Vitis, 32, 207-214.
Ponnamperuma F.N. 1972. Chemistry of Submerged Soils. Advances in Agronomy, 24, 29-96.
Ponnamperuma F.N., Tianco E.M. & Loy T. 1967. Redox equilibria in flooded soils: 1. The iron hydroxide system. Soil Science, 103, 374-382.
Porter R 1998. Weed supression using cover crops. The Australian Grapegrower and Winemaker, June, 29-33.
Pratt C.& Coombe B.G 1978. Shoot growth and anthesis in Vitis. Vitis, 17, 125-133.
Priestley J.H.& North E.E. 1922. Physiological studies in plant anatomy. III. The structure of the endodermis in relation to its function. New Phytol., 21, 111-139.
Prior L.D., Grieve A.M. & Cullis B.R. 1992a. Sodium chloride and soil texture interactions in irrigated field grown Sultana grapevines. 1. Yield and fruit quality. Aust. Journal Agric. Res., 43, 1051-1066.
Prior L.D., Grieve A.M. & Cullis B.R. 1992b. Sodium chloride and soil texture interactions in irrigated field grown Sultana grapevines. 2. Plant mineral content, growth and physiology. Aust. J. Agric. Res., 43, 1067-1083.
Prior L.D., Grieve A.M., Slavich P.G. & Cullis B.R. 1992c. Sodium chloride and soil texture interactions in irrigated field grown Sultana grapevines. 3. Soil and root system effects. Aust. J. Agric. Res., 43, 1085-1100.
Proebsting E. L. 1943. Root distribution of some deciduous fruit trees in a California orchard. Proc. Amer. Soc. for Horticulture Science, 43, 1-4.

Queen W.H. 1968. Radial movement of water and 32P through suberized and unsuberized roots of grape. Diss. Abstr. Sect. B, 29, 72-73.
Quispel A. 1947. Measurement of the oxidation-reduction potentials of normal and inundated soils. Soil Science, 63, 265-275.
Randall, W.& Coombe, B.G. 1978. Grape roots: repository of many mysteries. The Australian Grapegrower and Winemaker, 172, 29-30.
Reddy K.R., D'Angelo E.M. & Harris W.G. 2000. Biogeochemistry of wetlands. In: Handbook of Soil Science (ed M.E. Sumner), pp. G89-G119. CRC Press LLC, USA.
Rema J. M. and Pandey R. M. 1990. Seasonal variation in root density of Beauty Seedless grape. South Indian Horticulture, 38, 215.
Rengasamy P. 1987. Importance of calcium in irrigation with saline-sodic water - A viewpoint. Agricultural Water Management, 12.
Rengasamy P., Greene R. S. B., Ford G. W. & Mehanni A. H. 1984. Identification of dispersive behaviour in the management of Red-brown Earths. Australian Journal of Soil Research, 22, 413-431.
Rengasamy P.& Olsson K. A. 1993. Irrigation and sodicity. Australian Journal of Soil Research, 31, 821-837.
Reynolds A.G., Douglas A.W., Drought B. & Cantwell, R. 1995. Gro-mate soil amendment improves growth of greenhouse-grown Chardonnay grapevines. HortScience, 30, 539-542.
Rhoades J.D., Oster J.D., Ingvalson R.D., Tucker J.M. & Clark M. 1974. Minimizing the salt burdens of irrigation drainage waters. J. Environ. Quality, 3, 311-316.
Richards D. 1983. The grape root system. Hort Reviews, 5 , 127-168.
Richards D. and Cockroft B. 1975. The effect of soil water on root production of peach trees in summer. Aust. J. Agric. Res., 26, 173-180.
Richards D. and Cockroft B. 1974. Soil physical properties and root concentrations in an irrigated peach orchard. Aust. J. Exp. Agric. Anim. Husb., 14 , 103-7.
Richards D. and Rowe R.N. 1977. Root-shoot interactions in peach: the function of the root. Ann. Bot., 41, 1211-1216.
Richards L.A. 1954. Diagnosis and Improvement of Saline and Sodic Soils. United States Department of Agroculture, Washington, USA.
Rickman R.W., Letey J., Aubertin G.M. & Stolzy L.H. 1968. Platinum microelectrode poisoning factors. Soil Sci. Soc. Am. Proc., 32, 204-208.
Rios M.A.& Pearson R.W. 1964. The effect of some chemical environmental factors on cotton root behaviour. Soil Sci. Soc. Proc., 28, 232-235.
Ritchie J.T.& Adams J.E. 1974. Field measurements of evaporation from soil shrinkage cracks. Soil Sci Soc of Amer Proc , 38, 131-134.
Robards A.W., Clarkson D.T. & Sanderson J. 1979. Structure and permeability of the epidermal/hypodermal layers of the sand sedge (Carex arenaria L.). Protoplasma, 77, 291-311.
Robinson B. 2001. Manures, mulches and composts: Do we know what we are putting on our vineyards? The Austrailain Grapegrower and Winemaker, December, 20-21.
Robinson J.B. 1992. Grapevine Nutrition. In: Viticulture Volume 2: Practices (eds B. G. Coombe & P.R. Dry), Winetitles, Adelaide, SA.
Robinson J.B. Soil Ammendmant and nutrition: Getting it right in your vineyard. ASVO Seminar-Vineyard Development and Redevelopment. 34-36. 1993. Adelaide, Australia, Australian Society of Viticulture and Oenology.
Rogers W.S.& Head G.C. 1969. Factors affecting the distribution and growth of roots of perennial woody species. In: Root growth (ed W.J. Whittington), pp. 280-295. Butterworths, London.
Rom C.& Brown S.A. 1979. Water tolerance of apples on clonal rootstocks and peaches on seedling rootstocks. Compact Fruit Tree, 12, 30-33.
Roman R., Caballero R., Bustos A., Diaz J.A., Cartagena M.C., Vallejo A. & Caballero A. 1996. Water and solute movement under conventional corn in central Spain: 1. Water balance. Soil Sci. Soc. Am. J., 60, 1530-1536.
Ross P.J., Williams J. & McCown R.L. 1985. Soil temperature and the energy balance of vegetative mulch in the semi-arid tropics. I. Static analysis of the radiation balance. Aust. J. Soil Res., 23, 493-514.
Ross P.J., Williams J. & McCown R.L. 1985. Soil temperature and the energy balance of vegetative mulch in the semi-arid tropics. II. Dynamic analysis of the total energy balance. Aust. J. Soil Res., 23, 515-532.
Rowe R. N. 1993. The growth of grapevines: The role of roots. Australian and New Zealand Wine Industry Journal, 8, 326-328.

Rowell D.L. Oxidation and reduction. D.J. Greenland and M.H.B. Hayes. The Chemistry of soil proceses. 401-461. 1981. John Wiley & Sons Ltd.
Saayman D. 1976. Soil preparation methods for vineyards. Farming in South Africa - Oenological and viticultural Series, D3/1976.
Saayman D& Van Huyssteen L. 1983b. Preliminary studies on the effect of a permanent cover crop and root pruning on an irrigated Colombar vineyard. S Afr. J. Enol. Vitic., 4, 7-12.
Saayman D. & Van Huyssteen L. 1983a. Soil preparation studies: 2. The effect of depth and method of soil preparation and organic material on the performance of Vitis vinifera (var. Colombar) on a Clovelly/Hutton . Soil. S. Afr. J. Enol. Vitic, 3, 61-74.
Saayman D. and Van Huyssteen L. 1980. Soil Preperation Studies: 1. The effect of depth and method of soil preparation and of organic material on the performance of Vitis Vinifera (var. Chenin Blanc) on Hutton/Sterkspruit soil. S. Afr. J. Enol. Vitic., 107-121.
Safran B., Bravdo B. & Bernstein Z. 1975. L'irrigation de la vigne par goutte a goutte. Bul. Off. Intern. Vigne., 48, 405-429.
Saleh M.& Letey J. 1989. The effect of two polymers and water qualities on dry cohesive strength of three soils. Soil Sci. Soc. Am. J., 53, 255-259.
Saleh M.& Letey J. 1988. Polymer and water quality effects on flocculation of montmorillonite. Soil Sci. Soc. Am., 52, 1453-1458.
Sawaf H.M., Senfaz S., Adam S.O., Azaga A.K. & Ansari M.A. 1985. Vine root distribution under irrigation and rainfed conditions with supplementary underground irrigation. Acta Horticulturae, 158.
Scheper R.W.A. et al. 1995. The missing link in Phomopsis Cane and Leaf Spot disease. The Australian Grapegrower and Winemaker, 23-25.
Schillinger W.& Bolton F.E. 1996. Packing summer fallow in the Pacific Northwest: Seed zone water retention. Journal of Soil and Water Conservation, 51, 62-66.
Schneider E.C.& Gupta S.C. 1985. Corn emergence as influenced by soil temperature, Matric potential, and aggregate size distribution. Soil Sci. Soc. Am. J., 49, 415-422.
Schoknecht N. 1997. A Guide to the Main Soils of Western Australia. Agriculture Western Australia, Perth, Western Australia.
Scholl W. 1983. Erfahrungen mit der Chlorose der Weinreben. Mitt. Klosterneuburg, 29, 186-194.
Schwertmann U., Kodama H. & Fischer W.R. 1986. Mutual interactions between organics and iron oxides. In: Interactions of soil minerals with natural organics and microbes (eds P. M. Huang & M. Schnitzer), pp. 223-250. Soil Science Society of America, Madison, Wisconsin, U.S.A.
Seguin G. 1986. 'Terroirs' and Pedology of Wine Growing. Experimentia, 42, 861-873.
Seguin M.G. 1972. Reparation dans l'espace du systeme rediculaire de la vigne. Comp. Rendus Acad. Sci. Paris , 274 D, 2178-2180.
Shanmuganathan R.T.& Oades J.M. 1983. Modification of soil physical properties by addition of calcium compounds. Aust. J. Soil. Res., 21, 285-300.
Shaw R. 1988. Soil Salinity and Sodicity. In: Understanding Soils and Soil Data (ed Fergus I. F.), pp. 109-134. Australian Society of Soil Science, Queensland Branch, Brisbane, Australia.
Shaw R.H.& Buchele W.F. 1957. The effect of the shape of the soil surface profile on soil temperature and moisture. Iowa State Colledge J. Sci., 32, 95-104.
Shaw R.J.& Thorburn P.J. 1985. Prediction of leaching fraction from soil properties, irrigation water and rainfall. Irrigation Sci., 6, 73-83.
Shuttleworth W.J. et al. 1988. An integrated micrometeorolgical system for evaporation measurement. Agricultural and Forest Meteorology, 43.
Silberbush M., Gornat B. & Goldberg D. 1979. Effect of irrigation from a point source (trickling) on oxygen flux and on root extension in the soil. Plant and Soil, 52, 507-514.
Sinclair P. J., Osborne G. J., Hoogers R, Ireland D. P. & Boys A. D 1995. Soil and irrigation management practices to improve and sustain vineyard productivity. Final Report: Project DAN 7. Grape and Wine Research and Development Corporation, Adelaide, South Australia.
Skene J. K. M.& Poutsma T. J. 1962. Soils and Land Use in part of the Goulburn Valley, Victoria. Department of Agriculture, Melbourne, Victoria.
Smart R. 1994. The Smart Dyson Ballerina: Australia's viticultural revolution. Wine Industry Journal, 9, 328-329.
Smart R 1995. Two golden rules of viticulture. The Australian and New Zealand Wine Industry Journal, 10.

Smart R., Blackwell J. & Kirchof G. 1991. Does your vineyard need soil slotting? The Australian Grapegrower and Winemaker, 328, 7-9.
Smart R.& Robinson M. 1991. Sunlight Into Wine. Winetitles, Adelaide.
Smart R.E. Management of vigour and canopies in different environments. P. Hayes. Canopy Management. 3-6 . 1995. Adelaide, Australian Society of Viticulture and Oenology.
Smart R.E 1985. Principles of grapevine canopy microclimate manipulation with implictions for yield and quality: A Review. Am. J. Enol. Vitic., 36, 230-239.
Smart R.E. Vine manipulation to improve wine grape quality. Webb A.D. Grape and wine centennial proceedings. 362-375. 1982. Davis CA, University of California.
Smart R.E. 1983. Water Relations of Grapevines. Academic Press, Vol 7.
Smart R.E.& Coombe B.G. 1983. Water relations of grapevines. In: Water deficit and plant growth (ed T.T. Kozlowski), pp. 137-196. Academic Press, New York.
Smart R.E., Dry P.R., and Bruer D.R.G. Field temperatures of grape berries and implications for fruit composition. International symposium on the quality of the vintage. 227-231. 1977. Stellenbosch, South Africa, Oenological and Viticultural Research Institute.
Smart R.E., Turkington C.R. & Evans J.C. 1974. Grapevine response to furrow and trickle irrigation. Am. J. Enol. Vitic., 25, 62-66.
Smith K.A.& Mullins C.E. (Editors.) 1991. Soil Analysis, Physical Methods. Marcel Dekker, Inc., New York.
Smith M., Cole P. & Kriedl S. 1995. Improving efficacy of the biological insecticide, Bacillus thuriengiensis, for control of Lightbrown Apple Moth. The Australian Grapegrower and Winemaker, 71-74.
Smucker A.J 1987. Image Analysis of Video-Recorded Plant Root Systems. In: Minirhizotron Observation Tubes Methods and Applications for Measuring Rhizosphere Dynamics (ed H.M. Taylor), ASA Special Publication No. 50, USA.
So H. B., Smith G. D., Raine S. R., Schafer B. M. & Loch R. J. 1995. Sealing, Crusting and Hardsetting Soils: Productivity and Conservation. Australian Society of Soil Science, Queensland, Australia.
Soderland R.O., Clarnette L., Tisdall J., Adem H., Dry P.R., Smart R.E. & Brein C.J. 19?? Rejuvenation of Low Yielding Vineyards. ??, ??, ??
Soil Classification Working Group 1991. Soil Classification - A Taxonomic System for South Africa. In: Memoirs on the Agricultural Natural Resources of South Africa Government of the Republic of South Africa, Pretoria, South Africa.
Soil Survey Division Staff 1993. Soil Survey manual. USA Agriculture Handbook No. 18, Natural Resources Conservation Service, United States Department of Agriculture, Washington, DC, USA.
Soil Survey Staff 2000. Keys to Soil Taxonomy. United States Department of Agriculture, Natural Resources Conservation Service, US Government Printing Office, Washington, DC20402-9328, USA.
Soil Survey Staff 1999. Soil Taxonomy - A basic system of Soil Classification for Making and Interpreting Soil Surveys. USA Agriculture Handbook No. 436, Second Edition, Natural Resources Conservation Service, United States Department of Agriculture, Washington, DC, USA.
Sojka R. E. and Lentz R. D. 1996. Managing Irrigation-Induced Erosion and Infiltration with Polyacrylamide . Miscellaneous Publication No. 101-96, University of Idaho , College of Southern Idaho, Twin Falls, Idaho.
Southey J.M. Grapevine rootstock performance under diverse conditions in South Africa. Tucker C. Rootstock Seminar: A Worldwide Perspective. 1992. UCLA, Davis, Am. Soc. Enol. Vitic. 1992.
Southey J.M. 1992. Root Distribution of Different Grapevine Rootstocks on a Relatively Saline Soil. S. Afr. J. Enol. Vitic., 13, 1-9.
Southey J.M.& Archer E. 1988. The effect of rootstock cultivar on grapevine root distribution and density. In: The grapevine root and its environment (ed Van Zyl J.L.), pp. 57-73. Department of Agriculture and Water Supply, Pretoria.
Spiro M. 1964. Standard exchange current densities of redox systems at platinum electrodes . Electrochimica Acta, 9, 1531-1537.
Spoor G. 1981. Effective subsoiling. British Sugar Beet Review, 28-29.
Spoor G. 1988. Improving the effectevness of tillage operations. Lecture Notes, Darling Downs Institute of Advanced Education, Toowoomba, Queensland, Australia.
Spoor G.& Godwin R. J. 1978. An experimental investigation into deep loosening of soil by rigid tines. Journal of Agricultural Engineering Research, 23, 234-258.

Stace H.C.T. 1956. Chemical characteristics of Terra Rossa aoils and Rendzinas of South Australia. Journal of Soil Science, 7, 281-292.
Stace H. C. T., Hubble G. D., Brewer R., Northcote K. H., Sleeman J. R., Mulcahy M. L. & Hallsworth E. G. 1968. A Handbook of Australain soils. Rellim technical Publications, Glenside, South australia.
Stanford L 1998. The question of oversupply. Wine Industry Journal, August, 250-261.
Stevens R.M.& Douglas T. 1994. Distribution of grapevine roots and salt under drip and full-ground cover microjet irrigation systems. Irrigation Science, 15, 147-152.
Stevens R.M.& Harvey G. 1995. Effects of waterlogging, rootstock and salinity on Na, Cl, and K concentrations of the leaf and root, and shoot growth of sultana grapevines. Aust. J. Agric. Res., 46, 541-551.
Stevens R.M., Harvey G. & Aspinall D. 1995. Grapevine growth of shoots and fruit linearly correlate with water stress indices based on root-weighted soil matric potential. Aust. J. Grape Wine Res., 1, 58-66.
Stevens R.M., Harvey G. & Davies G. 1996. Separating the effects of foliar and root salt uptake on growth and mineral composition of four grapevine cultivars on their own roots and on Ramsey rootstock. J. Amer. Soc. Hort. Sci., 121, 569-575.
Stevens R.M., Harvey G. & Johns R.E. 1999. Waterlogging reduces shoot growth and bud fruitfulness in pot-grown grapevines with a split-root system. Aust. J. Grape Wine Res., 5, 91-98.
Stevens R.M.& Nicholas P.R. 1994. Root length and mass densities of Vitis vinifera L. cultivars 'Muscat Gordo Blanco' and 'Shiraz'. New Zealand J. Crop Hort. Sci., 22, 381-385.
Stevens R.M.& Prior L.D. 1994. The effect of transient waterlogging on the growth, leaf gas exchange, and mineral composition of potted Sultana grapevines. Am. J. Enol. Vitic., 45, 285-290.
Stoll M., Dry P., Loveys B., Stewart D. & McCarthy M. 2000. Partial rootzone drying - Effects on root distribution and commercial application of a new irrigation technique. Wine Industry Journal, 15, 74-77.
Striegler R.K., Howell G.S. & Flore J.A. 1993. Influence of rootstocks on the response of Seyval grapevines to flooding stress. Am. J. Enol. Vitic., 44, 313-319.
Stroosnidjer L. 1987. Soil evaporation : Test of a practical approach under semi-arid conditions. Netherlands Journal of Agricultural Science, 35, 417-426.
Sumner M. E. 1994. Amelioration of subsoil acidity with minimum disturbance. In: Subsoil Management Techniques (eds Jayawardane N. S. & Stewart B.A.), Advances in Soil Science. CRC Press.
Sumner M. E. 1995. Soil Crusting: Chemical and Physical Processes. The View Forward from Georgia, 1991. In: Proceedings of the Second International Symposium on Sealing, Crusting and Hardsetting Soils: Productivity and Conservation. (eds So H. B. et al.), Australian Society of Soil Science, Inc., Queensland Branch, Brisbane, Australia.
Sumner M. E.& Naidu R. 1998. Sodic Soils - Distribution, Properties Management and Environmental Consequences. Oxford University Press, New York.
Sumner M. E., Rengasamy P. & Naidu R. 1998. Sodic soils: a reappraisal. In: Sodic Soils - Distribution, Properties, Management and Environmental Consequences (ed Sumner M. E. and Naidu R.), Oxford University Press, New York.
Taylor H.M. 1974. Root behavior as affected by soil structure and strength. In: The plant root and its environment (ed E.W. Carson), pp. 271-291. Univ. Press of Virginia, Charlottesville.
Taylor H.M.& Burnett E. 1964. Influence of soil strength on the root growth habits of plants. Soil Sci., 97-98, 174-180.
Taylor H.M.& Gardner R.H. 1963. Penetration of cotton seedling taproot as influenced by bulk density, moisture content and strength of soil. Soil Sci., 96, 153-156.
Taylor H.M.& Ratliff L.F. 1969. Root elongation rates of cotton and peanuts as a function of soil strength and soil water content. Soil Sci., 108, 113-119.
Taylor J. K.& Hooper P. D. 1938. A Soil Survey of the Horticultural Soils in the Murrumbidgee Irrigation Areas, New South Wales. Bulletin No. 118, CSIRO, Melborne, Australia.
Tennant D. 1975. A test of a modified line intersect method of estimating root length. J. Ecol., 63, 995-1001.
Terblance J.H.& van Niekerk P.E 1979. Soil preparation for table grape vineyards in the winter rainfall region. Farming in South Africa - Table Grapes: Winter Rainfall, B2/1979.
Terry R.E.& Nelson S.D. 1986. Effects of polyacrylamide and irrigation method on soil physical properties. Soil Science, 141, 317-320.
Tinker P.B. 1976. Transport of water to plant roots in soil. Philosophical Trans. Royal Soc., 273, 445-461.
Tisdall, J.M. 1978. Ecology of Earthworms in Irrigated Orchards. In: Modification of Soil Structure (ed R.D.B.a.A.R.D. W.W. Emerson), Wiley, Chichester.

Tisdall J.M.& Huett D.O. 1987. Tillage in Horticulture. In: Tillage, New Directions in Australian Agriculture (eds Cornish P. S. & Pratley J. E.), pp. 72-93. Inkata Press, Melbourne, Australia.
Tisdall J.M.& Oades J.M. 1980a. The effect of crop rotation on aggregation in a Red-brown Earth. Aust. J. Soil Res., 18, 423-433.
Tisdall J.M.& Oades J.M. 1980b. The management of ryegrass to stabilize aggregates of Red-brown Earth. Aust. J. Soil Res., 18, 415-22.
Tisdall J.M.& Oades J.M. 1982. Organic matter and water stable aggregates in soils. Journal of Soil Science, 33, 141-163.
Tisdall J. M, Olsson K. A. & Willoughby P. 1984. Soil structural management and production in a non-cultivated peach orchard. Soil and Tillage Research, 4, 165-174.
Topp G.C., Watt M. & Hayhoe H.N. 1996. Point specific measurement and monitoring of soil water content with an emphasis on TDR. Canadian Journal of Soil Science, 76, 307-316.
Tucker B.M.& Beatty H.J. pH, Conductivity and Chlorides. In: Methods of Analysis of Irrigated Soils (ed Loveday J.), pp. 100-107. Commonwealth Bureau of Soils Technical Communication No. 54, Commonwealth Bureau of Soils , Farnham Royal, Bucks., England.
Turchenek L.W.& Oades J.M. 1978. Organo-mineral particles in soil. In: Modification of soil structure (eds W.W. Emerson et al.), pp. 137-144. John Wiley and Sons, New York.
Turner N.C. 1986. Adaption to water deficits: a changing perspective. Aust. J. Plant Physiol., 13, 175-190.
Upchurch D.R. 1987. Conversion of Minirhizotron-Root Intersections to Root Length Density. In: Minirhizotron Observation Tubes Methods and Applications for Measuring Rhizosphere Dynamics (ed H.M. Taylor), American Society of Agronomy, Special Publication no. 50, Madison, Wisconsin, USA.
Upchurch D.R.& Ritchie J.T. 1983. Root observations using a video recording system in mini-rhizotrons. Agronomy Journal, 75, 1009-1015.
Vadas P.A.& Sims J.T. 1998. Redox Status, Poultry Litter, and Phosphorus Solubility in Atlantic Coastal Plains Soils. Soil Sci. Soc. Am. J. 62, 1025-1034.
Van der Westhuizen, J.H. 1980. The effect of black plastic mulch on growth, production and root development of Chenin blanc vines under dryland conditions. S. Afr. J. Enol. Vitic., 1, 1-6.
Van Huyssteen L. The effect of soil management and fertilization on grape composition and wine quality. P.J. Williams, D.M. Davidson, and T.H. Lee. Proceedings of the seventh Australian wine industry technical conference. 16-25. 1990. Adelaide, SA, Winetitles.
Van Huyssteen L. The Effects of Soil Management and Fertilization on Grape Composition and Wine Quality with Special Reference to South African Conditions. Williams P.J., Davidson D.M., and Lee T.H. Seventh Australian Wine Industry Technical Conference. 16-25. 1989. The Australian Wine Research Institute.
Van Huyssteen L. 1983. Interpretation and use of penetrometer data to describe soil compaction in vineyards. S. Afr. J. Enol. Vitic., 4, 59-65.
Van Huyssteen L. 1984. Physical limitations in vineyard soils. Farming in South Africa - Oenological and Viticultural Series, D5/1984.
Van Huyssteen L 1989. Quantification of the compaction problem of selected vineyard soils and a critical assessment of methods to predict soil bulk density from soil texture. PhD Thesis, University of Stellenbosch.
Van Huyssteen L. 1988. Soil preparation and grapevine root distribution - a qualitative and quantitative assessment. In: The grapevine root and its environment (ed Van Zyl J.L.), pp. 1-15. Department of Agriculture and Water Supply. Technical communication No. 215, Pretoria, South Africa.
Van Huyssteen L.& Weber H.W. 1980a. The effect of conventional and minimum tillage practices on some soil properties in a dryland vineyard. S. Afr. J. Enol. Vitic., 1, 35-45.
Van Huyssteen L.& Weber H.W. 1980b. The effect of selected minimum and conventional tillage practices in vineyard cultivation on vine performance. S. Afr. J. Enol. Vitic., 1, 77-83.
Van Huyssteen L. and Weber H. W. 1980c. Soil moisture conservation in dryland viticulture as affected by conventional and minimum tillage practices. S. Afr. J. Enol. Vitic., 1, 107-121.
Van Zyl J.L. 1988. The Grapevine Root and Its Environment. Department of Agriculture and Water Supply, South Africa.
Van Zyl J.L. 1984. Response of Columbar grapevines to irrigation as regards quality aspects and growth. S. African J. Enol. Vitic., 5, 19-28.
Van Zyl J.L. 1988. Response of grapevine root growth and the role of roots as a source of nutrient reserves. In: The grapevine root and its environment (ed J.L. Van Zyl), pp. 30-43. Technical communication No. 215, Department of Agriculture and Water Supply. Pretoria, South Africa.

Van Zyl J.L. and Van Huyssteen L. Soil and water management for optimum grape yield and quality under conditions of imited or no irrigation. Proceedings Fifth Australian Wine Industry Technical Conference. 25-66 . 1984. Adelaide, SA, The Australian Wine Research Institute.

Veneman P.L.M.& Pickering E.W. 1983. Salt bridge for redox potential measurements. Comm. Soil Sci. Plant Anal., 14, 669-677.

Veneman P.L.M., Vepraskas M.J. & Bouma J. 1976. The Physical Significance of Soil Mottling in a Wisconsin Toposequence. Geoderma, 15, 103-118.

Verplancke H., Hartmann R. & De Boodt M 1978. Reducing Evaporation by Soil Conditioning and Mulching. In: Modification of Soil Structure (eds .Emerson W.W. et al.), Wiley and Sons, Chichester, UK.

Vogeler I., Clothier B.E. & Green S.R. 1997. TDR estimation of the resident concentration electrolyte in the soil solution. Aust. J. Soil Res., 35, 515-26.

Vogeler I., Clothier B.E., Green S.R., Scotter D.R. & Tillman R.W. 1996. Characterising water and solute movement by time domain reflectometry and disk permeametry. Soil Sci. Soc. Am. J. , 60, 5-12.

Vos J.& Groenwold J. 1987. The Relation between Root Growth along Observation Tubes and in Bulk Soil. In: Minirhizotron Observation Tubes Methods and Models and Applications for Measuring Rhhhizosphere Dynamics. American Socity of Agronomy, Special Publication No. 50, Madison, Wisconsin, USA.

Wakabayashi S., Ando Y. & Kimura Y. 1974. Studies on the root system of fruit trees growing on the volcanic ash soil in North Kanto district. 2. The vertical root distribution of grapevines planted in a particularly deep volcanic ash soil and some physical properties of the soil. Bul. Coll. agr. Utsunomiya Univ., 9, 15-20.

Walker G.R. 1988. The movement of isotopes of water during evaporation from a bare soil surface. Journal of Hydrology, 97.

Walker R.R. 1994. Grapevine response to salinity. Bulletin OIV (Off. Int Vign. Vin), 67, 634-661.

Walker R.R., Blackmore D.H., Cass A., and Clingeleffer P.R. Use of rootstocks to reduce chloride and sodium levels in export wines. Ninth Australian Wine Industry Technical Conference. 1995. Adelaide, Australia, Abstracts, page 34, Winetitles.

Walker R.R., Blackmore D.H., Clingeleffer P.R. & Cass A. 1998. Use of rootstocks to reduce chloride and sodium levels in export wines. Final Report, Project CSH 8GW, Grape and Wine Research and Development Corporation, CSIRO Plant Industry, Merbien, Victoria.

Walker R.R., Blackmore D.H., Clingeleffer P.R. & Yunusa I.A.M 1995. Salt tolerance and water use of sultanas grafted to a range of hybrid rootstocks. Final report, Project CSH 23DF, Dried Fruits Research and Development Council, CSIRO Division of Horticulture, Merbien, Victoria.

Wallace A. and Wallace G.A. Need for solution or exchangeable calcium and/or critical EC level for flocculation of clay polyacrylamides. R. E. Sojka and R. D. Lentz . Managing Irrigation-Induced Erosion and Infiltration with Polyacrylamide. 101. 1996. Moscow, Idaho, USA, University of Idaho.

Ward W.T. 1966. Geology, Geomorphology and Soils of the South-western Part of County Adelaide, SA. Soil Publication No. 23, CSIRO, Melbourne, Australia.

Watts P.J.& Hancock N.H. 1985. Evaporation and potential evaporation-A practical approach for agricultural engineers. Mechanical Engineering, 10, 231-240.

Weaich K., Bristow K.L. & Cass A. 1994. Simulating maize emergence using soil and climate data. Agronomy Journal, 88, 667-674.

Weast R.C. 1978. Handbook of chemistry and physics. CRC Press LLC, USA.

Weaver H.L. 1982. Modelling evaporation from bare soils under field conditions. Unpublished report, Agronomy and Soil Science, Washington State University, Pullman, Washington State, USA.

Weeks C., Pfeiffer K.A., and Auld S.J. Implications of vineyard redevelopment on winemaking. Lester D.C. and Lee T.H. Irrigation, salinity and grape quality; proceedings of a seminar. 1984. Adelaide, Australian Society of Viticulture and Oenology.

Wells R.C. 1914. Electrical activity in ore deposits. U.S. Geological Survey Bulletin, 548, 78.

Wesseling J. 1974. Crop growth and wet soils. In: Drainage for agriculture (ed J. van Schilfgaarde), pp. 7-37.

Wesseling J.& van Wijk W.R. 1957. Soil Physical Conditions in Relation to Drain Depth. In: Drainage of Agricultural Lands. (ed J. N. Luthin), pp. 461-504. American Society of Agrononomy, Madison, Wisconsin, USA.

West D.W.& Taylor J.A. 1984. Response of six grape cultivars to the combined effects of high salinity and rootzone waterlogging. J. Amer. Soc. Hort. Sci., 109, 844-851.

Wetherby K.G.& Oades J.M. 1975. Classification of carbonate layers in highland soils of the northern Murray mallee, SA and their use in stratigraphis and land-use studies. Australian Journal of Soil Research, 13, 119-132.

White I., Knight J.H., Zegelin S.J. & Topp G.C. 1994. Comments on 'Considerations on the use of time-domain-reflectometry (TDR) for measuring soil water content'. European Journal of Soil Science, 45, 503-508.
Whitfield M. 1971. A compact potentiometric sensor of novel design. In situ determination of pH, pS and Eh. Limnol. Oceanogr., 16, 829-837.
Whitfield M. 1972. The electrochemical characteristics of natural redox cells. Limnol. Oceanogr., 17, 383-393.
Whitfield M. 1974. Thermodynamic limitations on the use of the platinum electrode in Eh measurements. Limnol. Oceanogr., 19, 857-865.
Whiting J. Trial and demonstration vineyard results from north-east, central and southern Victoria . P. Hayes. Canopy Management. 33-34 . 1995. Adelaide, Australian Society of Viticulture and Oenology.
Whiting J. 1998. 1998. Grape Yields on Rootstock Trials. Letter to H. Armstrong, Natural Resources and Environment, Bendigo, Victoria.
Wildman W.E., Meyer J.L. & Neja R.A. 1974. Managing and modifying problem soils. Leaflet ATX-432, Division of Agricultural Sciences, University of California, Davis California.
Williams J., Ross P., and Bristow K. Prediction of the Campbell Water Retention Function from texture, structure and organic matter. Van Genuchten M. Th. and Lelj F.J. Proceedings of the International Workshop on Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils. 1989. Riverside, California, USA, University of California.
Williams J.& Shaykewich C.F. 1970. The influence of soil water matric potential on the strength properties of unsaturated soil. Soil. Sci. Soc. Am. Proc., 34, 835-840.
Wilson S.A. and Atkinson D. Water and mineral uptake by fruit tree roots. A. Riedacker and J. Gagnaire-Michard. Root physiology and symbiosis. Proc. Intern. Union For. Res. Org. Symp. 1979. Nancy, France.
Winkler A.J. 1963. General Viticulture. Jacaranda Press, Brisbane, Australia.
Wolpert J.A., Walker M.A. & Weber E. (Editors). 1992. Rootstock Seminar: A Worldwide Perspective. American Society for Enology & Viticulture, University of California, Davis, CA, USA.
Woodham R.C.& Alexander D. 1966. The effect of root temperature on development of small fruiting sultana vines. Vitis, 5, 345-350.
Yoder R.E., Johnson D.L., Wilkerson J.B. & Yoder D.C. 1998. Soil water sensor performance. Applied Engineering in Agriculture ASAE, 14, 121-133.
Zartman R.E.& Gichuru M. 1984. Saline irrigation water: effects on soil chemical and physical properties. Soil Science, 417-422.