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PROJECT UAD25

LONG TERM SUSTAINABILITY OF PRECISION IRRIGATION

Milestone 9 Final Report (July 22, 2010)

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Cover page: (*clockwise from top left*) Extracting intact soil cores for root length density measurement from a vine row at Tanunda, soil penetration resistance measurements in the Waite Soil Physics laboratory, measurement of subsoil infiltration rates in a vine row at Stanbridge (Murrumbidgee Irrigation Area), excavation ready for subsoil infiltration measurement and intact soil core sampling at Irymple (Sunraysia).

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SUMMARY

Irrigated vineyards in Australia have seen extensive adoption of drip irrigation. At the start of this project there was concern about the sustainability of drip irrigation based on previous field observations. Drip irrigation conserves water but the concentrated nature of its application was believed to cause serious soil structural decline directly under drippers. This project aimed to identify such decline under drippers in Barossa Valley vineyards, to establish the causes of the decline and to suggest management and monitoring strategies to deal with the problem.

To identify such decline we adopted a “paired site” approach and examined subsoil structural problems, at depths of 30-50 cm, directly under drippers, midway between well-spaced drippers (>2 m) and at nearby non-irrigated control points. While we were encouraged to find no evidence of any preferential subsoil structural decline under drippers, we were surprised to find that all the subsoils we examined were of such generally poor structure that there was little prospect of further decline. However, we also realized that application rates in the Barossa Valley are dwarfed by those used elsewhere and proceeded to extend our investigation to the finer-textured soils of Sunraysia and the Murrumbidgee Irrigation Area (M.I.A.). The story here was no different and it became clear that the structural status of subsoils in vineyards is generally poor and is probably undermining good water use efficiency by vines. In 22 distinct soils air-filled porosities were universally very low, resistance to root penetration was high and infiltration rates were frequently poor. A comparison of root length density with subsoil structural properties strongly suggests that poor aeration poses the chief limitation on root proliferation and water use efficiency.

There are few strategies available for subsoil structural improvement in the vine row. We confirmed that gypsum alone has no significant benefit in improving poor structure at depth when applied to a red-brown earth. An attempt to induce subsoil cracking by drying soil in an extended partial root zone drying experiment also failed to improve subsoil structure.

These are inherently poor subsoils and there is a clear need for greatly improved preparation procedures ahead of new plantings. There is also need for changes in the management of existing vineyards if efficiency of water use is to be improved. We believe these will necessarily include modified traffic, soil mounding and the use of calcium, mulching and cover crops *in* the vine row. Indeed, the recommendations of Cockroft for the stone fruit industry (Murray, 2007) seem just as relevant to viticulture but have not been demonstrated or adopted. In their review of soil properties in relation to vine performance, Lanyon *et al.* (2004) have also recommended that much closer attention be paid to soil preparation and management in vineyards.

This report details research conducted from the actual commencement of the project in August, 2006 to December, 2009 and constitutes the Final (Milestone 9) Report of the project.

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INTRODUCTION AND COURSE OF THE PROJECT

Background: Drip irrigation[1], is used extensively in Australian vineyards to conserve water. As this project began in 2006 there were believed to be soil problems that threatened the long-term sustainability of drip irrigation. Research postgraduate students (Clark, 2004; Currie, 2006) working through the CRC for Viticulture had made measurements, albeit at a limited number of sites, that suggested soil structural decline was occurring in drip-irrigated vine rows. There were two likely causes of this decline (Murray and Grant, 2007).

The first of these was the effect of water alone. Although areal application rates (ML/ha) might be relatively low, the concentrated nature of drip irrigation causes the soil beneath emitters to be wet for extended periods. As an example, total annual irrigation of 5 ML/ha via drippers is commonly concentrated into less than 20% of the whole vineyard floor and so may be equivalent to an additional 2500 mm rain. Irrigation events are of extraordinary duration, amount and intensity when seen in relation to local rainfall. These large, artificial increases in the concentration of water have the potential to degrade soil structure as soil is always mechanically weaker, and therefore vulnerable to structural decline, when it is wet.

The quality of irrigation water is a further issue, although not exclusively related to drip irrigation. Decreasing availability of water for irrigation inevitably leads to compromises in water quality and the use of saline bore water has been relatively common in recent years. Irrigation with saline water increases soil sodicity which promotes clay dispersion causing severe soil structural decline. As a good deal is already known about sodicity, it was decided to concentrate largely on the impact of water itself.

An early decision was made to focus on *sub*soil decline; this was prompted by two facts. Firstly, the original, initial objective of the project was "to assess the extent of precision irrigation-induced soil degradation on texture-contrast soils of the Barossa Valley". These soils generally exhibit a topsoil of sandy loam which changes abruptly to a clay at modest depths (10-50 cm); it was expected that problems with soil structure at and below this boundary would be more important for root growth and function than any structural changes in the sandier topsoil. Secondly, the management of soil structure in topsoil is relatively simpler than in subsoil where expensive, long-term interventions are required.

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[1] The term "*precision irrigation*" used to describe this project is used in a restricted sense (the application of precise amounts of water to crops at precise locations and times) rather than in the more general sense of differential irrigation which is adaptive, takes account of field variability and attempts to meet the needs of individual management zones (Smith, 2009). This project examined conventional, surface drip irrigation exclusively.

The original objectives of this project were then to assess the extent of these problems on texture-contrast soils in the Barossa Valley, to establish the roles of soil type and of the quality and amount of irrigation water in causing them, to quantify the vulnerability of soils to them and to develop and test management strategies to minimize and reverse them.

Early work in the project: From the outset we adopted a “paired site” approach to assessing the changes wrought by drip irrigation on subsoil structure by making field measurements directly beneath drippers and at non-irrigated controls. The location of suitable non-irrigated control points presented the major technical challenge of the project (p14). As the project began we employed field measurement of penetration resistance as a tool to assess subsoil structure. This measurement is relatively quick and offers the prospect of assessing an important soil structural property to considerable depth at several locations in one day. The method was also seen as the only means of soil structure assessment that is relatively accessible to growers (Murray and Grant, 2007). However, our early experience with this method demonstrated that, while it is useful, it was too blunt a research tool for our purposes (pp32-33) but one which, in a simpler form and used properly, offers a potential method for growers to assess soil structure.

As the project continued we pursued a strategy of excavating the topsoil by hand, making field measurements of infiltration and then withdrawing intact soil cores for laboratory measurement of other soil structural properties such as bulk density, water retention, penetration resistance and air-filled porosity under closely controlled conditions not possible in the field. Our results suggested that while decline may have occurred under drippers in some of the subsoils examined, the results were inconclusive due to subsoil variability and the uncertain reliability of control points midway between well-spaced (2 m) drippers within the vine row. We revisited these vineyards and one new vineyard (ten in all) and conducted further “paired site” field measurements based this time upon nearby non-irrigated “control” sites outside the vine row. This work confirmed that there is little evidence pointing to irrigation-induced structural decline in these subsoils and that, to some degree, their structural properties may have even benefited slightly from vineyard establishment.

While this finding seemed encouraging there was a more sinister conclusion; our measurements showed that the structural condition of all these subsoils is uniformly poor, leaving little avenue for further decline. Infiltration rates were generally low and both air-filled porosity and penetration resistance were unfavourable to respiration and root growth at field capacity (-10 kPa); we confirmed that they remained so as the subsoils dried to -50 kPa (pp33-45). Chemical analyses offered little support for the view that these poor subsoil structural conditions had been generated by sodicity (see pp45-50). We then attempted to confirm this hostility to root growth via extensive root length density measurements on 1 metre intact cores taken from the same locations (see pp50-55).

A change in direction: At this point in the project we had made measurements in 10 South Australian vineyards on 13 distinct soils and seen little evidence of any irrigation-induced structural decline. However, it seemed possible that the absence of decline caused specifically by irrigation resulted from the relatively modest water use (~1 ML/ha) in these vineyards. We decided that the situation may be different under much greater water applications elsewhere and we pursued similar measurements (albeit without further root length density measurements[2]) in Sunraysia and the M.I.A. The results of our observations in these regions on quite different soils and with approximately 5-10 times greater irrigation applications, confirmed both the lack of structural decline resulting from irrigation and the generally poor subsoil conditions in irrigated vineyards.

While these findings removed concerns about the sustainability of drip irrigation, they disclosed the universally poor conditions for root growth and function in many conventionally established and maintained vineyards. They pointed to the need for greatly improved preparation procedures for permanent plantings and of strategies for the ongoing maintenance of subsoil structure in the vine root zone in established vineyards.

Subsoil structure is extremely difficult to manage and so we investigated one established and one novel strategy for subsoil structure management. We demonstrated that substantial gypsum application (8t/ha) produces no significant subsoil improvements in a structurally degraded red-brown earth (pp55-59). Based on preliminary laboratory studies, we examined subsoil drying in a Partial Rootzone Drying (PRD) trial as a means of generating subsoil structure via cracking; our results showed this to be unsuccessful and even threw doubt on the efficacy of PRD itself in such poorly structured soils (pp59-60). Management options for the establishment and maintenance of subsoil structure are essential for the development of deep, extensive root systems in permanent plantings generally and for the improved water and nutrient use efficiencies that will follow.

Coombe vineyard (Waite Campus, The University of Adelaide, Urrbrae, South Australia.)

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[2] Root length density measurements proved labour-intensive, costly and time-consuming.

GENERAL METHODS

Site identification

The original sites chosen were largely duplex (texture-contrast) soils with abrupt changes in texture at depths of 10-50 cm. These are common in the Barossa Valley which was the original remit and focus of the project. As the work progressed however, it became clear that there were other important soils with gradational profiles, both in the Barossa Valley and elsewhere, whose structure may also be degraded by irrigation. As most measurements in duplex soils were actually made at depths of 23-52 cm, we chose 33-40 cm as the default depth in the absence of a clear texture contrast[3]. The project was focussed on subsoil because although topsoil is an important zone for nutrient and water uptake, it is more easily managed and quite frequently sandier and therefore less prone to severe structural damage of the kind we anticipated.

As we wished to compare the properties of the same soil with and without drip irrigation we sought out non-irrigated control points (*controls*). Our initial inspection of potential sites suggested that the lack of such controls was a major problem. At the commencement of the project many vineyards in the Barossa Valley were irrigated with well-spaced (*ca.* 2 metres) individual drippers so we chose the mid-point between such drippers in the vine row as a pseudo-control or a point where the soil received considerably less water than that immediately under a dripper. As the project progressed, we were obliged to examine sites elsewhere that had much higher water use. We also increasingly encountered vineyards with more closely spaced (~30 cm) “in-line” drippers and felt that we needed to revisit the availability of non-irrigated controls beyond the vine row. At this point we returned to our Barossa Valley sites and made new measurements directly under drippers and at adjacent non-irrigated control points beyond the vine row. These controls were generally sparsely vegetated, traffic-free areas such as adjacent (<10 m) unimproved land, points beyond the end of the vine row but within traffic turning circles or occasionally the mid-row between vehicle wheel tracks[4].

Choice of sites was based largely on subsoil texture (50 mm auger samples to 60 cm) and on the availability of suitable, non-irrigated controls. We specifically excluded sites where the soil at a depth of about 40 cm was relatively sandy; we regard such soils as being less likely to suffer the structural problems that were central to the project. As a good deal was already known about the long term impact of irrigation with saline water on

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[3] Measurements were made at the bottom of excavations and the practical depth limit for these was about 60 cm. In the field, texture changes were often harder to identify than in the laboratory during soil description so that many of our observations are below the actual point of texture change (see Table 1).

[4] Since we wanted to see the effect of irrigation, an ideal control point might have been a non-irrigated area of the same vineyard; needless to say, these were in short supply.

soil structure and because we wished to study the effect of water alone on soil structure, we also favoured sites with little history of saline water use. However, this was often difficult to ascertain or else ambiguous because of switching between water sources. Growers were routinely asked about irrigation water usage, water quality, soil amendments, cover cropping and tillage practices.

Subsoil structural measurements

Prior to soil structural measurements a rectangular 40 x 40 cm hole was excavated by hand to the depth just below the point at which there was a change in texture or, in the absence of such a change, 33-40 cm[5]; then the base of the hole was made level.

Infiltration rates

Infiltration rates were measured with a CSIRO disc permeameter; these are generally used for surface measurements of infiltration. The infiltration surface of the subsoil was carefully prepared using a technique developed for the purpose and designed to remove debris and minimize distortion of macropores. Sorptive data was gathered for several hours and the final infiltration rate was measured over several hours on the following day or later so that all final rates were determined at least 20 hours after the commencement of infiltration; samples used to determine initial and final volumetric water contents were also taken. Infiltration rates are notoriously variable but, because of time constraints, we could only produce one replicate of each measurement[6]. It is intended to use the full time series of these experiments to compute saturated subsoil hydraulic conductivities and to publish these, together with our measurement technique, in a refereed publication. In this report only the final infiltration rates are reported.

Penetration resistance

Soil penetration resistance measurements were initially measured in the field but changed to laboratory measurements. The significance of both kinds of measurements and the reasons for changing to laboratory-based methods are discussed in the *Results and Discussion* section below.

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[5] Depths were measured below the local surface in the inter-row area.

[6] A good deal of the spatial variability is commonly observed in surface soils; subsoils are probably less variable. Some of this variability may result from measurement artefacts because of unintended damage to the infiltration surface. We believe our technique has allowed us to largely overcome this problem; we observed good reproducibility on several occasions. An example of this is in Table 15 in the section *Shrinkage and cracking in clay subsoils* below.

Field penetration resistance measurements

Before measurements, the soil (which had often been recently irrigated by the grower) was levelled slightly and then wetted from a point source with 20 L of water applied at a constant rate of 2 L/hr. using a plastic pail with a flat base diameter of about 30 cm and fitted with a constant head device. This ensured there was no runoff or evaporation from the soil surface. In this way we attempted to simulate a 10 hour irrigation event.

After 36-48 hours, field penetration resistance (field PR) was measured with a Rimik Electronics CP40II field penetrometer (12.8 mm, 30° cone, recessed shaft) at 3 points that were 10 cm from the point of irrigation and arranged at 120° intervals around it. PR was measured at 25 mm intervals to a depth of 75 cm and soil water content was measured at 10, 30 and 50 cm. The instrument memory was downloaded to a PC.

Laboratory penetration resistance (bulk density, water content) measurements

From the base of each hole excavated for infiltration measurements, 4 cylindrical intact soil cores (50 x 50 mm) in numbered stainless steel rings were extracted. These were wrapped in plastic film and stored in an Esky in the shade.

In the laboratory the soil cores were trimmed carefully and weighed. Imperfections at each end of the core were filled with free flowing sand of known bulk density and water characteristic. One end of the core was covered with tightly stretched Nylon mesh and secured with a stout rubber band. The soil core was then placed in a shallow pond of pure water in the dark and allowed to saturate over several days. At intervals, cores were removed, excess water was drained and they were weighed to ensure equilibrium was established. At equilibrium the weights of cores (and any swelling) were noted (for water contents and bulk densities) and the cores were placed on ceramic plates to establish matric potentials of -10 and -50 kPa (2 cores at each potential). At equilibrium cores were weighed and measured as before then wrapped in plastic film to preserve their water contents.

Penetration resistance (PR) was measured using a Lloyd LF-plus Universal Test Machine and Nexygen Plus software. A stainless steel probe with an enclosed cone angle of 30°, cone diameter of 2.58 mm and recessed shaft diameter of 2.00 mm were driven 46 mm into the soil cores at 2.8 mm/min from a point just above the soil surface. Cone diameter was checked periodically using electronic calipers and area adjustments used during data processing. To avoid error from unconstrained soil movement during insertion, only data from 15-35 mm depth was used and insertions were spaced around the core, using a cardboard template, such that no insertion was closer to another, or the sampling ring, than five diameters of the cone. The template provided five potential insertion points, three insertions being standard and the other two being for extra insertions should the probe encounter an anomaly, such as a stone, during the first three insertions. Insertions were computer-controlled for consistent operation and to allow direct computer access to data, which entered in text format but was copied into an Excel spreadsheet for processing. Penetration resistance was measured as force in Newtons (N) and converted to cumulative work (N.m) by numerical integration over the probe displacement from 15-35 mm depth. This cumulative work was then converted to work-averaged penetration resistance (MPa) using the cone area and the total displacement (20 mm).

Air-filled porosity

Air-filled porosity was calculated at a given potential (ψ) from

$$AFP = 1 + (\rho_\psi/\rho_w)(\theta_0 - \theta_\psi) - (\rho_\psi/\rho_0)$$

Where ρ_ψ and ρ_0 are, respectively the bulk density of the soil at ψ and at saturation, θ_ψ and θ_0 are the gravimetric water contents under the same respective conditions and ρ_w is the density of water.

Soil chemical analysis

Air-dried soils (of known water content) were used to make 1:5 soil:water extracts with de-ionized water. Samples were shaken for 3 hours, allowed to settle, centrifuged[7] and the supernatant liquid divided into two aliquots, one to measure electrical conductivity (EC) and pH respectively, the other for chemical analysis by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICPAES).

Root Length Density

Intact soil cores of 38 mm diameter were taken to a depth of 1.2 m in the vine row with a “Dingo Ezi-Probe”. These were stored in clear acrylic tubes with end caps in a cool, dark room then transferred to a -20°C freezer within 24 hours. Each core was removed from the freezer the day before processing, allowed to come to room temperature and 4 x 10 cm lengths were cut from each core at the appropriate depths (A, B, C, D subsamples - see later). Surface soil was discarded and the remainder of the core was returned to the freezer. Roots were carefully washed from each sample and retained on a 1 mm sieve; material passing through the sieve was then retained on a 0.5 mm sieve. Material passing the 0.5 mm sieve was mainly composed of short pieces of dead roots, organic debris and mineral matter and was discarded. The >1 mm and 0.5-1 mm samples of separated roots were separately stored in sealed containers in 50% ethanol in a cool room at 5°C.

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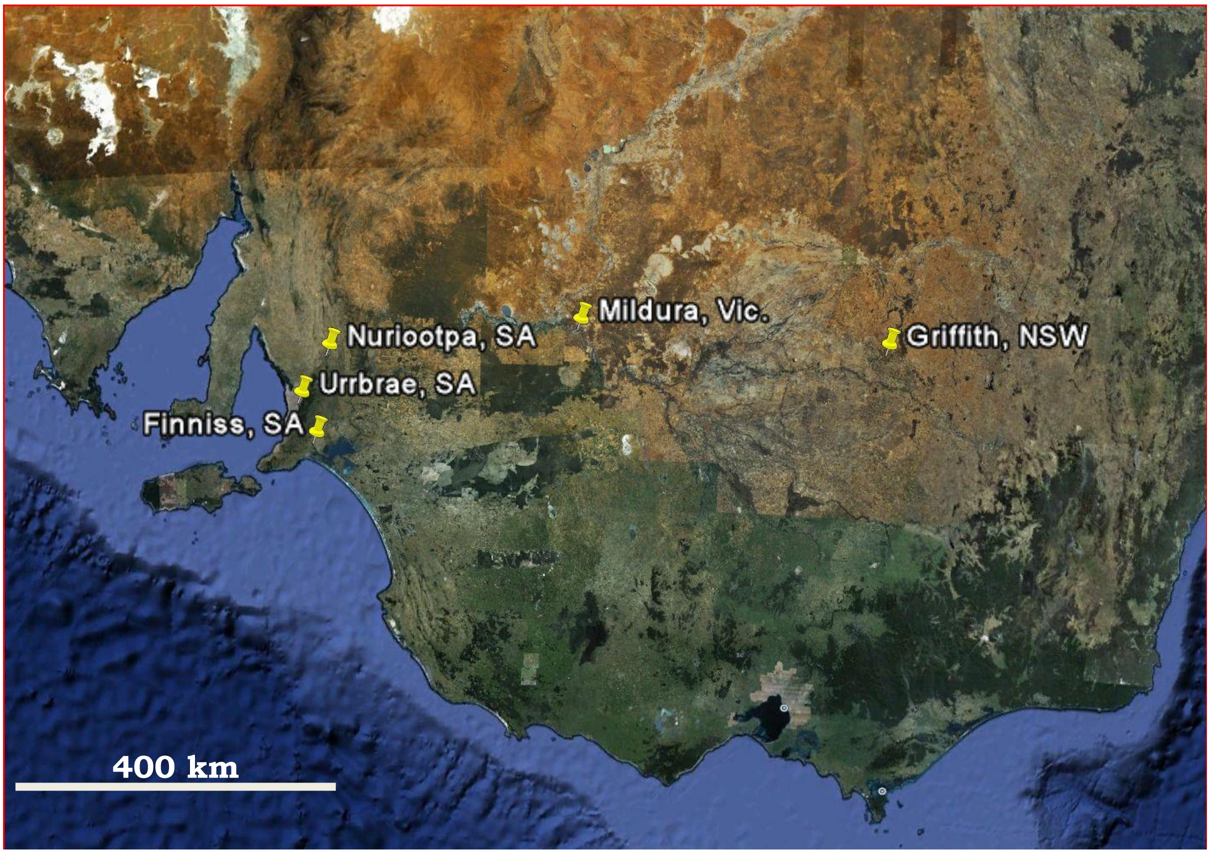
[7] Because these were subsoil samples, dispersed colloids were a *major* contaminant in the extracts and a great deal of work was done to remove these colloids by ultra-filtration and by freeze-thaw procedures developed in this lab during the project. This work is continuing because colloid contamination is frequently ignored in the analysis of soil-water extracts and we have shown that it is a source of *serious* error.

Samples (>1 mm only) in 50% ethanol were spread in 145 x 245 mm Perspex trays, pre-scanned to allow correction for scratches, and then scanned as grey-scale images at 800 dpi. Contrast, smoothing and object removal facilities were widely trialled to arrive at suitable settings to exclude spurious material during the batch analysis of images for root length with WinRhizo software.

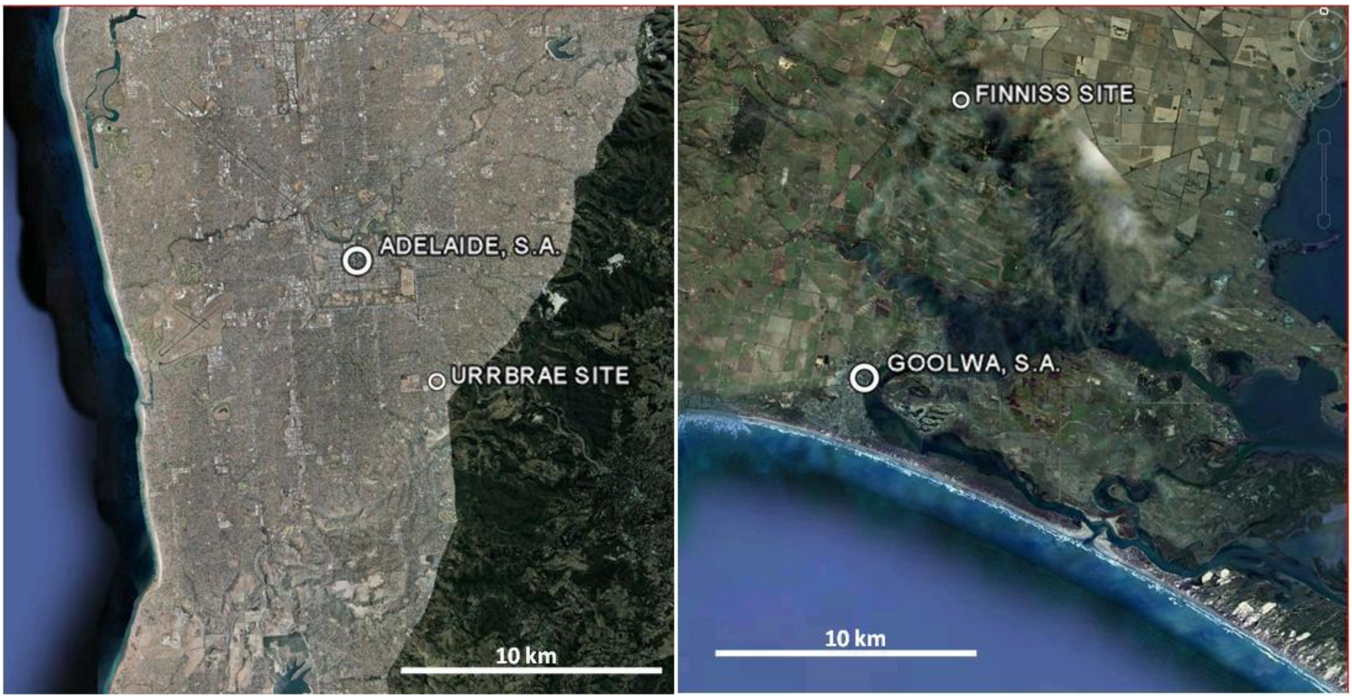
SITE INFORMATION

Subsoil structural measurements were made in 18 vineyards on 22 distinct soils. Measurements of field soil penetration resistance only were made at a 19th vineyard (Gomersal, Barossa Valley). Soil descriptions were based on samples removed with a 50 mm auger in 10 cm increments to 100 cm. The maps below show the location of field sites; Table 1 gives location data and soil information about each site.



Regional location of research sites. Finniss (Currency Creek), Urrbrae (Adelaide), Nuriootpa (Barossa Valley), Mildura (Sunraysia) and Griffith (Murrumbidgeee Irrigation Area – M.I.A.)

Barossa Valley sites



Adelaide (left) and Currency Creek sites

Sunraysia sites

M.I.A. sites

region	site	East	South	Isbell class.	depth of texture change (cm)	change classifier	sampling depth (cm)	soil description	vines	rootstock
Adelaide	Urrbrae	138^{0} 37.99'	34^{0} 58.04'	Red Chromosol	26	abrupt	40	Duplex; A-horizon 0-26 cm (fine sandy loam (pH=7.0) gravelly); B-horizon 26-100 cm (medium clay over heavy clay, some gravel throughout (pH=7.5), calcareous medium clay (pH=8.5) below 80 cm).	Tempranillo, Ondenc, Canocazo	own roots
Currency Creek	Finniss	138^{0} 49.51'	35^{0} 24.40'	Grey Chromosol	10	abrupt	33	Duplex; A-horizon 0-10 cm (sandy loam (pH=6.0)); B-horizon 10-100 cm (medium-heavy clay (pH=7.5-8.5) sodic, non- to highly calcareous to 90 cm, light-medium clay below 90 cm (pH=8.0) non-calcareous).	Cabernet	own roots
Barossa Valley	Gomersal	138^{0} 54.67'	34^{0} 32.12'	*Red Chromosol**	not recorded	not recorded	not recorded	not described	Shiraz	not recorded
Barossa Valley	Ebenezer-1	139^{0} 02.39'	34^{0} 24.96'	Red Chromosol	30	abrupt	30	Duplex; A-horizon 0-30 cm (sandy loam (pH=6.0)); B-horizon 30-100 cm (medium-heavy clay (pH=8.5); slightly calcareous 60-90 cm).	Shiraz	own roots
Barossa Valley	Ebenezer-1	139^{0} 02.16'	34^{0} 24.88'	Red Chromosol	10	abrupt	23	Duplex; A-horizon 0-10 cm (fine sandy loam (pH=6.0)); B-horizon 10-100 cm (light clay (pH=6.0) grading to medium-heavy clay (pH=9.0) by 40 cm depth; highly to very highly calcareous 50-100 cm).	Shiraz	own roots

Table 1: *The 23 distinct soils studied in this project and their descriptions. *The Gomersal site was used only for extensive field penetration resistance measurements and, apart from pH, EC and water content, the soil was not characterized.*

region	location	East	South	Isbell class.	depth of texture change (cm)	change classifier	sampling depth (cm)	soil description	vines	rootstock
Barossa Valley	Ebenezer-2	139^0 00.41'	34^0 25.46'	Brown Chromosol	50	abrupt	52	Duplex; A-horizon 0-50 cm (loamy sand (pH=6.0-6.5)); B-horizon 50-100 cm (clay loam coarse sandy (pH=6.5-8.0) with light clay (pH=7.5) 60-80 cm).	Semillon	own roots
Barossa Valley	Greenock-1	138^0 55.27'	34^0 26.65'	Red Chromosol	20	abrupt	40	Duplex; A-horizon 10-20 cm (sandy loam on fine sandy loam (pH=6.5-6.0)); B-horizon 20-100 cm (medium clay (pH=6.0)).	Shiraz	own roots
Barossa Valley	Greenock-2	138^0 55.39'	34^0 26.51'	Brown Chromosol	30	clear	43	Duplex; A-horizon 0-30 cm (light clay (pH=6.0)); B-horizon 30-100 cm (medium-heavy clay on heavy clay (pH=6.5-8.5) grading non- to highly-calcareous).	Grenache	own roots
Barossa Valley	Angaston	139^0 02.71'	34^0 31.11'	Red Chromosol	35	abrupt	35	Duplex; A-horizon 0-35 cm (fine sandy loam (pH=6.0)); B-horizon 35-100 cm (medium-heavy clay (pH=6.5)).	Viognier	not recorded
Barossa Valley	Bethany	138^0 57.58'	34^0 32.64'	Grey Vertosol	n/a	none	35	A-horizon 0-20 cm (medium clay (pH=7.5) highly calcareous); B-horizon 20-100 cm (medium-heavy clay on heavy clay (pH=8.0-9.0) very-highly calcareous).	Semillon	own roots

Table 1 (*continued*): *The 23 distinct soils studied in this project and their descriptions.*

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Region	location	East	South	Isbell class.	depth of texture change (cm)	change classifier	sampling depth (cm)	soil description	vines	rootstock
Barossa Valley	Tanunda-1	138^0 58.56'	34^0 31.49'	Red Chromosol	10	abrupt	32	Duplex; A-horizon 0-10 cm (fine sandy loam (pH=5.5)); B-horizon 10-100 cm (medium-heavy clay (pH=6.0-8.5) grading non- to highly calcareous).	Semillon	own roots
Barossa Valley	Tanunda-2	138^0 58.45'	34^0 31.67'	Grey Vertosol	n/a	none	35	A-horizon 0-20 cm (medium-heavy clay (pH=7.0) highly calcareous); B-horizon 20-100 cm (medium-heavy clay (pH=7.0-8.5) sodic, highly calcareous).	Shiraz	own roots, Rugeri 140
Barossa Valley	Nuriootpa	139^0 00.36'	34^0 28.55'	Red Sodosol	40	abrupt	34	Duplex; A-horizon 0-28 cm (sandy loam (pH=8.0)); B1-horizon 28-40 cm (clayey sand (pH=7.5) sodic); B2-horizon 40-100 cm (medium clay (pH=9.0) sodic throughout, calcareous at depth).	Reisling, MR 43-27	own roots
Sunraysia	Curlwaa	141^0 57.86	34^0 07.31	Grey Sodosol	20	clear	40	Duplex; A-horizon 0-10 cm (loam (pH=7.0)); B1-horizon 10-20 cm (light clay (pH=7.0)); B2-horizon 20-100 cm (medium clay (pH=7.0-6.0) very highly sodic).	Chardonnay	not recorded
Sunraysia	Boeill Creek-1	142^0 06.49'	34^0 09.49'	Grey Kandosol	0-40	not clear or abrupt	40	Gradational; A-horizon 0~10 cm (clay loam (pH=6.0)); B-horizon ~10-100 cm (light clay (pH=6.0) grading to medium clay (pH=6.5) highly sodic).	Cabernet	not recorded

Table 1 (*continued*): *The 23 distinct soils studied in this project and their descriptions.*

region	location	East	South	Isbell class.	depth of texture change (cm)	change classifier	sampling depth (cm)	soil description	vines	rootstock
Sunraysia	Boeill Creek-2	142^0 06.64'	34^0 09.50'	Red Sodosol	20	clear	40	Duplex; A-horizon 0-10 cm (fine sandy loam (pH=7.0)); B1-horizon 10-20 cm (fine sandy clay loam (pH=8.0)); B2-horizon 20-100 cm (light-medium clay (pH=8.0-8.5) very highly sodic, slightly-moderately calcareous at depth).	Cabernet	not recorded
Sunraysia	Irymple	142^0 08.65	34^0 14.83	Grey Kandosol	0-30	not clear or abrupt	33	Gradational; 0-100 cm (light clay on medium-heavy clay (pH=9.0-8.5) highly sodic, highly calcareous grading to nil at depth).	Sultana	not recorded
Sunraysia	Mildura South	142^0 07.76	34^0 14.09	Hypercalcic Calcarosol	10	not clear or abrupt	35	A-horizon 0-10 cm (fine sandy clay loam (pH=8.0) highly calcareous); B-horizon 10-100 cm (light-medium clay (pH=8.5) sodic, highly calcareous).	Sultana	not recorded
M.I.A.	Leeton	146^0 21.25'	34^0 31.73'	Red Chromosol	25	clear	30	Duplex; A-horizon 0-20 cm (sandy loam (pH=6.0)); B1-horizon 20-30 cm (sandy clay loam (pH=6.0)); B2-horizon 30-100 cm (medium clay (pH=6.0-8.0) sodic, slightly calcareous at depth).	Shiraz	own roots

Table 1 (*continued*): *The 23 distinct soils studied in this project and their descriptions. M.I.A.=Murrumbidgee Irrigation Area.*

region	location	East	South	Isbell class.	depth of texture change (cm)	change classifier	sampling depth (cm)	soil description	vines	rootstock
M.I.A.	Stanbridge-1	146^0 12.32'	34^0 30.69'	Red Chromosol	15	clear	30	Duplex; A-horizon 0-10 cm (sandy clay loam (pH=6.5)); B1-horizon 10-20 cm (light-medium clay (pH=6.5)); B2-horizon 20-100 cm (medium clay (pH=7.0-8.0) sodic, slightly calcareous 50-80 cm, sandy clay loam (pH=7.0) below 90 cm).	Shiraz	own roots
M.I.A.	Stanbridge-2	146^0 12.29'	34^0 30.68'	Black Chromosol	10	clear	30	Duplex; A-horizon 0-10 cm (light-medium clay (pH=6.0)); B2-horizon 10-100 cm (heavy clay (pH=6.0-8.0) sodic, slightly calcareous below 60 cm).	Shiraz	own roots
M.I.A.	Whitton	146^0 11.35'	34^0 32.82'	Brown Vertosol	n/a	none	36	A-horizon 0-10 cm (medium clay (pH=6.0)); B-horizon 10-100 cm (medium-heavy clay (pH=6.0-8.0 to 80 cm, pH=7.5 below 80 cm)).	Chardonnay	own roots
M.I.A.	Hanwood	146^0 04.55'	34^0 21.29'	Black Kandosol	0-30	not clear or abrupt	37	Gradational; A-horizon 0~10 cm (light clay (pH=7.0)); B1-horizon ~10~20 cm (light-medium clay (pH=7.0)); B2-horizon ~20-100 cm (medium clay (pH=6.0-8.5) slightly-moderately calcareous below 60 cm).	Shiraz & Chardonnay	Ramsey

Table 1 (*continued*): *The 23 distinct soils studied in this project and their descriptions. M.I.A.=Murrumbidgee Irrigation Area.*

RESULTS & DISCUSSION

Subsoil structural measurements

Infiltration rates

Infiltration rates are determined by soil texture and structure. Soil texture is usually a given but soil structure is critically dependent on land management. In all but the sandiest soils, the infiltration rate may plummet under poor management because of low organic matter content, heavy traffic or irrigation with saline water but it may soar when there are cracks, old root channels or other bio-pores in the soil. Lanyon *et al.* (2004) note that while there may be some debate about the various soil properties universally suited to good vine performance, good infiltration and drainage is essential regardless of climate or soil type. However, good infiltration is not sufficient for good soil structure; a dense, hard soil matrix, hostile to root growth but punctuated by the occasional macropore may be well drained but still present major obstacles to root proliferation. The value of infiltration rates is twofold; they determine the duration of water-logging events and they may provide a crude indication of opportunities for root growth as a good deal of infiltration occurs through pores large enough to accommodate roots. However, this is complicated by the fact that pores that could contribute to infiltration might also be blocked by living roots.

Infiltration rates are notoriously variable; those measured in this project were no exception and ranged over 4½ orders of magnitude from 0.015 to 482 mm/hr. These results are summarized below.

Table 2 shows that there is no general trend in infiltration rate due to irrigation alone but that the coefficients of variation are all greater than 2.

Position	n	average	standard deviation	coeff. var.	min.	max.
under drippers	50	16	37	2.3	0.071	218
between drippers	36	39	111	2.8	0.14	482
non-irrigated control points	22	10	22	2.1	0.015	120

Table 2: *An overall summary of subsoil infiltration rates (mm/hr) in vineyards directly under drippers, mid-way between well-spaced (>2 metres) drippers and at non-irrigated control points.*

Figure 1 shows the sorted distribution of infiltration rates observed.

Table 3 shows that about one third of observations within vine rows yielded poor infiltration rates (i.e. < 1 mm/hr). Interestingly, the data suggests that these instances are more common amongst non-irrigated control points; this is discussed below. One need only consider rainfall and irrigation event duration and intensities to realize that such soils will be prone to intermittent and sometimes lengthy water-logging events.

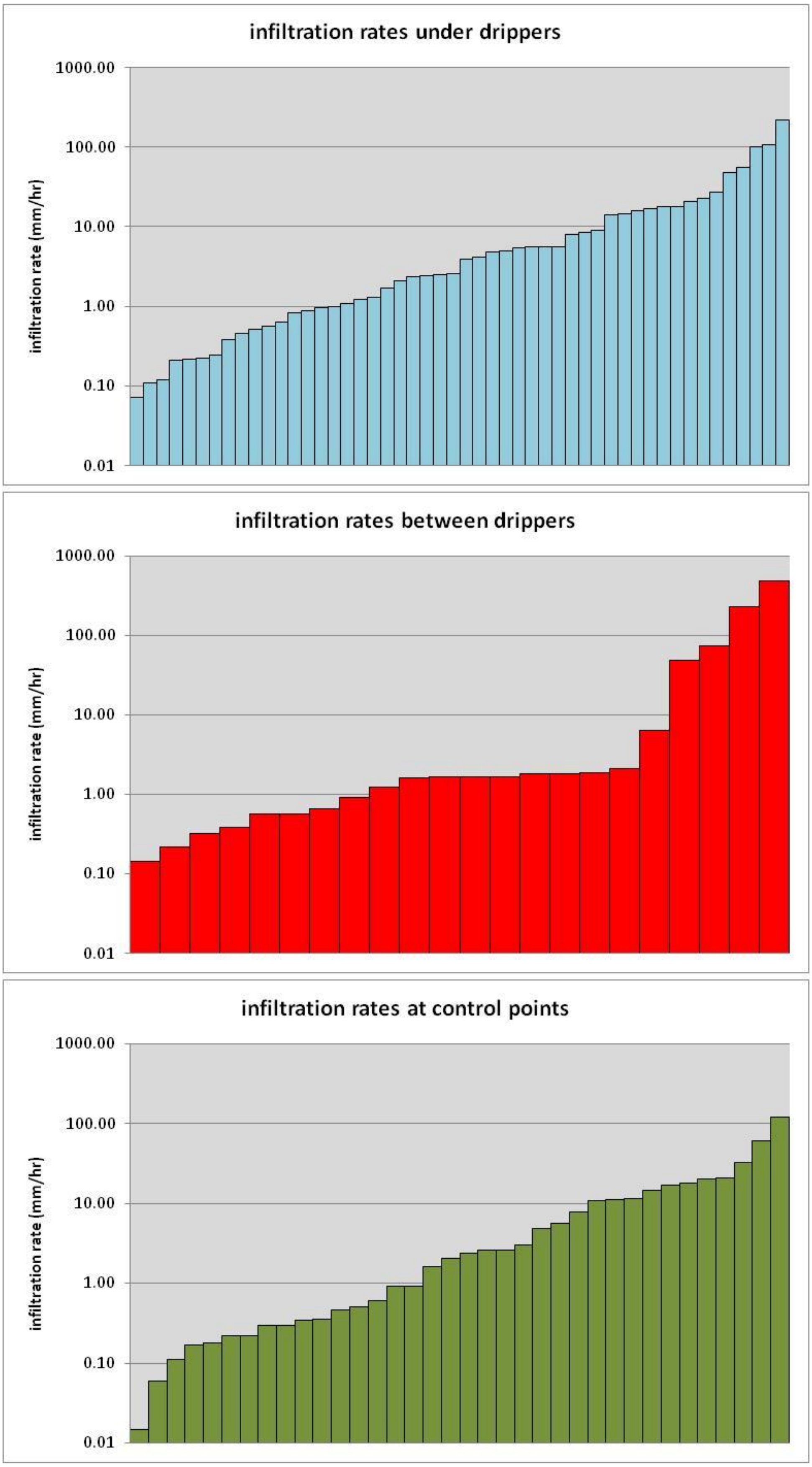

Figure 1: *subsoil infiltration rates in vineyards directly under drippers, mid-way between well-spaced (>2 metres) drippers and at non-irrigated control points.*

Such low infiltration rates will have a further effect upon the wetting pattern under the dripper; a soil that has an infiltration rate of 1 mm/hr undergoing an extended period of drip irrigation at 2 L/hr will produce a wetted zone that reaches at least 0.8 metres from the point directly under the dripper. This might be useful if the vine roots extend into the inter-row sufficiently (if not prevented by traffic compaction) but could also represent a rather large anoxic volume in the root zone. It may also diminish PRD effects by allowing some water to move into the "dry side" of the vine. Of course at lower infiltration rates, these concerns are magnified.

infiltration rate (mm/hr)	under drippers	between drippers	non-irrigated control points
<1	32%	36%	44%
<10	72%	82%	69%

Table 3: *An overall summary of the distribution of subsoil infiltration rates (mm/hr) in vineyards directly under drippers, mid-way between well-spaced (>2 metres) drippers and at non-irrigated control points.*

location	infiltration rate (mm/hr)						ratio-vine row: control
	site ave.	std. dev.	vine row ave.	std. dev.	control ave.	std. dev.	
ADELAIDE							
Urrbrae	106	158	118	182	70	70	1.7
BAROSSA	13	14	14	21	10	11	1.4
Bethany	17	26	11	22	33	40	0.34
Ebenezer 2	0.58	0.81	0.76	0.88	0.037	0.032	21
Nuriootpa	5.2	5.1	4.6	5.1	7.1	6.3	0.65
Ebenezer 1	11	20	13	22	5.9	7.0	2.2
Tanunda 1	0.58	0.53	0.68	0.59	0.28	0.090	2.4
Tanunda 2	6.1	11	2.4	2.1	17	22	0.14
Greenock	19	34	20	40	14	4.1	1.4
Angaston	44	91	63	110	5.3	3.8	12
CURRENCY CREEK							
Finniss	39	88	78	121	0.17	0.050	460
M.I.A.	5.0	3.8	6.4	3.7	3.7	5.0	1.8
Hanwood	12	7.5	13	6.1	10	11	1.3
Stanbridge	0.78	0.75	0.67	0.77	0.90	1.0	0.74
Leeton	6.8	6.6	11	7.5	3.0	3.8	3.6
Whitton	0.84	0.37	1.1	0.21	0.54	0.11	2.1
SUNRAYSIA	6.7	1.9	8.3	2.4	5.2	2.2	1.6
Boeill Creek	3.2	3.3	5.5	not replicated	0.92	not replicated	6.0
Irymple	1.4	1.2	2.4	0.071	0.41	0.15	5.9
Mildura South	21	5.1	24	4.6	18	4.5	1.3
Curlwaa	1.5	1.3	1.3	1.1	1.7	1.9	0.78

Table 4: *A vineyard summary of subsoil infiltration rates (mm/hr) in vine rows (includes points directly under drippers and mid-way between well-spaced (>2 metres) drippers in some vineyards) and at non-irrigated control points. The ratio of vine row to control point infiltration rates is also shown. Values highlighted in yellow are averages of values observed in a region.*

Table 4 shows that, while there is considerable variability, the average infiltration rates at our sites in the Barossa, M.I.A. and Sunraysia are of similar magnitude.

Figure 2a shows that there are no systematic differences within vine rows between infiltration rates directly under, and mid-way between well-spaced drippers; based on the original hypothesis of this project, it was expected that there would be. However, Figure 2b and the last column of Table 4 shows that in about 70% of cases, infiltration rates within vine rows were generally higher than at control points. This is, of course, exactly the opposite of what was expected and suggests that the process of vineyard preparation, vine growth and irrigation has, if anything, improved infiltration in these soils.

Infiltration rate measurement (clockwise from top left): a subsoil surface prepared for measurement, levelled permeameter in place ready to commence measurement, simultaneous measurements underway directly beneath and mid-way between well-spaced (2 metres) drippers.

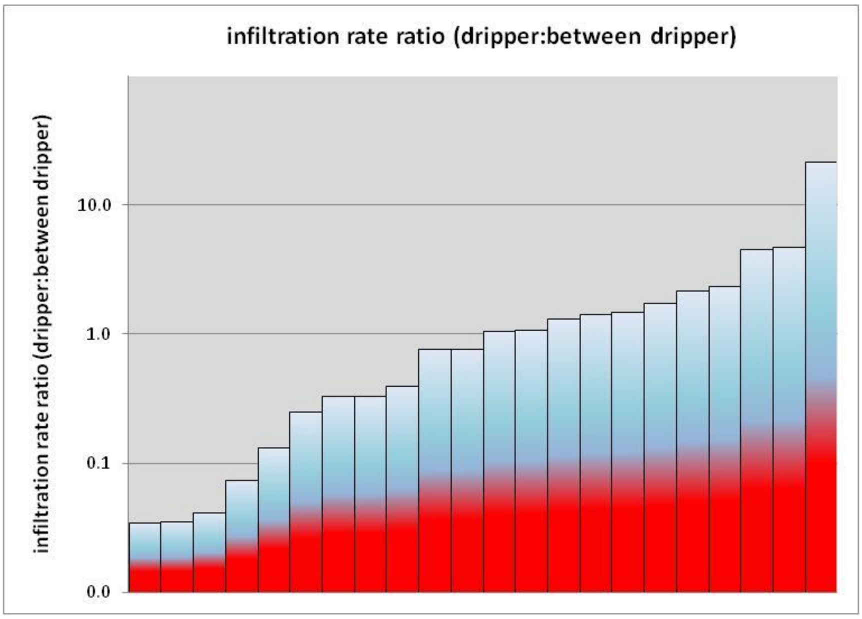

Figure 2a: *The ratio of subsoil infiltration rates (mm/hr) directly under drippers to that mid-way between well-spaced (>2 metres). Values lower than 1 suggest poorer infiltration under the dripper.*

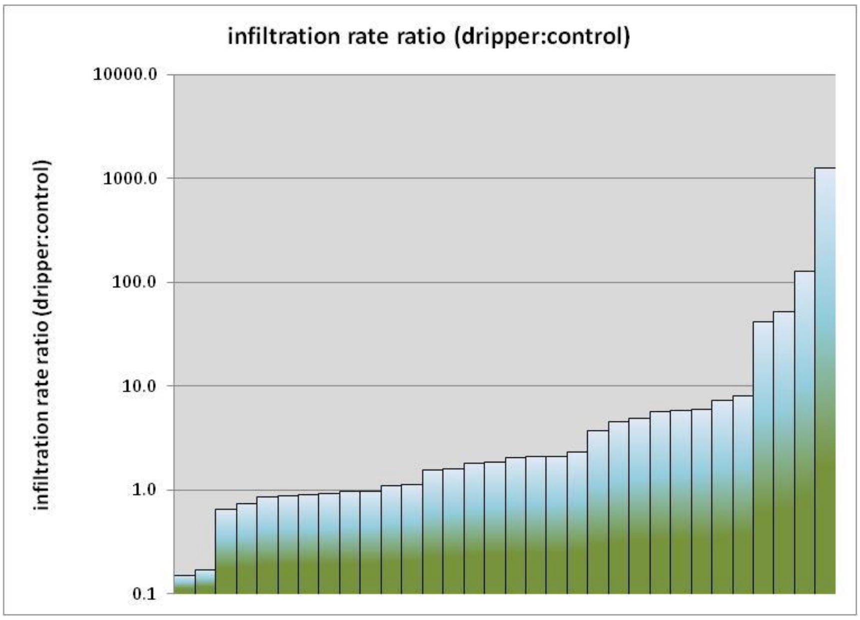

Figure 2b: *The ratio of subsoil infiltration rates (mm/hr) directly under drippers to that at non-irrigated control points. Values lower than 1 suggest poorer infiltration under the dripper.*

The reason for this is not clear although it may be that some vestigial cracks from the original deep-ripping have remained or, more probably, that early colonization of the subsoil by young vine roots, and their subsequent death and decay have produced sufficient macropores to enhance infiltration. However, this effect is relative; as discussed above, there are a substantial number of sites with poor infiltration rates (i.e. <1 mm/hr) as can be seen in Figure 1 .

Penetration resistance

Soil penetration resistance (PR) is used as an indication of the mechanical hostility of soil towards root growth. The measurement of soil penetration resistance (PR) with a rigid probe is universal practice but is a poor simulation of root growth itself[8]. However, it is generally acknowledged that increases in PR are accompanied by decreasing root extension (Marshall *et al.*, 1996). Olsson and Cockroft (2002) have argued that PR should be less than 0.5 MPa for unrestricted root growth while there is wide agreement that PR values above 2 MPa prevent root growth altogether.

For any given soil, PR increases with bulk density but is reduced by increasing soil water content. While bulk density changes with management (e.g. traffic compaction), water content can change on a much shorter time scale; this presents a serious problem for field observations. Generally this has been approached by making measurements when the soil is at field capacity but even this may be difficult to do when crop transpiration, evaporation and lateral movement of water into drier soil change the water content on a time scale of minutes. At best, such field measurements offer some insights into the actual values of PR that roots contend with but, under such variable conditions, they don’t allow meaningful comparisons to be made across time or space.

Field measurements

Soil water content and PR were measured at 25 mm intervals to a depth of 75 cm at 35 locations in two 9 year old vineyards (Gomersal, Ebenezer 1) in the Barossa Valley. The measurements reported here are confined to 30-50 cm depth near the interface of the A and B horizons. At each of three points within each location (under drippers and between drippers in the vine row and at the midpoint between vine rows) replicated measurements (x3) were made on recently irrigated soil (24-48 hours) from which evaporation was prevented.

Despite strenuous efforts to ensure that soil at field sites used for PR measurements was at field capacity water content, we found that we could generally only attain about 80% of this water content during measurements in the growing season. In the early stages of the project we identified field PR as a measurement that may have potential for growers themselves to assess soil structural conditions. Based on our experience we believe the critical use of field penetration resistance as a simple tool to compare soils and identify soil structural changes should generally be confined to late winter when more uniform soil water contents prevail and when the absence of the vine canopy allows easy access for measurements in the vine row.

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[8] Roots grow by *forward* extension of the root tip to exploit weaknesses or voids created by *radial* expansion of the root (Marshall *et al.*, 1996).

Although *average* water contents were not significantly different between the under-dripper, between-dripper and mid-row positions, there was considerable variation in water content at each position (C.V. = 0.09-0.30). A good deal of this variability is believed to arise from deep ripping which produces visible three-dimensional variations in soil texture near the A-B boundary of these soils.

site	**average penetration resistance (MPa) at 30-50 cm depth**				% <1 MPa	% >2 MPa	% >4 MPa
	range[a]	under dripper	between drippers	mid row			
Gomersal	0.9-4+	2.1	2.0	2.0	7	38	13
Ebenezer 1	1.3-4+	3.5	2.7	2.6	0	80	40

Table 5: *A summary of subsoil penetration resistances measured in the field directly under drippers, mid-way between well-spaced (>2 metres) drippers and at the midpoint between vine rows.* [a]*4 MPa is the measurement limit of the field instrument.*

Table 5 shows that virtually all of the PR values observed pose a major obstacle to root growth. Notwithstanding variability in soil water content and the difficulties of attaining field capacity, it is important to note that these penetration resistances were measured after typical irrigation events when the sub-soil was at its weakest but not water-logged. This seems to confirm that many of the benefits of deep-ripping prior to planting are long gone and that the soil has returned to a hard matrix punctuated by occasional decayed root channels[9]. The general picture is one of rather hostile sub-soils in which the “window” of opportunity for root elongation may be quite narrow.

Laboratory measurements

Our early experience with measurements of PR in the field made it clear that far more reliable observations could be made on intact soil cores in the laboratory where water contents could be completely controlled. At first these were conducted at field capacity (-10 kPa) when the soil is at its wettest (and weakest) for practical purposes. At a later stage in the project we began to include measurements at -50 kPa which we regarded as a practical subsoil “refill point” for many irrigated enterprises. PR values measured under these conditions ranged from about 0.3 to 4.4 MPa at field capacity (-10 kPa) and from about 0.4 to 4.8 MPa at -50 kPa. These results are summarized below.

Table 6 and Figure 3 show an overall summary of PR; each observation (of the n values recorded) is the average of 6-15 replicates depending on sample variability. There is no general trend in PR due to irrigation alone other than

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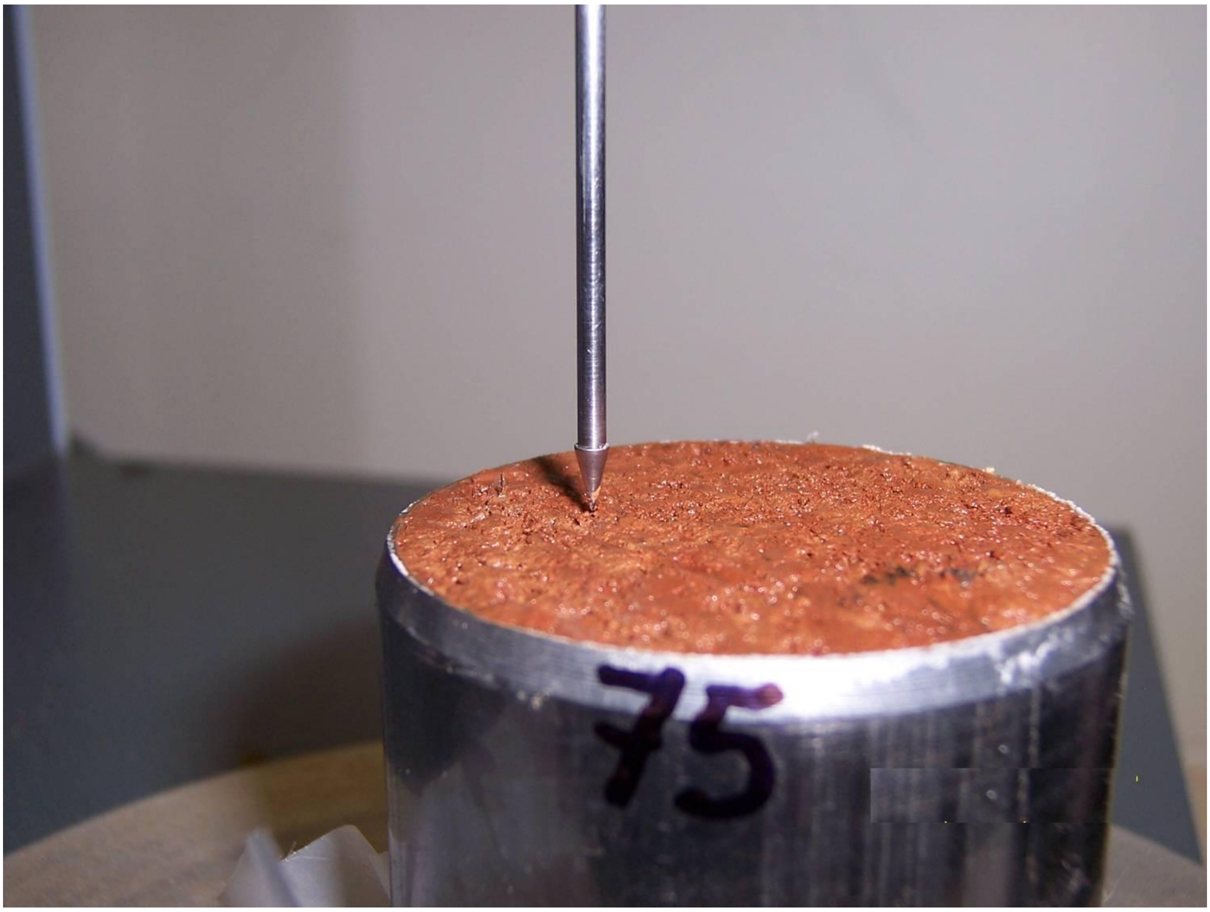
[9] Infiltration and PR measurements are complementary in this respect. Infiltration in finer-textured soils is largely dependent on continuous macropores (if they exist) while PR is largely a property of the soil matrix.

a tendency to be lower in the vine row than at non-irrigated control points; this will be discussed below.

	penetration resistance (MPa) at -10 kPa					
position	n	average	standard deviation	coeff.var.	min.	max.
under drippers	52	1.03	0.45	0.43	0.27	2.85
between drippers	23	1.00	0.27	0.27	0.55	1.65
non-irrigated control points	37	1.35	0.72	0.53	0.40	4.36
	penetration resistance (MPa) at -50 kPa					
under drippers	30	1.25	0.77	0.62	0.46	4.70
between drippers	2	*1.97*	*1.35*	*0.68*	*1.02*	*2.92*
non-irrigated control points	35	1.51	0.87	0.58	0.36	4.79

Table 6: *An overall summary of subsoil penetration resistances measured in the laboratory at field capacity (-10 kPa) and at -50 kPa. Intact subsoil cores were taken in vineyards directly under drippers, mid-way between well-spaced (>2 metres) drippers and at non-irrigated control points.*



Laboratory measurement of penetration resistance. Micropenetrometer probe about to enter an intact soil core

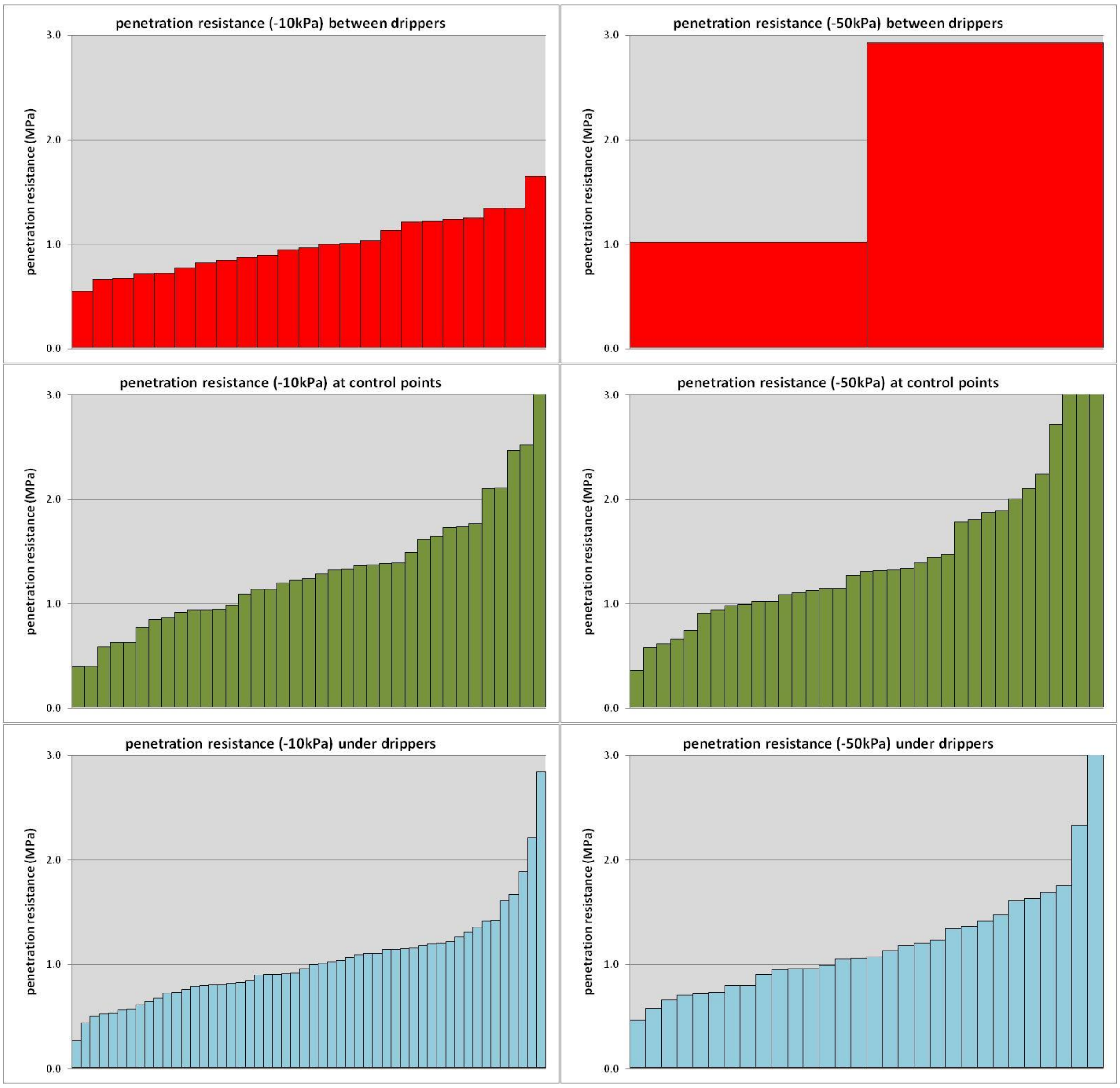


Figure 3: *Subsoil penetration resistances at field capacity (-10 kPa) and at -50 kPa in vineyards directly under drippers, mid-way between well-spaced (>2 metres) drippers and at non-irrigated control points.*

Table 7 shows that PR tends to be concentrated in the range 0.5-2 MPa; 90% of observations at field capacity (-10 kPa) and 82% at -50 kPa fell in this range. There were few observations of PR below 0.5 or above 2 MPa in the vine row. However, there were a substantial number above 2 MPa at non-irrigated control points. Plant roots must either grow into existing pores or else create new ones; infiltration rates measured in this project suggest that such pores are scarce and there is little doubt that PR values in this range present obstacles to root growth.

	-10 kPa		
penetration resistance (MPa)	under drippers	between drippers	non-irrigated control points
<0.5	4%	0	5%
<2	96%	100%	86%
	-50 kPa		
<0.5	3%	0	3%
<2	93%	*50%*	80%

Table 7: *An overall summary of the distribution of subsoil penetration resistances measured in the laboratory at field capacity (-10 kPa) and at -50 kPa. Intact subsoil cores were taken in vineyards directly under drippers, mid-way between well-spaced (>2 metres) drippers and at non-irrigated control points.*

Table 8 shows that the average penetration resistances at our sites in the Barossa, M.I.A. and Sunraysia are of similar magnitude.

location	penetration resistance (MPa) at -10 kPa						ratio-vine row: control
	site ave.	std. dev.	vine row ave.	std. dev.	control ave.	std. dev.	
ADELAIDE							
Urrbrae	1.50	0.81	1.32	0.83	2.04	0.60	0.65
BAROSSA	1.06	0.54	0.99	0.33	1.28	0.93	0.78
Bethany	0.87	0.21	0.81	0.22	1.02	0.11	0.80
Ebenezer 2	1.50	1.25	0.92	0.24	3.23	1.60	0.28
Nuriootpa	1.05	0.25	1.11	0.27	0.86	0.01	1.3
Ebenezer 1	0.92	0.36	0.83	0.32	1.38	0.01	0.60
Tanunda 1	1.04	0.44	1.25	0.23	0.40	0.00	3.1
Tanunda 2	0.83	0.17	0.81	0.10	0.87	0.39	0.94
Greenock	1.06	0.29	0.96	0.27	1.35	0.02	0.71
Angaston	1.40	0.43	1.55	0.45	1.10	0.15	1.4
CURRENCY CREEK							
Finniss	0.64	0.16	0.54	0.03	0.74	0.19	0.73
M.I.A.	1.24	0.52	0.98	0.20	1.50	0.62	0.65
Hanwood	1.62	0.82	0.93	0.15	2.32	0.29	0.40
Stanbridge	1.13	0.45	1.05	0.44	1.21	0.61	0.86
Leeton	1.30	0.32	1.07	0.10	1.53	0.29	0.70
Whitton	0.89	0.06	0.86	0.07	0.93	0.02	0.92
SUNRAYSIA	1.30	0.34	1.18	0.40	1.41	0.23	0.84
Boeill Creek	1.27	0.36	1.22	0.56	1.32	0.25	0.92
Irymple	1.38	0.27	1.23	0.12	1.53	0.34	0.80
Mildura South	1.19	0.39	0.91	0.01	1.48	0.36	0.61
Curlwaa	1.34	0.43	1.37	0.74	1.32	0.11	1.0

Table 8a: *A vineyard summary of subsoil penetration resistances (MPa) at field capacity (-10 kPa) in vine rows (includes points directly under drippers and mid-way between well-spaced (>2 metres) drippers in some vineyards) and at non-irrigated control points. The ratio of vine row to control point penetration resistances is also shown. Values highlighted in yellow are averages of values observed in a region.*

location	penetration resistance (MPa) at -50 kPa						ratio-vine row: control
	site ave.	std. dev.	vine row ave.	std. dev.	control ave.	std. dev.	
ADELAIDE							
Urrbrae	2.81	1.49	2.96	2.45	2.65	0.77	1.1
BAROSSA	1.29	0.90	1.15	0.62	1.40	1.09	0.82
Bethany	0.97	0.30	0.85	0.39	1.09	0.26	0.78
Ebenezer 2	2.05	1.83	1.13	0.09	2.96	2.59	0.38
Nuriootpa	2.29	0.64	2.27	0.93	2.31	0.59	0.98
Ebenezer 1	1.10	0.02			1.10	0.02	
Tanunda 1	0.73	0.31	0.99	0.04	0.47	0.16	2.1
Tanunda 2	0.85	0.14	0.83	0.17	0.87	0.17	0.95
Greenock	0.90	0.16	0.84	0.17	1.02		0.82
Angaston	1.18	0.22			1.18	0.22	
CURRENCY CREEK							
Finniss	0.71	0.21	0.63	0.23	0.78	0.23	0.81
M.I.A.	1.34	0.56	1.12	0.34	1.56	0.66	0.72
Hanwood	1.97	0.78	1.43	0.36	2.51	0.71	0.57
Stanbridge	1.26	0.18	1.21	0.22	1.30	0.21	0.93
Leeton	1.19	0.35	1.00	0.48	1.37	0.04	0.73
Whitton	0.96	0.15	0.85	0.07	1.08	0.11	0.79
SUNRAYSIA	1.49	0.48	1.42	0.51	1.56	0.48	0.91
Boeill Creek	0.94	0.30	0.89	0.22	0.99	0.45	0.90
Irymple	1.64	0.23	1.44	0.04	1.83	0.06	0.79
Mildura South	1.78	0.33	1.69	0.09	1.86	0.55	0.91
Curlwaa	1.61	0.59	1.66	0.95	1.57	0.35	1.1

Table 8b: *A vineyard summary of subsoil penetration resistances (MPa) at -50 kPa in vine rows (includes points directly under drippers and mid-way between well-spaced (>2 metres) drippers in some vineyards) and at non-irrigated control points. The ratio of vine row to control point penetration resistances is also shown. Values highlighted in yellow are averages of values observed in a region.*

Figure 4 shows that there are no systematic differences within vine rows between PR directly under, and mid-way between well-spaced drippers; based on the original hypothesis of this project, it was expected that there would be. However, Figure 4 and the last column of Tables 8a & b show that in about 80% of cases, PR within vine rows was less than at control points. As with infiltration rates this is the opposite of what was expected and suggests again that the process of vineyard preparation, vine growth and irrigation has, if anything, reduced PR in these soils. However as discussed above, there is little doubt that most of the soils examined have penetration resistances that are likely to retard good root development.

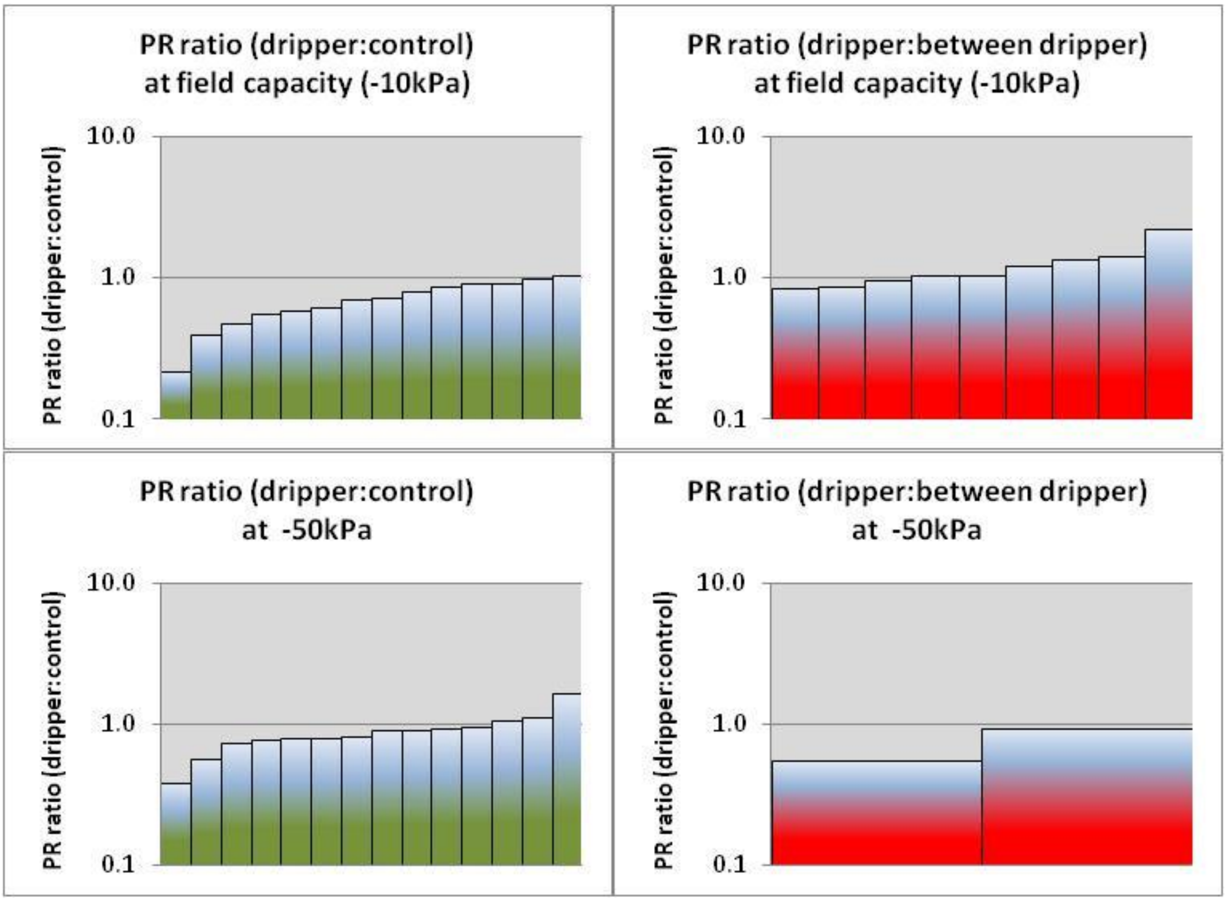
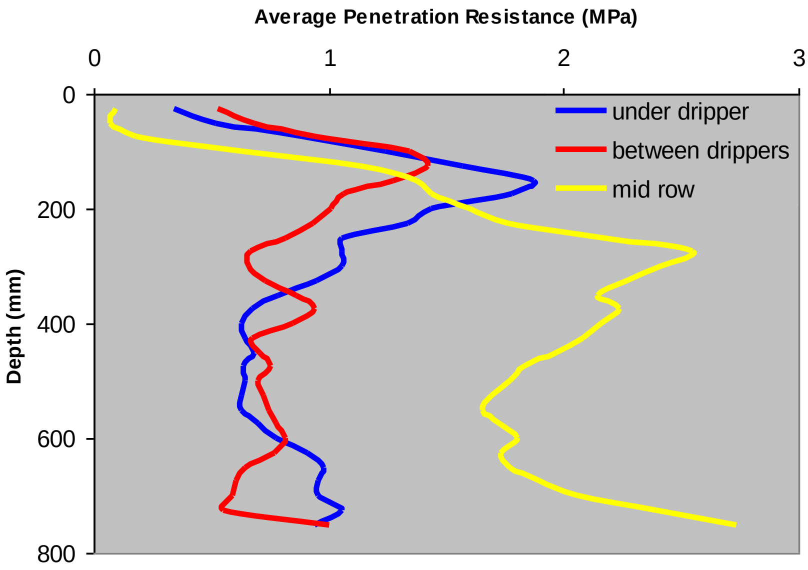


Figure 4: *Subsoil penetration resistance ratios (dripper:control & dripper:between dripper) in vineyards. "dripper" refers to a position directly under a dripper, "between dripper" refers to a point mid-way between well-spaced (>2 metres) drippers and "control" refers to an adjacent non-irrigated control point.*



Measured field penetration resistance profiles at recently irrigated (24-36 hrs) locations in a vineyard.

Air-filled porosity

Root respiration (and biological activity in general) requires oxygen; for vines this is particularly true during flushes of root growth in Spring[10]. Oxygen is necessarily limited in soils where the available pore space is filled with water for long periods. The diffusion of oxygen into the soil from the atmosphere is a complex process that depends on the size and continuity of gas-filled pores so that air-filled porosity (AFP) is really only a surrogate measurement for oxygen availability. Nevertheless, there is general acknowledgment that low AFP deprives plant roots of oxygen and suppresses root growth and activity.

Critical values of AFP are ambiguous because plant response to oxygen availability depends on the plant itself and because porosity does not of itself determine the connectivity of gas-filled pores in a soil. Indeed, AFP is only a measurement of *gas*-filled pores where the gas may have a range of oxygen concentrations from atmospheric to zero. Despite these difficulties, it is widely agreed that an AFP value of about 0.25 at field capacity is ideal and that 0.1 is minimal for unlimited root respiration.

At a given bulk density, in the absence of substantial swelling or added compaction, the sum of air-filled porosity and water content is fixed so that AFP declines as water content increases. For any given soil, AFP decreases as bulk density increases (e.g. via traffic compaction).

As with penetration resistance, AFP was at first measured at field capacity (-10 kPa) when the soil is at its wettest (and least aerated) for practical purposes. At a later stage in the project we began to include measurements at -50 kPa which we regarded as a practical subsoil “refill point” for many irrigated enterprises. AFP values measured under these conditions ranged from about 0 to 0.11 at field capacity (-10 kPa) and from about 0.003 to 0.18 at -50 kPa. These results are summarized below.

	air-filled porosity at -10 kPa					
position	n	average	standard deviation	coeff.var.	min.	max.
under drippers	52	0.038	0.025	0.66	0.002	0.108
between drippers	23	0.045	0.026	0.59	0.014	0.106
non-irrigated control points	37	0.034	0.019	0.56	0.006	0.089
	air-filled porosity at -50 kPa					
under drippers	30	0.064	0.043	0.67	0.006	0.178
between drippers	2	*0.120*	*0.040*	*0.33*	*0.091*	*0.148*
non-irrigated control points	37	0.053	0.030	0.56	0.012	0.136

Table 9: *An overall summary of subsoil air-filled porosities at field capacity (-10 kPa) and at -50 kPa. Intact subsoil cores were taken in vineyards directly under drippers, mid-way between well-spaced (>2 metres) drippers and at non-irrigated control points.*

---

[10] Oxygen concentration in soil also determines soil *redox potential*. This influences the availability of both nutrients and toxic species in soil solution.

Table 9 and Figure 5 show an overall summary of AFP. There is no general trend in AFP due to irrigation alone.

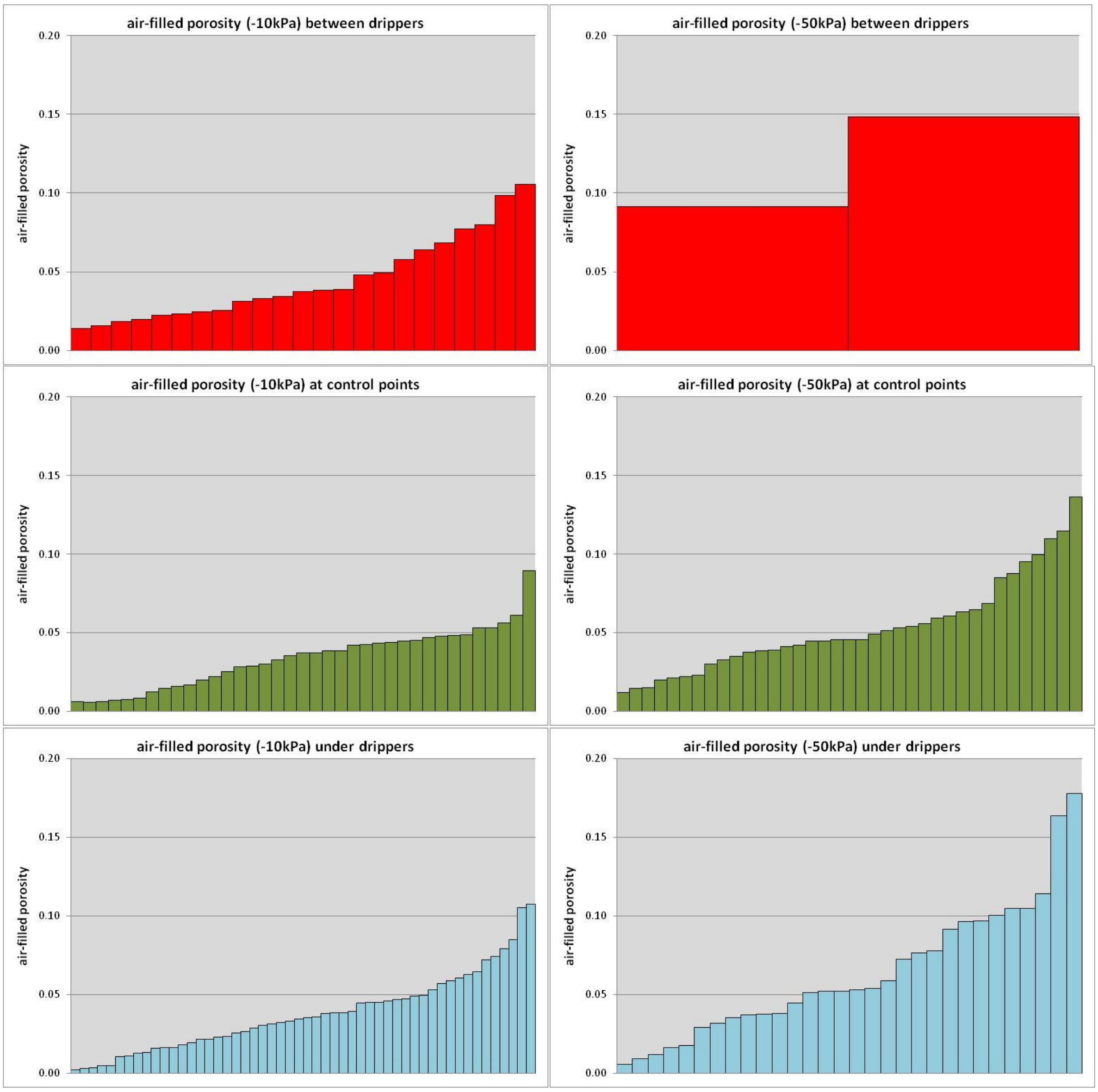


Figure 5: *Subsoil air-filled porosities at field capacity (-10 kPa) and at -50 kPa in vineyards directly under drippers, mid-way between well-spaced (>2 metres) drippers and at non-irrigated control points.*

Table 10 shows that virtually all soil samples examined at field capacity had less than the minimum requisite AFP of 0.1; at the refill point the situation is scarcely better. This suggests that poor aeration may be the most significant problem in these soils. As many of these subsoils also have low infiltration rates, they are likely to remain water-logged for extended periods after rain or irrigation.

	-10 kPa		
air-filled porosity	under drippers	between drippers	non-irrigated control points
<0.05	75%	70%	86%
<0.10	96%	96%	100%
	-50 kPa		
<0.05	40%	0	57%
<0.10	80%	*50%*	92%

Table 10: *An overall summary of the distribution of subsoil air-filled porosities at field capacity (-10 kPa) and at -50 kPa. Intact subsoil cores were taken in vineyards directly under drippers, mid-way between well-spaced (>2 metres) drippers and at non-irrigated control points.*

Table 11 shows that the average air-filled porosities at our sites in the Barossa, M.I.A. and Sunraysia are of similar magnitude.

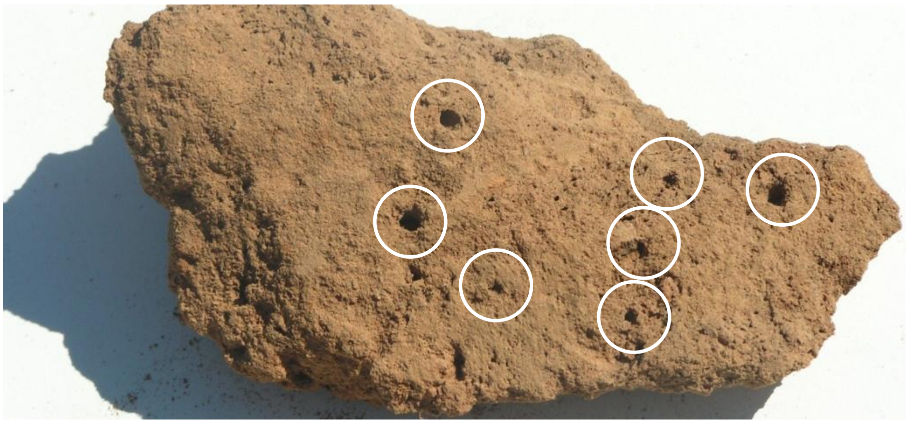
location	**air-filled porosity at -10 kPa**						ratio-vine row: control
	site ave.	std. dev.	vine row ave.	std. dev.	control ave.	std. dev.	
ADELAIDE							
Urrbrae	0.076	0.030	0.080	0.028	0.061	0.040	1.32
BAROSSA	0.037	0.021	0.036	0.025	0.036	0.015	0.99
Bethany	0.027	0.014	0.022	0.012	0.042	0.009	0.53
Ebenezer 2	0.015	0.009	0.017	0.010	0.010	0.003	1.64
Nuriootpa	0.055	0.013	0.055	0.015	0.057	0.006	0.96
Ebenezer 1	0.052	0.025	0.055	0.027	0.039	0.000	1.43
Tanunda 1	0.029	0.010	0.028	0.008	0.034	0.018	0.81
Tanunda 2	0.031	0.014	0.030	0.016	0.033	0.006	0.92
Greenock	0.037	0.028	0.037	0.033	0.036	0.009	1.01
Angaston	0.039	0.010	0.040	0.006	0.039	0.020	1.01
CURRENCY CREEK							
Finniss	0.030	0.025	0.050	0.014	0.009	0.005	5.55
M.I.A.	0.025	0.013	0.024	0.015	0.026	0.014	0.95
Hanwood	0.028	0.013	0.037	0.011	0.018	0.002	2.01
Stanbridge	0.038	0.008	0.033	0.010	0.043	0.001	0.76
Leeton	0.028	0.020	0.023	0.005	0.032	0.034	0.71
Whitton	0.007	0.006	0.003	0.000	0.011	0.007	0.31
SUNRAYSIA	0.039	0.012	0.041	0.018	0.038	0.007	1.08
Boeill Creek	0.028	0.022	0.028	0.024	0.027	0.030	1.03
Irymple	0.037	0.008	0.035	0.004	0.038	0.014	0.92
Mildura South	0.056	0.015	0.067	0.010	0.044	0.001	1.53
Curlwaa	0.038	0.011	0.034	0.018	0.041	0.006	0.83

Table 11a: *A vineyard summary of subsoil air-filled porosities at field capacity (-10 kPa) in vine rows (includes points directly under drippers and mid-way between well-spaced (>2 metres) drippers in some vineyards) and at non-irrigated control points. The ratio of vine row to control point air-filled porosities is also shown. Values highlighted in yellow are averages of values observed in a region.*

location	air-filled porosity at -50 kPa						ratio-vine row: control
	site ave.	std. dev.	vine row ave.	std. dev.	control ave.	std. dev.	
ADELAIDE							
Urrbrae	0.105	0.051	0.127	0.072	0.082	0.025	1.55
BAROSSA	0.064	0.041	0.078	0.047	0.054	0.033	1.45
Bethany	0.048	0.028	0.058	0.028	0.039	0.034	1.47
Ebenezer 2	0.031	0.017	0.021	0.022	0.040	0.003	0.54
Nuriootpa	0.077	0.048	0.104	0.063	0.050	0.008	2.07
Ebenezer 1	0.018	0.005	-	-	0.018	0.005	-
Tanunda 1	0.069	0.032	0.096	0.006	0.042	0.005	2.31
Tanunda 2	0.051	0.002	0.053	0.001	0.050	0.002	1.05
Greenock	0.125	0.032	0.139	0.035	0.112	0.034	1.24
Angaston	0.080	0.049	-	-	0.080	0.049	-
CURRENCY CREEK							
Finniss	0.037	0.017	0.034	0.026	0.039	0.016	0.88
M.I.A.	0.039	0.022	0.036	0.023	0.042	0.023	0.81
Hanwood	0.043	0.009	0.046	0.011	0.039	0.009	1.18
Stanbridge	0.067	0.032	0.062	0.015	0.072	0.053	0.86
Leeton	0.032	0.020	0.024	0.008	0.040	0.029	0.59
Whitton	0.014	0.006	0.011	0.002	0.018	0.008	0.60
SUNRAYSIA	0.068	0.019	0.076	0.017	0.059	0.021	1.32
Boeill Creek	0.063	0.032	0.068	0.052	0.057	0.016	1.20
Irymple	0.056	0.026	0.068	0.033	0.045	0.021	1.53
Mildura South	0.095	0.008	0.101	0.006	0.090	0.007	1.12
Curlwaa	0.056	0.028	0.066	0.043	0.046	0.010	1.44

Table 11b: *A vineyard summary of subsoil air-filled porosities at field capacity (-50 kPa) in vine rows (includes points directly under drippers and mid-way between well-spaced (>2 metres) drippers in some vineyards) and at non-irrigated control points. The ratio of vine row to control point air-filled porosities is also shown. Values highlighted in yellow are averages of values observed in a region.*

Figure 6 shows that there is no systematic difference between average AFP values measured in the vine row and at controls. Within the vine row values *between* drippers appear to be systematically a little larger than those directly under drippers. This may be due to some blockage of pores by roots under drippers.



Macropores in a subsoil clod from a Red Chromosol at Tanunda. Continuous macropores promote infiltration, relieve anoxia in the surrounding soil matrix and provide pathways for root growth.

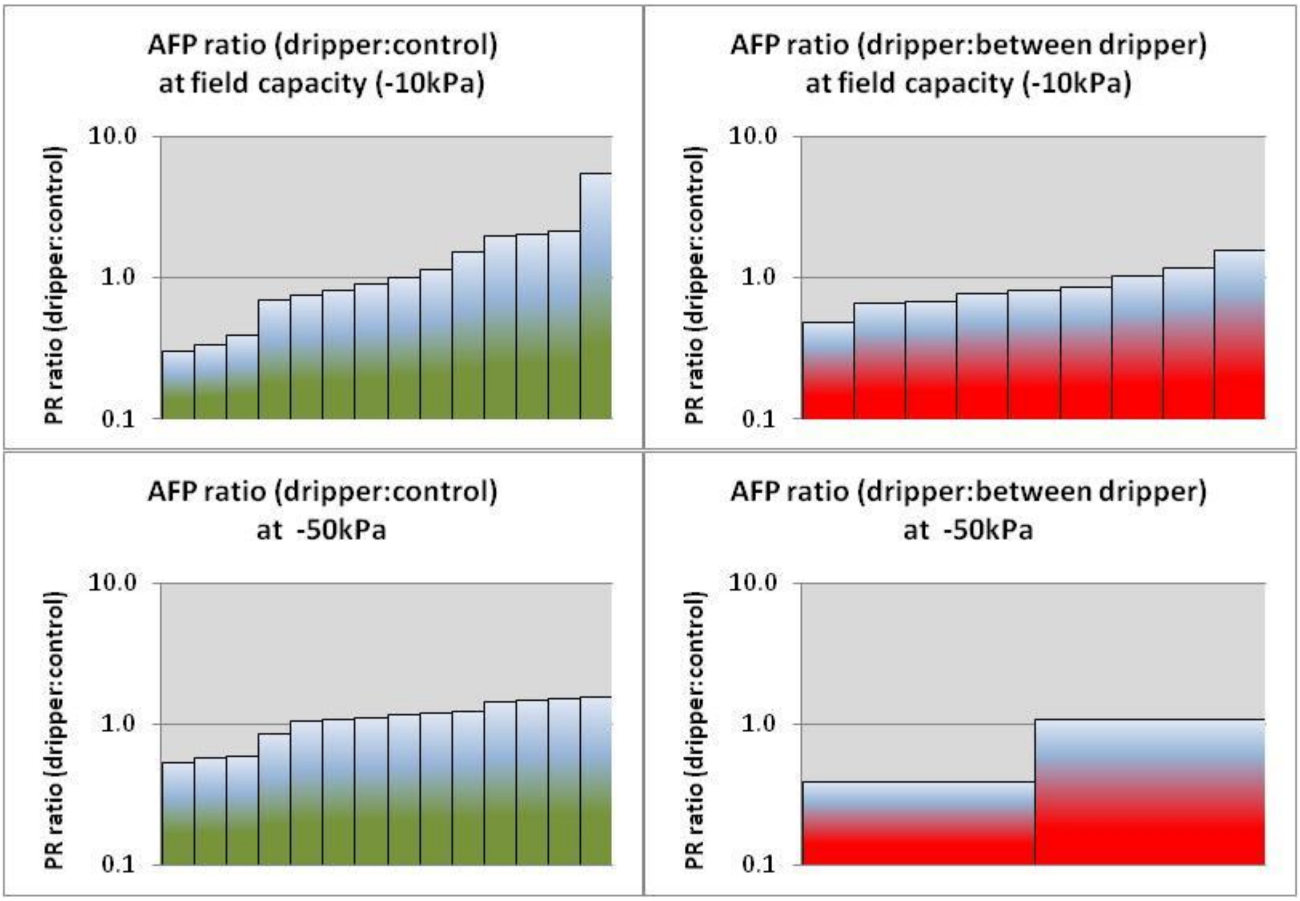


Figure 6: *subsoil air-filled porosity (AFP) ratios (dripper:control & dripper:between dripper) in vineyards. "Dripper" refers to a position directly under a dripper, "between dripper" refers to a point mid-way between well-spaced (>2 metres) drippers and "control" refers to an adjacent non-irrigated control point.*

Penetration resistance and air-filled porosity - a conjunction of poor conditions for root growth

The greatest threat to soil structure is the loss of large pores or macroporosity as this inevitably reduces infiltration rate and air-filled porosity and increases penetration resistance. This simultaneous reduction in the supply of oxygen to growing roots, its persistence when infiltration is poor, together with increased mechanical resistance to root growth inevitably limits the spread of roots.

This loss of macroporosity frequently results from traffic compaction but also from the collapse of wet, structurally unstable soils because they are sodic or have low organic matter contents. More importantly, its loss is hastened by the absence of the very processes that created it and sustained it in the first place *viz.* root growth and other biological activity in the soil[11].

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[11] During our field work, sightings of earthworms in vineyards were practically non-existent.

Figure 7 summarizes the situation in the soils examined in this project. Less than 5 % of the samples have *both* adequate air-filled porosity (AFP > 0.1) *and* penetration resistance which is low enough (PR < 2 MPa) to permit root growth. Lanyon *et al.* (2004) in their review have drawn particular attention to the lack of knowledge about the effect of high soil strength and anoxia on vine performance.

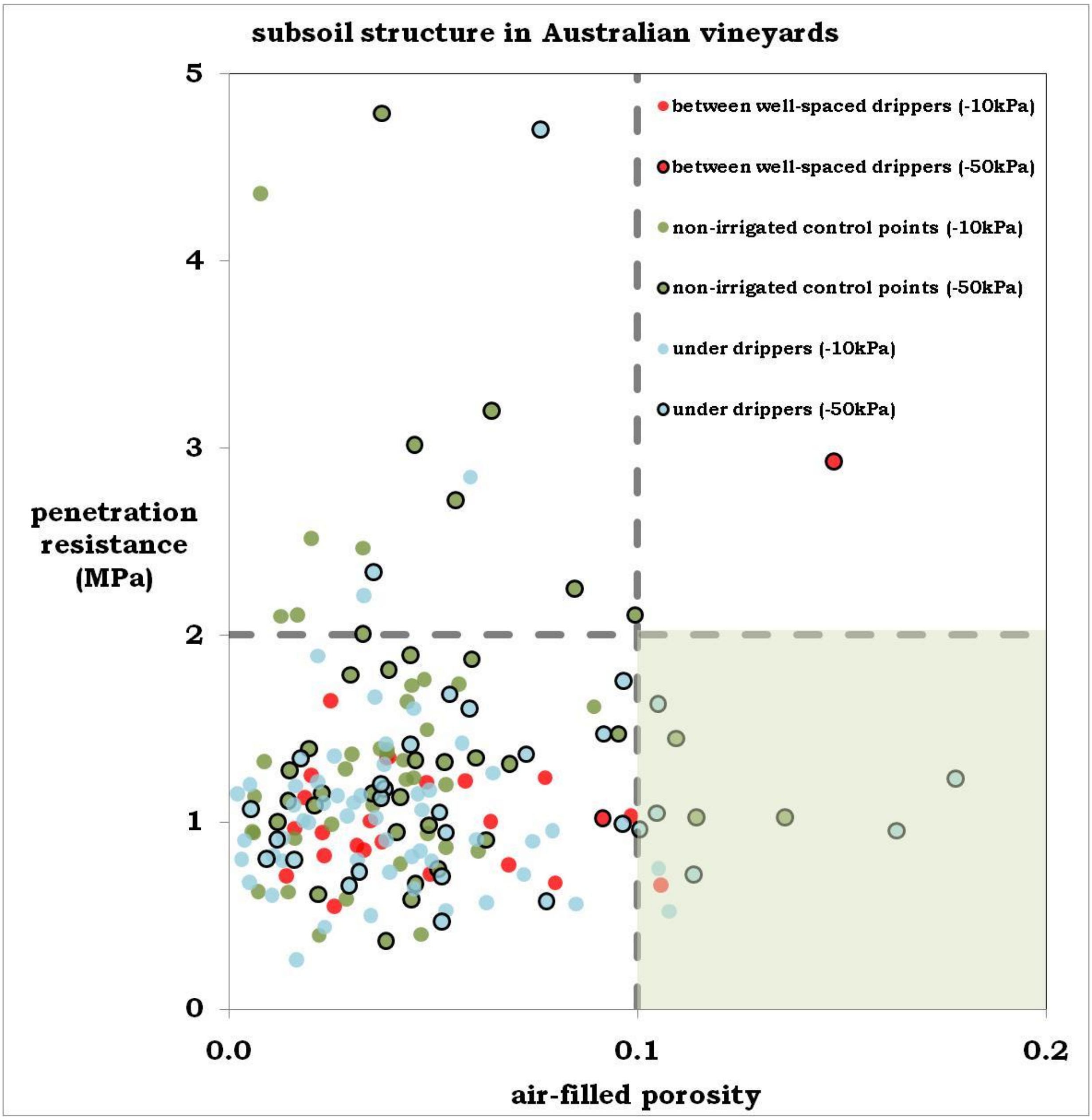

Figure 7: *Penetration resistance and air-filled porosity for 179 subsoil samples from 122 locations in 18 vineyards in 5 distinct regions. Samples are from positions directly under drippers, mid-way between well-spaced (>2 metres) drippers and from adjacent non-irrigated control points. Measurements were made at field capacity (-10 kPa) and at -50 kPa.*

This means that virtually all of these subsoils are hostile to root activity over the range -10 to -50 kPa and probably well beyond. This situation is shown in Figure 8. A soil with sufficient macropores allows roots to grow and function over the full range of soil water contents from field capacity to the permanent wilting point. The loss of these macropores reduces air-filled porosity and increases penetration resistance leading to a much narrower range of water contents in which the roots can function and grow. This necessarily reduces water use efficiency. For many of the subsoils we have studied, it is quite clear that the width of the "window" of available water shown in the figure below is zero. At any water content the soil is either too strong or too anoxic to permit root growth, or else both.

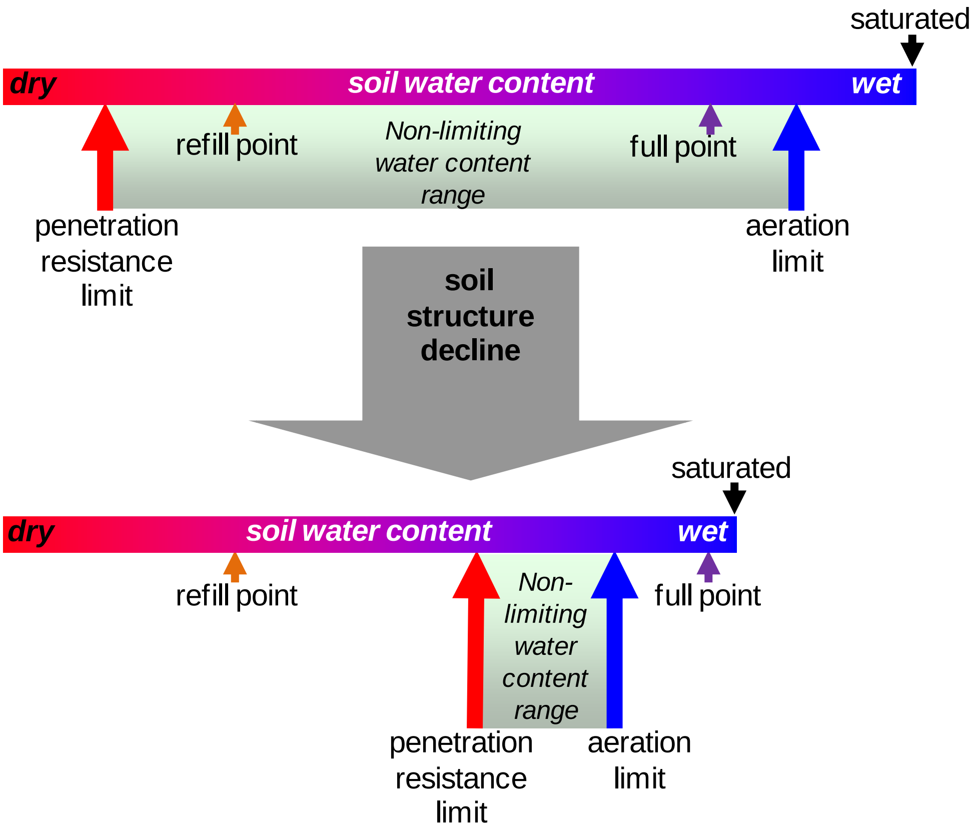

Figure 8: *The "window" of non-limiting water contents being closed by soil structure decline. Subsoils with poor structure are a lost resource because their water contents make them inhospitable for root activity much of the time. Adapted from Letey (1985).*

Soil chemical analysis

As background information and to disclose soil chemical properties that might impact upon subsoil structure (such as very high or low pH and sodicity - SAR[12]), 1:5 soil water extracts were tested for pH, EC and analysed for 20 elements[13]. These results are summarized in Table 12.

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[12] SAR = Sodium Adsorption Ratio = $[Na^+]/([Ca^{2+}]+[Mg^{2+}])^{½}$ where $[M^{n+}]$ are solution concentrations (mmol/L).

[13] Al, B, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, S, Se, Ti, Zn

region	soils	samples	$pH_{av.}$	pH range	$SAR_{av.}$	SAR range	$EC_{av.}$	EC range
Adelaide	1	7	5.7	5.1-6.0	1.1	0.3-2.4	0.23	0.08-0.43
Barossa Valley	9	56	6.8	5.7-7.7	2.8	0.3-12.6	0.16	0.02-0.46
Currency Creek	1	6	7.2	6.8-7.4	8.0	5.0-10.6	0.51	0.25-0.89
M.I.A.	5	16	6.7	6.1-7.6	3.1	0.8-5.7	0.22	0.02-1.22
Sunraysia	5	16	7.6	6.1-9.1	12.5	0.6-48.9	0.71	0.10-2.5

Table 12: *A summary of 1:5 soil:water extract properties for 101 subsoil samples that were subsamples of those used to measure subsoil structural properties.*

None of the concentrations of water-extractable macronutrients, micronutrients or soil contaminants were noteworthy[14].

Soil pH was largely in the range 6-8 (87% of samples) so that pH was probably not a significant influence on soil structural stability in these soils. Soil structural stability is largely affected by pH>8.5 (3%) or by pH<5.5 (2%). In two thirds of cases pH values in the vine row and at control points were within 0.5 units of one another. In the case of the largest differences between them (up to 1 unit), the pH in the vine row was lower, possibly due to fertilizer use (e.g. Ammonium fertilizers).

Only 7% of samples were saline (EC>0.7 dS/m); the worst of these were mainly from the control points at the Curlwaa and Boeill Creek sites in Sunraysia which were naturally saline. There were only two instances of salinity observed in vine row samples (Finniss, Stanbridge). In South Australia, EC was almost invariably higher (x2) in the vine row than at control points. In Sunraysia and the M.I.A. this was reversed; EC was considerably lower (x4) in the vine row. These trends reflect the facts that, while soil samples from South Australia were overwhelmingly less naturally saline, irrigation water quality was poorer and water usage was much lower so that leaching was much less dramatic than in the vineyards of Sunraysia and the M.I.A.

Unlike salinity, sodicity was widespread; overall, 42% of samples were sodic (SAR>3) and 15% were strongly sodic (SAR>7.5)[15]. As with salinity, *strongly* sodic soils were mostly in Sunraysia, mainly at control points, at Currency Creek and in one Barossa Valley vineyard (Tanunda 2). Moderate sodicity generally occurred in all regions. As with salinity, sodicity in Sunraysia and the M.I.A. was mainly at control points but in South Australia it was also common in the vine row. The trends in SAR are very similar to those in EC. In South Australia SAR was invariably higher in the vine row (x2) compared to controls while in Sunraysia and the M.I.A., SAR was lower in the vine row (x5). The reasons for this are probably as stated above for salinity. These relationships are shown in Figure 9 .

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[14] The only exception to this may be Boron. Some results suggested that a proper Boron assay may be needed. This has no impact upon subsoil structure.

[15] The assumption is made here that Exchangeable Sodium Percentage (ESP) ≈ 2 x $SAR_{1:5}$.

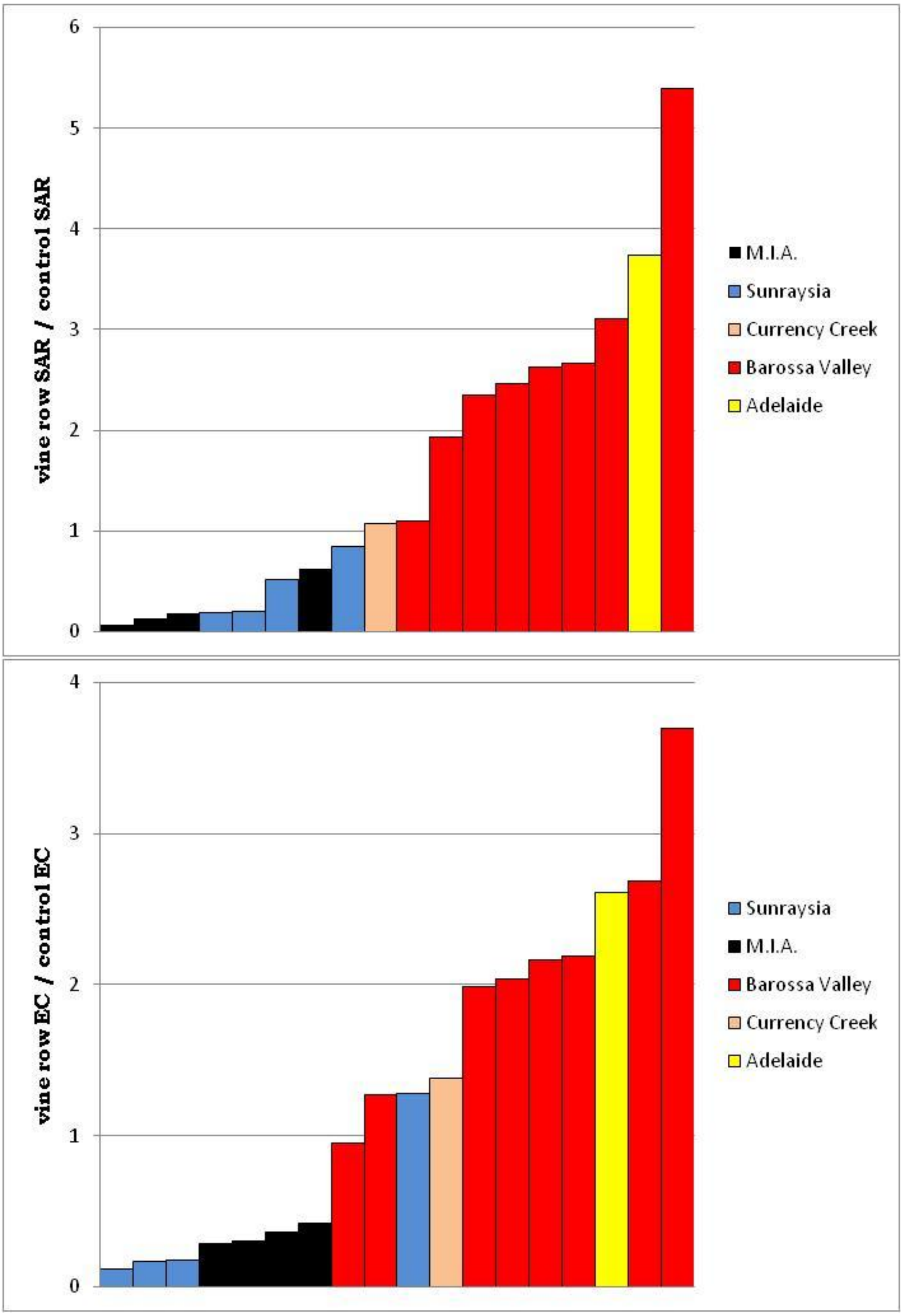

Figure 9: *Sodicity (SAR) and salinity (EC) ratio (vine row/control point) in subsoil samples from vine growing regions. Values greater than 1 denote higher sodicity and salinity in the vine row than at control points.*

Of the 18 vineyards studied in this way 6 were consistently sodic *in* the vine row; these are shown in Table 13. In all but one of these vineyards (Ebenezer 1) the origin of the sodicity appears to be clear. Many of the Barossa Valley vineyards have a history of irrigation with bore water of poor quality but have now (since about 2002) switched to a source of better quality (*ca.* 0.5 dS/m, Barossa Infrastructure Limited or B.I.L. water). However, although salinity may be leached relatively quickly, sodicity may persist. Sodicity at the Bethany, Tanunda 2 and Finniss vineyards probably arises from extended use of saline water. At Bethany and Tanunda 2, the soils have high exchange capacities so that sodicity will be leached more slowly by winter rainfall. By comparison, a neighbouring vineyard to Tanunda 2 (Tanunda 1)) is irrigated with exactly the same water, has a smaller exchange capacity and is less sodic ($SAR_{av.}$=3.7).

The level of sodicity in the Finniss vineyard is not surprising given the irrigation water quality; the elevated sodicity at the control points near this vineyard derives from previous land use as a dairy pasture sprinkler-irrigated with water from the same source. The Boeill Creek and Curlwaa vineyards in Sunraysia are clearly on naturally saline-sodic soils but have been leached by water of relatively good quality.

location	average SAR		average EC (dS/m)		water quality (dS/m)
	vine row	control	vine row	control	
Bethany	4.8	0.9	0.24	0.25	2.4 until 2001 then ~1
Ebenezer 1	4.8	1.5	0.28	0.10	<1
Tanunda 2	7.6	2.9	0.31	0.14	2.8
Finniss	8.3	7.7	0.59	0.43	3.7 (average 2006/7)
Boeill Creek	3.5	29	0.40	1.4	~0.1
Curlwaa	18	29	0.73	2.0	~0.1

Table 13: *Average 1:5 SAR and EC values in vineyards that were consistently sodic in the vine row.*

It is interesting to note that soil samples taken at the Nuriootpa site ($EC_{av.}$=0.11 dS/m; $SAR_{av.}$=1.7) showed little evidence of irrigation for 11 years (1989-2000) with bore water of marginal quality ($EC \approx 3$ dS/m; $SAR \approx 8$). As this soil has received no gypsum treatment, both salinity and sodicity have presumably been leached by winter rainfall and improved irrigation water (EC=0.5 dS/m; SAR=2.7).

These considerations, together with the unexplained sodicity at Ebenezer 1, make it difficult to be certain about the origins of sodicity in each of these soils. Local hydrology (especially groundwater accession) and soil mineralogy as well the histories of seasonal rainfall, irrigation water quality[16], application rates and gypsum application are all important contributing factors here. Information about these is often anecdotal and falls far short of the detailed and reliable knowledge required.

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[16] The common practice of mixing (“shandying”) irrigation water from various sources, depending on the severity of water restrictions, further obscures the origins of sodicity.

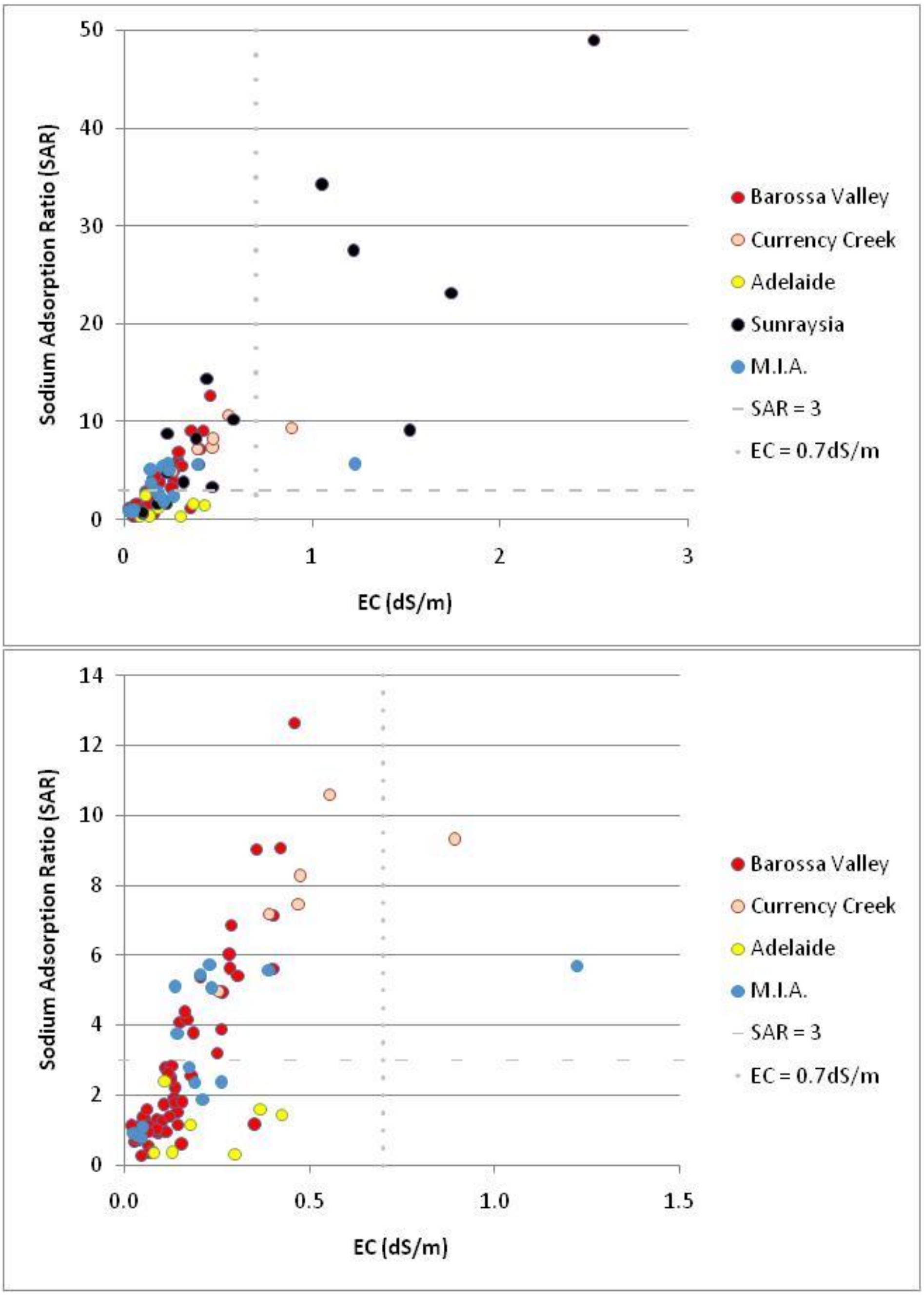

Figure 10: *Relationship between sodicity (SAR) and salinity (EC) in 1:5 soil:water extracts of subsoil samples from vine growing regions. The lower graph has the data for Sunraysia removed.*

The relationship between sodicity and salinity for the sites studied is shown in Figure 10. It is clear that, as with most Australian soils, salinity derives largely from sodium rather than from the other important bases (Ca, Mg, K).

Sodicity generally poses a serious threat to soil structural stability; sodic soils are notoriously prone to clay dispersion and, in consequence, the development of strong, dense profiles. The leaching of salinity and sodicity from these profiles does not undo that structural damage but only removes the “chemical signature” of salt-affected soil (EC, SAR). However there is little evidence here that sodicity, either natural or induced by irrigation, is the underlying cause of the almost universally poor subsoil structure in these soils or of the structural differences between the vine rows and their control points.

Measures of subsoil structural decline in the vine row relative to control points can be made by comparing their structural properties. The ratios of infiltration rates, penetration resistances and air-filled porosities in the vine row to those same properties at control points are shown in Tables 4, 8 and 11. None of these three measures show any significant correlation with a similar ratio for sodicity (SAR) for which the data is shown in Figure 9. This suggests that other factors are at work in determining subsoil structure but, more importantly, may also indicate that the scope for further decline, in what are already structurally poor subsoils, is limited.

Root length density

Many of the soils studied in this project have an abrupt change in texture at a depth of 10-50 cm. This seems likely to be a point where there is also a substantial change in conditions for root growth. The sandier topsoil with more biological activity (roots and other biota), higher organic carbon and less overburden is less likely to exhibit poor infiltration rates, high strength and poor aeration.

To augment our measurements of subsoil structure we decided to measure root length densities (RLD) at various depths. The objective here was to look for abrupt changes in RLD that might reflect similar changes in the capacity of the subsoil to support good root proliferation. To do this we collected 204 intact cores (38 mm) of soil to a depth of 120 cm; the cores were collected from 51 locations within the vine rows of 9 vineyards. We identified the exact location of each point where we had previously made subsoil structural measurements and withdrew 4 replicate cores from within 40 cm of that location. For each core we identified the depth of the change in texture, or in the absence of a change, chose 40 cm as a reference depth (z=0). We cut four smaller cores from the main core as shown below.

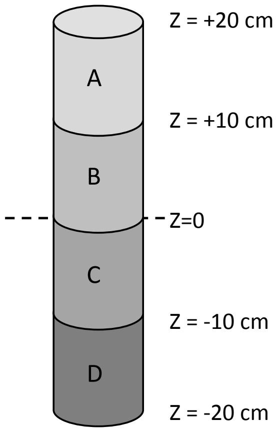

Figure 11: *soil cores (40 mm diameter) taken for measurements of root length density. “Z=0” refers either to the position of the boundary between A and B horizons or, in the absence of such a boundary, to 40 cm below the local soil surface.*

Figure 12 shows mean RLD data for the 9 vineyards studied. The range of measured values is similar to those observed elsewhere (Stevens and Douglas, 1994; Kirchhof *et al.*, 1991)) with about 95% of values in the range 0.1-2.4 cm/cm^3. There are no systematic changes of RLD with depth and certainly none of the sort that might be expected if there are abrupt changes at some depth in the soil properties that govern root growth. Indeed the decrease in RLD with depth is quite small ($[RLD_C/RLD_B]_{av.}$ = 0.95, $[RLD_D/RLD_B]_{av.}$ = 0.91). This may be because, in duplex or texture-contrast soils, abrupt changes in texture have been "blurred" by deep ripping prior to planting as this depth frequently coincides with the depth of deep ripping. This means that we may be dealing with a more diffuse zone over which soil properties change, rather than with the narrow band expected in undisturbed duplex soils[17]. In about 70% of cases, RLD is greater under drippers but this is variable ($[RLD_{\text{under dripper}}/RLD_{\text{between dripper}}]$ = 1.31; std. dev. = 0.66). The frequency distribution of RLD between and under drippers is shown in Figure 13; there are no dramatic differences between the shapes of these distributions because of depth or position.

The most significant feature of the RLD data is that there are clear differences between vineyards. This appears to be largely due to aeration. Figure 14 shows a modest positive correlation between average root length density and air-filled porosity in vine rows for the vineyards studied. The correlations are better in drier soil (i.e. -50 kPa) presumably because the soil is considerably drier than -10 kPa for most of the time that roots are growing. These relationships suggest that increased air-filled porosity is associated with increased root length density. These relationships suggest that, over the range of average vine row AFP (0.02-0.14), RLD more than doubles.

The roles of penetration resistance (PR) and infiltration rate (IR) are less clear. At the time of writing this report a critical comparison has only been made between *mean* RLD and *mean* soil properties for the 9 vineyards; we are currently examining individual data from each of the 51 locations in these vineyards and are confident that an even clearer picture will emerge. An attempt to correlate RLD data with all 3 soil physical properties (AFP, PR, IR) has met with mixed success, although the analysis of the -50 kPa data is quite encouraging. Sensibly, RLD should decrease as PR increases and roots encounter more resistance. RLD should increase with IR both because infiltration is a crude indicator of the availability of potential root channels and because it also gives an indication of the duration of "anoxic events" in soils with the same AFP. Our current analysis of the mean data suggests that, compared to AFP, RLD is less sensitive to PR and much less sensitive to IR. The implication here is that the availability of oxygen to roots is the dominant factor in determining root success in these soils and that PR may possibly succeed AFP as the dominant factor if AFP improved markedly.

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[17] These three dimensional changes in the soil profile may also be the origin of some of the variability in our infiltration, penetration resistance and air-filled porosity measurements.

It is significant that Lanyon *et al.* (2004) have pointed out that the effects of soil hardness and anoxia on vine performance are issues requiring attention.

Figure 12: *Root length densities (cm/cm³) at 3 depths (mean of 4 replicates each) at 51 sites in 9 vineyards. Levels B,C,D refer to Figure 11.*

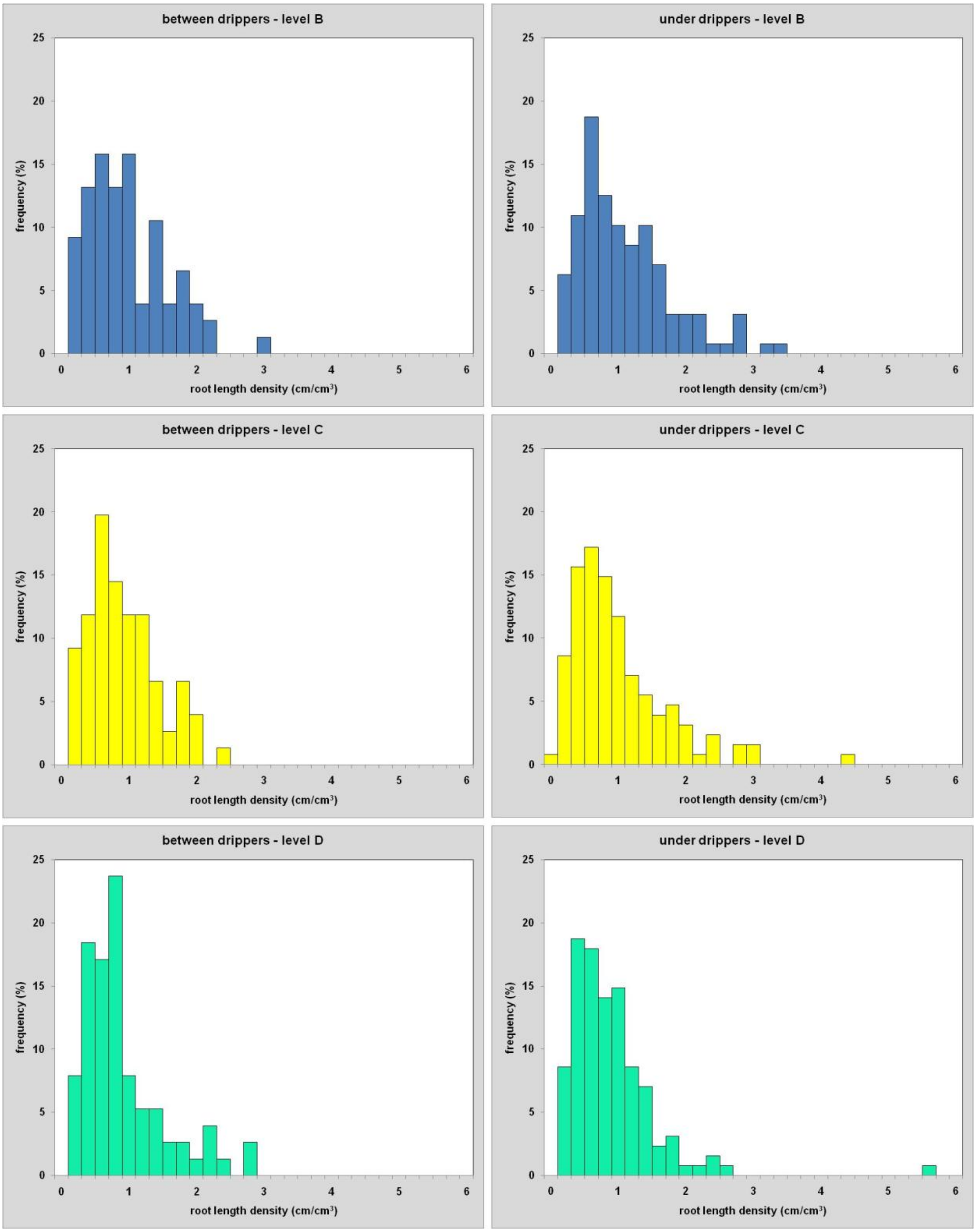
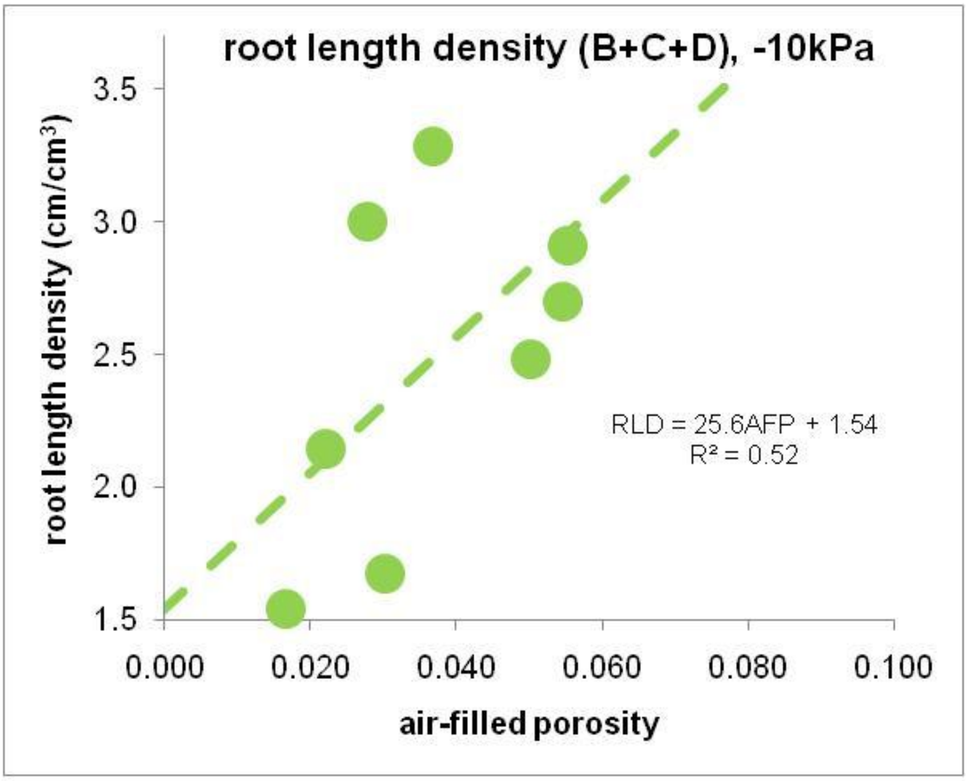


Figure 13: *Overall frequency distribution of root length densities (cm/cm^3) between and under drippers. "Between" refers to points mid-way between well-spaced (>2 metres) drippers (76 points each); "Dripper" refers to points directly beneath drippers (128 points each). Levels B,C,D refer to Figure 11.*



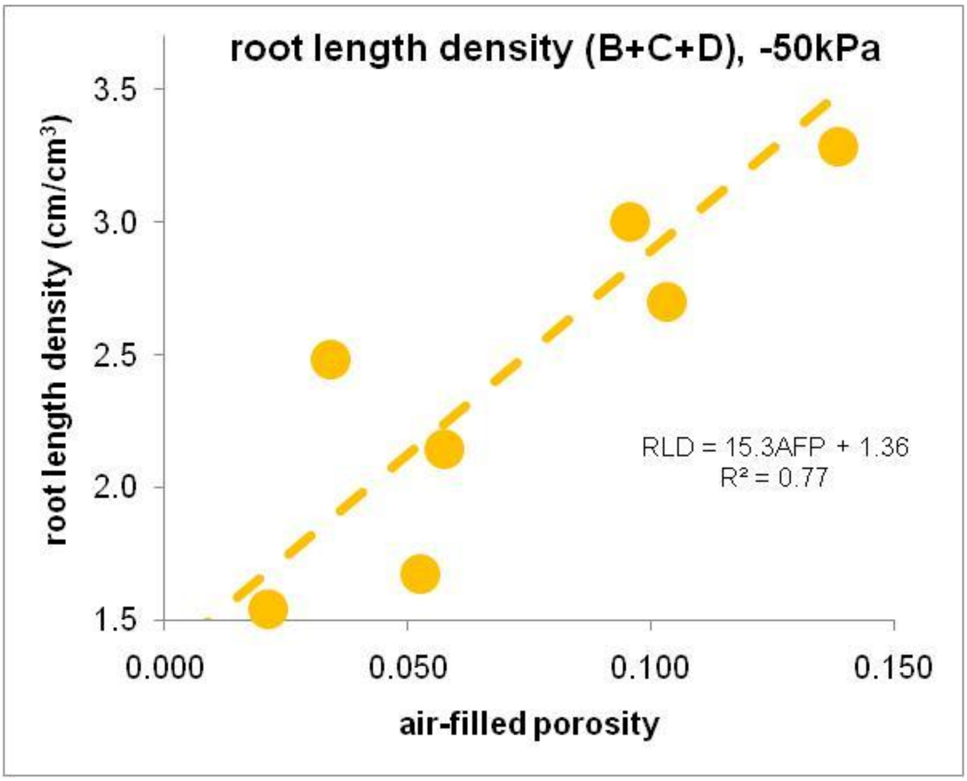


Figure 14: *Relationships between average root length density and average air-filled porosity at two matric potentials in nine South Australian vineyards. Levels B,C,D refer to Figure 11.*

In interpreting this RLD data it is important to acknowledge that the common methods of measuring RLD make no distinction between dead and living roots so that RLD is an imperfect measure of root *activity* unless the much more difficult distinction can be made between dead and living roots. (Smit *et al.*, 2000).

Prospects for the improvement of subsoil structure

As it is generally understood, soil structure is the size and continuity of the larger pores or voids in soil; these determine drainage, aeration and penetration resistance. At the surface there are a number of interventions and natural processes available to improve soil structure. These necessarily involve some sort of soil disturbance by tillage, roots, biological activity or, in clay soils, by the cracking that accompanies shrinkage during drying. However, altering subsoil structure is a much greater challenge. Deep tillage in the root zone of a permanent planting causes substantial root pruning, disturbs only a fraction of the root zone and, without ongoing efforts to sustain what is created by, for example, an intensive cover crop regime, may offer only short-lived benefits. The subsoil enjoys only a fraction of the root and other biological activity of the surface soil and careful plant selection is needed to ensure that the deep roots of a cover crop plant can create good structure and place carbon at depth. The shrinkage and cracking of clay soils is less intense in the subsoil because the changes in soil water content are less extreme. Experiments with various cover crop plants were well beyond the scope of this project and we were unaware of existing sites where in-row cover crops had been embraced by the grower. We believe that the combination of plant roots and calcium sources offer the only viable prospects of managing soil structure in established plantings.

Gypsum

There is a general acceptance of the fact that calcium, usually applied as gypsum for this purpose, can “improve” the structure of soils that contain clay. However, there appears to be no evidence that calcium *alone* can improve structure that is already poor[18]. What is not generally appreciated is that calcium can only improve the structural *stability* of soil. In other words, the role of calcium is to stabilize soil structural features once they have already been created by some disturbance such as those discussed above.

During this project we had the opportunity to assess the benefits of calcium in a gypsum trial within the SARDI vineyard at the Nuriootpa Research Centre. This vineyard had a history of irrigation with saline, sodic groundwater and the trial was established to assess the impact of gypsum. We made field measurements, of the kind we had made in several vineyards as discussed above, at a depth of about 48 cm. We also made laboratory measurements designed to remove problems with soil variability.

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[18] Dissolved calcium only removes the “chemical signature” of sodicity by displacing and leaching exchangeable sodium.

Field measurements

The field trial consisted of a no-gypsum control and several rows where both the amount and method of application of gypsum varied[19]. We made replicated measurements directly under drippers in the control row, and in each of two rows that had received gypsum at a rate of 8t/ha, applied in each of the two previous years, one as broadcast gypsum and the other as dissolved gypsum applied via drippers. The results are summarized in Table 14.

application method	air-filled porosity				infiltration rate (mm/hr)		penetration resistance (MPa)			
	-10 kPa		-50 kPa				-10 kPa		-50 kPa	
	avge.	s.d.	avge.	s.d.	avge.	s.d.	avge.	s.d.	avge.	s.d.
none	0.025	0.011	0.036	0.003	2.8	2.8	2.4	0.0	2.2	0.3
surface applied	0.033	0.026	0.028	0.019	0.6	0.5	2.4	0.4	2.7	0.0
dissolved	0.049	0.013	0.040	0.012	0.7	0.1	1.8	0.6	2.1	0.2

Table 14: *Subsoil structure directly under drippers after substantial gypsum applications (2 x 8t/ha) in a vineyard.*

There is no evidence of improvement in subsoil structure as a result of substantial gypsum applications. There is also little evidence (Table 15) of a reduction of subsoil sodicity except perhaps for a slight decrease in both salinity and sodicity for dissolved gypsum application; however, without subsoil structural improvement, there is little value in these modest gains in sodicity and salinity. It is possible that the broadcast gypsum has been blown away from the vine row or else dissolved by rain and either washed off the vine row or else passed through the soil via "bypass" flow leaving much of the soil profile unchanged.

application method	$SAR_{1:5}$	$EC_{1:5}$
none	7.5	0.45
none	10.0	0.53
surface applied	8.3	0.53
surface applied	8.8	0.57
dissolved	5.4	0.30
dissolved	7.3	0.39

Table 15: *Subsoil sodicity and salinity under drippers after substantial gypsum applications (2 x 8t/ha) in a vineyard.*

Laboratory measurements

In order to reduce problems with soil variability, we wished to examine more closely the impact of sodicity and calcium treatment on subsoil structural

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[19] These measurements were made in February-April, 2009. Irrigation water quality was poor (bore water, EC=3 dS/m, SAR=8) during 1993-2002, good (EC=0.5 dS/m) from 2003-2008 and reverted to a majority of bore water during November 2008-March 2009.

properties in single soil samples. Six intact subsoil cores (75x50 mm) were taken from the same control row of the gypsum trial and at the same depth as we made the field measurements discussed above. Each of the six cores was subjected to the following sequence:

1. saturated from the field moist condition in the laboratory, brought to -50 kPa and the air-filled porosity and penetration resistance measured.

2. leached with at least 5 pore volumes of saline/sodic “irrigation water”. The salinity was high (~80 dS/m; 1500 mmol_c/L) and three different levels of sodicity were used (SAR = 5, 10, 15). This treatment was designed to give three different levels of soil sodicity (exchangeable sodium percentages, ESP = 5, 10, 15). Each level of sodicity was replicated once. The cores were then leached with pure water until non-saline (leachate EC < 1 dS/m), brought to -50 kPa and the air-filled porosity and penetration resistance measured.

3. leached with at least 5 pore volumes of a strong calcium solution to remove all sodicity, then with pure water until non-saline (EC < 1 dS/m), brought to -50 kPa and the air-filled porosity and penetration resistance measured.

As shown in Figure 9 , there was no evidence of improvement and only a weak systematic change in infiltration rates; the rates themselves were in a similar range (0.4-10.2 mm/hr.) to those measured directly in the field (0.8-4.8 mm/hr.)[20].

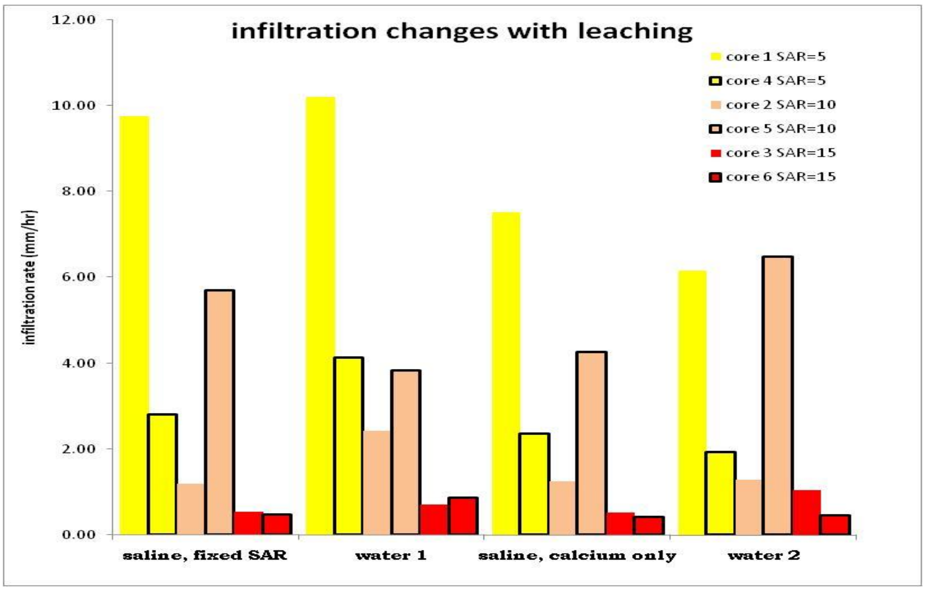

Figure 15: *Changes in infiltration rate of intact subsoil cores during leaching with (in order) saline solutions of fixed SAR, pure water, saline, calcium only solution and pure water.*

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[20] The relatively high value of infiltration rate for core 4 *may* have resulted from competitive edge flow, a common artifact in measuring hydraulic properties of soil cores in the laboratory.

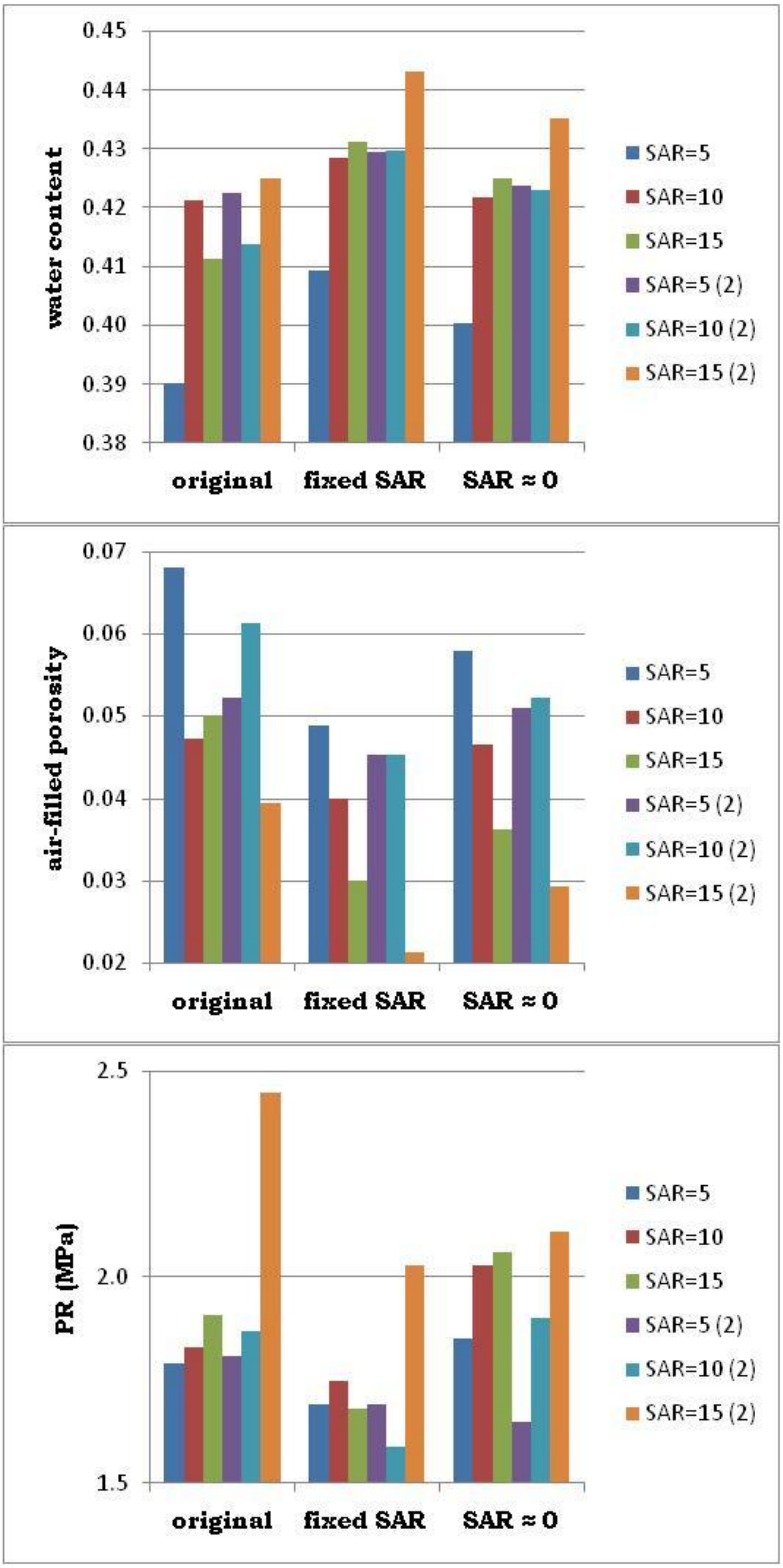

Figure 16: *Volumetric water content, air-filled porosity and penetration resistance (PR) at -50 kPa of 6 intact subsoil cores as sampled (“original”), in 3 defined non-saline, sodic states (replicated once; SAR = 5, 10, 15; “fixed SAR”) and in a non-saline, non-sodic state after leaching with calcium solution and water (“SAR ≈ 0”).*

Figure 16 shows changes in subsoil structural properties during the procedure described above; the trends are virtually the same for each subsoil core. In going from the original "field" state to a non-saline, sodic state, water content increases and air-filled porosity (AFP) and penetration resistance (PR) both decrease. When the sodicity is removed by calcium to give a non-saline, non-sodic soil, the trends are reversed. The trends in AFP and PR are simply what would be expected from the changes in water content and the origin of these changes is unclear.[21] However, one fact emerges clearly: improvements in AFP and PR are marginal to non-existent; only the structural *stability* of the soil has changed – the structure itself is still poor and needs to be regenerated by disturbance.

Shrinkage and cracking in clay subsoils

In earlier work (Currie, 2006) showed in the laboratory that allowing a clay subsoil, of the kind commonly studied in this project, to dry to the permanent wilting point (-1500 kPa) appeared to cause sufficient cracking to produce tenfold improvements in infiltration rate. In this project we had the opportunity to confirm this effect in the field. A partial rootzone drying (PRD) trial at the Nuriootpa Research Centre was used for this purpose. Instead of alternately irrigating either side of vines, one side was allowed to dry for a complete growing season and then allowed to pass through the following winter[22]. At this point three "paired sites", each consisting of a location on the dry and one on the wet side of a vine, were excavated to 35-40 cm and infiltration rates were measured in each. The results are summarized in Table 16 ; these show that there were no significant trends in infiltration rates.

location	infiltration rate (mm/hr)			avge.	std. dev.
dry side	0.7	2.1	1.3	1.4	0.7
wet side	1.7	1.1	1.3	1.4	0.3

Table 16: *Subsoil infiltration rates after prolonged drying ("dry side") and normal drip irrigation ("wet side") in a vineyard.*

The apparent failure to induce subsoil cracking in this experiment is probably due to the fact that the soil on the dry side remained wetter than the permanent wilting point throughout the experiment. This is possible because the subsoil infiltration rate is so poor that there was a substantial lateral spread of water from the dripper on the wet side towards the dry side. This, of course, raises a question about whether PRD can ever be completely

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[21] It is possible that leaching may have dissolved some cementing agents, allowed increased soil swelling to occur and prompted an increased water content in the "fixed SAR" state.

[22] It was argued that any subsoil cracking needs to survive winter to be useful; this could occur if, for example, the cracks were filled with debris from a sandier topsoil or else colonized by roots.

effective in a soil with such poor infiltration characteristics[23]. For the purpose of improving poor subsoil structure, the prospect of allowing the whole root zone to dry to wilting point is not an attractive one.

Six subsoil infiltration measurements underway in a partial rootzone drying (PRD) trial at Nuriootpa in the Barossa Valley. The "wet" and "dry" sides of vines alternate along the vine row; 3 measurements were made at positions that had not been irrigated for an entire growing season and 3 at positions that had been irrigated normally.

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[23] It is also worth noting that cracking during long drying events has not improved the subsoil structure at non-irrigated control points.

Conclusions & recommendations

Conclusions

The principal objective of this project was to investigate the sustainability of drip irrigation on duplex soils in the Barossa Valley in terms of its expected capacity to degrade soil structure. In relation to local rainfall, drip irrigation delivers a large amount of water to a small volume of soil but despite this, we have seen no evidence that drip irrigation *of itself* causes any decline in subsoil structure; this even appears to be true in soils that have some history of saline water use. In one respect this is a pleasing outcome because it helps to assure the future of an irrigation method well-suited to a climate of declining water availability. We believe the absence of such a problem can be ascribed to three factors.

1. The competitive removal of water from the soil directly beneath a dripper by vine transpiration, by drainage and by lateral movement into the drier surrounding soil ensures that this soil does not remain sufficiently wet for long enough to sustain structural damage.

2. In the case of saline water application winter leaching may be sufficient to limit soil sodicity to an extent that avoids clay dispersion and further damage to subsoil structure[24]. However, saline water use poses a serious risk to soil structure, especially in clays, and winter leaching may only protect some soils from the effects of moderately saline water sources.

3. The subsoils studied in this project all have poor structure and the opportunities for further structural decline have been reduced accordingly. This is a far more serious issue and changes the focus of the project from one of avoiding irrigation-induced structural damage to one of correcting what appears to be the natural state of affairs.

In relation to this last point, it is interesting to reflect on the fact that most of the non-irrigated control points we used in this work had subsoil structure that was *worse* than in the vine row suggesting that there may have been modest benefits from vineyard establishment and management. This observation might have been different if the controls had been neighbouring, dense stands of undisturbed native vegetation where the soil structure and the plant community had evolved together over a long period; this would perhaps represent the best structural condition a given soil can achieve in that climate. However, no such controls were available; ours were generally adjacent, traffic-free, sparsely vegetated, unimproved areas that had not had the benefit of deep tillage. This suggests that in the absence of long-standing, dense vegetation, this is the natural state of these soils and that dense plantings, combined with either deep tillage or else long periods

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[24] The presence of calcium carbonate at $pH \leq 8.5$ may also limit sodicity and structural damage.

of time, might be required to partially restore their structural potential. In this respect it is clear that none of our controls represented something to be emulated in the vine row.

Figure 7 summarizes the universally poor subsoil conditions we observed. Less than 5% of the 179 soil samples we examined had sufficient air-filled porosity (>0.10) and low enough strength (penetration resistance <2 MPa) to permit adequate root growth. If we adopt the strength criterion of Olsson and Cockroft (2002) for unrestricted root growth (penetration resistance <0.5 MPa), then *none* of the 179 soil samples qualify. This outcome was unexpected and suggests that the water use efficiency of vines in such soils are impaired by constrained root growth and function.

This view is supported by the observation of a positive correlation between average root length density and air-filled porosity in vine rows in 9 vineyards; this will be further clarified by data analysis currently underway. This suggests that the availability of oxygen to roots is a critical factor in determining root growth and function in these soils and tends to reinforce the relevance of the current NPSI project "Optimizing delivery and benefits of aerated irrigation water" (Midmore and Bhattari). The combined delivery of oxygen to the root zone along with subsoil structural improvements that reduce penetration resistance may deliver substantial improvements in root volume and activity and, consequently, important gains in water use efficiency and yield. However it is important to recognize that the improvement of oxygen supply to roots without any structural remediation in the subsoil is only treating the symptoms of poor subsoil structure. We believe that soil strength may succeed aeration as the main obstacle to root function if aeration improves markedly in the absence of any structural improvements in the subsoil.

The poor aeration conditions in vineyard subsoils has a further implication for the use of winery wastewater for irrigation. The addition of water containing high concentrations of dissolved organic carbon and a correspondingly high chemical oxygen demand may place an additional demand on the soil atmosphere in these soils. Regular additions of such water to the root zone of a plant already starved of oxygen may create unforeseen problems.

The observation of subsoil conditions hostile to root growth and function is frequently countered with the argument that grape vines are durable plants and that a "distressed" product is often grown for quality rather than yield. There is no doubt that a valid and complex debate exists around this issue (Lanyon *et al.*, 2004). However, in an age of "triple bottom line" reporting, fruit and wine quality cannot be considered in isolation. We believe that the decision to place wine grape vines under stress is one that growers ought to be able to make and implement themselves with more abstemious water use, rather than simply enduring the lack of flexibility that attends poor soil conditions and water restrictions. Improvements in the poor subsoil conditions observed in this project might afford more rain-fed Australian wine grape vineyards and more efficient water use in grape production generally.

Recommendations

Based on the discussions above our conclusions remain much as they were in December 2007 (Milestone 5)[25]. The universal, inherently poor structural status of the subsoils we have examined suggests that the greatest need here is not so much the prevention of decline in subsoil structure in these vineyards, but rather a gradual improvement of its natural state and ongoing maintenance by suitable management practices. These subsoils represent a potential resource which needs to be improved and controlled if water and nutrient use efficiency is to be maximized via the encouragement of deeper, more extensive root systems. We suspect that the current situation in many vineyards is that vine roots spend the growing season "trapped" between a shallow topsoil, where they are critically dependent upon regular applications of water and a hostile subsoil where high strength and anoxia prevent them from taking "refuge".

Strategies for the creation and maintenance of soil structure have been discussed in some detail and implemented by Cockroft and his co-workers (See Murray, 2007) in the stone fruit industry but little of this appears to have made its way into grape production.[26] The potential benefits of these practices in vineyards have also been discussed in a review by Lanyon *et al.* (2004).

There are three basic approaches to the improvement of soil structure in the root zone.

1. Increase the volume of topsoil that roots have access to so that they are less reliant on a hostile subsoil. This involves mounding of the vine row soil by removing topsoil from the inter-row where it is of less use. This needs to be done with careful regard for slope and shape so that runoff and erosion do not occur and may require winter stabilization with a shallow, fibrous-rooted cover crop such as rye grass. As mounding also increases the surface:volume ratio of the vine row, there will be potentially greater evaporative water losses and temperature excursions in the root zone. This means that application of a surface mulch during the growing season must be considered[27].

2. Remove stresses that degrade subsoil structure. This largely involves the removal of heavy vehicle wheel compaction near the vine row; this is

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[25] At this point we had only carried out fieldwork in South Australia.

[26] It is as well to recall here that these recommendations for the stone fruit industry were largely aimed at maximizing yields. For wine grapes this may not be appropriate; berry quality, improved water use efficiency and reduced irrigation dependence may be the main concerns here.

[27] Lanyon *et al.* (2004) also point out potentially adverse effects of mounding on conventional machinery operations and on the ease of hand pruning and picking.

concentrated in the top 40-50cm. In this regard the use of over-the-row equipment which produces a single wheel track in the mid-row is ideal. The application of saline irrigation water also places subsoil structure at risk. This is particularly true in clay soils where salinity is leached in winter but where sodicity is heavily buffered and remains to promote dispersion and structural decline. The avoidance of flooding in the inter-row area during winter may also be an important agent of structural collapse especially if vehicular traffic is present.

3. Improve the structure of the subsoil[28]. Tillage adjacent to the vine row is often used to relieve compaction due to wheels. However, this may cause significant root pruning and is reversed when wheel traffic resumes. There is little doubt that plant roots are critical in the creation of structure and the placement of carbon at depth. It is clear from our results that vine roots are insufficient for this task and the aid of winter-active plant roots *in the vine row* is needed to help colonize the subsoil, stabilize the soil surface and, through their activities and decay, create a larger, biologically active soil volume for vine roots in the growing season.

Existing vineyards: Most of the recommendations above could be implemented in existing vineyards but their practical and economic feasibility is beyond the scope of this project and, until they are demonstrated in field trials, are ultimately a matter for individual growers. During field work we have seen vine rows being mounded by 20-30 cm in established vineyards[29] but there does not appear to have been any attempt to stabilize these with fibrous-rooted plants in winter or to use a mulch in the growing season. There has been little evidence of reduced wheel traffic; this is quite understandably a matter of the cost and availability of over-the-row equipment. Many vineyards have a winter inter-row cover crop but many are bare and even clean-tilled and there is no use of other plants in the vine row during winter. As discussed above, the long-term improvement and maintenance of subsoil structure, requiring as it does soil disturbance at depth, must necessarily be largely based upon the activities of plant roots. The under-vine bank is generally bare of all but the vines themselves in winter; this seems to represent a lost opportunity for stabilization of the soil surface and for the improvement of subsoil structure by the creation of macropores, by increased soil biological activity and by the placement of carbon at depth.

New plantings: There is also a clear need for more rigorous soil preparation and maintenance of subsoil structure under new permanent plantings on these soils[30]. Here again, Cockroft and his co-workers have discussed these

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[28] An important pre-requisite in the improvement of soil structure is to maximize structural *stability*. In the case of subsoils, this largely involves the removal of sodicity by calcium applications, usually gypsum.

[29] This appears to cause no problems unless there is physical damage to the vine butt admitting pathogens or else a graft is covered.

[30] These recommendations assume that a thorough soil survey will be made first.

issues in some detail, in relation to stone fruit production (See Murray, 2007) but their recommendations do not seem to have been transferred to viticulture. Lanyon *et al.* (2004) have also discussed the modification of soil profiles prior to establishment.

In the absence of long-standing native vegetation, the natural state of the subsoils we have examined in this project appears to be one of poor aeration and high strength. This means that better, stable subsoil structure needs to be created and then maintained. As many of these subsoils are structurally unstable it is important to improve this stability *before* disturbance by deep tillage so that the durability of tillage operations is maximized. This can usually be done with surface application of gypsum[31] as a calcium amendment[32]. This application of calcium may need to be substantial (>10 t/ha) and to have sufficient time to modify the soil *before* tillage and earthworks commence[33]; the effects of this amendment can be assessed with augered soil samples and analysis of soil:water extracts.

Deep tillage and mounding should be the next step to maximize the potential root zone; this can be done as a single operation. Cockroft and his co-workers (see Murray, 2007) and Lanyon *et al.* (2004) have noted that much more careful attention is needed for deep tillage so that it is done with appropriate implements at the correct soil water content and have discussed this in some detail. At present a good deal of deep tillage is carried out on structurally unstable soils using inappropriate tines and often at water contents that lead to smearing and plastic remoulding of the subsoil.

The subsoil structure created by deep tillage has a short lifetime in many soils because it is not stabilized and has all but vanished after perhaps two years. Something needs to be added to the soil at this point to stabilize what has been created. Because of the poor oxygen status of the soils we have studied, we feel that the deep incorporation of organic matter such as plant residues or compost in all but sandy soils might have unintended consequences due to its oxygen demand. In this respect we believe that living plants roots are the best tools to stabilize this newly created subsoil structure. Dense plantings of species with taproots that colonize the subsoil, together with species that have fibrous root systems to stabilize the surface soil need to be established and given time to create a deep potential root zone for vines. This crop can then be sprayed prior to vine planting and the vineyard managed as discussed above for existing vineyards.

There is no doubt that this recommended effort and length of time (1-2 years) leading up to vine planting is daunting but we believe that this is not

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[31] Dissolved calcium removes sodicity but also stabilizes structure even in the absence of sodicity.

[32] Gypsum and lime differ greatly in their solubilities. The use of lime as a calcium source is appropriate when soil pH < 5.5; at intermediate pH (5.5-7), co-application of lime and gypsum may be useful. However, because of the limited mobility of lime, its application will be most effective in combination with tillage.

[33] As gypsum needs to be dissolved and leached, autumn application will be most effective.

inappropriate for an enterprise that has a lifetime of perhaps 50 years during which the work will be amortized in water use efficiency and vine performance. A cost/benefits analysis of the above recommendations in relation to viticulture is beyond the scope of this project but certainly needs to be made because this approach may offer growers greater flexibility in terms of quality and yield as well as long-term efficiencies in resource use.

Recommendations for further research

Field trials: The recommendations above for existing and new vineyards are not new. Similar recommendations can be found in the work of Cockroft and his co-workers (see Murray, 2007) for the stone fruit industry and in the review of soil properties and vine performance by Lanyon *et al.* (2004). The arguments for adoption of these recommendations in viticulture are compelling, especially in light of our observations in this project. However, we feel that the rate and extent of adoption of these recommendations will be slow unless they are demonstrated by field trials. Accordingly, we believe the most urgent need for further research in this area is the establishment of one or two regional field trials to explore and promote the benefits of good soil structural management.

Lanyon *et al.* (2004) bemoan the fact that while alteration of soil properties is a slow process and the impact of soil management takes 3-5 years, most research efforts attempt to report effects after only 1 year. Clearly there is need for field trials based on a more “diffuse” funding model so that the impacts of soil structure management, especially on water use efficiency, can be properly assessed and promoted over a sensible period.

Some of the issues that should be addressed in such trials are:

1. Strategies for the management of existing, conventionally established vineyards[34].

2. Preparation for new permanent plantings[35].

3. Vineyard plant ecology. The potential for plant roots to colonize hostile subsoils, to stabilize surface soil, to enhance soil biological activity and to increase soil organic carbon cannot be ignored. It is clear that vine roots alone are not up to these tasks.

4. Lanyon *et al.* (2004) refer to possible, unintended consequences of good soil preparation in terms of increased vine vigour. The extent of this effect and its control by irrigation and nutrient management needs to be clarified.

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[34] This might include elements of the current NPSI project “Optimizing delivery and benefits of aerated irrigation water” (Midmore and Bhattari) as poor aeration seems to be a major vineyard problem.

[35] This might be co-funded with other irrigated commodities as vines are certainly not the only crop these problems apply to.

Existing sites of "heroic" vineyard preparation and management: During this project we became aware that there are instances of vineyard preparation and management that are quite unconventional. Although these are rare, we feel that they are worthy of comparison with conventional operations on the same soils. A survey to locate and then study these enterprises might be helpful in formulating field trials, in demonstrating viability and in promoting adoption of good soil management strategies. In particular, unconventional approaches to deep tillage, mounding and the use of plant-based strategies to ameliorate soil could provide valuable but inexpensive information.

Aeration problems under higher water use: The root length density (RLD) measurements made in this project suggest that poor aeration is a major limitation to root growth and function. However, we were unable to extend these observations beyond South Australia to Sunraysia and the M.I.A. where water use is 5-10 times higher but where the infiltration rates we observed were generally lower. This strongly suggests that there is an even larger problem in the finer-textured soils of these other two grape growing regions. The combination of more water with poorer drainage suggests longer periods of anoxia and therefore of reduced root activity; paradoxically, this root activity includes water uptake. RLD measurements from our sites in Sunraysia and the M.I.A. would be a valuable extension of this project. As mentioned previously, conventional RLD measurement is an imperfect reflection of root activity and direct physiological observations of vine water uptake may be even more useful.

Saline water – evaluating the risk: A serious threat to subsoil structure comes from an inevitable increase in the use of saline water from bores or from water re-use schemes. We have already seen old groundwater sources reactivated during the drought. However, in the course of the project we have been surprised by the fact that although some of the soils we examined had a history of exposure to saline bore water, there was little evidence that their structure had been damaged further. We suspect that these subsoils may have been saved from further structural decline by leaching with winter rainfall[36]. This is not a straightforward issue as salinity is generally removed by leaching *before* sodicity. This is because sodicity is not easily leached, especially in soils of finer texture (clays) because of their substantial cation exchange capacity. The implication here is that irrigated soils may be able to sustain more saline water without accumulating exchangeable sodium if the process is relieved by sufficient winter rainfall. At this point we do not know how saline this water could be in a given winter rainfall zone without creating problems. We believe that some simple leaching studies of intact soil cores might help to answer this question and provide growers with better guidelines for irrigation water quality in relation to soil type in a given climate.

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[36] Their existing poor structural state may also have minimized further decline!

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Communication activities

Conference presentations

Oral

1. "*Long Term Sustainability Of Precision Irrigation*" ANCID October, 2006 (Darwin)
2. "*Physical root zone constraints generated by irrigation*" ANCID August, 2007 (Bundaberg)
3. "*Subsoil hydraulic conditions in drip-irrigated vineyards*" Irrigation Australia Conference May, 2008 (Melbourne)[37]
4. *"A tough neighbourhood to grow up in: Root zone conditions in Australian vineyards"* (invited presentation) Barossa Viticulture Conference: Future Challenges – Grower Strategies for Success. July, 2010 (Tanunda)

Poster

1. "*Long Term Sustainability Of Precision Irrigation*" ANCID October, 2006 (Darwin)
2. "*Field soil penetration resistance in two drip-irrigated vineyards*" ANCID August, 2007 (Bundaberg)
3. "*Salinity, soil structure and plant nutrition*" Irrigation Australia Conference May, 2008 (Melbourne)
4. "*A tough neighbourhood to grow up in – Root zone conditions in Australian vineyards*" Irrigation Australia Exhibition June, 2010 (Sydney)

Full paper

"*Subsoil hydraulic conditions in drip-irrigated vineyards*" Irrigation Australia Conference May, 2008 (Melbourne)

Research forums/workshops/symposia

1. "*Long Term Sustainability Of Precision Irrigation*" GWRDC Soil Water Initiative research meetings August, 2007; August, 2008; September, 2009 (Adelaide).
2. "*Long Term Sustainability Of Precision Irrigation*" Horticulture Australia Limited Soil Health Workshop. February, 2007 (Adelaide).
3. "*Long Term Sustainability Of Precision Irrigation*" Centre for Soil Plant Interactions Workshop. November, 2006. (Adelaide)
4. "*Long Term Sustainability Of Precision Irrigation*" NPSI Researchers Workshop September, 2008 (Canberra).

Magazine & Newspaper interviews

1. "*The Rural*" newspaper (Wagga). April, 2009
2. *Australian Viticulture Magazine*. (March/April, 2006) "*Is drip irrigation degrading your soil?*"

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[37] An abstract for an *oral* paper "*Subsoil structural conditions in drip-irrigated vineyards in the Mildura area*" was assigned a poster at the Irrigation Australia Conference October, 2009 (Swan Hill) where few presentations dealt with soil-related issues. We did not attend.

3. *Australian Viticulture Magazine*. (May/June 2009) "*Irrigation research gives life to Australian soils*".

Radio interview

National Radio News Room (Bathurst). April, 2009

Workshops

1. "*Long Term Sustainability Of Precision Irrigation*" Integrated Soil Management Workshop. 13th Australian Wine Industry Technical Conference. August, 2007 (Adelaide).
2. Postgraduate student training workshop in root zone measurements. February, 2009.

NPSI Investor/Partner Forums

Oral

1. "*Long Term Sustainability Of Precision Irrigation*" October, 2006 (Darwin)
2. "*Long Term Sustainability Of Precision Irrigation*" September, 2008 (Canberra)
3. "*Long Term Sustainability Of Precision Irrigation*" July, 2010 (Sydney)

Oral & poster

"*Long Term Sustainability Of Precision Irrigation*" August, 2007 (Bundaberg)

NPSI publications

1. *"The impact of irrigation on soil structure"* R.S. Murray & C.D. Grant. 2007. (http://npsi.gov.au/products/pn20619)

2. *"A review of Dr Bruce Cockroft's work for Australian irrigated horticulture"* R.S. Murray. 2007. (http://npsi.gov.au/products/pn21945)

3. "*Long Term Sustainability Of Precision Irrigation*" Research Bulletin (http://npsi.gov.au/products/pn20656)

4. *"Irrigation Essentials - Research and innovation for Australian irrigators"* (http://npsi.gov.au/products/npsi109) (contributing author)

5. *"Digging deep and the quest for super soils"* Irrigation Update Volume 9 (http://npsi.gov.au/products/pn22125) *"Irrigation and the root zone"* (contributing author)

6. "*Drip irrigation has little effect on structure*" http://npsi.gov.au/news/2010/jan/21/drip-irrigation-has-little-effect-structure (interview/editing)

7. *“Subsoil constraints in irrigated Australian vineyards”* Research Bulletin (in preparation)

8. *“Grower guidelines for the management of soil structure in irrigated vineyards”* (in preparation)

Other communications activities have included informal talks with many growers and regular formal presentations made to Project Steering Committee members. Video material about the project was prepared but not completed due to the demise of Land & Water Australia.

Further activities planned for the remainder of 2010 are:

1. Presentation to the “Grape to Graze” tour after the 19th World Congress of Soil Science Congress (August 9).
2. Letter to growers: we are writing to all growers who participated in the project to advise them of our observations in their vineyards and the implications of these.
3. Refereed publications: we are currently assembling data for 3 manuscripts to be submitted to *The Australian Journal of Soil Research.*

St John's Lutheran Church, Ebenezer, Barossa Valley next to one of the project field sites.

Knowledge assets generated

In examining the impact of precision irrigation on soil structure this project has produced unanticipated results.

1. The extent of subsoils with *inherently* hostile structural properties at shallow depths across vineyards in the Barossa Valley, Currency Creek, Urrbrae, Sunraysia and the M.I.A. seems virtually universal in finer-textured soils and poses a threat to good water use efficiency.

2. There is no evidence of *additional* structural damage due to irrigation so that the important question is not one of avoiding damage due to irrigation, but rather one of creating and maintaining good subsoil structure in soils that are inherently poor.

3. The major physical limitation in these subsoils appears to be aeration.

4. An improved technique for measuring subsoil hydraulic properties has been developed and used successfully.

5. Project results have been communicated as posters and oral presentations at conferences and workshops (ANCID 2006, 2007; Irrigation Australia 2008; AWITC Soil Management Workshop; Centre for Soil Plant Interactions Symposium; HAL Soil Health Workshop) and in NPSI publications. Publications in refereed Soil Science literature are in preparation.

Adoption potential

The management approaches necessary to overcome these subsoil problems and to remove the severe constraints they place on the development of root systems, are largely to be found in the work of Bruce Cockroft and his co-workers which we have reviewed extensively (Murray, 2007) and also in a review by Lanyon *et al.* (2004). These principles have so far been mainly confined to horticulture in the Goulburn Valley but, with the looming challenges of climate change and water scarcity and this project's observation of uniformly poor subsoils in one of Australia's premier wine-growing districts and elsewhere, the time is overdue for the extension of these principles into viticulture. We believe that adoption will be enhanced substantially by field trials or demonstration sites.

Impact potential

The wider adoption of sound principles for the creation and management of good soil structure in permanent plantings has a number of advantages. The deeper foraging of root systems in receptive subsoils will lead to:

Lower cost to growers from:

- increased water use efficiency
- increased nutrient use efficiency
- plants that are better buffered against disease, water and nutrient stresses and climate change

Environmental benefits can be expected from:

- reduced environmental water use as plants access winter rainfall stored at depth
- improved knowledge about the management of soil resources

Autumn begins at Bethany in the Barossa Valley.