

Managing soil salinity in groundwater irrigated vineyards



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Front cover - View over the rainfall re-direction trial at Padthaway - looking West.

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1. ABSTRACT

In SE South Australia, vines are grown with supplementary irrigation drawn from medium salinity groundwater. In salt affected vineyards, the soil located under the vine was saline and sodic, whereas that in the mid-row was non-saline and non-sodic. Winter rains leached $\frac{3}{4}$ of the salt and halved sodicity, however salinity remained above a threshold for concern and soils at depth remained sodic. Over two seasons, we assessed whether various changes to vineyard floor management could reduce vine and soil salinity and soil sodicity. The most effective change consisted of mounding soil in the mid-row and covering it with plastic to re-direct rain falling there towards the soil under vine. This re-direction of rainfall reduced soil salinity by 38% on average and reduced the concentrations of sodium and chloride in juice by 35% on average.

Over three seasons, we supported a grower operated salinity monitoring network. Sites were located in Cabernet Sauvignon vineyards spread across the Limestone Coast GI. Network records showed that soil salinity and salt concentrations in fruit were below levels of concern in all three seasons. Fruit Cl^- concentrations, but not Na^+ concentrations, reflected between vineyard variations in salt loads. Soil water extractors provided a measure of soil salinity that was readily obtainable in the vineyard. This measure could be used as a guide to vineyard salinity status. Extracts with salinity above 7 dS/m indicated excessive soil salinity. For extracts with salinity between 7 and 3.5 dS/m, the soil salinity could be either excessive or below the level of concern, and, for values in this range, a definitive assessment of vineyard salinity status could only be obtained by application of other methods. Extracts with values of salinity below 3.5 dS/m indicated that the soil salinity was below the level of concern.

We combined samples taken during the project with those taken a decade ago to assess whether annual cycles of saline high SAR irrigation in summer and non-saline low SAR rain in winter had caused an increase in soil sodicity and salinity. Above average winter rain in 2011 reclaimed sodic and saline soils. This indicated that any change in soil structure wrought by a decade of these cycles was not yet a significant impediment to leaching of salts and displacement of sodium from the clay exchange sites.

Over 200 growers have attended our presentations at workshops and seminars. Presentations at conferences and steering committee meetings have reached over another 100 growers. A large corporate winery (not involved as a collaborator in the current project) is working with SARDI to pilot rainfall re-direction in vineyards in SE Australia.

2. EXECUTIVE SUMMARY

Over the last decade, grape growers in SE South Australia have had their water entitlements converted to volumetric allocations, experienced a reduction in annual rainfall and seen a rise in the salinity of groundwater which is used for irrigation. Irrigators have moved away from flood and sprinkler irrigation, which was still widely used in the last decade of the 20th century, to precision irrigation applied with drippers. Annual application rates have decreased from between 4 and 6 ML/ha down to 2 or less ML/ha. In middle of the first decade in the 21st century, salinity damage was emerging in some vineyards. In response the Limestone Coast Wine Industry Council convened a Root Zone Salinity Workshop in May 2006 at Padthaway. The current project addresses concerns raised following this workshop viz.,

- characterising soil and vine salt status in vineyards affected by salinity
- developing techniques to more sustainably manage these vineyards
- extending knowledge about salinity management tools by supporting a salinity monitoring network in the Limestone Coast GI
- quantifying effects of long term precision irrigation with saline water on soil structure

Three salt affected vineyards were assessed at the close of the irrigation season in 2009. The high concentrations of sodium and/or chloride in leaves indicated that salinity was causing yield loss. Soils under the vine were saline and sodic with average values for salinity and ESP of 7.7 dS/m and 16%, respectively. However, soils in the mid-row were non-saline and non-sodic with average values for salinity and ESP of 0.6 dS/m and 4%. Re-sampling at one of these sites after winter (365 mm rain) showed that rainfall had leached soil salts and reduced sodicity with average under-vine values for salinity and ESP declining over winter from 9.3 to 2.5 dS/m and from 21 to 12%, respectively. In soils located under the vines in between drippers, the infiltration rate of rainwater was high, indicating that the high ESP was not adversely affecting conductivity of these soils to low salinity water. However indirect evidence points to reduced infiltration into the surface soil located nearer the drippers. The soils under the vine were mounded and a reduction in infiltration would direct rain toward the mid-row. The flushing of soil salts by winter rain was not sufficient to bring the salinity of soils to values below the threshold for salinity damage to vines. In part, this may reflect the persistence of a high ESP in deeper soils which may have limited drainage.

Under saline supplementary precision irrigation, the salts are added with the irrigation and the water to flush salt through the soil is provided by rain. The salinity of a soil is indicative of the balance between these two processes. Insufficient rain leads to salt build up and sufficient prevents it. Soils under the vines were saline, whereas those in the mid-row were non-saline. Rain reaching mid-row soils was in excess of that required to prevent salinisation. Re-direction of this excess water to the soils under vine would reduce soil salinity in this region provided that subsoil drainage rates were high enough to support the extra flushing. We hypothesised that changes in floor management which direct rain from the mid-row toward the soil under vine and which address high ESP in the soils at depth under the vine, may assist in reducing salinity damage.

At the end of the irrigation season in the 2010, a trial was installed in a salt affected Chardonnay vineyard where soils from the mid-row had been mounded under the vine to a depth of about 0.2 m. The treatments consisted of a control (designated A), the removal of soil mounded under the vine (B), the application of calcium nitrate to 1 m wide strip of soil under the drip line (C), the covering of the mid-row with plastic to reduce losses from evapotranspiration (D), relocating the mounded soil under vine to the mid row and covering it

with plastic (E), and E combined with the application of calcium nitrate to 1 m wide strip of soil under the drip line (F). The trial ran for two seasons, 2011 and 2012 (year of harvest). Effects on soil salinity were assessed by measuring the salinity of the soil under the vine at the opening and close of the irrigation seasons. Measures of sodium and chloride concentration in leaves and fruit were used to assess the effect of treatments on vine salinity. The significances of different floor management regimes were tested with ANOVA and a set of contrasts.

Relative to salinity levels observed in vines and soils in the 2009 and 2010 seasons, those observed in the control, treatment A, during the trial were low, excepting soil salinity at the close of the 2012 season which had returned to pre-trial levels. Low soil salinity in the control was not associated with variation in the depth of winter rain, but rather a variation in the depth of within season rain; when this was higher, irrigation depths were lower and hence so too was the annual salt load added to the vineyard.

Redirection of rain from the mid-row, treatments E and F, reduced the salinity of soils under the vine at the ends of the 2010 and 2011 seasons and at the openings of the 2011 and 2012 seasons; removal of the under vine mound, treatment B, reduced soil salinity at the end of the 2011 and the opening of the 2012 seasons. Within season rainfall in the 2012 season was low, less than a third of that in 2011 and just half of that in 2010. None of the treatments had an effect on the salinity of soil under the vine at the close of the 2012 season. At this time, the salinities of soils located at a quarter and half way across the row were also measured. In the control, treatment A, measurements of salinity and sodicity showed that the values had returned to the higher levels present at the end of the 2010 season. Redirection of rainfall (E and F) had increased the salinity of soils located at a quarter and half way across the row; addition of calcium nitrate (C and F) had increased the salinity of soils located half way across the row. The sodicity of deeper soil under the vine was measured at the close of the 2012 season. Redirection of rainfall (E and F) and addition of calcium nitrate (C and F) reduced soil sodicity by about 50%.

Measurements of salt concentration in plant organs represent an integration of salt pressure throughout organ development. In both seasons, redirection of rainfall (E and F) lowered leaf petiole sodium concentrations and leaf petiole and lamina chloride concentrations, and removing the under vine mound (B) lowered petiole chloride concentrations. In one of two seasons, covering the mid-row with plastic (D) reduced sodium and chloride concentrations, and removing the under vine mound (B) reduced petiole sodium and lamina chloride concentrations.

In 2011 and 2012 seasons, redirecting rainfall (E and F) lowered sodium and chloride concentrations in the juice. In 2012, the concentrations of both ions were also reduced by removing the under vine mound.

Treatments did not affect yield. They caused small reductions in juice °Brix and increases in juice titratable acidity.

Salinity monitoring sites were installed in a grower operated network at 14 sites across the Limestone Coast region before the 2010 season. The project staff provided each participant in the network with training and on-going support in sampling techniques. Sites were located in drip irrigated vineyards planted to Cabernet Sauvignon on own roots growing on mainly clay loam soils. Soil solution samplers were installed at each site at 0.3 and 0.6 m depth. Participants collected data on irrigation water and soil solution salinity, and rainfall depth and irrigation volumes. This data was cross related to measures of soil and vine salinity undertaken by project staff. Participants received biennial collations of all data and this

provided them the opportunity to benchmark their salinity measures against those of other network members. Soil solution salinity rose during the irrigation season and fell with winter rains. This readily obtainable measure of soil salinity did not provide a reliable basis upon which to predict either the standard measure of soil salinity (EC_e) or standard measures of vine salt status (sodium and chloride concentrations in petiole and juice). However, all measures of EC_{sw} below 3.5 dS/m had corresponding EC_e values below the threshold of 2.1 dS/m for vine salinity damage and all measures of EC_{sw} above 7 dS/m had corresponding EC_e measures above the threshold. In between these two values, there was a grey area where more conventional sampling techniques need to be applied to establish vineyards salinity status.

SARDI assessed the effect of a decade of saline irrigation on soil physical and chemical properties by comparing a set of current measurements of these properties with those made a decade ago at the same site by CSIRO Plant Industry. Soils were sodic and saline in 1997 and again when measured in 2009; the salinity of soil in the top 0.6 m was 5.0 dS/m and the sodicity (ESP) was 13%. After, above average winter rain in 2011 the salinity of soils in top 0.6 m was 2.1 and the sodicity (ESP) was 7%. The sodic soils had been subject to annual cycles of saline high SAR irrigation in summer and non-saline low SAR rain in winter over the previous decade. The return to non-saline and non-sodic state in 2011 indicates that any change in soil structure wrought by a decade of these cycles was not yet a significant impediment to leaching of salts and displacement of sodium from the clay exchange sites. Comparison between two set of soil moisture release characteristics determined at either end of the decade showed they were different, however this may have been due to slight differences in the soil composition (5% gravel content in the earlier sample), rather than the effects of a decade of saline irrigation.

Communication activities included: three journal papers, five conference papers, this final report, six steering committee meetings, three factsheets, seven workshops and seminars, and nine salinity monitoring network summary sheet mail outs.

3. BACKGROUND

In the Padthaway region, salinity pressure on supplementary irrigated vineyards has increased due to recent rises in the salinity of groundwater used for irrigation combined with a reduction in water available for leaching (caused by the introduction of volumetric allocations and a trend in the last decade for annual rainfall to be about 50 mm less than the long term average).

One dimensional modelling of the effect that these changes in water and salt inputs have on predicted soil salinity showed that whilst salinity increased it still remained below the level at which salinity affects vines. The model was sensitive to assumptions about the effectiveness of rainfall and the level of evapotranspiration from the mid-row.

A one off measure of salt distribution made during the Padthaway Salt Accession Study (van den Akker 2005) showed that horizontal distribution across the vineyard row was highly heterogeneous with salt accumulating in soils under the vine and being near absent from those in the mid-row. Horizontal homogeneity of salt distribution is an underlying assumption in one-dimensional models of soil salt balance. Given that this assumption was not met, then one-dimensional model cannot accurately reflect soil salt dynamics. It is unclear whether the one off observation of salt distribution is characteristic of salt distribution in the salt affected vineyards of Padthaway.

Improvements in the management of saline irrigation require an improved understanding of the salinisation processes together with tools with which managers can readily assess a vineyard's salinity status. Currently the tools used to assess this status are the same as those in use amongst researchers. They all require samples to be processed in a laboratory before a result can be had. Managers need a tool with which they can readily obtain measures of salinity in the vineyard.

In supplementary irrigation districts, the use of saline irrigation water exposes the soil to an annual cycle of drip irrigation with saline high SAR water in summer followed by flushing with non-saline low SAR rainfall in winter. Repeated exposure to such cycles caused a deterioration in the structure of soils in vineyards of the Barossa (Clark 2004). Soils in the vineyards of Padthaway are exposed to a similar water regime and it is unclear whether this regime is leading to an alteration in their structure.

In response to the emergence of salinity as an issue of concern for some vineyards in the Limestone Coast Wine region, SARDI developed an interdisciplinary project aimed at delivering a pathway to sustainability for the region's groundwater irrigated vineyards. This project had four objectives:

1. Develop hydro-geology scenarios for the Padthaway district
2. Develop strategies for root zone salinity management
3. Develop strategies for prevention of soil structure decline
4. Select rootstocks for premium grape production at Padthaway

Objective 1 was to be delivered by the Department for Water Land and Biodiversity. SARDI has undertaken to deliver objectives 2 to 4. Figure 1 shows the locations of sites at which this work was undertaken. The Grape and Wine Research and Development Corporation supported SARDI to address objective 4. This aspect of the project was reported on in October 2011 (http://www.gwrdc.com.au/webdata/resources/project/SAR_09-03.pdf).

At the time of project inception, it was envisaged that modelling of the vadose zone using Hydrus 2-D would provide an avenue to link objectives 1 and 2. This aspect initially received support from the Caring for Our Country (CFOC) program, however within the first year of the project's life the direction of the CFOC program altered to reflect the change in Federal government. Support for this aspect lapsed. Objectives 2 and 3 have been supported by the SE Natural Resource Management Board (until changes in the Caring for our Country funding program), CRC for Irrigation Futures and the National Program for Sustainable Irrigation. Work on these components forms the basis of this report to the National Program for Sustainable Irrigation in June 2012.

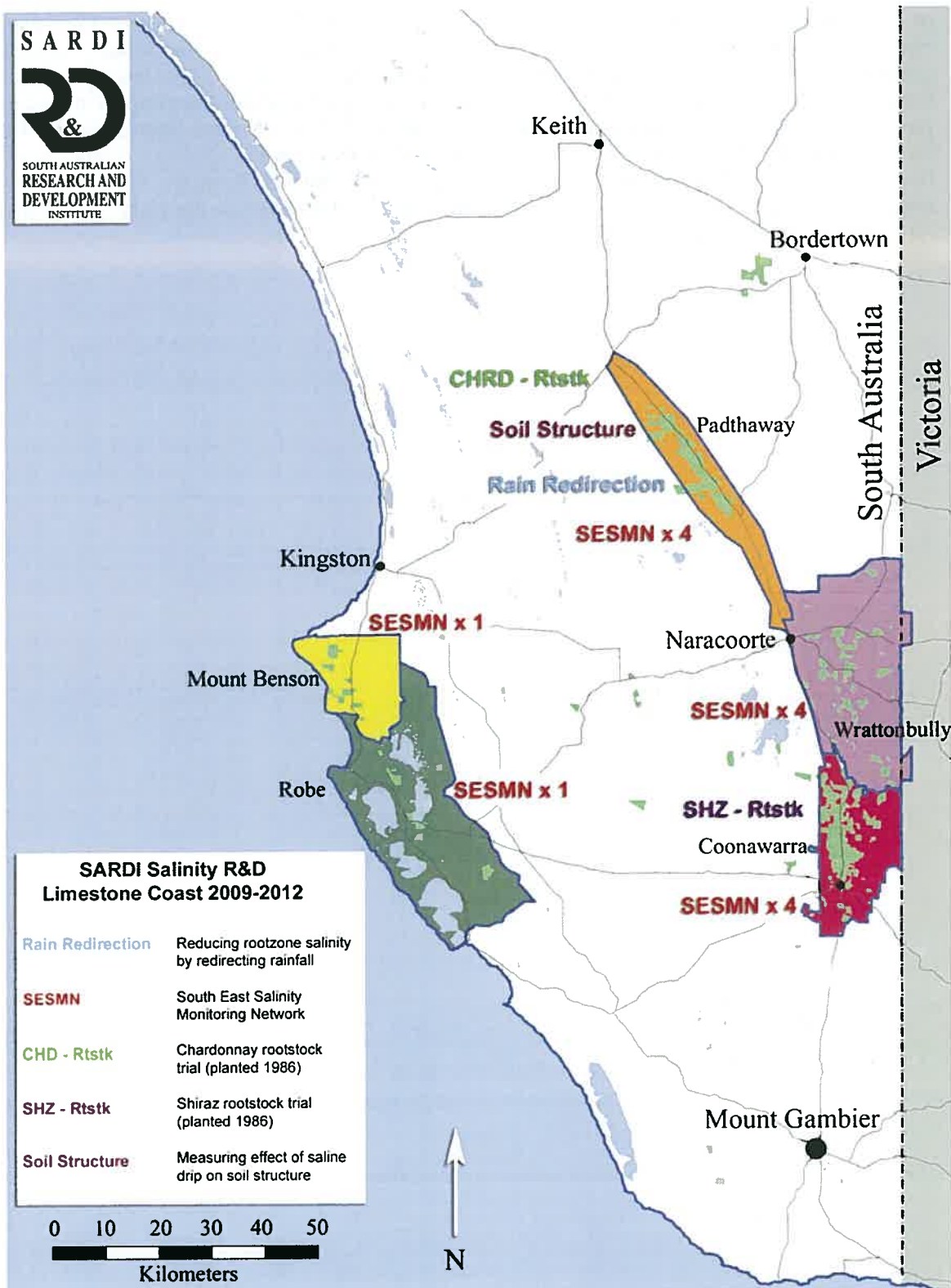


Figure 1. Location of SARDI salinity research sites in the Limestone Coast, 2009-2012.

4. PROJECT AIMS

1. Identify soil factors associated with the deterioration of vine performance in groundwater-irrigated vineyards.
2. Test techniques which reduce the accumulation of salts in the plants and soils of groundwater-irrigated vineyards.
3. Identify which physio-chemical properties of soils change in response to a decade of irrigation with saline groundwater.
4. Extend knowledge about salinity management tools by supporting a network of industry-operated sites for the monitoring soil salinity and grape juice quality across in the Limestone Coast Geographical Indicator (GI).
5. Pro-actively communicate via workshops and publications, the project's progress and outcomes to the Limestone Coast regional and national viticulture industries.
6. Develop guidelines for minimising effect of soil salinity on wine quality based on outcome of field experiment, literature review and monitoring.

Output 1

Measure soil chemical and physical properties in groundwater-irrigated vineyards where poor vine performance has been associated with salinity.

Performance Targets:

- Liaise with industry to identify and gain access to salinity-damaged vineyards in Padthaway
- Measure and describe the spatial variations in soil salinity and sodicity and, measure grapevine salt status
- Determine the effect that soil sodicity has on the infiltration rate of low salinity water (rainfall)

Output 2

Devise and trial management techniques which will address the poor vine and soil salt status observed in groundwater-irrigated vineyards suffering from salinity damage.

Performance Targets:

- Identify the soil properties which have the greatest effect on the leaching of soluble salts from the soils of salinity damaged vineyards
- Devise treatments which could plausibly improve leaching of salts, liaise with industry to identify a suitable field site and install a field experiment to test these treatments
- Assess the efficacy of the treatments by measuring their effects on the soil and grapevine salt status, the yield and vegetative growth of grapevines and fruit quality

Output 3

In a Padthaway vineyard, irrigated with saline groundwater, compare measurements of physio-chemical properties of soils made in 1997 and 1999 with those made in 2009 and 2011.

Performance Targets:

- For soil on the Padthaway Flats, determine relationships between values of salinity and sodium absorption ratio in 1:5 water extracts of soil and the values in saturated extracts of soil
- Liaise with current and ex-CSIRO staff to determine exact location of soil sampling sites in the 1990's and to access data derived from these samples
- Resample sites and determine changes in physio-chemical properties of soils

Output 4

In partnership with industry, establish a network of monitoring sites for soil salinity and grape juice quality in the Padthaway, Coonawarra, Wrattenbully and Mt Benson/Robe districts.

Performance Targets:

- Assist industry to build a set of criteria for network membership which emphasised similarity of sites with regard to vine stocks, irrigation method and soil types; install soil water monitoring sites and train network members in their operation
- Support operation of the network by the provision of sampling consumables, analysis of collected samples and collation of data with associated weather and irrigation data
- Investigate the nature of the relationships between the salinity of water extracted from the soil and standard measures in use to assess vineyard salt status

Output 5

Pro-actively communicate outputs.

Performance Targets:

- Establish a steering committee comprising funders, industry representatives from the Limestone Coast and researchers involved in the field of salinity management of grapevines. Provide the committee with project updates and the opportunity for consultation on at least three occasions during the project
- Use regional workshops and seminars to present project findings to the Limestone Coast grower group
- Use scientific and technical publications and presentations at national conferences to inform the national viticultural industry and other users of supplementary irrigation
- Summarise findings in a final report to NPSI

Output 6

Develop guidelines

Performance Targets:

- Develop guidelines for minimising effect of soil salinity on wine quality based on outcome of field experiment, literature review and monitoring

5. SOIL FACTORS ASSOCIATED WITH THE DETERIORATION OF VINE PERFORMANCE IN GROUNDWATER-IRRIGATED VINEYARDS

5.1 Introduction

Towards the end of the first decade of 21st century the rate of increase in the area of drip-irrigated vines damaged by salinity in Padthaway began to cause concern. Canopy damage was associated with high levels of Cl^- and Na^+ in the vine and which can translate into negative effects on wine quality. Such damage was not present when these vines were under flood irrigation in the 1990's.

Since the mid 1990's, irrigation amounts have decreased from about 400 mm under flood to 200 mm under drip; the average annual rainfall of 420 mm has dropped slightly below that of 495 mm in the 1980's and 1990's, and irrigation water salinity has been rising by about 0.02 dS/m per annum to reach up to 2.7 dS/m by 2005.

The effects that changes in depths of irrigation and rainfall and the salinity of irrigation water have on the soil salinity can be estimated from data on the salinity of irrigation water and the various components of the annual water balance. For steady state conditions (inputs equal outputs) the annual water balance can be specified as:

$$I + R = ET + D \quad \text{Equation 5-1}$$

with I, R, ET and D representing the depths of irrigation, rainfall, evapotranspiration and drainage. Cleugh (2006) estimated the annual depth of ET in a Padthaway vineyard as 530 mm. The value of the annual depth for drainage can be estimated by substituting this value for ET into Equation 5-1 with the aforementioned values of irrigation and rain under flood and drip. The effect that variations in depth of drainage and the salinity of applied water (EC_w , irrigation and rain) have on soil salinity (EC_e) can be estimated using a one-dimensional model specified as:

$$EC_e = EC_w * (I + R) / D \quad \text{Equation 5-2}$$

Substituting the value for drainage and irrigation water salinity under flood and drip in to Equation 5-2 gives values for soil salinity of 0.9 and 1.4 dS/m, respectively. These calculation assume that rain was 100% effective. If rain effectiveness is set at 80%, then the respective values for soil salinity become 1.3 and 7.7 dS/m. Note that soil salinity under drip irrigation is far more sensitive to variation in rainfall effectiveness. Conversely, if inter-row water use (estimated as 100 to 170 mm annually by Cleugh (2006)) is reduced, then the respective values become 0.8 and 0.9 dS/m.

The values of 0.9 and 1.4 dS/m are both well below the threshold value of 2.1 dS/m above which salinity causes own-rooted vines begin to undergo yield decline (Zhang et al. 2002). However, an assumption implicit in any one-dimensional model is that the spatial distribution of any modelled parameter is homogeneous. Data collected from 2 vineyards during the Padthaway salt accession study (van den Akker 2005) shows that this assumption may not apply. Chloride concentrations (an analogue for salinity) in the soil under the vines were greater than those in the soils of the mid-row.

In the Padthaway area, three vineyards which industry had identified as succumbing to salinity were sampled in order to: measure the spatial variation in soil chemical properties, characterise vine salt status and, in one of the three, measure the effect of winter rain on soil chemical properties and determine whether differences in soil chemical properties and vineyard floor management affected the rate at which low salinity water infiltrates into the soil.

5.2 Materials and methods

5.2.1 Vineyard descriptions

Two large corporate vignerons in Padthaway, South Australia, identified three salt affected vineyards; an own rooted Chardonnay vineyard which was planted in 1996 and located 12 km south of Padthaway and two own rooted Shiraz vineyards which were planted between 1969 and 1971 and located 7 km south of Padthaway.

In all three vineyards, drippers were used to apply supplementary irrigation with medium salinity groundwater (1.9 – 2.3 dS/m). Table 1 shows analysis undertaken by the Australian Water Quality Centre of water from the two bores supplying irrigation water to the Chardonnay vineyard.

At all sites the soil had been prepared for installation of trellis posts by ripping to a depth of about 0.8 m along the vine row. In the Chardonnay vineyard, soil from the mid-row had been mounded under the vine to height of about 0.2 m. The soil had not been mounded in a nearby Chardonnay vineyards managed by the same corporate vignerons. Soils in the Shiraz vineyards had not been mounded.

Table 1. Analysis of irrigation water drawn from bores supplying the Chardonnay vineyard; EC in dS/m, cations and anions in mM. Sample date 26/4/2006.

Parameter	Bore 5	Bore 6
EC	2.09	2.14
Calcium	2.69	2.89
Magnesium	2.24	2.23
Sodium	10.70	11.05
Potassium	0.19	0.18
SAR*	4.8	4.9
adjRNa†	6.0	6.2
Chloride	12.43	12.82
Sulphate	0.61	0.59
pH	7.60	7.50

* calculation as per Sumner (1995).

† Adjusted SAR after Ayers and Westcot (1985).

5.2.2 Vine salt status

Leaf lamina were collected from opposite basal bunches after harvest in April 2009. If there were less than ten leaves remaining opposite the basal bunches, then leaves were collected from opposite basal tendrils.

Leaf blades were dried at 70°C for at least 72 hours and ground using a Micro Hammer-Cutter Mill (Culatti AG, Zurich, Switzerland) to pass through a 0.5 mm mesh.

The Cl⁻ concentration was measured by silver ion titration with a Buchler chloridometer (Labconco, Kansas City, MO, USA). Duplicate extracts were prepared by adding 20-100 mg of dry sample to 4 mL of an acid solution containing 10% (v/v) glacial acetic acid and 0.1 M nitric acid and 4 drops of gelatine reagent. The Na⁺ concentration was measured by Inductively Coupled Plasma Optical Emission Spectroscopy (ICPOES, Varian Vista-Pro, Varian, Melbourne, Australia).

5.2.3 Soil salinity and sodicity measures

In all three vineyards, the soils were sampled in April at the end of the 2009 irrigation season. A hand auger (0.1 m diameter head) was used to collect samples in 0.1 – 0.2 m depth intervals. Samples were taken from under-vine (between two drippers) and in the mid-row. The soils in the mounded Chardonnay vineyard were re-sampled in November 2009 prior to the start of the 2010 irrigation season.

Soil salinity was measured as the electrical conductivity of the extract from a saturated paste (EC_e) following the method of Rayment and Higginson (1992). Electrical conductivity was reported in dS/m at 25°C.

Soil sodicity was assessed using measures of Sodium Adsorption Ratio (SAR) calculated from measurements of the concentrations of sodium, magnesium and calcium in the saturated paste extract (SAR_e) using formula described in Sumner (1995). Concentrations of cations were measured by Inductively Coupled Plasma Optical Emission Spectroscopy (ICPOES, Varian Vista-Pro, Varian, Melbourne, Australia). The percentage of soil cation exchange sites occupied by sodium (ESP) was estimated from measures of SAR_e using the relationship described in Sumner (1995).

5.2.4 Infiltration rates of low salinity water

The effect of soil chemistry on the infiltration rates of de-gassed rainwater ($EC \sim 0.09$ dS/m) was measured at the Chardonnay vineyard in October and November 2009 with a Cornell Sprinkler Infiltrometer, as described in Ogden et al. (1997). The device is shown in-situ in Figure 2. The sprinkler infiltrometer was operated as per instrument manual (www.soilhealth.cals.cornell.edu/research/infiltrometer/infil_manual.pdf).

Rates of infiltration were measured on soil mounds located under the vine, between two drippers, and on soil in the mid-row. Measurements were thrice replicated. Soil samples were collected from outside the infiltration ring of each replicate for assessment of EC_e and SAR_e . Intact soil cores were taken in the mounded vineyard for determination of bulk density. The measures of infiltration rates were repeated at the neighbouring vineyard where the soil had not been mounded under vine.

A vadose zone hydrological tracer Brilliant Blue (FD&C Blue 1) dye was used to investigate whether the ripping of soil during vineyard establishment had created cracks along which water preferentially flowed during infiltration (Flury and Fluhler 1995, Mon et al. 2006). A 0.2 m diameter infiltrometer ring was inserted into the soil on top of the under vine mound to a depth of 0.07 m; the ring was loaded with 1 L of degassed rainwater and after this had completely infiltrated, the ring was then loaded with 2 L of Brilliant Blue in degassed rainwater (1.26 mmol/L). After infiltration was complete, the distributions of the tracer in the horizontal and vertical planes were recorded with a digital camera.



Figure 2. Cornell sprinkler infiltrometer during measurement of infiltration into soil mounded under the vines.

5.3 Results and discussion

5.3.1 Leaf sodium and chloride concentrations in salinity damaged vines

The concentrations of Na^+ and Cl^- in leaves sampled after harvest are shown in Table 2. Stevens et al. (2011a) demonstrated that salinity has osmotic and toxic effects on field vines, and that the toxic effect is proportional to the concentration of Na^+ in leaf lamina. Stevens et al. (2011b) found that yield loss occurred when the concentration of Na^+ in leaf lamina at harvest was above 223 mmol/kg. The concentrations of Na^+ in leaves from both Shiraz vineyards were well in excess of 223 mmol/kg. Walker et al. (2002, 2004) found in own rooted Sultana vines that yield loss occurred when the concentration of Cl^- in leaf lamina at harvest was above 367 mmol/kg.

The Cl^- concentration in the leaves from the Chardonnay vineyard was well in excess of this value. In all three vineyards, the concentrations of either Na^+ or Cl^- in leaves were above values associated with yield loss in field grown vines due to excess soil salinity.

Table 2. The concentration of sodium and chloride (mmol/kg d.w.) in leaf lamina sampled after harvest in the 2009 vintage.

Cultivar	Sodium	Chloride
Chardonnay	65	497
Shiraz	347	318
Shiraz	395	311

5.3.2 Spatial variation in soil salinity and sodicity

5.3.2.1 Salinity

In supplementary irrigated vineyards where vines were suffering salinity damage, the average salinity of soils under the vine, 7.7 dS/m, was high relative to the average of 0.6 dS/m in soils from the mid-row (Figure 3). The average of all values from under vine and the mid row was 4.2 dS/m (Figure 3). This value is well above the threshold value of 2.1 dS/m for salinity damage in own-rooted vines (Zhang et al. 2002), however the value from the mid row soils is well below the threshold.

The pattern of low salt accumulation in the mid-row and high salt accumulation under vine is the opposite of that seen with drip irrigation in full irrigation areas where the highest salinity occurs in mid row soils and the lowest in soils under the drip line (Groot Obbink and Alexander 1977, Stevens and Douglas 1994).

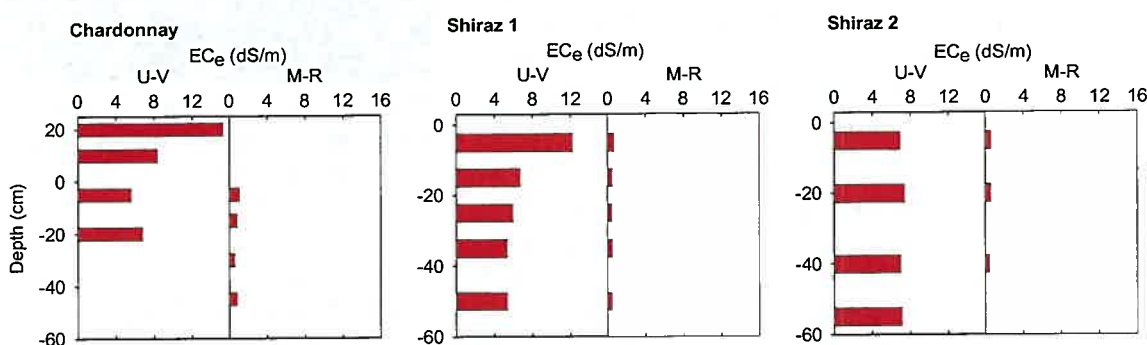


Figure 3. The effect of depth and location across the row (under vine, U-V and mid-row, M-R) on soil salinity (EC_e) in three Padthaway vineyards where vines displayed salt damage. Depth of 0 cm represents original ground level and that of +20 cm the height of the mound.

In full irrigation areas most of the crop water requirements are supplied by irrigation, whereas in supplementary irrigation areas rain is sufficient to meet most of the requirement. In full irrigation areas, the traditional approach to preventing salt accumulation has been to add irrigation water in excess to crop requirements (Ayers and Westcot 1985). This excess flushes salts to below the root zone. Under supplementary irrigation, irrigation water is the source of salt and the water to flush the salt through the soil is provided by rain. Supplementary irrigation can generally use higher salinity water than full irrigation because rainfall dilutes the salts added in irrigation water. Under supplementary irrigation, adding more irrigation to managing soil salinity reduces this advantage because, as the proportion of irrigation to rain increases, the effects of salt dilution by rainfall diminish.

The salinity levels of soils under the vine is well above the threshold for salinity damage to vines and the degree of flushing provided by rain is insufficient to prevent salinity damage to vines. In contrast, the salinity of soils in the mid-row is well below the threshold and the degree of soil flushing provided by rain is in excess of that necessary to prevent salinity damage to vines.

5.3.2.2 Sodicity

The average values of the SAR_e in soils from under the vine and the mid-row were 13.0 and 2.5 respectively (Figure 4). These values of SAR_e equate to exchangeable sodium percentages (ESP) of 16 and 4%, respectively. Soils with ESP greater than about 6 can become dispersive when flushed with low salinity water such as rain (Sumner 1995). Dispersion causes a reduction in the hydraulic conductivity of the soil. Loss of hydraulic conductivity reduces leaching of salts. The high salinity in the soils under the vine may be due to the low permeability of sodic soils to rainfall, rather than insufficient rain to flush salts.

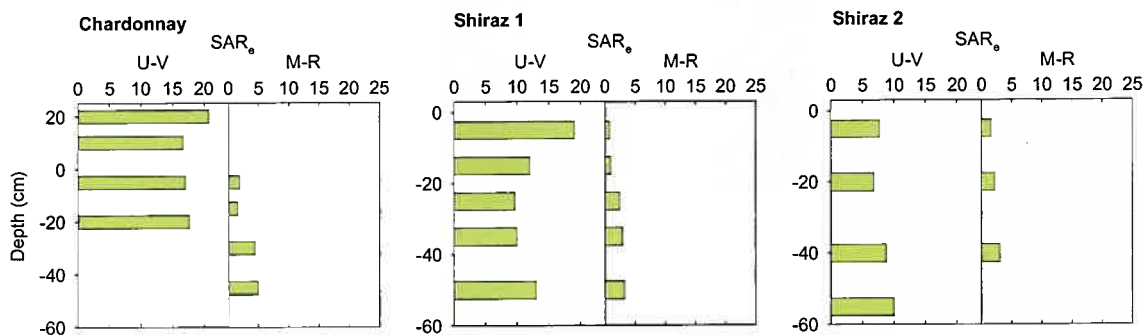


Figure 4. The effect of depth and location across the row (under vine, U-V and mid-row, M-R) on the sodium adsorption ratio (SAR) of the saturated paste extract in three vineyards where vines displayed damage from salinity. Depth of 0 cm represents original ground level and that of +20 cm the height of the mound.

5.3.3 Infiltration rates of low salinity water

The rate of infiltration of de-gassed rainwater into soils under the vine was higher than that into soils in the mid-row (Figure 5). The bulk density of surface soils on the under vine mounds 1.26 ± 0.07 (mean and standard error) was lower than the value of 1.41 ± 0.04 in the mid-row. Soils under vine mounds were non-saline with an average value of 1.1 dS/m, but sodic with an average SAR_e of 5.8 corresponding to an ESP of 7.9 (Figure 5). Based on the ESP value this soil would be considered sodic (Sumner 1995), however the high rate of infiltration by low salinity water indicates that the soil was not exhibiting sodic behaviour.

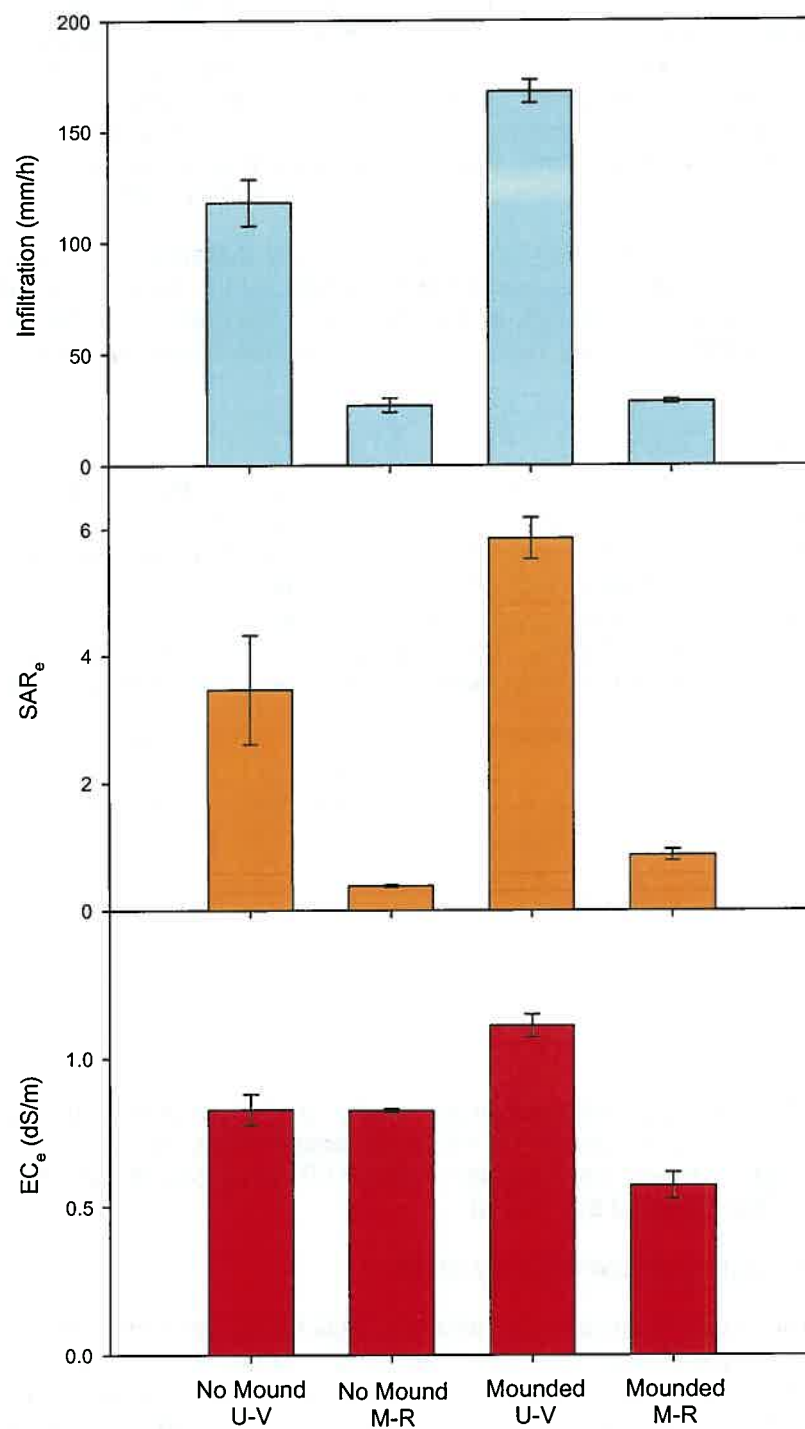


Figure 5. The infiltration rates of degassed rainwater into soil located under vine (VL) and in the mid-row (MR) in vineyards where the no soil mounding had occurred and where soil had been mounded under the vine and the EC_e and SAR_e in the 0-10 cm depth soil sample.

The infiltration rate of under-vine soils was determined mid way between drippers. The rates were in excess of 100 mm/h. At the Chardonnay vineyard the drippers delivered 2.1 L/h. In soil with an infiltration rate of 100 mm/h, the surface area required to fully absorb this amount of water would be less than 0.03 m² and if the wetted area was to be take a circular form, then the diameter of the circle would be less than 0.2m.

Figure 6 shows the soil wetting following operation of the drippers at the Chardonnay vineyard. Dripper spacing is 0.6 m and the diameter of the wetted area below each dripper is closer to 0.4 m. It is likely that the soil immediately under the drippers had a lower rate of infiltration that that between drippers.

Figure 7 shows ground cover at the end of winter 2009 in an adjacent Chardonnay vineyard where the soil had not been mounded. Moss had preferentially established at sites immediately under the dripper. Moss prefers damp sites such as those with soil which drains poorly and its pattern of growth in this vineyard would support a contention that infiltration rates for winter rain in the immediate vicinity of dripper were slower, and hence the soil wetter, in the area of soil within about 0.15 m radius of a point on the soil surface immediately under the dripper.

Figure 8 shows the vineyard floor following 11 mm of rain in early spring 2009, five months after the last irrigation event. The surface of soils in between drippers is dry, whereas the surface of soils immediately surrounding drippers is still wet. In between drippers, the length of time elapsed between completion of infiltration and taking of the photograph was sufficient for the soil surface to dry. In contrast, the wet soil surface under the drippers probably indicates that infiltration has been slower and the length of time that has elapsed between its completion and taking of the photo was insufficient for the soil surface to dry. Removal of soil mounded under the vine may temporarily improve infiltration rates.



Figure 6. Wetting patterns under drippers at the Chardonnay vineyard in November 2009.



Figure 7. Haloes of moss growth under drippers in adjacent Chardonnay vineyard in August 2009.



Figure 8. Soil surface wetness after 11 mm rain in the preceding 24 h. Note that surface soil between drippers is dry, whereas that immediately surrounding drippers is still wet.

None of the foregoing explains why the infiltration rates under the vine in both mounded and non-mounded vineyards were higher than those in the mid-row. During establishment of the vineyard, the soils under the vine had been prepared for installation of trellis posts by ripping to a depth of about 0.8 m. This preparation may have created preferential flow paths. If these pathways exist, then the distribution of a hydrological tracer should be highly heterogeneous. Figure 9 shows that the distribution of the dye tracer is homogeneous indicating that water flowed throughout the soil cross section rather than along distinct paths.



Figure 9. Horizontal distribution of dye tracer after infiltration of 32 mm of rainwater followed by 64 mm of dye solution.

5.3.4 Effects of winter rain on soil salinity and sodicity

The high infiltration rates in “sodic” soils measured with the infiltrometer are supported by observation of the effect that 365 mm of rain between April and November 2009 had on soil values of EC_e and SAR_e . Rain leached salts from the soil resulting in 75% reduction in the salinity of soils under the vine from 9.3 to 2.5 dS/m (Figure 10). Rain also reduced the SAR_e by about 50% from 18 to 9. The reductions in both parameters were greatest in surface soils, about 80% in each, and least in deeper soils, about 50% for EC_e but only 20% for SAR_e .

Winter rainfall percolates through mounded saline-sodic soils and reduces both soil salinity and sodicity of soils in and underlying the mound. The permeability of the sodic soil to rain was sufficient to allow salinity to be reduced to levels near the threshold value below which salinity does not cause vine damage.

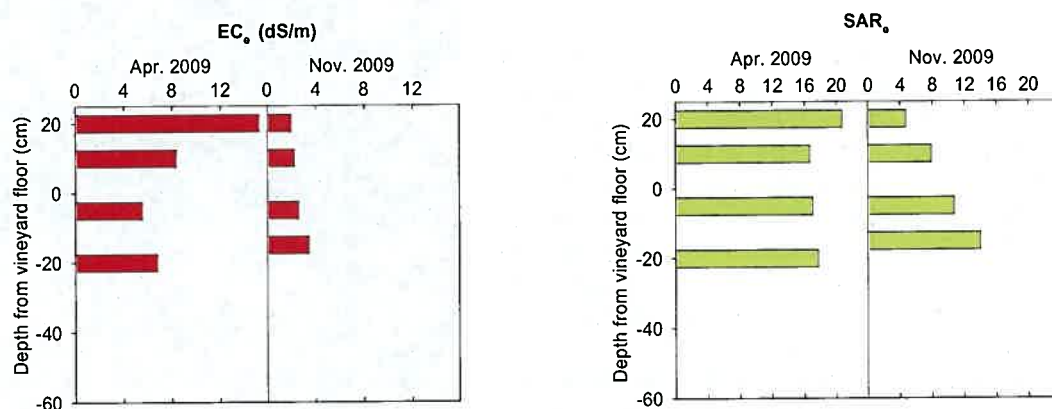


Figure 10. The effect of depth and winter rainfall (365 mm) on the salinity (EC_e) and sodicity (SAR_e) of the saturation paste extract of soils sampled from under the vine in a Chardonnay vineyard where mid-row soils had been mounded under the vine.

6. MANAGEMENT TECHNIQUES WHICH REDUCE THE ACCUMULATION OF SALTS IN THE PLANTS AND SOILS OF GROUNDWATER-IRRIGATED VINEYARDS

6.1 Introduction

Soil salinity and sodicity levels were investigated in three salt affected vineyards at Padthaway which received saline supplementary precision (drip) irrigation. At the end of the irrigation season, the salinity of soils under the vine along the drip line was well above threshold at which salinity begins to cause yield loss, whereas values in soils from the mid-row were well below the threshold value. In all three vineyards, the concentrations of either Cl^- or Na^+ in the leaf were elevated to toxic levels. Saline soils also had high SAR_e . A more detailed investigation in one of these vineyards showed that despite the high soil SAR_e , winter rains leached about 75% of the salt and halved the value of SAR_e in soils under the vine. However, soil salinity still remained above the threshold for salinity damage to vines and it was unclear whether high soil SAR_e at depth had impeded drainage. In this vineyard, soil was mounded under the vine line.

Despite elevated soil SAR_e , the rainfall infiltration rate into the surface of mounded soil between drippers was high, however indirect evidence suggests that infiltration rate into soil nearer the drippers was much lower. It was unclear whether impeded infiltration on the top of the mound near drippers increased the flow of rain off the mound toward the mid-row.

Soil salinity levels in part reflect the rate of drainage and this is controlled by factor affecting the soil water balance (section 5.1). If inputs to this balance are held constant, then a reduction in one output leads to an increase in another. Evapotranspiration and drainage are outputs. The former represents water use by the vine and by the mid-row. A reduction in mid-row water use should lead to an increase in drainage and this would be expected to reduce soil salinity.

Under saline supplementary precision irrigation, the salts are added with the irrigation and the water to flush salt through the soil is provided by rain. The salinity of soil is indicative of the balance between these two processes. Insufficient rain leads to salt build up and sufficient prevents it. In salt affected vineyards, the salinity of soils under the vines was well in excess of the threshold value for damage to vines, whereas the salinity of soil in the mid row was well below the threshold. Rain falling on the mid-row was in excess of that required to maintain soil salinity below the threshold. Re-direction of this excess to the under vine would reduce soil salinity in this region provided subsoil drainage rates were high enough to support the extra flushing.

A field trial was installed to test whether vine salt status and soil salinity could be affected by:

- reducing re-direction of rainfall off the under vine mound toward the mid row by removing the under vine mound
- reducing evapotranspiration losses from the mid row by covering with plastic
- reducing sodicity of soil under the vine by application of a highly soluble calcium source, $\text{Ca}(\text{NO}_3)_2$
- re-directing rain falling on the mid row toward the under vine by moving the soil mounded under the vine to the mid-row to form a mound and covering it with plastic.

6.2 Materials and methods

6.2.1 Vineyard description

The experiment was installed in a commercial own-rooted Chardonnay vineyard located about 12 km south of Padthaway. The vineyard was planted in 1996 with Chardonnay clone I10V1 at row by vine spacing of 2.75 by 1.8 m. Rows were orientated east-west and vines were trained on a two-wire vertical trellis with wires at 1.1 and 1.6 m height. Soils were a sandy loam to medium clay over clay with underlying limestone. In 2002, the soil in the mid-row was pushed under the vine to form a mound which was 0.2 m higher than the vineyard floor in mid-row (Figure 11). Vines were irrigated with 2.1 L/h drippers spaced at 0.6 m. Water for irrigation was drawn from bores. These were sampled biennially and subject to the same analysis as the EC_{1:5} soil solutions. The average salinity over the two seasons of the trial was 2.3 dS/m.

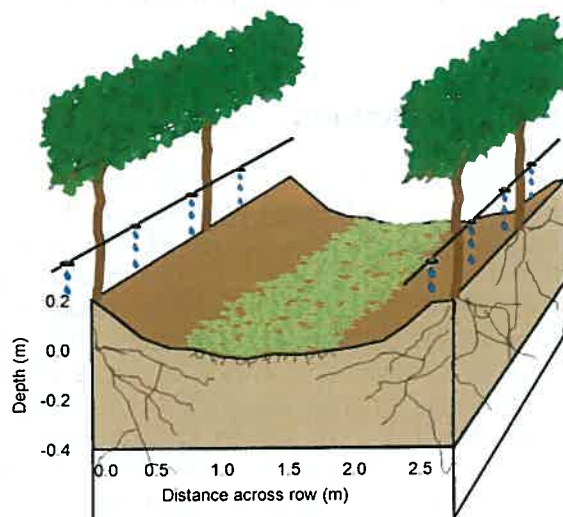


Figure 11. An across the row cross section of the soil surface in the Chardonnay vineyard, showing mounding under the vine and dripper lines (inter row distance 2.75 m).

6.2.2 Trial design and analysis

The trial was laid out as a double Latin square design after harvest in the 2010 season. Installation was completed in February 2010. Each square contained six replicates of six treatments. Each plot consisted of five rows of four vines. All soil and plant measurements were collected from the two central vines in the middle row.

Figure 12 shows the six treatments which included a control and five treatments which tested various combinations of the following changes to vineyard floor management:

- remove the soil which had been mounded under-vine
- cover the surface of the mid row with plastic
- apply calcium to the soil under-vine
- mound soil in the mid-row and cover the surface with plastic.

In treatments B, E and F, the under-vine mounding was removed with an excavator and cleaned up by shovel. Soil removed from under-vine was either exported from the block, treatment B, or mounded in the mid-row mounds to a height of 20 cm and an approximate width of 1 m, treatments E and F. Mid-row mounds were graded and compacted prior to covering with black plastic sheeting (UV stabilised polyethylene 200 μ m thick by 2 m wide).

In all treatments, the soil was ripped to a depth of about 0.3 m at a distance of approximately 0.6 m into the row from the vine line. In treatments D, E and F, a 0.2 m deep trench was excavated along the rip line and black plastic sheeting was laid in the mid-row to cover a width of 1.35 m. Edges of the sheeting buried in the trenches and the trenches re-filled. The

mounding of soil under vine line in 2002 had left the surface of the mid-row with a slight concavity and the plastic sheet in treatment D held about 10 mm of water before shedding to either side (Figure 13). Plastic sheeting was replaced as required over the life of the trial in order to ensure treatment integrity.

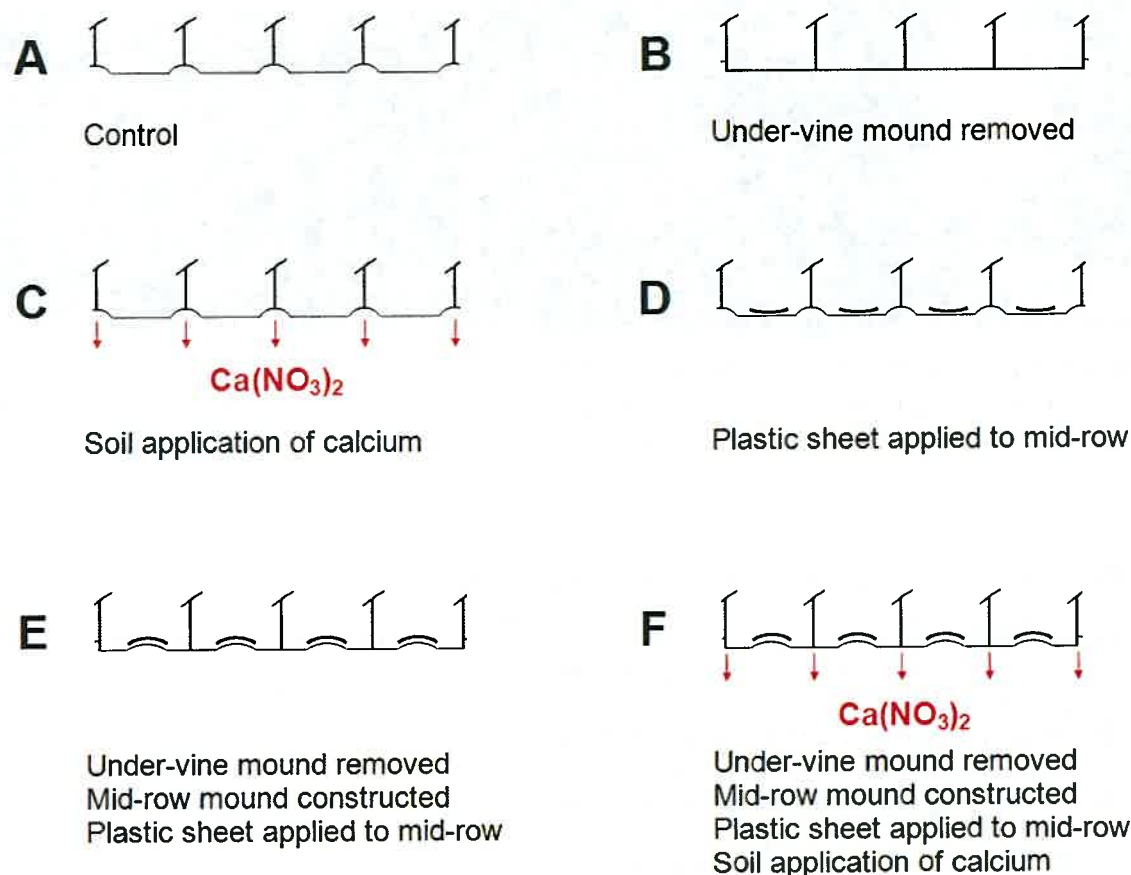


Figure 12. Ideograms of the six treatments.

In the winter of 2010 and 2011 calcium was applied as $\text{Ca}(\text{NO}_3)_2$ to treatments C and F. It was sprayed over a one metre wide strip centred on the vine line at an annual rate of 0.87 t/ha of calcium. The equivalent of applying gypsum (100% pure) at a biennial rate of 7.5 t/ha.

Data on leaf and fruit concentrations of Na^+ and Cl^- were analysed as row, column, (12 by 6) linear model and data on soils, vegetative and fruit growth were analysed as a Latin square (6 by 6 row, column linear model) in GenStat 13th Edition (VSNi, Hemel Hempstead, UK) or Statistix Version 8 (Analytical Software, Tallahassee, FL). Covariates (pre-trial measures of fruit Na^+ and Cl^- concentrations) were included in models fitted to data on leaf and fruit concentrations of Na^+ and Cl^- , and retained in the final model if the *P* value of their significance was 0.1 or less. The significance of various management interventions was assessed with the use of contrasts, see Table 3 for specification of contrasts.



Figure 13. Ponding of rain in treatment D to a depth of about 10 mm on the plastic sheet covering a soil surface with a concave cross section. Rainfall redirection via plastic covered mid-row mound in treatments E & F. Field day at trial site.

Table 3. Specification of contrasts used in data analyses.

Management option	Contrast specification
1. Removing the soil mounded under the vine line	A vs B
2. Reducing mid-row evapotranspiration by covering the mid row soil with plastic	A vs D
3. Redirecting rain falling on the mid-row to the soils under the vine line	AC vs EF
4. Applying a source of highly soluble calcium ($\text{Ca}(\text{NO}_3)_2$) to the soil under the vine line	AE vs CF
5. Testing for an interaction between 3 and 4	AF vs EC

6.2.3 Meteorological, irrigation and soil measurements

Rainfall data were sourced from the local Bureau of Meteorology automatic weather station (station number 026100 for Padthaway South). Data on the reference evapotranspiration (ET_0) and rainfall over the period 1951 to 2012 were generated by running a data drill at <http://www.nrm.qld.gov.au/silo/> in March 2012.

Data on irrigation depths were sourced from vineyard management records. Samples of irrigation water were collected at least twice per season. The salinity was measured using a temperature compensated conductivity meter (model CON510, Eutech, Singapore) and reported at 25°C.

Soils were sampled at the beginning and end of irrigation seasons between April 2010 and March 2012. This sampling regime produced in five samples through the life of the trial viz.,

April 2010, September 2010, March 2011, October 2011 and March 2012. Six replicates were sampled with hand auger (0.1 m diameter head) from in between two drippers, 0.3 m from the drip line, at multiple depths as shown in Table 4. Soils were air dried (40°C).

In March 2012, additional soil samples were collected at a quarter and half the row width, that is at 0.69 and 1.37m from the drip line.

Table 4. Soil sampling depths (from original ground level) for each treatment.

Treatments A, C and D	Treatments B, E and F
+0.1 m to 0.0 m	
0.0 m to -0.1 m	0.0 m to -0.1 m
*-0.1 to -0.2 m	-0.1 to -0.2 m
-0.2 to -0.3 m	*-0.2 to -0.3 m
-0.3 to -0.4 m	-0.3 to -0.4 m

*Samples only collected in March 2012.

Soil salinity was measured as the electrical conductivity of 1:5 soil:water extracts ($EC_{1:5}$) following method of Rayment and Higginson (1992). The soil pH was measured on the 1:5 soil:water extract following the method of Rayment and Lyons (2011). Electrical conductivity was measured on duplicate samples (<4% RSD between duplicates) using a temperature compensated conductivity meter (model CON510, Eutech, Singapore) and reported at 25°C. The pH was measured using a temperature compensated pH meter (model pH 510, Eutech, Singapore) and reported as pH (1:5 soil:water) at 25°C.

For samples taken in March 2012, the water content of soils was assessed gravimetrically and the $SAR_{1:5}$ was calculated from measures of sodium, magnesium and calcium concentrations in the 1:5 soil:water extract of samples taken from between 0.3 and 0.4 m below surface of the current soil at 0.3 m from the drip line. Values of $SAR_{1:5}$ were converted to ESP based on the relationship of Rengasamy et al. (1984). Cations and sulphur were measured by Inductively Coupled Plasma Optical Emission Spectroscopy (ICPOES). The sample was nebulised into the plasma of a Spectro ARCOS (Spectro Analytical Instruments, Kleve, Germany). The emission spectra of the elements of interest were measured simultaneously.

The values of soil bulk density used to convert gravimetric values of soil water content to volumetric were determined in the vineyard in late 2009. Volumetric samples of soil were obtained with brass rings (0.07 m diameter and 0.07 m depth). Soil was dried at 100 °C until it reached a constant weight.

Conversion between the measurements of $EC_{1:5}$ and EC_e was based on a relationship determined in soils taken from a nearby vineyard on the same soil series. Soils were sampled at 0-0.1, 0.25-0.35 and 0.55-0.65 m depths. The samples were divided, air dried and either saturated paste or 1:5 soil:water extracts were prepared.

6.2.4 Plant measurements of tissue Na^+ and Cl^- concentrations

Measurements of tissue Na^+ and Cl^- concentrations were undertaken in all 12 replicates. Leaf petiole samples were collected from opposite the basal inflorescences at flowering (E-L stage 23-25) in the 2010, 2011 and 2012 seasons. Leaf lamina were collected opposite to basal bunches at harvest (E-L stage 38) in the 2011 and 2012 seasons. If there were less than 10 basal inflorescences or bunches, then leaves were collected from opposite basal

tendrils. The petioles and lamina were dried at 70°C for at least 72 hours and ground using a Micro Hammer-Cutter Mill (Culatti AG, Zurich, Switzerland) to pass through a 0.5 mm mesh.

Berry samples were collected at harvest (E-L stage 38) in the 2010, 2011 and 2012 seasons. The fruit was crushed in a hand press and the extracted juice was clarified by centrifuging at 10397 x g for 10 minutes. Samples were frozen for later measurement of Na⁺ and Cl⁻ concentrations.

The Cl⁻ concentration was measured by silver ion titration with a Buchler chloridometer (Labconco, Kansas City, MO, USA). Duplicate extracts were prepared by adding 1 mL aliquot of juice to 3 mL of an acid solution containing 10% (v/v) glacial acetic acid and 0.1 M nitric acid and 4 drops of gelatine reagent.

The Na⁺ concentration was measured by ICP (Spectro Analytical Instruments, Kleve, Germany). Leaf sample extracts were prepared using 100-300 mg of dried, ground sample in a nitric acid and hydrogen peroxide digestion. Samples were diluted to 25mL and cold digested over night. Following this, the temperature of samples was increased over a 2.5 hour time period to a maximum not exceeding 125°C. Juice samples were analysed as per Wheal et al. (2011).

6.2.5 Measurement of photosynthesis and plant water relations

In 2012, the values of pre-dawn and early afternoon leaf water potential and gas exchange were measured in six replicates on 31 January and 2 February 2012, respectively. Leaf gas exchange was measured with a LICOR-6400 portable infra-red gas analysis system (LI-COR, Lincoln, USA). Prior to entering the chamber air was scrubbed of CO₂ and then CO₂ was injected to produce an air stream in which the concentration of CO₂ remained constant at 400 µL/L. For early afternoon measures the leaf was illuminated with light emitting diodes with quantum flux of 1800 µE/m².s. The relative humidity of the sample stream and the cuvette air temperature were maintained at ambient values.

Data were included in analyses when value of LICOR stability statistic was equal to 1. The stability statistics was calculated from the coefficients of variation for CO₂ and H₂O concentrations in the sample air stream and the flow rate over a 15 second sampling period, and the slope of the rate of change in the mean values. If %CV were all less than 1% and slopes less than 1 for all 3 parameters, then the stability statistic was equal to 1 and derived values of assimilation and related variables were considered stable.

Within less than 10 minutes after measurement of leaf gas exchange, the leaf was enclosed in aluminised plastic bag, excised and sealed within a Scholander Pressure Bomb (Scholander et al. 1965, Turner and Long 1980). Within 30 s of leaf excision, the chamber was pressurised at a rate of 0.01 MPa/s with the end-point to pressurisation observed using a binocular microscope under 10-fold magnification. Dry and wet bulb temperatures were measured with an aspirated psychrometer at a height of 2 m above-ground level. The VPD was calculated from these measures using an algorithm from Sargent (1980).

6.2.6 Measurement of vegetative growth, yield and fruit maturity

Vegetative growth was assessed by measurement of the leaf area index (LAI) in six replicates. The LAI was measured just prior to harvest in 2011 and 2012 using an LAI-2000 Plant Canopy Analyser (LI-COR, Lincoln, NE, USA). Measurements were based on a modified version of a method described by Ollat et al. (1998). Measurements were collected

on the two central vines of each plot with LAI calculated from six sets of 'two above canopy and ten below canopy' readings. Three of these sets were measured parallel to the vines and three sets were measured diagonal to the vines (Figure 14).

Measurements were collected at dusk with lens facing away from sun. 'Below' canopy readings were measured along a 2m distance (every 0.2 m) at a height of 0.2 m above the original soil surface. 'Above' canopy readings were measured in the same orientation as the corresponding below readings at a height of 2.5 m. Above canopy readings were interpolated.

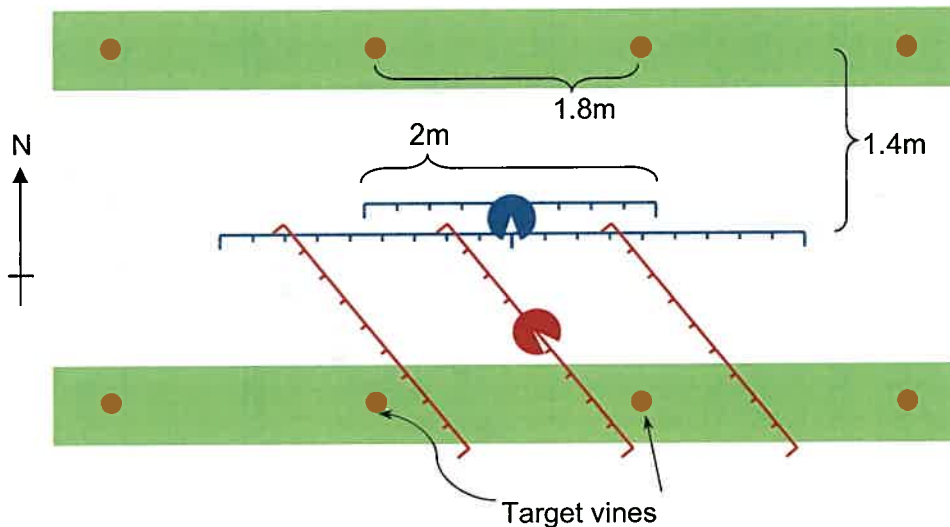


Figure 14. Above vine view of LAI-2000 data collection protocol, parallel and diagonal to two vines. The lens was masked with a 45° view cap which was aligned south for parallel to vine measurements and south east for diagonal to vine measurements.

Fruit growth was assessed at harvest by measurement of yield, bunch number and weight of a 100-berry sample in six replicates. For these measurements the unit vine length was set as the within-row inter-vine distance (sampled butt to butt). Measurements were made in 2010, 2011 and 2012. The 100-berry sample was generated by sampling bunches on both sides of the vine and picking berries from the left, right, top, bottom, back and front of the bunch. The samples were transported from the field to the laboratory in chilled insulated containers.

The fruit was crushed in a hand press and the extracted juice was clarified by centrifuging at 10397 x g for 10 minutes. In all years, the total soluble solids concentration was measured on clarified juice by digital refractometer and expressed as °Brix 20°C. In 2011 and 2012, pH and the concentration of titratable acid (TA) were measured using an auto-endpoint TA and pH meter (Metrohm, Ionenstrasse, Switzerland); the juice was titrated against 0.133 M NaOH. After measurement, samples were frozen for later measurement of Na⁺ and Cl⁻ concentrations.

6.3 Results and discussion

6.3.1 Soil salinity

6.3.1.1 EC_e to $EC_{1:5}$ relationship

Measurements of EC_e had a highly significant linear relationship with those of $EC_{1:5}$. The values of $EC_{1:5}$ explained 91% of the variation in EC_e . The slope of the relationship, 6.53:1, is similar to the value of the conversion factor, 6.6, which Cass et al. (1996) proposed as applicable for soils in the same texture class (sandy clay, clay loam) as those at the Padthaway site.

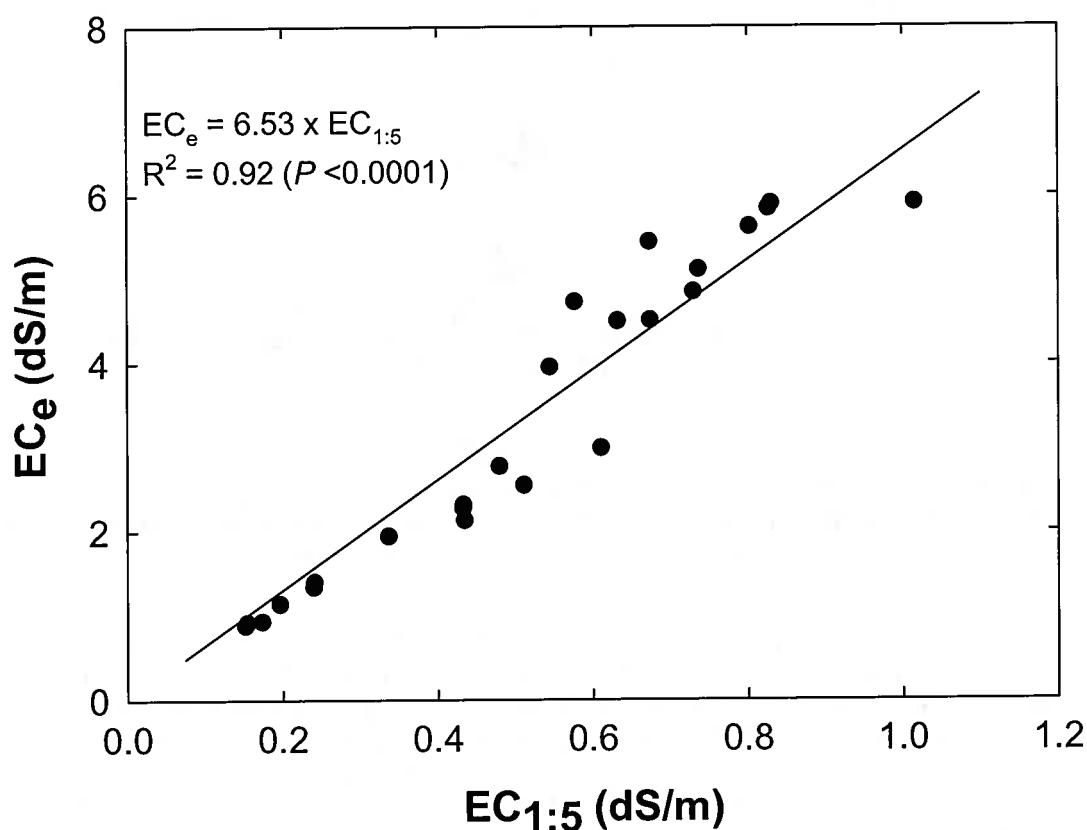


Figure 15. The relationship between soil EC_e and soil $EC_{1:5}$ for shallow clay loam over calcareous clay on calcrete at Padthaway. Under vine soil cores were co-sampled with Rob Walker (CSIRO Plant Industry).

6.3.1.2 Seasonal variation in the salinity of soil under the vine

Pre-trial measures showed that salt accumulation in the soil was focussed under the vine and drip line and not in the mid-row. Figure 16 shows a time series of the measurements of soil salinity taken from under the vine between the end of the 2010 and 2012 seasons. It was generated by combining measurements taken before the trial installation with those taken in the control treatment during the trial. The value of salinity in the soil under the vine remained above the threshold for salinity effects on yield in own rooted vines of 2.1 dS/m (Zhang et al. 2002). Salinity rose over the season in the 2010 and 2012 seasons, but not in

the 2011 season. Depths of rain in the winter were similar at 361, 330 and 312 mm for the 2009, 2010 and 2011 winters, respectively. Irrigation was the source of salt. In 2010 and 2012 the depths of irrigation, 241 and 238 mm, respectively, were double that of 120 mm in 2011.

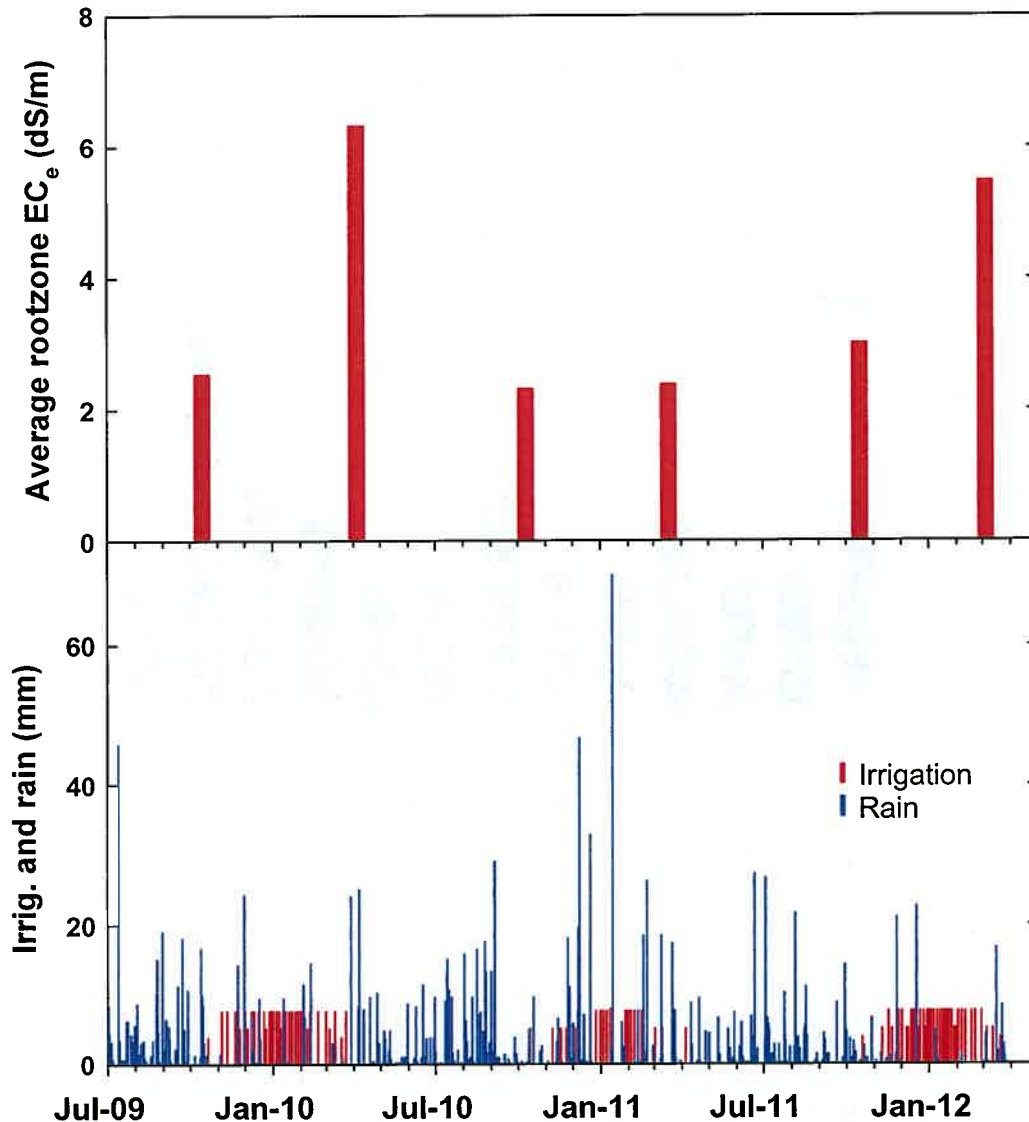


Figure 16. The time course of soil salinity, rain and irrigation over three seasons in a Chardonnay vineyard in Padthaway.

Rain provides water to flush salts. The within season rainfall of 316 mm in 2011 was at least 90% more than the depths of 168 and 95 mm which fell in 2010 and 2012. Between season differences in soil salinity were associated with between season differences in depths of irrigation and depths of within season rainfall. Over three seasons, reduced 'within season' accumulation of soil salt was associated with a higher 'within season' depth of rainfall and lower within season depth of irrigation.

It should be noted that the within season rainfall in 2011 was more than double the long term average (Figure 17).

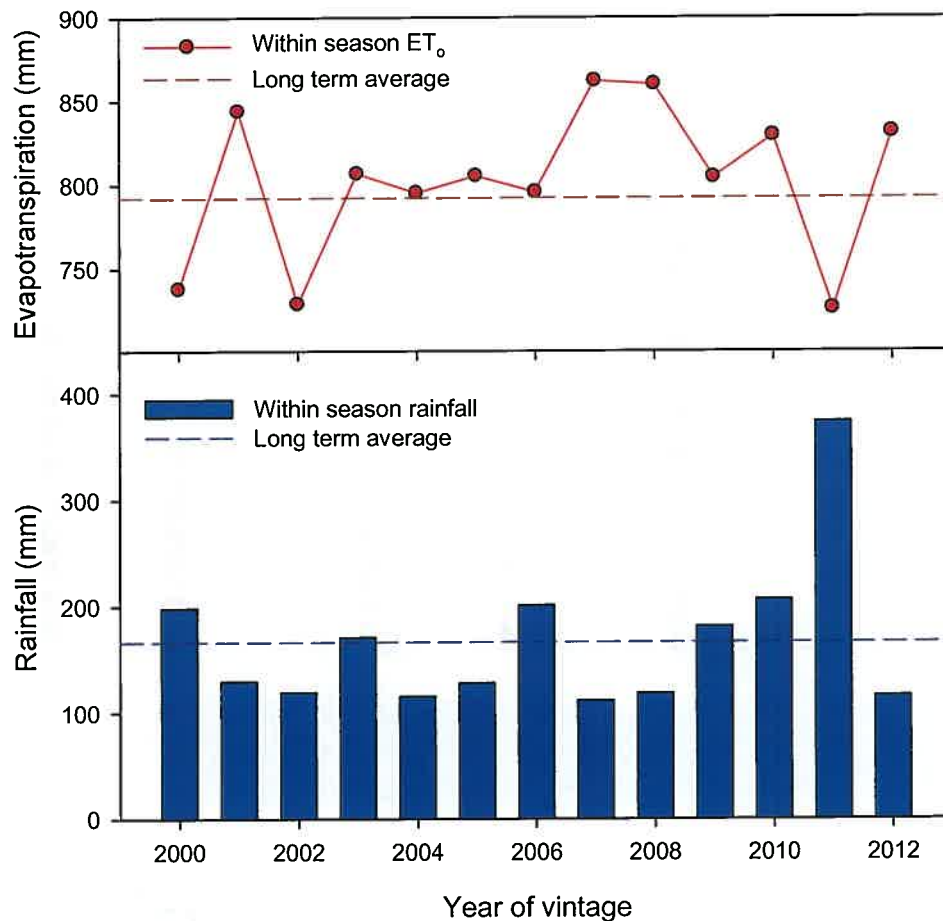


Figure 17. The within season (November to April inclusive) evapotranspiration (FAO56) and rainfall for the last 12 seasons. Dotted lines show the long term within season average values (seasons 1951 – 2012).

The soil salinity in the control treatment varied with depth (Figure 18). Over the period between the ends of season in 2010 and in 2012, the average salinity in the topsoils, 3 dS/m, was less than that of 5 to 6 dS/m in the sub soil. In the topsoil, salinity values were below 1.5 dS/m for the entire 2011 season and the opening of the 2012 season, whereas during the same period the values in the subsoil remained above 3.0 dS/m. Data from the beginning of the 2010 season (Figure 10) shows that the deeper soils also had higher values of sodicity. It is not clear why rainfall in winter of 2010 produced a 5 dS/m drop in the salinity of deeper soils, whereas a similar depth of rain in the winter of 2011 produced a slight increase in salinity.

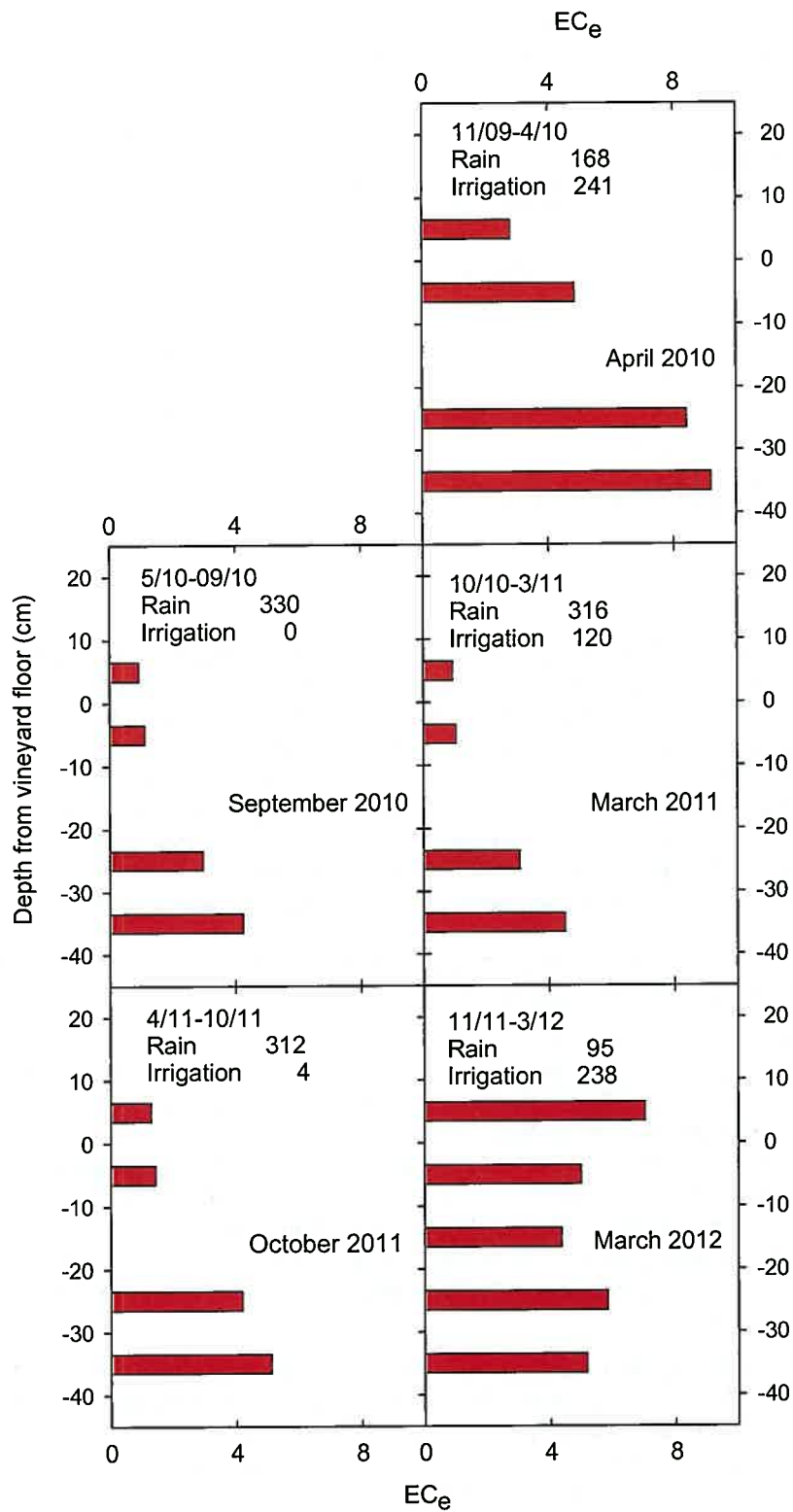


Figure 18. The variation of EC_e under the vine with depth from the end of the irrigation season in 2010 to its end in 2012. Rain and irrigation depths refer to the 5-7 month period preceding soil sampling.

Table 5. The effect and significance[†] of different floor management options on the average salinity (expressed as EC_e, dS/m) of soil sampled from under the vine line in autumn and spring.

Management options	(No 1) Remove U-V [‡] mound		(No 2) Reduce evapotranspiration from M-R soils		(No. 3) Re-direct rain falling on M-R to U-V		(No. 4) Add Ca(NO ₃) ₂		(No. 5) Interaction No. 3 by No. 4	
Option status	No	Yes	No	Yes	No	Yes	No	Yes		
Contrast	A	vs B	A	vs D	AC	vs EF	AE	vs CF	AF	vs CE
Sampling Date										
7/04/2010 [§]	7.0	4.4**	7.0	5.0	5.6	3.9*	5.2	4.2	5.2	4.1
21/09/2010 [§]	2.0	1.6	2.0	2.0	2.3	1.4***	1.7	2.0	1.8	1.9
17/03/2011 [§]	2.2	1.5*	2.2	2.0	2.2	1.2***	1.7	1.6	1.6	1.7
18/10/2011 [§]	2.9	1.4***	2.9	2.4	3.0	1.4***	2.0	2.0	2.0	2.1
5/03/2012 [§]	5.6	4.5	5.6	5.6	5.7	4.4	4.7	5.3	5.2	4.8

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

[‡]U-V, under vine; M-R, mid row.

[§] geometric means.

The different vineyard floor management options significantly affected soil salinity (Table 5). Both removal of the under vine mound and re-directing rain falling in the mid-row to the under vine lowered soil salinity by between 31 and 54%. Neither the addition of Ca(NO₃)₂ nor the reduction in evapotranspiration from the mid-row affected soil salinity. Both re-direction of rainfall and removal of the under vine mound lowered soil salinity at the end of the 2010 and 2011 seasons. The effect in 2010 was established in the two months between installation of the trial and soil sampling. Rainfall during this period was 71 mm. Re-direction of rainfall reduced soil salinity at the openings of the 2011 and 2012 seasons by 40% on average. Removal of the under vine mound was less effective.

6.3.1.3 Effect of floor management treatments on the two-dimensional distribution of soil salinity and moisture

Data collected from soils sampled under vine, a quarter way into the row and mid-row in March 2012, were used to characterise the two-dimensional distribution of soil water and soil salinity in the root zone. Figure 19 shows for each treatment the variation in the volumetric water content with depth and distance from vine line. Floor management treatment did not affect the average value of the volumetric water content of soil between 0 and 0.4 m depth from the original surface averaged over the entire row (Table 6). Separately considering the data from at each of the three distances into the row shows that floor management treatments did not affect values under the vine and in the mid-row, but at ¼ way into the row the addition of Ca(NO₃)₂ increased the volumetric soil content by 35% from 0.168 m³/m³ to 0.226 m³/m³ (Table 6).

Figure 20 shows for each treatment the variation in the soil salinity with depth and distance from vine line. Floor management affected the value of the average salinity of soils with re-direction of rainfall increasing the salinity by 25% from 2.7 to 3.3 dS/m and the addition of Ca(NO₃)₂ increasing salinity by 21% from 2.7 to 3.3 dS/m (Table 6). Within a treatment, distance from the vine row, rather than depth, was the greater source of variation in values of soil salinity. Separate contrasts were conducted for the three data sets at different distances from the vine (Table 6). Floor management had no effect on the values under the vine with an average of 5.1 dS/m. At a ¼ way in to the row, re-direction of rainfall increased salinity by 45% from 1.5 to 2.2 dS/m and there as a trend ($P = 0.08$) for addition of Ca(NO₃)₂

to increase salinity by 27% from 1.7 to 2.1 dS/m. In the mid-row, re-direction of rainfall increased salinity by 159% from 1.1 to 2.9 dS/m and the addition of $\text{Ca}(\text{NO}_3)_2$ increased it by 21% from 1.8 to 2.2 dS/m.

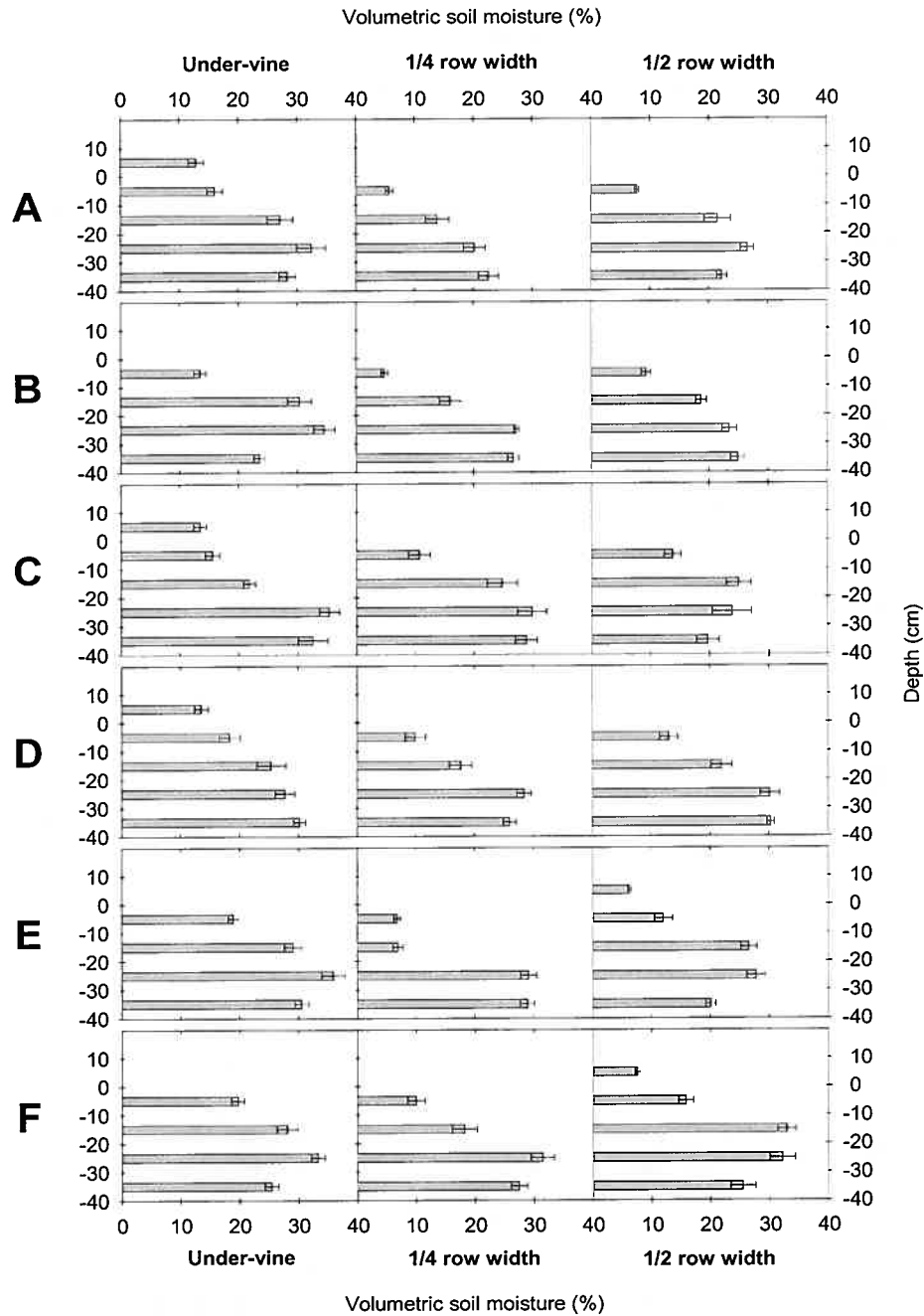


Figure 19. The effect of floor treatment, depth and distance from the vine row on soil volumetric water content (% v/v) in March 2012 at the end of the irrigation in the 2012 season. Bars represent the standard error.

In treatment A, the control, the average salinity in March 2012 between depths 0 – 0.25 m of 5 dS/m under the vine and 1.0 dS/m in the mid-row were similar to the values of 6.1 and 0.8 dS/m, respectively, measured in the same vineyard in April 2009 before installation of the trial (Figure 3). Between these dates the salinities of soil under the vine were much lower (the salinity of soil in the mid-row was not measured).

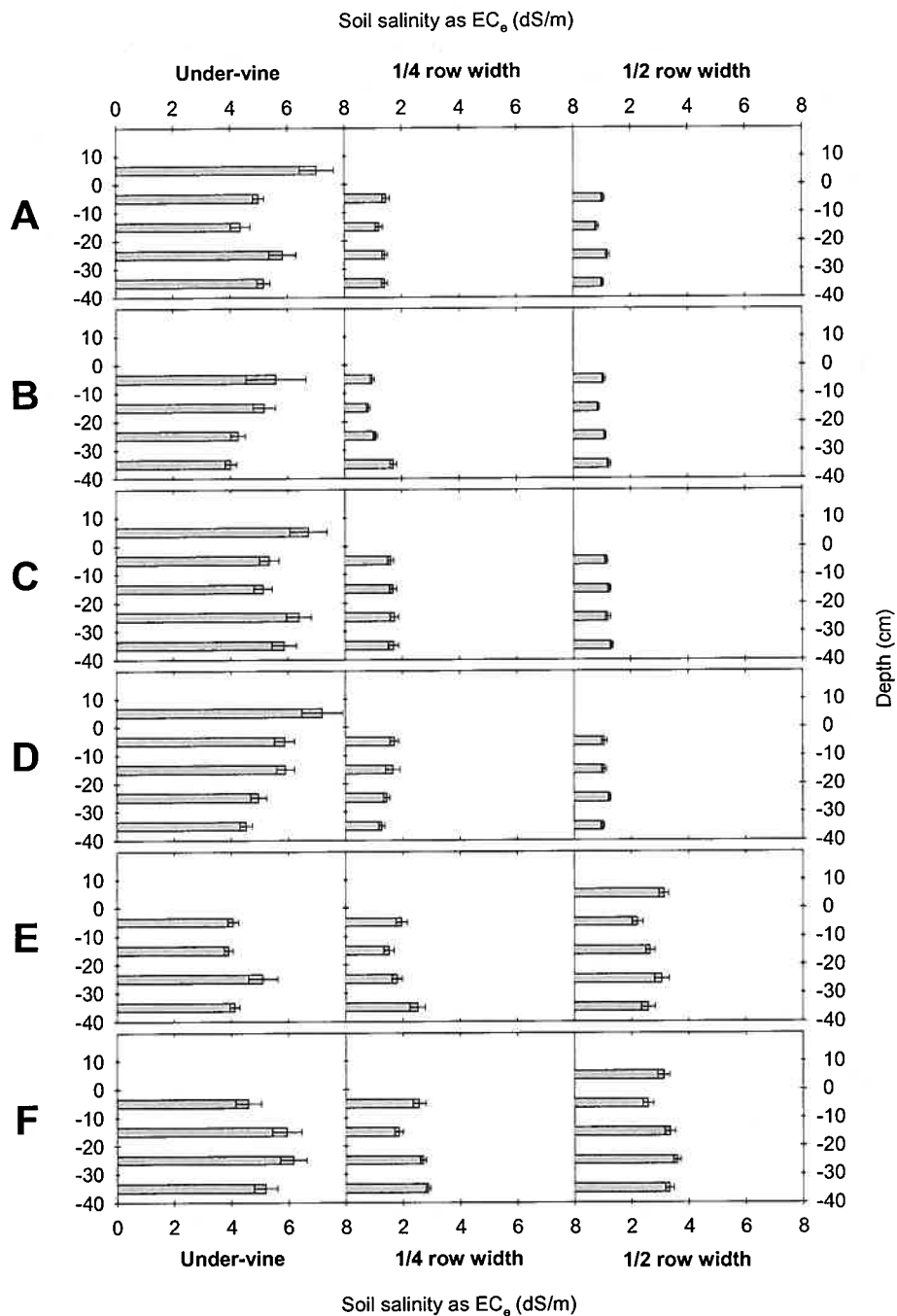


Figure 20. The effect of floor treatment, depth and distance from the vine row on soil salinity in March 2012 at the end of the irrigation in the 2012 season. Bars represent the standard error.

Table 6. For soils sampled the end of the irrigation in the 2012 season in March, the effect and significance[†] of floor management treatments on the volumetric soil water content (m³/m³), and average salinity of soil expressed as EC_e (dS/m) between 0 and 40 cm depth across the entire row (VWC, EC_e all), under vine (VWC, EC U-V), ¼ way into the row (VWC, EC_e ¼ row) and mid row (VWC, EC_e M-R).

Management options	(No 1) Remove U-V [‡] mound		(No 2) Reduce evapotranspiration from M-R soils		(No. 3) Re-direct rain falling on M-R to U-V		(No. 4) Add Ca(NO ₃) ₂		(No. 5) Interaction No. 3 by No. 4	
Option status	No	Yes	No	Yes	No	Yes	No	Yes		
Contrast	A	vs B	A	vs D	AC	vs EF	AE	vs CF	AF	vs CE
Parameter										
VWC all	0.203	0.209	0.203	0.228	0.219	0.223	0.208	0.233	0.218	0.224
VWC U-V	0.260	0.255	0.260	0.253	0.262	0.277	0.273	0.265	0.263	0.275
VWC ¼ row	0.156	0.185	0.156	0.200	0.195	0.199	0.168	0.226**	0.187	0.207
VWC M-R	0.195	0.186	0.195	0.231	0.199	0.193	0.184	0.208	0.203	0.189
EC _e all	2.5	2.3	2.5	2.7	2.7	3.3*	2.7	3.3*	3.11	2.91
EC _e U-V	5.1	4.8	5.1	5.4	5.4	4.9	4.7	5.6	5.3	5.0
EC _e ¼ row	1.4	1.1	1.4	1.5	1.5	2.2*	1.7	2.1	1.9	1.8
EC _e M-R	1.0	1.1	1.0	1.1	1.1	2.9***	1.8	2.2*	2.1	1.9

[†]*<0.05, **<0.01, *** <0.001.

[‡]U-V, under vine; M-R, mid row.

6.3.1.4 Effect of floor management treatments on soil sodicity

Winter rainfall in 2009 had less affect on soil sodicity than soil salinity and its effect on sodicity diminished with depth (Figure 10). For soil at 0.3 - 0.4 m depth, Table 7 shows the effect of floor management treatments on the salinity and the sodicity and its determinants at the end of the irrigation in the 2012 season.

Table 7. The significance[†] of floor management treatments on the soil salinity (expressed as EC_e, dS/m), pH, concentrations (mM) of Na⁺ Ca²⁺ and S (expressed as SO₄²⁻) and SAR in the 1:5 soil:H₂O extract of soil sampled from between 0.3 and 0.4 m depth from the surface in March 2012.

Management options	(No 1) Remove U-V [‡] mound		(No 2) Reduce evapotranspiration from M-R soils		(No. 3) Re-direct rain falling on M-R to U-V		(No. 4) Add Ca(NO ₃) ₂		(No. 5) Interaction No. 3 by No. 4	
Option status	No	Yes	No	Yes	No	Yes	No	Yes		
Contrast	A	vs B	A	vs D	AC	vs EF	AE	vs CF	AF	vs CE
[§] EC _e	5.5	3.9	5.5	4.8	5.8	4.4	4.7	5.4	5.2	5.0
pH	8.5	8.7	8.5	8.6	8.4	8.2	8.4	8.2*	8.3	8.3
[§] Na ⁺	9.3	6.6*	9.3	6.6*	8.0	4.9***	7.2	5.4*	6.3	6.2
[§] Ca ²⁺	0.7	0.5	0.7	0.8	0.9	1.4*	0.8	1.5**	1.1	1.1
[§] SO ₄ ²⁻	0.39	0.22	0.39	0.26	0.31	0.15**	0.24	0.19	0.24	0.19
[§] SAR _{1:5}	8.4	7.7	8.4	5.7	6.5	3.2***	6.1	3.4***	4.5	4.7

[†]*<0.05, **<0.01, *** <0.001.

[‡]U-V, under vine; M-R, mid row.

[§] geometric means.

Floor management treatments had no effect on the value of the salinity in the soil at 0.3 - 0.4 m depth from the surface. The average value was 4.8 dS/m. Addition of $\text{Ca}(\text{NO}_3)_2$ lowered soil pH by 0.02 units.

All four management options reduced the concentration of Na^+ by between 25 and 39%. The effects of addition of $\text{Ca}(\text{NO}_3)_2$ and re-direction of rain were additive because the interaction term was not significant. Both addition of $\text{Ca}(\text{NO}_3)_2$ and re-direction of rain increased the concentration of Ca^{2+} by 38% on average; again the effects were additive. Re-direction of rain halved the concentration of soluble sulphur and therefore the positive effect of rainfall re-direction on Ca^{2+} concentration was not related to the mobilisation of gypsum. Changes in SAR followed on from treatment which increased Ca^{2+} , rather than those which reduced Na^+ . Both addition of $\text{Ca}(\text{NO}_3)_2$ and re-direction of rain reduced SAR by 47% on average. The effects were additive.

The value of $\text{SAR}_{1:5}$ in treatment A in March 2012 was 8.4, which equated to an ESP of 18.2. In April 2009, the SAR_e of soil at 15-25 cm depth was 17.7 (Figure 4) which equated to a ESP of 20.7. In common with salinity, the values of ESP in the control treatment on these two dates were also similar.

6.3.2 The effect of floor management treatments on the sodium and chloride concentrations in leaves and fruit.

Re-directing rain falling on the mid row to the under vine lowered petiole Na^+ concentrations in both seasons by 23% on average (Table 8). In the 2012 season, removing the under vine mound lowered Na^+ concentration by 15%, reducing evapotranspiration from the mid row lowered it by 25% and adding $\text{Ca}(\text{NO}_3)_2$ lowered it by 13%. The significance of the interaction term, No 5, indicates that the latter effect was not present in treatment C.

Removing the under vine mound and re-directing rainfall reduced petiole Cl^- concentrations in both seasons by 22% on average (Table 8). In 2011 season, adding $\text{Ca}(\text{NO}_3)_2$ lowered it by 12%, and the significance of the interaction term, No 5, indicates that the effect was not present in treatment C. In the 2012 season, reducing evapotranspiration from the mid row lowered it by 21%.

In treatment A, the petiole Na^+ concentrations of 0.07% and 0.10% in the 2011 and 2012 seasons, respectively, were less than the value of 0.15% measured in the vineyard in the 2010 season prior to installation of treatments. Likewise, the Cl^- concentrations of 0.89% and 0.73% in the 2011 and 2012 seasons, respectively, were less than the value of 1.09% in the 2010 season.

The Na^+ and Cl^- concentrations in the petiole sampled at flowering are robust indicators of whether the salinity pressure on the vine that has been sufficient to cause yield loss. The concentrations of Na^+ and Cl^- in treatment A were well below the levels of 0.5% and 1.5%, respectively, that are indicative of a salinity pressure sufficient to reduce yield (Robinson et al. 1997).

Table 8. The significance[†] of effects of floor management treatments on the concentrations of Na⁺ and Cl⁻ in the leaf petiole (% d.w.) sampled at flowering and juice (mg/L) from fruit sampled at harvest and in the concentration of Cl⁻ in leaf lamina (% d.w.) sampled at harvest.

Management options	(No 1) Remove U-V [‡] mound		(No 2) Reduce evapotranspiration from M-R soils		(No. 3) Re-direct rain falling on M-R to U-V		(No. 4) Add Ca(NO ₃) ₂		(No. 5) Interaction No. 3 by No. 4	
Option status	No	Yes	No	Yes	No	Yes	No	Yes		
Contrast	A	vs B	A	vs D	AC	vs EF	AE	vs CF	AF	vs CE
Petiole										
[§] Na ⁺ 2011	0.068	0.057	0.068	0.079	0.070	0.057*	0.065	0.061	0.059	0.067
Na ⁺ 2012	0.101	0.086*	0.101	0.075***	0.088	0.063***	0.081	0.07*	0.083	0.067***
[§] Cl ⁻ 2011	0.89	0.71**	0.89	0.81	0.86	0.70*	0.83	0.73*	0.76	0.79
[§] Cl ⁻ 2012	0.73	0.58***	0.73	0.58***	0.68	0.49***	0.59	0.56	0.60	0.55*
Lamina										
[§] Cl ⁻ 2011	0.60	0.53	0.60	0.59	0.62	0.47***	0.54	0.55	0.53	0.56
Cl ⁻ 2012	0.62	0.49*	0.62	0.56	0.61	0.47***	0.54	0.54	0.55	0.53
Juice										
[§] Na ⁺ 2011	33	29	33	36	33	28*	31	30	30	30
[§] Na ⁺ 2012	29	21***	29	27	28	18***	24	22	23	23
[§] Cl ⁻ 2011	69	60	69	79	77	52*	61	68	60	69
[§] Cl ⁻ 2012	62	37***	62	54	59	29***	42	42	43	40

[†]* < 0.05, ** < 0.01, *** < 0.001.

[‡]U-V, under vine; M-R, mid row.

[§]geometric means.

Re-directing rain falling on the mid-row to the under vine reduced lamina Cl⁻ concentrations by 24% the 2011 and 2012 seasons (Table 8). Removing the under vine mound reduced Cl⁻ concentration by 22% in the 2012 season.

In both seasons, re-directing rain falling on the mid row to the under vine lowered juice Na⁺ and Cl⁻ concentrations on average by 25 and 40%, respectively (Table 8). In the 2012 season, removing the under vine mound lowered Na⁺ and Cl⁻ concentrations by 29%.

In Treatment A, the Na⁺ concentrations in juice of 33 and 29 mg/L in the 2011 and 2012 seasons, respectively, were less than the value of 46 mg/L measured in the 2010 season prior to installation of treatments. Likewise, the Cl⁻ concentrations of 66 and 62 mg/L in the 2011 and 2012 seasons, respectively, were less than the value of 138 mg/L in the 2010 season.

In addition to yield loss, excessive salinity can elevate the salt concentrations in the fruit to a level which reduces the marketability of wine made from such fruit. The production of white wine does not cause much change in the Na⁺ and Cl⁻ concentrations and the ratios of concentrations in wine to those in juice are about 1:1 (Rankine et al. 1971). Over the 2011 and 2012 seasons the maximum concentration of Na⁺ and Cl⁻ in juice extracted from fruit in Treatment A, were 66 and 33 mg/L, respectively. These concentrations are well below the maximum for Cl⁻ specified in the Australian and New Zealand food standard (FSANZ, 2010) and the maxima for Na⁺ specified for entry into markets in Switzerland, South Africa and some provinces in Canada (Stockley 2009).

The presence of NaCl in wine can also alter taste. Bastian et al. (2010) investigated whether tasters could detect or recognise NaCl in white wine over NaCl concentrations ranging from below 100 mg/L to 2400 mg/L. They found that 63% of tasters could not detect NaCl in white wine at 100 mg/L and that 98% of tasters could not recognise NaCl at this concentration. The concentrations of Na⁺ and Cl⁻ in juice from the 2011 and 2012 seasons were below the levels of detection and recognition for most tasters.

6.3.3 Effect of floor management on vine water relations and gas exchange

Vine water relation and gas exchange were measured just before harvest in the 2012 season. The afternoon value of vapour pressure deficit (VPD) was 2.5 kPa. Floor management treatments had no effect on either pre-dawn or early afternoon values of leaf water potential, the average values were -0.4 and -1.3 MPa, respectively (Table 9). It also did not affect values of leaf photosynthetic rate and stomatal conductance with averages of 11.2 $\mu\text{mol CO}_2/\text{m}^2.\text{s}$ and 0.126 $\text{mol H}_2\text{O}/\text{m}^2.\text{s}$, respectively.

Table 9. The effects of floor management treatments on the early afternoon leaf photosynthetic rate (A, $\mu\text{mol CO}_2/\text{m}^2.\text{s}$) and stomatal conductance (g, $\text{mol H}_2\text{O}/\text{m}^2.\text{s}$) and early afternoon and pre-dawn leaf water potentials (Ψ_{AFT} and Ψ_{PD} , respectively, MPa) in early February 2012.

Management options	(No 1) Remove U-V [†] mound		(No 2) Reduce evapotranspiration from M-R soils		(No. 3) Re-direct rain falling on M-R to U-V		(No. 4) Add Ca(NO ₃) ₂		(No. 5) Interaction No. 3 by No. 4	
Option status	No	Yes	No	Yes	No	Yes	No	Yes		
Contrast	A	vs B	A	vs D	AC	vs EF	AE	vs CF	AF	vs CE
Parameter										
A	11.2	11.4	11.2	11.2	11.4	11.8	11.6	11.6	11.4	11.8
g	0.126	0.140	0.126	0.125	0.130	0.128	0.127	0.131	0.127	0.131
Ψ_{PD}	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4
Ψ_{AFT}	-1.3	-1.2	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3	-1.3

[†]U-V, under vine; M-R, mid row.

Leaf water potential declines with increases in soil salinity and decreases in soil water content. In well watered vines, pre-dawn leaf water potential is near -0.1 MPa (Williams et al. 2011). A 3 dS/m increase in the salinity of the saturated paste extract depresses this value by about -0.13 MPa (Stevens 2005). A few weeks after harvest, the ECe for the whole of profile and for soil under the drip line were 2.5 and 5.1 dS/m (Table 6). If the vines were well watered, then after accounting for the effect of soil salinity on pre-dawn water potentials, the values of these potentials should range from -0.2 to -0.3 MPa. The recorded value was more negative than the lower end of the range and this indicates that the vines were experiencing water stress caused by a soil water deficit. In the absence of stress, afternoon leaf water potential on days with a afternoon values of VPD at 2.5 kPa should be above -1.0 MPa (Stevens et al. 2010); the observed value of -1.3 MPa is well below this. Both Stevens et al. (2010) and Williams (2012) have found that at leaf water potentials of -1.3 MPa, the rate of leaf photosynthesis was about 11 $\mu\text{mol CO}_2/\text{m}^2.\text{s}$ which both authors found to be about 70% of the values in non-stressed vines. Given the observed values of soil salinity, leaf photosynthesis and leaf water potential, it is likely that the vines were affected by both salinity and water stress.

6.3.4 Effect of floor management on vegetative growth, yield and fruit quality

Generally, floor management treatments had no effect on yield, LAI and fruit composition. When present, the exceptions were not sustained across two seasons. Floor management treatments had no effect on yields in 2011 and 2012 seasons and none on the yield components, bunch number per vine and berry weight, excepting the 7% increase in berry weight associated with removal of the under-vine mound in the 2012 season (Table 10). Floor management treatments had no effect on LAI excepting the 8% reduction caused by re-directing mid-row rainfall in the 2011 season.

Grapevine yield is proportional to water use (Williams et al. 1992) and the absence of a response in yield to mound removal would support a contention that mound removal had not caused any change in water use. Thus, reductions in soil salinity under treatments in which mounds had been removed cannot be attributed to depression of crop evapotranspiration with an associated increase in leaching fraction.

In 2011 season, floor management treatments had no effect on fruit composition, except for the addition of $\text{Ca}(\text{NO}_3)_2$ which increased titratable acidity by 5%. In 2012, re-directing rain falling on the mid-row and reducing evapotranspiration from the mid-row decreased °Brix by 5% and raised titratable acidity by 7% (Table 10).

Table 10. The effects of floor management treatments on leaf area index (LAI), yield (kg/vine), number of bunches per vine (Bun. No), berry weight (BerryW, g), total soluble solids concentration in juice (°Brix), juice pH and titratable acidity of juice (TA, g/L) in the 2011 and 2012 seasons.

Management options	(No 1) Remove U-V [†] mound		(No 2) Reduce evapotranspiration from M-R soils		(No. 3) Re-direct rain falling on M-R to U-V		(No. 4) Add $\text{Ca}(\text{NO}_3)_2$		(No. 5) Interaction No. 3 by No. 4	
Option status	No	Yes	No	Yes	No	Yes	No	Yes		
Contrast	A	vs B	A	vs D	AC	vs EF	AE	vs CF	AF	vs CE
Parameters										
LAI 2011	2.61	2.39	2.61	2.71	2.69	2.48*	2.51	2.67	2.58	2.59
LAI 2012	2.25	2.04	2.25	2.52	2.30	2.25	2.25	2.30	2.24	2.30
Yield 2011	7.5	6.6	7.5	8.5	7.7	8.2	8.0	7.8	7.6	8.2
[§] Yield 2012	8.8	8.9	8.8	10.0	8.9	9.1	8.8	9.2	9.1	9.0
Bun.No 2011	75	70	75	80	77	82	80	79	77	82
[§] Bun.No 2012	85	85	85	91	87	88	86	89	87	87
BerryW 2011	0.96	1.00	0.96	1.07	1.00	0.97	0.99	0.98	0.95	1.03
BerryW 2012	1.04	1.12*	1.04	1.07	1.06	1.07	1.04	1.08	1.06	1.06
°Brix 2011	18.5	19.2	18.5	18.4	18.4	18.5	18.6	18.3	18.4	18.5
°Brix 2012	17.7	17.9	17.7	16.9*	17.5	16.9*	17.3	17.1	17.3	17.0
pH 2011	2.90	2.89	2.90	2.92	2.91	2.91	2.90	2.91	2.90	2.91
pH 2012	2.93	2.89	2.93	2.90	2.93	2.91	2.92	2.93	2.92	2.92
TA 2011	11.5	11.8	11.5	11.7	11.7	11.5	11.3	11.9*	11.7	11.4
[§] TA 2012	10.4	10.8	10.4	11.1*	10.6	11.3**	10.8	11.2	10.9	11.0

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

[†]U-V, under vine; M-R, mid row.

[§]geometric means.

7. SOUTH-EAST SALINITY MONITORING NETWORK

7.1 Introduction

In the SE of South Australia, the greater focus on salinity management tends to be in the north of the region, however an interest in building skills in this field extends across the entire region. A key aspect of a salinity management program is the ability to readily obtain measures of salinity in the vineyard. Current criteria used to assess vineyard salinity status are the same as those used by researchers. The measures on which they are based are not readily obtainable in the vineyard. They have slow turn around time because they require sample processing in a laboratory and are relatively expensive. The Technical Subcommittee of the Limestone Coast Wine Industry Council (LSCWIC) and SARDI sought to build skills in salinity management by establishing the South-east salinity monitoring network (SESMN). Members of the network would be supported through:

- the supply, installation and tuition in the use of a tool, a soil water extractor, that could readily obtain measures of salinity in the vineyard;
- the collation and sharing of measures across the network so that a network member could readily compare their measures with those of other (anonymous) members;
- the provision of an ancillary sampling program which tested links between these salinity measures and those currently used to assess vineyard salinity status.

Researchers have measured salinity in order to understand the effects it has on vineyard productivity and the marketability of the fruit. They have demonstrated that the deleterious effects of saline irrigation on the vine are due to an osmotic effect in which the increase in the concentration of dissolved salt in the soil solution imposes an osmotic drought on the plant and a toxic effect in which the tissue concentrations of chloride (Cl^-) and sodium (Na^+) increase to toxic levels. The link between the former effect and vine yield has been characterised as a function of the salt concentration in the saturated paste extract of soil, the " EC_e " (Prior et al. 1992). And, the link between the latter as a function of the Na^+ and Cl^- concentrations in leaf petioles sampled at full bloom and leaf lamina sampled at harvest (Robinson et al. 1997, Stevens et al. 2011b).

The economic sustainability of a vineyard is determined not only by yield, but also by the quality of wine made from the fruit. Excessive concentrations of Na^+ and Cl^- in wine can affect taste (Bastian et al. 2010, Walker et al. 2003) and access to markets (Stockley 2009). These levels can be directly linked to those in the juice (Rankine et al. 1971). The measures of EC_e and Na^+ and Cl^- concentrations in leaf and fruit require laboratory analysis, have a cost which is prohibitive to high frequency sampling and the time elapsing between sampling and return of a result can be significant.

The links that vine productivity and wine quality have with measures of EC_e and Na^+ and Cl^- concentrations in leaves and fruit are not unique. They can be readily modified by grape variety, rootstock, irrigation method and soil type (Downton 1977, Prior et al. 1992, Stevens et al. 2011a, Zhang et al. 2002).

The LSCWIC and SARDI established the salinity monitoring network in early 2009. Criteria used to select sites sought to ensure that the data collected by the network as a whole was representative of a significant component of viticulture in the Limestone Coast Region and that data from one site was readily comparable with those from other sites.

7.2 Materials and methods

7.2.1 Network sites

7.2.1.1 Network site characteristics

Sites were distributed across the region with four in Padthaway, four in Wrattenbully, four in Coonawarra, one in Mt Benson and one in Robe (Figure 1). All sites were located in own-rooted Cabernet Sauvignon vineyards that were drip irrigated with saline water and where frost protection was not provided via the use of overhead sprinklers. The dominant soil type was a clay loam (Table 11).

Table 11. Distribution of dominant soil types across network sites.

Geographical indication zone	Dominant soil type
Padthaway	Clay loam over medium calcareous clay over limestone
Wrattenbully	Clay loam over terra rossa over limestone
Coonawarra	Clay loam or terra rossa over limestone
Mt Benson	Red brown sandy loam
Robe	Deep calcareous sand

7.2.1.2 Site establishment and support for network operation

In winter 2009, SARDI installed two SENTEK SoluSAMPLER™ soil water extractors at each monitoring site. Soil water extractors were installed at depths of 0.3 m and 0.6 m, between two vines at a distance of 0.1 m from the drip emitter. During installation, each network member received instruction in the use of the soil water extractors. They were provided with a support pack containing: hard copies of installation manuals, NPSI salinity management guidelines and SARDI instructions on the collection and storage of soil water samples (Figure 21).

Network members were requested to prime samplers at least once per month. Soil water samples and annual bore water samples were collected between winter 2009 and summer 2012. Samples were stored in a cool location until collected by SARDI staff. The salinity of all water samples (EC) was by measured SARDI using a temperature compensated conductivity meter (model CON510, Eutech, Singapore) and reported at 25°C.

Each network participant received reports which presented the time courses of variation in soil salinity, rainfall, and irrigation in graphical form for each site. Reports also contained data collected by SARDI on the concentrations of Na⁺ and Cl⁻ in leaves and juice. Nine reports were produced over the three years, about one every four months. Each site was identified by number only. This ensured that participant anonymity was protected during sharing of data over the project life.



Figure 21. Salinity monitoring network support pack.

7.2.1.3 Supporting measures

Soils were sampled at 0.3 and 0.6 m at all sites in November 2010. The more saline sites were re-sampled in November 2011 and March 2012. Soils were collected within 0.2 m of the soil water extractors. Where sample weight was greater than 300 g, then the soil salinity was measured on the saturated paste extract (EC_e), otherwise it was measured on the 1:5 soil:water extract ($EC_{1:5}$) following the methods of Rayment and Higginson (1992). Electrical conductivity was reported in dS/m at 25°C. Soil salinity data was reported as EC_e using a conversion factor. This was generated by analysing paired data from soil samples which had been split so that both $EC_{1:5}$ and EC_e could be measured. Analysis showed a strong linear dependence of EC_e on $EC_{1:5}$, Figure 22.

Analysis of the relationship between salinity measured in the soil (EC_e) with salinity measured in the soil water (EC_{SW}), was also based on paired soil and soil water samples which were collected on the same day. If the soil water extractor did not yield a water sample on the date of soil sampling, then the salinity of soil water was estimated as the average of the salinities of the last sample collected before and the first sample collected after the date of soil sampling. If more than 20 mm irrigation or rainfall fell during this period, then this approach to estimation was considered invalid and the data was recorded as a missing value.

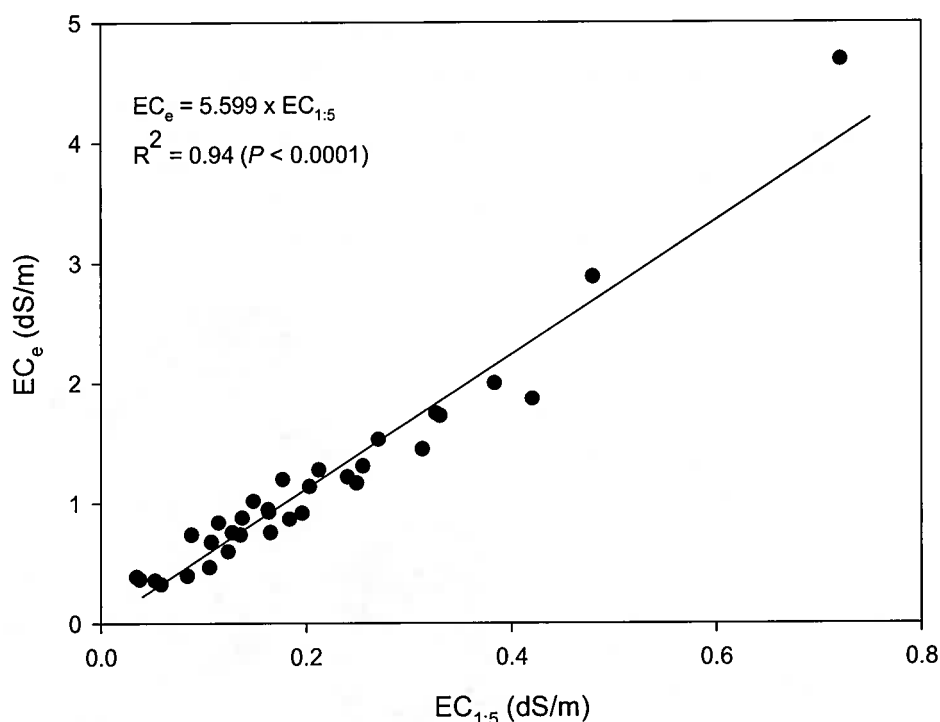


Figure 22. Relationship between soil $EC_{1:5}$ and soil EC_e for a range of soils across the Limestone Coast (2009-2012).

Leaf and berry samples were collected from the two vines, one on either side of the soil water extractors. Leaf petioles collected at flowering (E-L stage 23-25) and leaf lamina and berry samples collected at harvest (E-L stage 38). Sampling and sample processing followed procedures described in sections 5.2.2 and 6.2.4.

Data on irrigation depths were sourced from vineyard management records. Information on the salinity of irrigation water was sourced from a combination of vineyard management

records, onsite SARDI sampling and the online monitoring service – ‘Drillhole Enquiry System’ (<https://des.pir.sa.gov.au/deshome.html>).

Rainfall data were sourced from Bureau of Meteorology automatic weather stations in Padthaway (station number 026100), Naracoorte (station number 026099), Coonawarra (station number 026091), Cape Jaffa (station number 026095) and Robe (station number 026105).

7.3 Results and discussion

7.3.1 Feedback to network participants

At about 4-monthly intervals, each network participant was provided with data from all 14 sites displayed in graphical form. Figure 23 and Figure 24 show such data for site numbers 5 and 9, respectively.

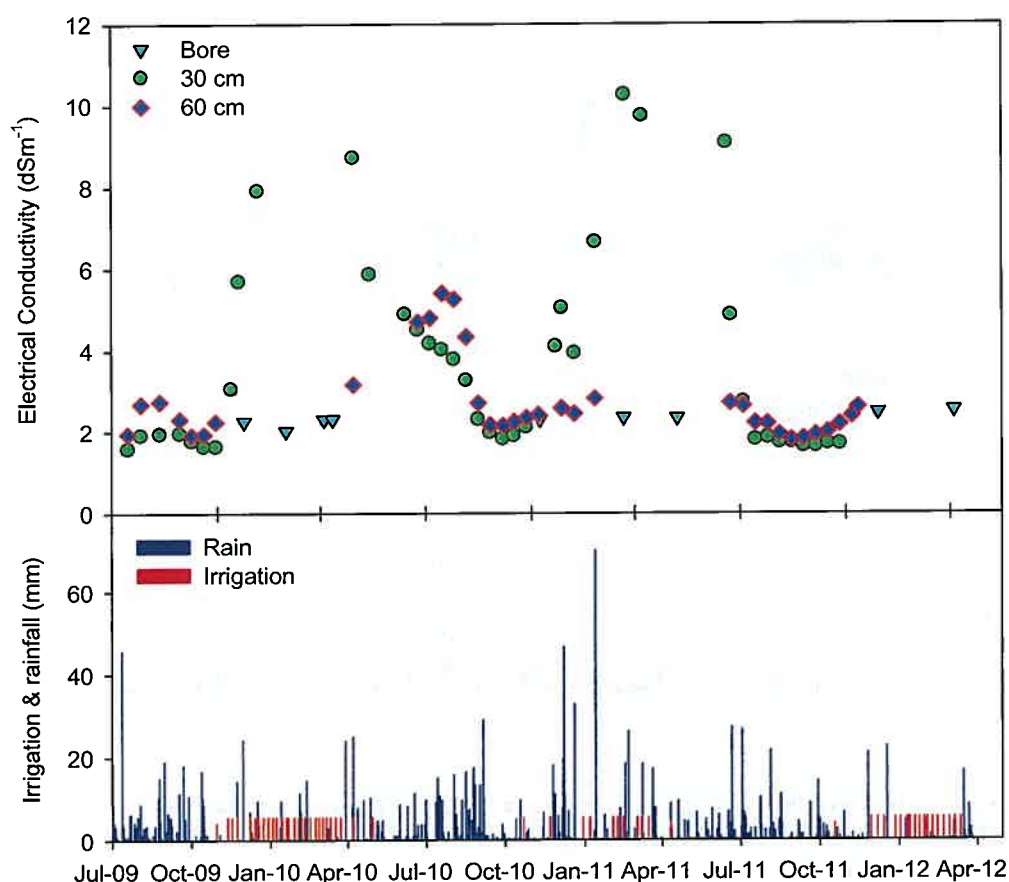


Figure 23. The variation with time in the salinity of bore water and samples generated by the soil water extractor, and associated rainfall and irrigation at Site 5.

In common with other sites, more samples were generated from the soil water extractors during periods with higher rainfall. Thus, the frequency of data in mid-winter was much higher than in summer. In the season with the lowest rainfall, 2012, no samples were extracted from site 5. At both sites and both depths, the lowest values of salinity in soil

water occurred at the end of winter. In 2010 and 2012, both sites received irrigation and the salinity of water extracted from soil at 0.3 m rose following on from commencement of irrigation. Site number 9 did not receive irrigation in the 2011 season and the salinity of water extracted from the soil over this period underwent less of a rise than that in site number 5.

There was strong participation in the network over the entire 3 seasons as evidenced by the number of soil water samples which were collected and submitted to SARDI in each of the three seasons (Table 12) and good attendance at a monitoring site field day.

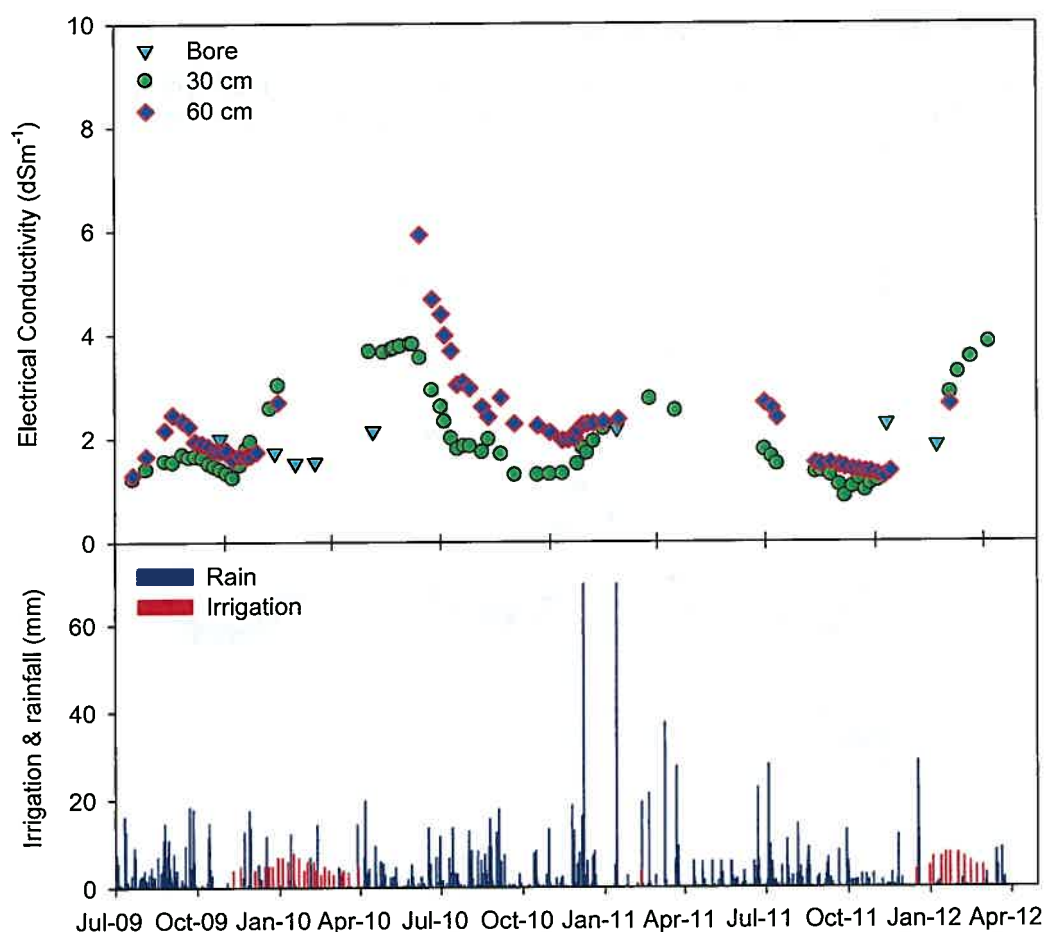


Figure 24. The variation with time in the salinity of bore water and in the salinity of samples generated by the soil water extractor and associated rainfall and irrigation at Site 9. No irrigation applied in 2011.

7.3.2 Salinity characteristics of Cabernet Sauvignon vineyards in the monitoring network

Across the Limestone Coast, rain varied between season and geographical indication (GI) zone. In the 2010 and 2012 seasons, rain was winter dominant with the depths of between 44

season rain, in both seasons, greater than those of within-season rain (Table 12). This contrasts with the 2011 season in which the depth of between season rain was similar to that within season. In all seasons, the depths of both within and between season rains in Coonawarra were about 15% higher than those in Padthaway and Wrattenbully, excepting the within season rain in the 2012 season.



Figure 25. Demonstration of soil water extractors at a Padthaway field day, 2010.

Seasonal depths of irrigation also varied with season and GI zone (Table 12). In all three seasons the average depth of irrigation applied in Padthaway was greater than those in Coonawarra and Wrattenbully. In the 2010 and 2012 seasons the average irrigation depths in Coonawarra and Wrattenbully were between 46% and 80%, respectively, of those in Padthaway. In the 2011 season, the average irrigation depths in Coonawarra and Wrattenbully were less than 10% of those at Padthaway.

The salinity of groundwater sources for irrigation in the properties in Padthaway and Wrattenbully were similar and about 40% higher than those at Coonawarra (Table 13). Irrigation is the main source of salt and the annual salt load presented to a vineyard is the product of irrigation depth and bore salinity. The annual vineyard salt loads in Padthaway in 2010 and 2012 were about twice those in Coonawarra and Wrattenbully. In the 2011 season, the vineyard salt load in Padthaway was about 10-fold or more than that in Coonawarra and Wrattenbully.

The salinity of soil water is about two and half times that of the saturated extract ($EC_e = 0.4 \times EC_{sw}$), Figure 26. In salt affected Padthaway vineyards at the end of the 2009 season, the EC_e 's of soils located under the vine line at about 0.3 and 0.6 m depth were both about 6

dS/m (Figure 3). The equivalent values for a soil water extract would have been about 15 dS/m. Between, July 2009 and March 2012, the average values across the salinity monitoring network from both depths were a third or less than those in the salinity affected vineyards (Table 12). Further, maximum values only exceeded these values in one GI zone and then only during one of the six periods under consideration. The average values were also all below the soil water salinity threshold of 5.3 dS/m (approximately equivalent to an EC_e of 2.1 dS/m) for yield loss due to salinity (Zhang et al. 2002). Whilst salinity values in soil water were well below those associated with salinity decline, there was still considerable variation in values across the zones.

In general, a higher annual vineyard salt load was associated with a higher salinity of the soil water extracts. The average values in Padthaway were greater than those in the other geographical indication zones at both 0.3 and 0.6 m (Table 12). However, the differences in soil salinity between GI zones were not necessarily proportional to the differences in vineyard salt load. In the 2011 season, the average salt load in Padthaway vineyards was 10-fold that in vineyards in the other GI zones, however soil salinity at Padthaway at both 0.3 and 0.6 m was only about 2.5-fold greater than values in other GI zones. In both the 2010 and 2012 seasons, vineyard salt loads at Padthaway were about twice those in other zones. In 2010, soil salinity at 0.3 m was less than 1.5 fold those in other zones and the values of salinity at 0.6m depth were similar across all zones. In 2012, the salinity of soil at Padthaway at both depths was about 2.5-fold greater than that at Wrattenbully and nearly 4-fold greater than that at Coonawarra.

In salinity affected vines in Padthaway at the end of the 2009 season, the concentrations of Na^+ in the leaf lamina ranged from 65 to 395 mmol/kg and that for Cl^- from 311 to 497 mmol/kg (Table 2). Across the 2010 to 2012 seasons, the average concentrations of Na^+ and Cl^- in leaf lamina sampled at harvest in the salinity monitoring network were less than half these levels (Table 13). Further the average and maximum concentrations of Na^+ and Cl^- in leaf petiole sampled at flowering and lamina sampled at harvest were all below levels associated with salinity damage (Prior et al. 1992, Robinson et al. 1997, Stevens et al. 2011b).

Table 12. The average and range of values of the depth of rain and irrigation, and salinities of soil water extracted from 0.3 and 0.6 m depth for within and between season periods in the different geographical indication zones. Subscript following averages refers to the number of sites or observations.

Parameter	Padthaway			Wrattonbully			Coonawarra			Mt Benson / Robe		
	Avg _n	Max	Min	Avg _n	Max	Min	Avg _n	Max	Min	Avg _n	Max	Min
Rain (mm)												
Jul – Sep 09	257			260			309			333		
Oct 09 – Mar 10	180			181			205			150		
Apr – Sep 10	355			342			414			433		
Oct 10 – Mar 11	382			432			440			286		
Apr – Sep 11	286			291			387			319		
Sep 11 – Mar 12	121			123			118			140		
Irrigation (mm)												
Jul – Sep 09	0 ₃	0	0	0 ₄	0	0	0 ₄	0	0	0 ₁	0	0
Oct 09 – Mar 10	167 ₃	290	74	100 ₄	120	81	135 ₄	223	6	37 ₁	37	37
Apr – Sep 10	5 ₃	12	0	1 ₄	6	0	0 ₄	0	0	0 ₁	0	0
Oct 10 – Mar 11	75 ₃	141	29	5 ₄	11	0	6 ₄	24	0	0 ₁	0	0
Apr – Sep 11	4 ₃	8	0	0 ₄	0	0	0 ₄	0	0	19 ₁	19	19
Sep 11 – Mar 12	175 ₃	347	78	85 ₄	103	68	111 ₂	218	3	n/a		
Salinity 0.3 m (dS/m)												
Jul – Sep 09	1.8 ₁₂	2.7	1.4	1.4 ₂₅	1.7	0.9	1.2 ₁₆	1.7	0.8	0.8 ₉	1.1	0.6
Oct 09 – Mar 10	2.8 ₁₆	7.9	1.3	1.8 ₃₃	3.2	0.9	1.9 ₁₀	6.5	0.8	1.4 ₁₆	5.1	0.5
Apr – Sep 10	3.8 ₂₃	8.7	1.0	2.5 ₄₈	7.1	1.0	5.0 ₁₂	14.5	0.9	1.4 ₁₃	3.4	0.4
Oct 10 – Mar 11	4.1 ₂₁	10.3	1.2	1.4 ₃₅	2.8	0.8	1.9 ₂₄	4.7	0.7	1.0 ₇	1.3	0.4
Apr – Sep 11	2.9 ₂₁	9.1	0.9	1.0 ₁₆	1.8	0.6	1.0 ₂₄	3.6	0.6	0.4 ₂	0.5	0.4
Sep 11 – Mar 12	3.4 ₁₉	8.3	1.6	1.5 ₂₀	3.8	0.6	0.7 ₅	1.3	0.5	0.9 ₂	1.2	0.5
Salinity 0.6 m (dS/m)												
Jul – Sep 09	2.3 ₁₂	2.8	1.5	2.2 ₂₄	3.7	1.2	2.8 ₁₆	10.1	0.8	0.7 ₉	1.0	0.6
Oct 09 – Mar 10	2.0 ₁₀	2.7	1.4	1.9 ₃₃	3.1	1.2	2.6 ₉	5.8	0.6	1.0 ₁₂	1.7	0.6
Apr – Sep 10	4.3 ₂₀	9.1	0.8	2.9 ₃₄	5.9	1.0	3.6 ₆	8.2	1.0	1.0 ₁₃	1.6	0.6
Oct 10 – Mar 11	4.2 ₂₁	8.6	0.9	1.7 ₃₅	2.5	1.0	1.4 ₉	3.7	0.5	0.6 ₇	0.8	0.4
Apr – Sep 11	4.1 ₂₀	9.0	0.8	1.6 ₁₅	3.0	0.8	1.0 ₂₂	2.5	0.4	0.6 ₂	0.6	0.6
Sep 11 – Mar 12	3.7 ₂₂	8.0	1.6	1.4 ₁₉	2.6	1.0	1.0 ₆	1.5	0.7	0.6 ₂	0.7	0.6

The values of soil salinity at Padthaway were higher than those at Coonawarra and Wrattenbully (Table 12). However, the three-season averages of the concentrations of Na⁺ in leaf petiole and lamina and juice at Padthaway were similar to those at Coonawarra and Wrattenbully. That is, the large variations across GI zones in values of vineyard salt loads and soil salinity were not causing a variation in the concentration of Na⁺ in the vines.

Table 13. The average and range of values of irrigation water salinity, and Na⁺ and Cl⁻ concentrations in leaf petiole sampled at full bloom, leaf lamina and juice from fruit sampled at harvest for different geographical indication zones. Subscript following averages refers to the number of sites or observations.

	Padthaway			Wrattonbully			Coonawarra			Mt Benson / Robe		
	Avg _n	Max	Min	Avg _n	Max	Min	Avg _n	Max	Min	Avg _n	Max	Min
Irrigation EC (dS/m)												
2010	2.18	2.3	1.9	2.315	2.7	1.5	1.62	1.6	1.6	0.84	0.8	0.7
2011	2.45	2.5	2.3	2.67	2.8	2.2	n/a			1.01		
2012	2.34	2.5	1.8	2.55	2.9	1.9	1.52	1.8	1.2	0.81		
Petiole Na⁺ (%)												
2010	0.074	0.10	0.06	0.084	0.11	0.05	0.074	0.09	0.05	0.152	0.19	0.11
2011	0.054	0.06	0.04	0.064	0.07	0.04	0.074	0.10	0.06	0.152	0.19	0.12
2012	0.064	0.08	0.05	0.054	0.08	0.03	0.074	0.09	0.05	0.101	0.10	0.10
Petiole Cl⁻ (%)												
2010	0.724	0.92	0.60	0.604	0.73	0.44	0.544	0.72	0.37	0.492	0.54	0.45
2011	0.724	1.01	0.52	0.554	0.64	0.39	0.404	0.54	0.32	0.492	0.55	0.43
2012	0.654	0.82	0.49	0.464	0.51	0.39	0.424	0.57	0.31	0.341	0.34	0.34
Juice Na⁺ (mg/L)												
2010	18.94	24.0	15.6	14.94	18.5	12.1	16.24	21.9	13.8	27.02	27.5	26.6
2011	15.54	18.0	13.0	17.34	21.0	16.0	17.84	22.0	16.0	30.52	38.0	23.0
2012	19.14	21.5	15.1	14.24	17.5	11.8	20.53	26.9	16.9	15.41	15.4	15.4
Juice Cl⁻ (mg/L)												
2010	53.14	86.3	28.4	16.44	35.5	6.0	14.94	27.7	3.9	20.92	32.7	9.2
2011	35.84	49.1	26.8	30.74	53.6	14.9	26.14	31.3	20.0	28.92	29.5	28.2
2012	58.84	90.7	23.3	28.04	46.5	17.2	34.53	55.4	18.1	41.01	41.0	41.0
Lamina Na⁺ (mmol/kg)												
2010	37.04	68.3	15.2	39.64	49.6	22.6	40.64	43.5	37.4	73.52	84.8	62.2
2011	24.24	33.5	14.8	27.54	34.8	17.4	28.84	32.6	25.7	62.42	72.2	52.6
2012	28.84	35.2	20.4	31.94	51.8	20.0	28.54	36.1	19.6	62.21	62.2	62.2
Lamina Cl⁻ (mmol/kg)												
2010	138.5 ₄	205.5	77.6	103.5 ₄	132.0	59.5	87.8 ₄	100.6	74.1	153.2 ₂	177.7	128.8
2011	112.9 ₄	159.4	55.7	80.3 ₄	93.9	67.8	81.9 ₄	91.2	76.6	133.6 ₂	160.2	107.0
2012	137.1 ₄	186.0	65.6	88.6 ₄	124.9	40.8	91.1 ₄	103.0	74.4	150 ₁	150.0	150.0

Unlike Na⁺, the across zone variation in the values of Cl⁻ concentration in leaves and juice did in part mirror those in soil salinity and vineyard salt load. The average values of salt loads and soil salinity in Padthaway were about twice those in Coonawarra and Wrattenbully, as too were the average values of Cl⁻ concentration in the juice (Table 12, Table 13). However, values in the leaf, both petiole and lamina, at Padthaway were only 30% higher than values at Wrattenbully and 50% higher than values at Coonawarra.

Simple measures of vine salt exposure, such as annual vineyard salt load or average soil salinity, could not be related to the Na⁺ concentration in various vine organs, but could be related to the concentrations of Cl⁻. These relationships were not straight forward because the proportionality between changes in vine salt exposure and changes in concentration of Cl⁻ was dependent on the vine tissue in which the Cl⁻ measure was undertaken.

7.3.3 Relationships between salinity of water extracted from the soil and established criteria used to assess vineyard salinity status

The effect of salinity on vine yield has been well characterised as a function of the salinity of the saturated paste extract (Prior et al. 1992, Zhang et al. 2002), but not as a function of the salinity of the soil water extract. The former measure is not readily available in the vineyard. Soil salinity was measured by both techniques at sites across the monitoring network and the relationship between these measures is shown in Figure 26. Whilst the relationship is highly significant, the EC of soil water was not a good predictor of EC_e , that is, it accounted for only 51% of the variation in EC_e . The data set also had a narrow range with only a few entries that had values above the threshold EC_e value for salinity damage to vines of 2.1 dS/m. In order to extend the range, the data set was expanded by adding data gathered in other vineyards located within and without the Limestone Coast.

Figure 27 shows the relationship. The variation in EC_e as a function of EC_{sw} can be described with an equation in the form of either $y = a + bx$ or $y = bx$. Fitting of the former to the data gives the relationship $EC_e = 0.38 + 0.31 \cdot EC_{sw}$ ($R^2 = 0.71$, $P < 0.001$). Hoffman et al. (1989) fitted a similar equation to data obtained in a plum orchard. The value of their constant 0.3 was similar to that found in the present study, however the value of their coefficient 0.6 was double that found in the present study. Fitting the simpler latter form of the equation accounted for 68% of the variation in EC_e . Whilst it is highly significant, the level of variance it accounts for is not sufficient to make it a good calibration. However the relationship indicates the potential for EC_{sw} measures to be used as guides. For instance, at EC_{sw} of less than about 3.5 dS/m, no value of EC_e was above the threshold for salinity damage of 2.1 dS/m. Thus any measure below 3.5 dS/m indicates acceptable soil salinity. With the exception of one data point, any measure of EC_{sw} above 7 dS/m indicates an EC_e greater than 2.1 dS/m, that is an unacceptably high level of soil salinity. Values of EC_{sw} between about 3.5 and 7 dS/m remain in the grey area where there is a near equal chance of soil EC_e being higher or lower than the threshold. For values in the grey area, characterising vineyard salt status would require the application of other techniques.

Ultimately it is the vine that declines under saline conditions and we investigated whether EC_{sw} was a reasonable predictor of indicators of this decline such as concentrations of Na^+ and Cl^- in leaf petioles sampled at flowering. As noted in the summary data, the concentrations of Na^+ in vine tissue did not seem to respond to variations across GI zones and seasons in the soil salinity and annual vineyard salt load (the amount of salt added in irrigation water). Figure 28 illustrates this point graphically.

The highest value of the leaf petiole Cl^- concentrations recorded in the monitoring network was well below the level of 1.5% which is indicative of a toxic effect of salinity. Addition of data from other regions did not address this shortcoming. Figure 29 shows that the petiole Cl^- has a highly significant dependence on EC_{sw} . EC_{sw} accounted for 57% of the variation in petiole Cl^- concentrations.

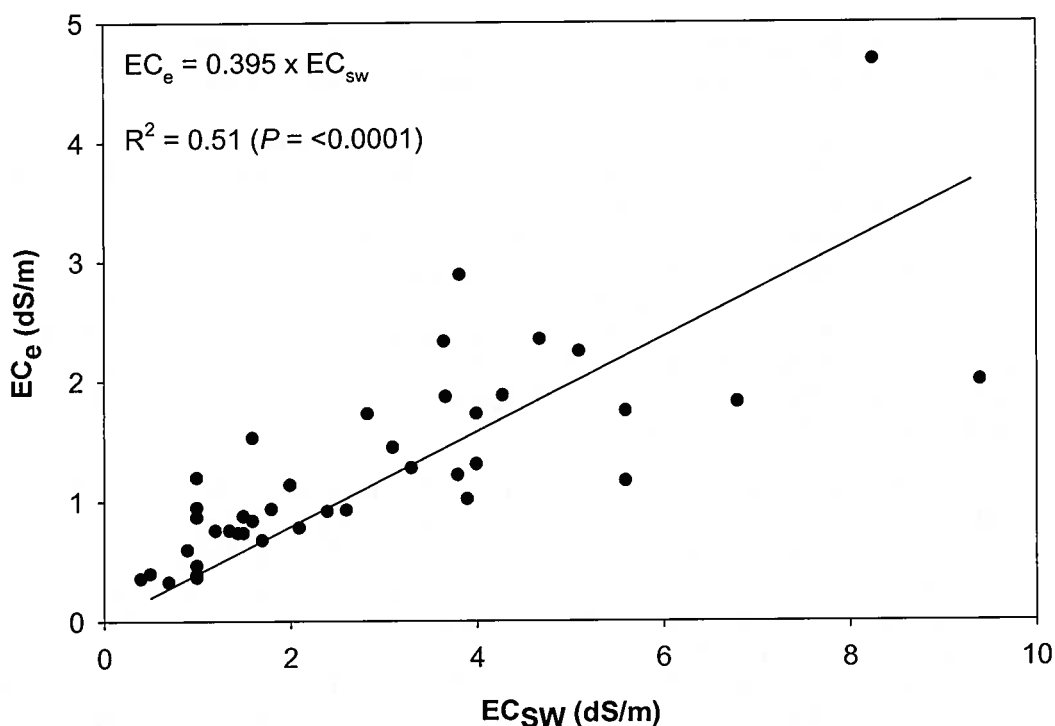


Figure 26. Relationship between soil water salinity (EC_{sw}) and soil salinity (EC_e) as measured by SESMN, Limestone Coast, SA (sandy loam, clay loam and calcareous clay).

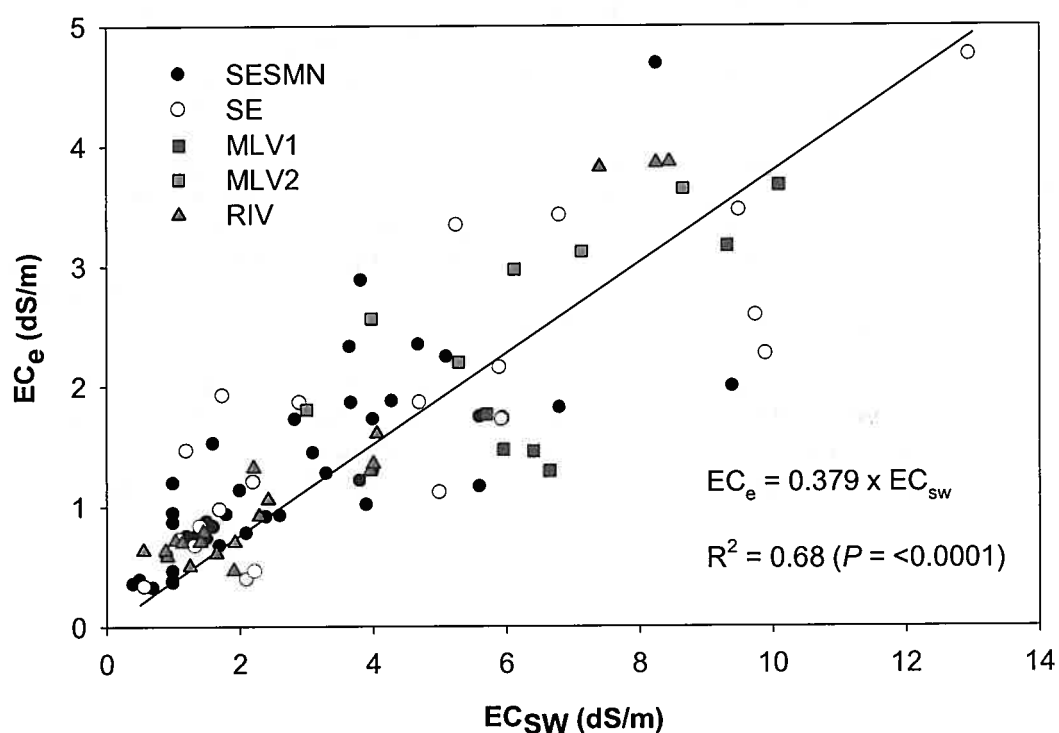


Figure 27. Relationship between soil water salinity (EC_{sw}) and soil salinity (EC_e) as measured by the South East, Limestone Coast with supplementary data sourced from sites in the Limestone Coast, McLaren Vale and the Riverland, SA.

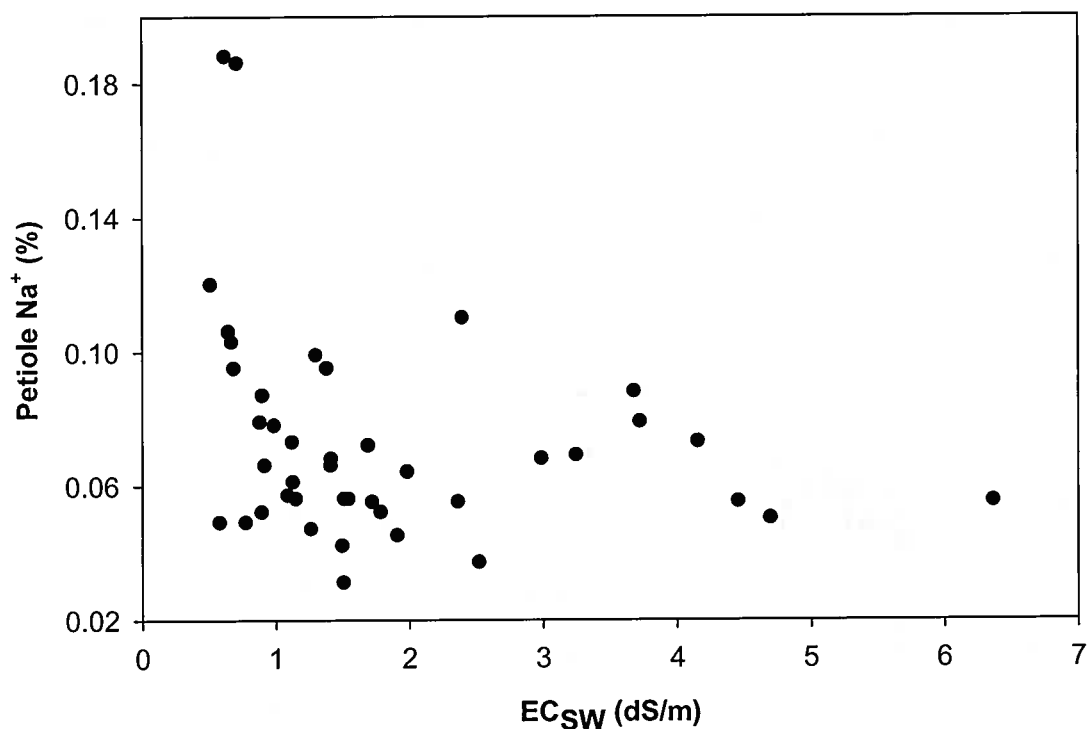


Figure 28. Relationship of soil water salinity (EC_{sw}), measured between budburst and flowering, and concentration of Na^+ in the leaf petiole sampled at flowering. SESMN, Limestone Coast.

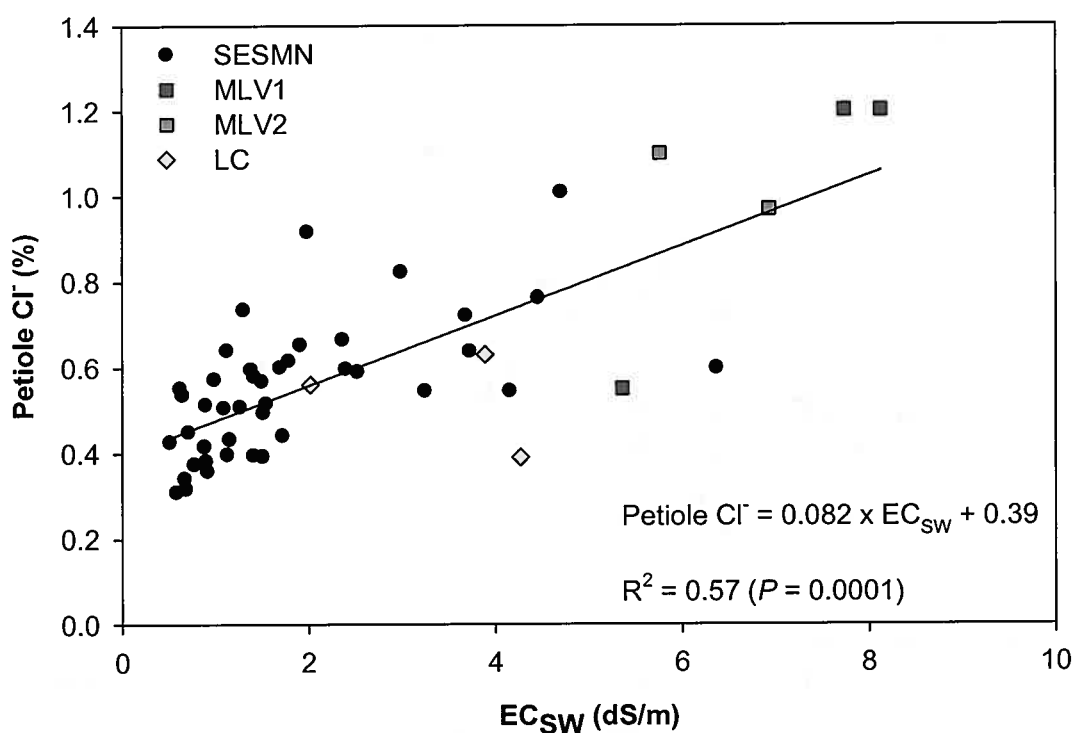


Figure 29. Relationship of soil water salinity (EC_{sw}), measured between budburst and flowering, and concentration of Cl^- in the leaf petiole sampled at flowering. SESMN, Limestone Coast and data from McLaren Vale and Langhorne Creek, SA.

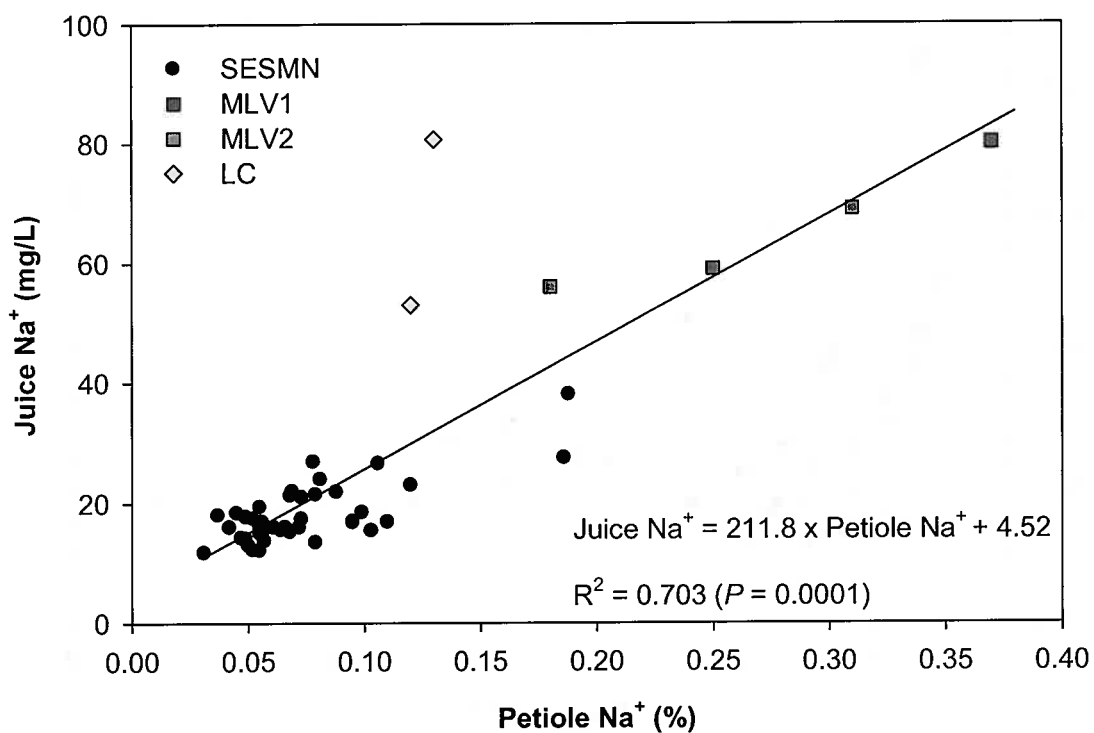


Figure 30. For data from red wine grapes, the relationship between Na^+ concentration in the petiole at flowering and that in the juice at harvest.

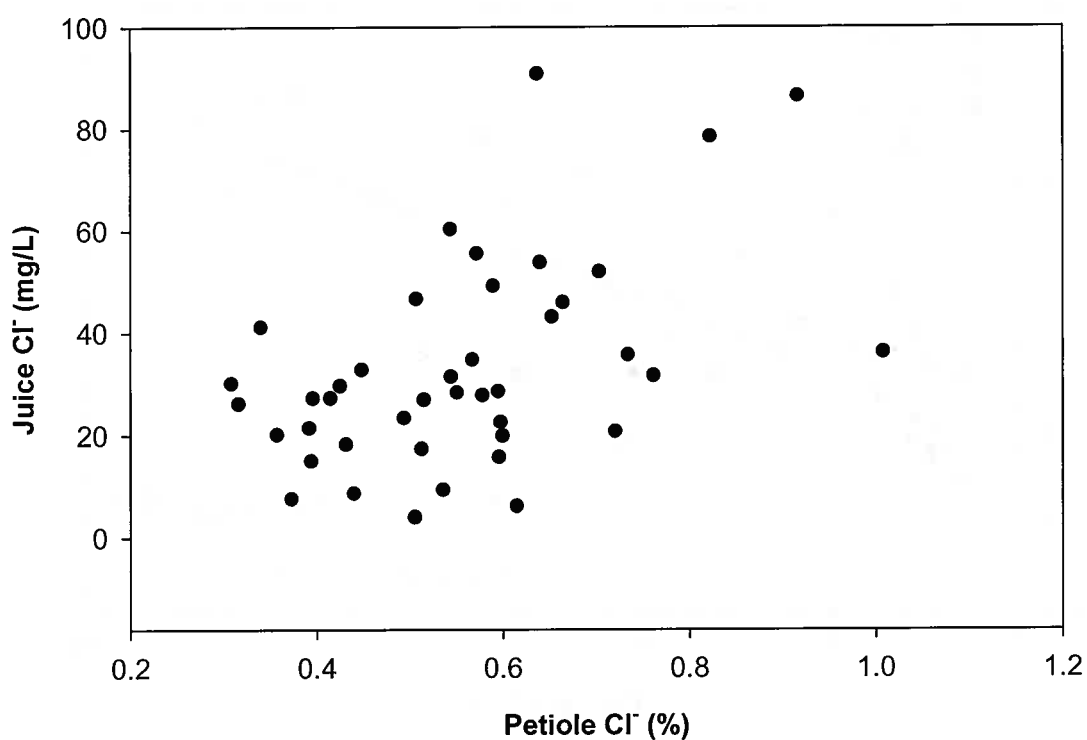


Figure 31. The relationship between Cl^- concentration in the petiole at flowering and that in the juice at harvest for the SESMN.

The soil water extractors were not able to generate samples near harvest because of the dry soil conditions, that is the soil water matric suction was greater than 50-80 kPa of suction that can be applied to the samplers (water columns undergo cavitation at suctions in this range). Thus the data to investigate the relationships between juice concentrations of Na^+ and Cl^- and EC_{sw} were not available. Instead we investigated whether measurements in leaf petioles sampled at flowering could predict levels of the same ions in the juice at harvest.

Some overseas markets have upper limits for Na^+ in wine, the lowest is that in Switzerland of 60 mg/L (Stockley 2009). Vinification of red wine grapes increases the Na^+ concentration and that in wine is about 130% that in juice (Rankine et al. 1971). Accounting for the effects of vinification in red wine grapes, the juice Na^+ concentration that is equivalent to the Swiss standard for wine is 46 mg/L. The highest value of Na^+ concentration in juice samples from the monitoring network was 39 mg/L. In all three seasons, fruit sampled from vineyards in the monitoring network had Na^+ concentrations well below the limits set by overseas markets.

The maximum value of juice Na^+ concentration, 39 mg/L, was well below the average of 145 mg/L which was recorded at Padthaway in 1989 - 1994 Australia wide survey of juice Na^+ concentrations (Leske et al. 1997). The high values at Padthaway during this period were attributed to use of irrigation systems which wet the foliage (Johnstone et al. 1993). Further, the maximum value of 39 mg/L it was at the bottom end of the range of these values found in Australian fruit.

Data determined on red wine grapes grown outside of the monitoring network was added to that from the SESMN to expand the range of values of Na^+ concentrations over which the relationship between juice and petiole concentrations of Na^+ were investigated. Figure 30 shows this relationship. All instances of petiole Na^+ concentration less than 0.012% also had juice concentrations less than 46 mg/L of Na^+ .

Bastian et al. (2010) found more than 37% of tasters could detect salt in Shiraz wine at NaCl concentrations of 100 mg/L or less (equivalent to 60 mg/L of Cl^-), but that only 2% of tasters could recognise NaCl at this concentration. For data from the monitoring network, Figure 31 shows that juice Cl^- concentration was always less than 60 mg/L where petiole Cl^- concentrations at flowering were less than 0.55%.

8. PHYSIO-CHEMICAL PROPERTIES OF SEQUENTIALLY SAMPLED SOILS SEPARATED BY A DECADE OF IRRIGATION WITH SALINE GROUNDWATER

8.1 Introduction

Saline ground waters in the Padthaway district have a high SAR. Irrigation with such waters can lead to depletion of calcium on the soil clay exchange complex and an enrichment of sodium (Na^+). Clay particles which have been enriched with Na^+ can become unstable when the salinity of soil water drops following rains (Quirk and Schofield 1955). Soils that contain Na^+ enriched clays and disperse in response to a decrease in the salinity of soil water are called sodic soils (Sumner 1995). The likelihood that a soil will exhibit this behaviour is quantified by measuring the percentage of clay exchange sites occupied by Na^+ ; the measurement is referred to as the exchangeable Na^+ percentage (ESP). The value of ESP can also be calculated from measures of the SAR of soil water obtained either as an extract of a saturated soil paste (SAR_e) or the 1:5 soil: H_2O extract ($\text{SAR}_{1:5}$). The threshold values at above which sodic soil behaviour emerges are 3 for an $\text{SAR}_{1:5}$ (Rengasamy et al. 1984) and 6 for an ESP (Naidu et al. 1995). Often a soil with a high ESP is called sodic based on an assumption that it would disperse if leached with low salinity water such as rain.

Dispersed clay particles can migrate in the larger soil pores. Their migration creates small voids and their settling and coalescence in the larger pores leads to a loss of larger voids. The net result is a change in the distribution of pore sizes in the soil. Pore size distribution is related to two important soil properties: the soil hydraulic conductivity and the soil water retention characteristics. The former is a major determinant of the rate at which water and solutes move within the soil under the influence of gravity. The latter is an important determinant of the proportion of the soil water reservoir that is accessible to the plant. The rate at which water infiltrates into soil and drains from it is reduced by decreases in the number of larger pores and increases in the number of smaller pores. The same change reduces the amount of water released from the soil interstices over the range of suctions exerted by plant roots.

Repeated cycles of drip irrigation with saline high SAR water in summer followed by winter dominant rains caused a deterioration in the structure of soils in vineyards of the Barossa (Clark 2004). Soils in the vineyards of Padthaway are exposed to a similar water regime and it is unclear whether this regime is leading to an alteration in their structure.

In 1997 and 1999, CSIRO undertook a range of soil measurements at Padthaway in a vineyard which was planted in 1992 with a CSIRO rootstock trial. Prior to 1992, the land was used for broad acre cropping. This site was revisited in 2009 and 2011 and a similar range of soil measurements were undertaken. Between these dates the soils have received over decade of drip irrigation with saline groundwater. Comparison between serial measures will be used to identify changes in soil properties over this period.

8.2 Materials and methods

8.2.1 Vineyard description and site selection

The vineyard was located south of Padthaway and planted in 1992 with Chardonnay on own roots and a range of rootstocks. Walker et al. (2010) describes planting material, vineyard

layout, trellising and irrigation system. Between 1999 and 2012 seasons, the average annual depth of irrigation was 318 mm. Soils were a sandy loam to medium clay over clay with underlying limestone. In 2002, the soils in the mid-row were pushed under the vine to form a mound which was 0.8 to 1.0 m wide and at its peak 0.2 m higher than the vineyard floor in mid-row (as per site described in Figure 11). Water for irrigation was drawn from bores. The bore in use during the 1996 and 1997 seasons had a salinity of 2.5 dS/m and the bore in use in the 2009 through to 2011 seasons had a salinity of 1.8 dS/m.

Rainfall data were sourced from the Padthaway Bureau of Meteorology automatic weather station (station number 026100). Data on the salinity of irrigation water was sourced from the online drillhole enquiry system, <https://des.pir.sa.gov.au/deshome.html>.

8.2.2 Soil sampling

Soils were sampled by hand auger after harvest in the 1997, 2009 and 2011 seasons. Samples were taken at the surface to a depth of 0.1m and at 0.3, and 0.6 m depth at all 3 sampling times and from 0.9 m depth in all but the 2009 sampling (depth is relative to surface prior to mounding of soil under the vine). Samples were located mid way between 2 drippers at about 0.15 - 0.3 m into the row from the drip line. The 1997 and 2011 samplings were located on opposing sides of the same vines.

In 1999, a soil pit was dug midway between the eastern and western ends of the rows. The profile was described to a depth of one metre and three replicates of undisturbed cores (0.076 m diameter and 0.05m length) were collected from both of the two dominant horizons at depths of 0.1 – 0.15 m and 0.4 – 0.45 m. In 2011 soil pits were dug at the eastern and western ends of the row and midway between. The profiles of all three pits were described to a metre. In each pit, three replicate undisturbed cores were taken from the two dominant horizons at depths 0.1 – 0.15 m and 0.4 to 0.45 m. Core specifications followed guidance given in McIntyre (1974). Disturbed soil samples were collected at the same time.

8.2.3 Particle size analysis

Particle size distribution in the 1997 samples was determined following the method of Gee and Bauder (1986) and in the 2011 samples following the method of Indorante et al. (1990). Gravel content on the 1999 and 2011 samples was equated to the fraction of air dried soil that did not pass a 2 mm sieve.

8.2.4 Soil salinity, sodicity and cation exchange complex analysis.

The salinity and SAR were measured on 1:5 soil:water extracts prepared following Rayment and Higginson (1992). Electrical conductivity was reported in dS/m at 25°C. In 1997 the exchangeable cations Ca^{2+} , Mg^{2+} , Na^{+} and K^{+} were analysed by Flame Atomic Absorption Spectrometry and in 2011 by Inductively Coupled Plasma Optical Emission Spectroscopy (ICPOES), Spectro ARCOS (Spectro Analytical Instruments, Kleve, Germany).

Exchangeable cations and cation exchange capacity (CEC) were determined following method 15D2 of Rayment and Higginson (1992) using NH_4Cl solution at pH 8.5. Samples were pre-treated for soluble salts prior to extraction. CEC, ammonium and Cl^{-} were analysed using segmented flow colorimetry Lachat QC8500 Series 2 (Lachat Instruments, Milwaukee USA).

8.2.5 Soil moisture release characteristics

Determinations of the soil moisture release characteristics with undisturbed soil cores collected in 1999 and in 2011 were both undertaken at the same laboratory, Soil Water Solutions SA. Soil cores were weighed upon receipt and, if cavities were present, then their volume was measured with dry sand. If soils were not fully wet, then they were placed on a ceramic tension plate and further water added to wet them up. There was no significant swelling.

The plates were then set to simulate a water table 5 cm below the core base. They were then allowed to drain for 12 hours and weighed. This provided the water content at 0.5 kPa tension. The water table was then lowered to 100 cm 'depth' - equivalent to a suction of 10 kPa and the cores allowed to equilibrate and then weighed. This process was repeated at 300 cm and 700 cm water tension (suction of 30 and 70 kPa, respectively).

The cores were then oven dried to remove all water and weighed again. The volume, the dry weight of soil and the amount of water in the soil at each stage was then calculated along with density, total porosity and air filled porosity at field capacity (-10 kPa) following methods described by Jackson (1972).

Small samples of disturbed soil were used to measure water holding at higher suction levels. These loose soils were formed into a slurry, and then placed onto a ceramic plate and subjected to air pressure of 200 kPa for 7 days, then removed and the gravimetric water content measured. This process was repeated on a similar set of soils at 1500 kPa for 14 days to provide wilting point water content. These water content values (measured as g/g) were converted to a volume basis by multiplying by the density calculated from the core samples.

Relative hydraulic conductivity and pore size distribution were calculated from water retention data using the Advanced Water Retention Curve Analysis software (Soil Water Solutions, <http://www.soilwater.com.au/>).

Readily available water (RAW) was defined as the water released between matric suctions of 8 kPa (field capacity) and 60 kPa. Total available water (TAW) was defined as the water released between matric suctions of 8 and 1500 kPa (permanent wilting point).

8.3 Results and Discussion

8.3.1 Profile description

The soil profile is shown in Figure 32 and described in Table 14. In 1999 and 2011, different soil pedologists described the soil profile to a depth of one metre. Despite subjective differences in horizon nomenclature and definitions of surface aggregate sizes (due to poor aggregation), both pedologists described a brown gradational soil with textures in the heavy loam to light friable clay range with mild mid layer mottling and grading into a calcrete rubble, then sheet calcrete.



Figure 32. The vine row side of a soil pit opened in 2011. Red line marks location of original vineyard floor prior to mounding of mid row soils under the vine in 2002.

Table 14. Description of soil profile in 1999 and 2011. The 1999 description is pers comm. Rob Walker, CSIRO Plant Industry, Waite Campus, Adelaide.

Depth (m)		Horizon	Colour [†]	Mottles		Texture [§]	Structure	Size (mm)
Upper	Lower			%	Colour [‡]		Shape	
1999 (1 pit)								
0	0.2	A1	VDkGr/Br/Yl/Rd	0		L Cl	Granular	20-50
0.2	0.3	B1	DkGr/Br/Yl/Rd	20/5	Yl/Or	L Cl	Granular	< 20
0.3	0.8	C1	Yellowish Br	50/5	Yl/Or	L Cl	Granular	< 20
0.8	1.0	Rock	White	0			Massive	
2011 (3 pits)								
+0.2	0	Mound	Dk Br				Massive	
0	0.2	A1	Gr Br			Si Cl Lm, L Cl	Polyhedral	3-5
0.2	0.3	B21	Br			Si Cl Lm, L Cl	Polyhedral	3-5
0.3	0.5	B22	Br	30	7.5 YR 5/7	L Cl	Polyhedral	3-5
0.5	0.8	B2k or C	Pale Br	40	10 YR 7/8	L - M Cl	Polyhedral massive	5-8
0.8		Rock						

[†]Br, Dk,Gr,Rd and Yl: Brown, Dark, Gray, Red and Yellow.

[‡]2011 colours refer to Munsell colour system.

[§]Cl, L, LM, M and Si: Clay, Light, Loam, Medium and Silty.

8.3.2 Particle size analysis, bulk density and porosity

Particle size analysis in 1997 and 2011 showed that the soils from the A horizon had the same texture, sandy clay loam, at both sampling times (Figure 33, Figure 34).

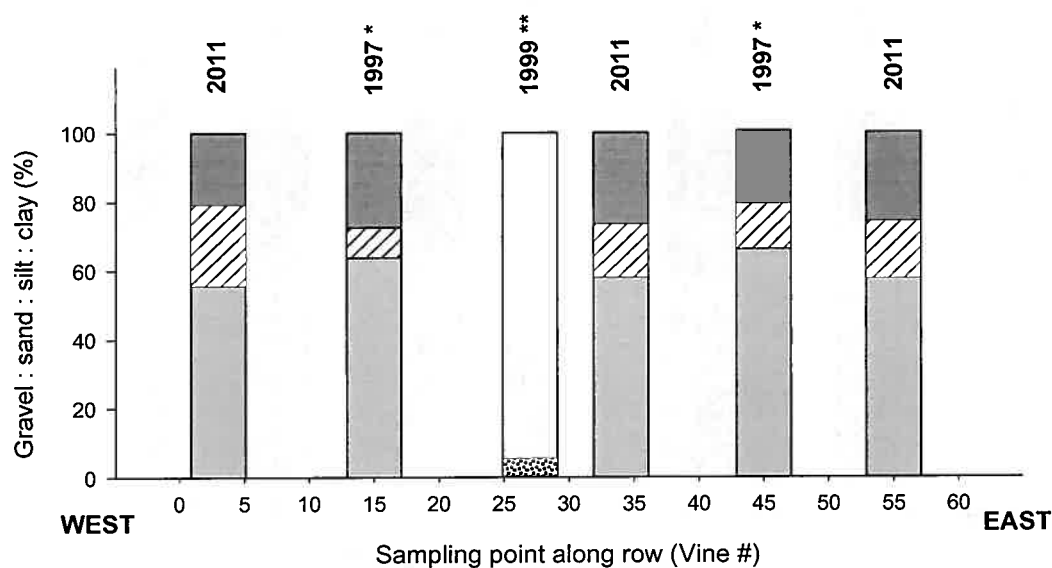


Figure 33. Records of soil texture analysis for samples taken in 1997, 1999 and 2011 from the A horizon at different distances along the vine row in a Chardonnay vineyard at Padthaway. Inter vine distance 1.8 m.

* No information on gravel content.

** No information on % sand:silt:clay.

The 1997 data set did not contain information on the gravel fraction. The 2011 analyses all returned a zero percent gravel fraction. In 1999, a gravel analysis was also undertaken on soils from the A horizon during the determination of soil moisture release characteristics. These samples had an average of 5% gravel. Although soils on all sample dates had the same texture, those sampled in 1999 had 5% gravel, whereas those sampled in 2011 had no gravel.

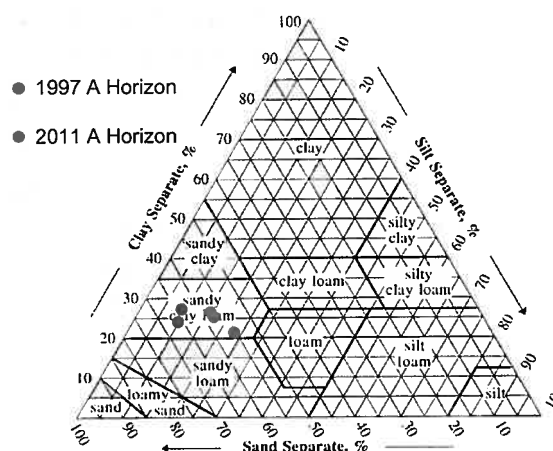


Figure 34. Soil texture triangle showing data from the A horizon in 1997 and 2011.

In the B horizon, particle size analysis was undertaken on samples from 0.3 and 0.6 m depth in 1997 and from 0.45 m depth in 2011. Figure 35 shows that the percentage of sand tends to increase moving from west to east along the row. Amongst the 2011 samples this tendency was reflected on the texture triangle as a texture change from a clay loam to sandy clay loam (Figure 36). The 1997 data set did not contain information on the gravel fraction. One of the 2011 samples returned a 7% percent gravel fraction.

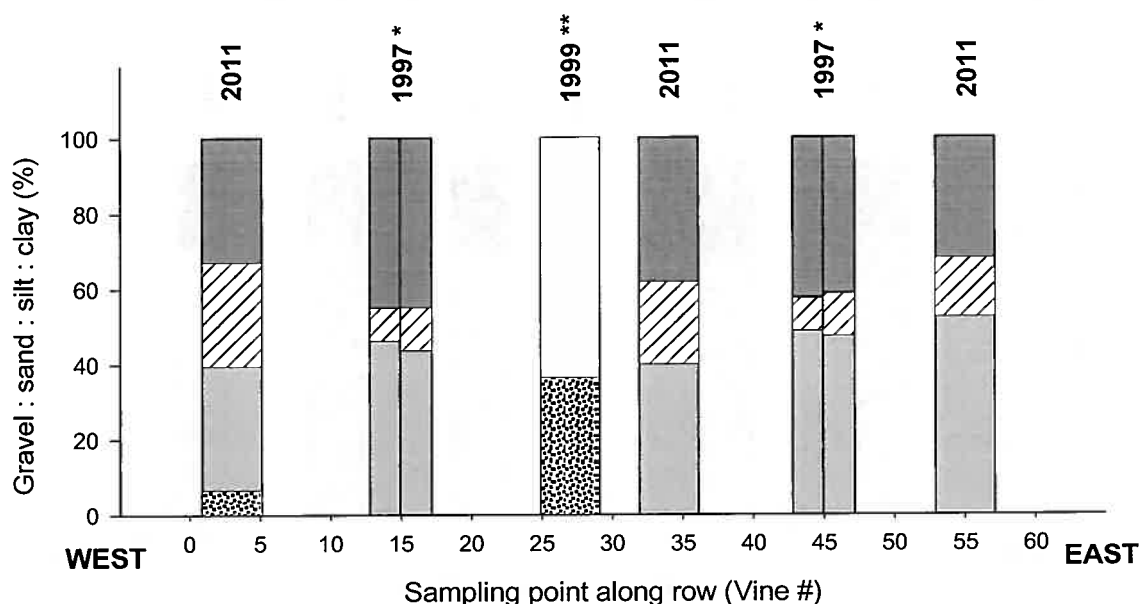


Figure 35. Records of soil texture analysis for samples taken in 1997 and 2011 from the B horizon at different distance along the vine row in a Chardonnay vineyard at Padthaway. Inter vine distance 1.8 m.

Right & left histograms for 1997 samplers indicate 0.3 & 0.6 m depth samples.

* No information on gravel content.

** No information on % sand:silt:clay.

In 1999, a gravel analysis was also undertaken on soils from the B horizon during the determination of soil moisture release characteristics. In 1999, the sample had an average of 37% gravel. Although there was only a slight texture change in between 1997 and 2011, there was a major change in the % gravel. A change of this magnitude would support a contention that the 1999 sample used for measurement of soil moisture release characteristics came from the C horizon that can be seen to begin at between 0.5 and 0.6 m depth in Figure 32. Whereas the sample used for same purpose in 2011 came from the B horizon.

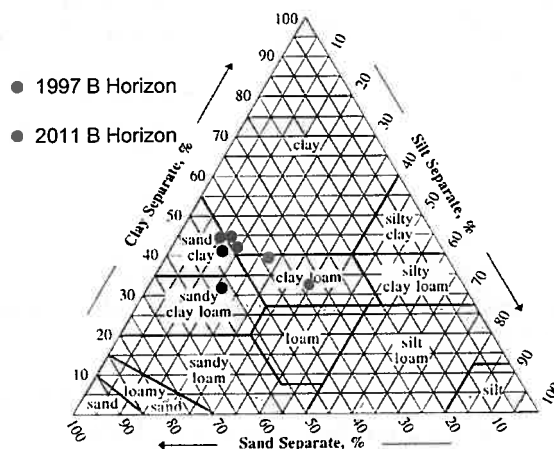


Figure 36. Soil texture triangle showing data from the B horizon in 1997 and 2011.

In soil sampled from the A horizons in 1999 and 2011, the values of bulk density, total porosity and air filled porosity at 10 kPa matric suction were equivalent with averages of 1.39 t/m³, 47.7%v/v and 14.5%v/v, respectively Table 15. Values of these parameters in the B horizon were also equivalent with averages of 1.22 t/m³, 52.5%v/v and 19.5%v/v, respectively Table 15.

Table 15. The bulk density (t/m³), total porosity (%v/v) and air filled porosity (%v/v) at matric suction of 10 kPa in soil sampled from the A horizon (0.1 – 0.15 m) and B horizon (0.4 – 0.45 m) in 1999 and 2011.

Year	A horizon		B horizon	
	1999	2011	1999	2011
Bulk density (t/m ³)	1.35	1.43	1.21	1.23
Total porosity (%v/v)	49.2	45.9	51	54
Air filled porosity (% v/v)	17.7	11.3	24	15

Air filled porosity is the minimum volume of air available to plants at the wettest drained condition (Cass 1999). Values of 25% equate to sandy or well structured soils with highly available oxygen. Values below 10% equate to poor connectivity of pores, low oxygen availability and a suppression of root respiration. While the change over time in air filled porosity in the A horizon is not significant, the reduction from 18 % to 11 % is noteworthy for its proximity to the critical threshold value of 10 %. Conditions were better in the B horizon.

8.3.3 Salinity, sodicity and cation exchange complex analysis

The values of soil salinity at the surface and 0.3 m depth were equivalent at three sampling dates between 1997 and 2011, the values at 0.6 m depth increased between 1997 and 2009 and then decreased between 2009 and 2011 (Table 16). In contrast with values of EC_e, the values of ESP in surface soil underwent a large decline between 2009 in 2011 (Table 16). The values of ESP also decreased between 2009 and 2011 at 0.6 m depth.

Table 16. The effect of depth and season on the values of soil salinity (EC_e) and exchangeable sodium percentage (ESP). The 1997 data is pers. comm. Rob Walker, CSIRO Plant Industry, Waite Campus, Adelaide.

Depth (m)	EC_e (dS/m)			ESP (%)		
	1997	2009	2011	1997	2009	2011
0-0.1	1.6	3.7	1.3	13.3 ^a	10.2 ^a	2.5 ^b
0.3	2.9	2.6	2.2	13.4	12.3	7.8
0.6	3.0 ^b	5.5 ^a	3.2 ^b	13.6 ^{ab}	17.5 ^a	10.6 ^b
0.9	3.1	n/a	4.0	13.7	n/a	15.2

Values of a parameter at a given depth followed by different letters are significantly different at $P = 0.05$.

The concentrations of exchangeable Ca^{2+} and K^+ in soils showed little variation with depth between the surface and 0.9 m (Table 17). Those of Na^+ and Mg^{2+} underwent a 7-fold and two-fold increase, respectively between the surface and 0.9 m depth.

Table 17. The salinity (dS/m), concentrations of exchangeable cations and cation exchange capacity (cmol_c/kg) in soils at the end of the 2011 season.

Depth (m)	EC_e	Exchangeable cations, pH 8.5					CEC (NH ₄)
		Ca	Mg	Na	K	Total	
0-0.1	1.3	12.5	3.2	0.5	1.0	17.2	20.0
0.3	2.2	13.9	4.7	1.7	0.6	20.8	23.1
0.6	3.2	14.9	7.0	2.8	1.0	25.6	27.0
0.9	4.0	11.8	6.6	3.7	1.3	23.3	24.5

Soil Moisture Release Characteristics

Figure 37 shows the soil water retention curves which were generated from A horizon soils in 1999 and 2011. The lowest matric suction applied in 1999 was 1 kPa and in 2011 was 0.5 kPa. Water held in pores at 0.1 kPa was estimated by assuming that the water content was equivalent to the total porosity, 0.49 in 1999 and 0.46 in 2011. This non-measured portions of the water retention curves are represented by a dashed lines.

The values of readily (RAW) and total available water (TAW) from 1999 curve were 47 and 128 mm/m, respectively. For the 2011 curves, the values were 39 and 122 mm/m for RAW and TAW, respectively. The average value of RAW in the A horizon in 2011 was 17% less than that in 1999. The value of TAW had also declined, but only by 5%.

Soil moisture release characteristics provided an input into software which calculated the effect of variation in soil matric suction on relative hydraulic conductivity. The relationships for soil sampled from the A horizon soils in 1999 and 2011 are shown Figure 38. The relationship for soil sampled in 2011 is similar to that for soil sampled in 1999.

Pore size distributions for the soils sampled in 1999 and 2011 are shown in Figure 39.

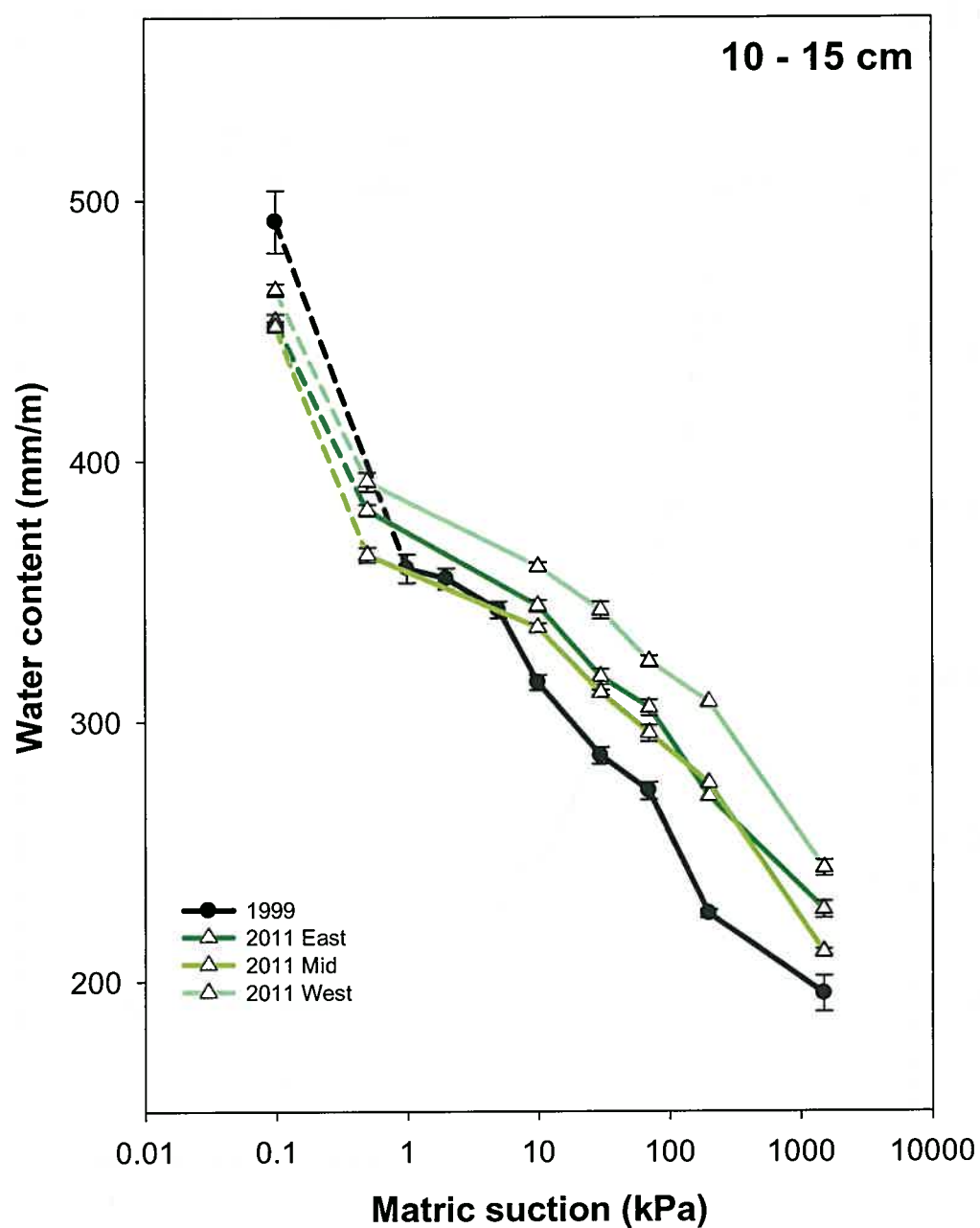


Figure 37. The soil moisture release characteristics for the A horizon in a Chardonnay vineyard at Padthaway determined in 1999 and again, after 12 seasons of saline irrigation, in 2011. The 1999 data is pers comm. Rob Walker, CSIRO Plant Industry, Waite Campus, Adelaide.

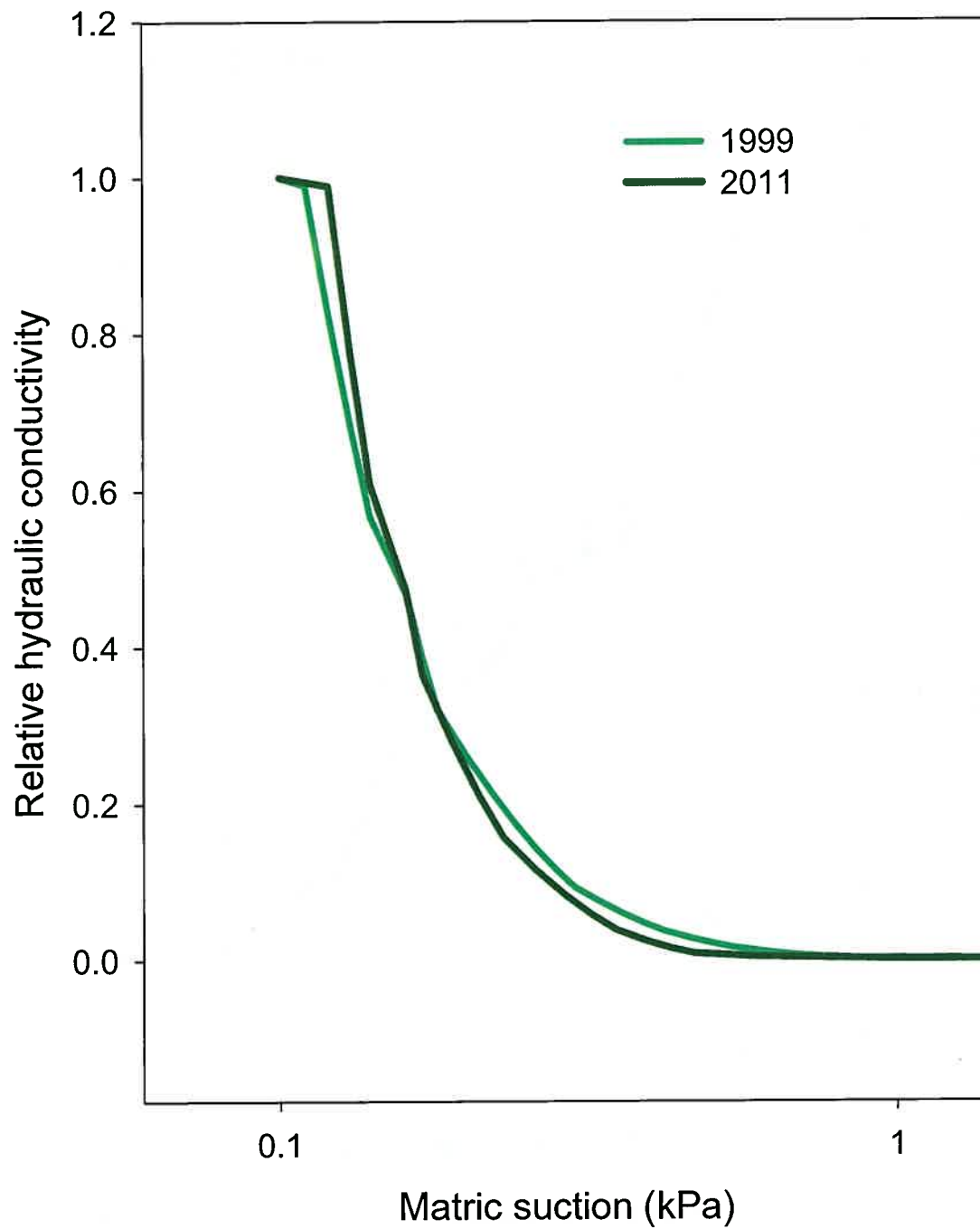


Figure 38. The relationships between calculated relative hydraulic conductivities and soil matric suction for soils sampled from the A horizon in 1999 and 2011.

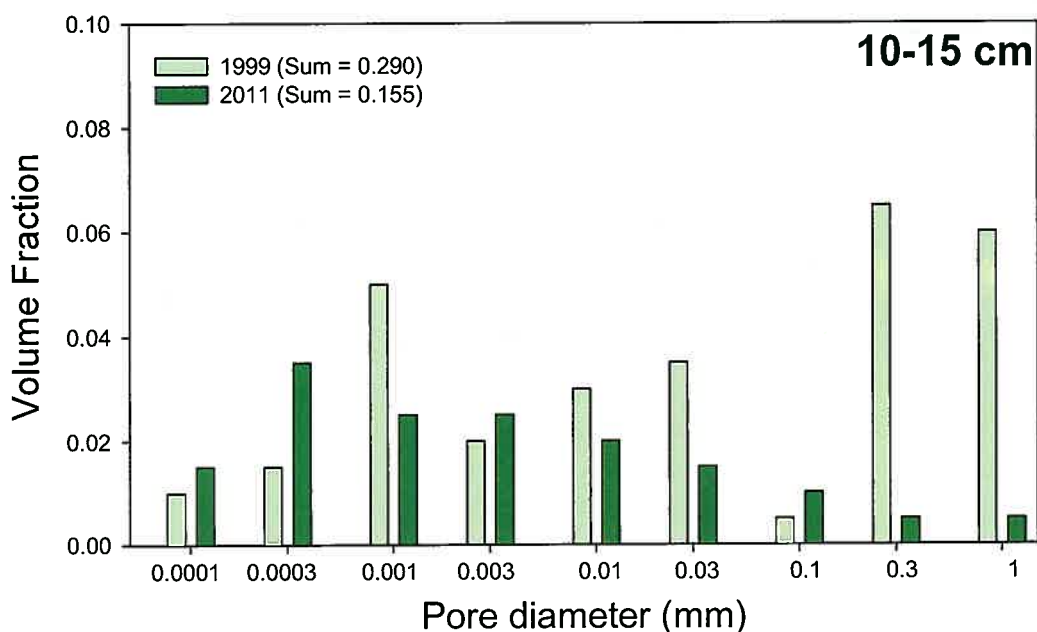


Figure 39. The pore size distribution in soils from the A horizon in a Chardonnay vineyard at Padthaway determined in 1999 and again, after 12 seasons of saline irrigation, in 2011. The 1999 data is pers. comm. Rob Walker, CSIRO Plant Industry, Waite Campus, Adelaide.

The proportion of soil volume occupied by pores in the size range of 1×10^{-4} – 1 mm in the 1999 sample was 29%, whereas that in the 2011 sample was 15.5%. In the 1999 sample, with a total porosity of 49%, 20% of soil volume consisted of pores outside of this range, whereas the 2011 sample, with a total porosity of 49%, 30 % of the soil volume consisted of pores outside of this range. The 2011 sample had less pores in the size range of 0.3 - 1 mm and held a greater volume of water at suction greater than 1500 kPa than the 1999 sample. These changes indicate that the 2011 sample has less macro-pores and more fine pores than the soil in 1999. As a result it had lower air filled porosity at field capacity (AFP) and lower TAW. Soil with a combination of an AFP of 11% and a TAW of 122 mm/m have been rated as insufficient to support the growth of moderately vigorous vines on wide spacing (Cass 2002). These changes could indicate:

- that the sample taken in 2011 was not from the same soil as that sampled in 1999 – the presence of 5% gravel in the 1999 sample and absence of gravel in the 2011 sample would support this interpretation
- that finer soil particles had migrated into larger pores from the unconsolidated mid-row soil which was mounded above the A horizon in 2002
- that cycles of saline irrigation and accompanying rise in the soil ESP followed by winter rain and fall in the soil ESP had caused dispersion.

The soil in the B horizon in 1999 had 37% gravel, whereas soil sampled from 3 sites in 2011 had 7%, 0% and 0% gravel. In 2011 a fourth pit was opened just to the west of the 1999 sample location at vine number 17 (Figure 35) and at this location the high gravel content of soils at 0.4 to 0.45 m depth precluded samplers from obtaining a core that was undisturbed. The samples obtained in 2011 were representative of the soil profiles seen in three of four pits. They are obviously different from the soil sample in 1999 and the tabulated soil water retention data (Table 18) supports this distinction.

Table 18. Gravel content and soil water release data for B horizon soil sampled in 1999 and 2011. The 1999 data are pers comm. Rob Walker, CSIRO Plant Industry, Waite Campus, Adelaide.

Year	Vine #	Gravel (%)	Matric suction (kPa)									
			Sat.	0.5	1	2	5	10	30	70	200	1500
			Water content (mm/m)									
1999	27	36.5	542	n/a	384	364	337	299	260	244	187	166
2011	3	6.7	546	434	n/a	n/a	n/a	400	390	377	350	341
2011	33	0.0	529	410	n/a	n/a	n/a	369	354	344	325	288
2011	54	0.0	452	340	n/a	n/a	n/a	310	291	283	n/a	267

9. OUTCOMES AND RECOMMENDATIONS

Output 1

Measure soil chemical and physical properties in groundwater-irrigated vineyards where poor vine performance has been associated with salinity.

Performance Targets:

- Liaise with industry to identify and gain access to salinity-damaged vineyards in Padthaway
- Measure and describe the spatial variations in soil salinity and sodicity and, measure grapevine salt status
- Determine the effect that soil sodicity has on the infiltration rate of low salinity water (rainfall)

Three salt affected vineyards were assessed at the close of the irrigation season in 2009. The high concentrations of chloride in leaves (375 mmol/kg) indicated that salinity was causing yield loss. Soils under the vine were saline and sodic with average values for salinity (ECe) and ESP of 7.7 dS/m and 16%, respectively. However, soils in the mid-row were non-saline and non-sodic with average values for salinity and ESP of 0.6 dS/m and 4%.

Re-sampling at one of these sites after a wet winter (365 mm rain) showed that rainfall had leached soil salts and reduced sodicity with average under-vine values for salinity and ESP declining over winter from 9.3 to 2.5 dS/m and from 21 to 12%, respectively. In soils located under the vines in between drippers, the infiltration rate of rainwater was high (> 100 mm/h), indicating that the high ESP was not adversely affecting conductivity of these soils to low salinity water. However indirect evidence points to reduced infiltration into the surface soil located nearer the drippers.

Many of the studies into the effect that soil sodicity has on soil hydraulic conductivity have been based on the use of disturbed soil samples which have been re-packed into columns. No such studies have been undertaken on the Padthaway soils with high ESP that displayed satisfactory hydraulic conductivity to low salinity water.

We recommend that such tests be undertaken on the soil to ascertain whether laboratory approach to characterising sodic soil behaviour mirrors the observed behaviour of the soil in-situ.

Output 2

Devise and trial management techniques which will address the poor vine and soil salt status observed in groundwater-irrigated vineyards suffering from salinity damage.

Performance Targets:

- Identify aspects of the soil water and salt balances which have the greatest effect on the leaching of soluble salts from the soils of salinity damaged vineyards
- Devise treatments which could plausibly improve leaching of salts, liaise with industry to identify a suitable field site and install a field experiment to test treatments
- Assess the efficacy of these treatments by measuring their effects on the soil and grapevine salt status, the yield and vegetative growth of grapevines and fruit quality

Under saline supplementary precision irrigation, the salts are added with the irrigation and the water to flush salt through the soil is provided by rain. The salinity of a soil is indicative of the balance between these two processes. Insufficient rain leads to salt build up and sufficient prevents it. Soils under the vines were saline, whereas those in the mid-row were non-saline. Rain reaching mid-row soils was in excess of that required to prevent salinisation. Re-direction of this excess water to the soils under vine would reduce soil salinity in this region provided that subsoil drainage rates were high enough to support the extra flushing. We hypothesised that changes in floor management which direct rain from the mid-row toward the soil under vine and which address high ESP in the soils at depth under the vine, may assist in reducing salinity damage.

At the end of the irrigation season in the 2010, a trial was installed in a salt affected Chardonnay vineyard where mid-row soils had been mounded under the vine to a depth of about 0.2 m. We assessed whether changes to vineyard floor management could reduce vine and soil salinity and soil sodicity. Changes included: removing soil mounded under the vine to prevent re-direction of rain toward the mid-row, mounding soil in the mid-row to re-direct of rain falling there towards the soil under vine, applying soluble calcium to soil surface to reduce soil sodicity, and increasing leaching by covering soils in the mid-row with plastic to reduce evapotranspiration. The trial ran for two seasons, 2011 and 2012 (year of harvest). Effects on soil salinity were assessed by measuring the salinity of the soil under the vine at the opening and close of the irrigation seasons. Measures of sodium and chloride concentration in leaves and fruit were used to assess the effect of treatments on vine salinity.

Removing soil mounded under vine and re-directing rain from the mid-row toward the soil under vine reduced soil salinity. Applying calcium and re-directing rain from the mid-row toward the soil under vine reduced soil sodicity. All changes to floor management reduced the concentrations of Na^+ and Cl^- on at least one occasion and in at least one tissue type. Re-directing rain from the mid-row toward the soil under vine reduced the concentration of both ions, in both seasons and in both leaves and fruit, other treatments had lesser effects.

Treatments did not affect yield. They caused small reductions in juice Brix and increases in juice titratable acidity.

This was a proof of concept trial which has shown that re-direction of rainfall from the mid row using soil mounds covered with plastic reduces vine and soil salinity in clay loam soils at Padthaway. Are the same results achievable in other locations with different soils and climates?

We recommend that proof of concept trials be conducted in other locations.

We tested whether the concept of rainfall re-direction had merit by covering mid row soil mounds with plastic. The level of input in repair and replacement of plastic was too high to be commercially viable. Other fields such as water harvesting have developed commercially viable approaches to re-directing rainfall (Richardson et al. 2004).

We recommend that techniques used in water harvesting be tested for their suitability for use in re-directing rainfall from soils in the mid row to those under the vine.

Output 3

In a Padthaway vineyard, irrigated with saline groundwater, compare measurements of physio-chemical properties of soils made in 1997 and 1999 with those made in 2009 and 2011.

Performance Targets:

- For soil on the Padthaway Flats, determine relationships between values of salinity and sodium absorption ratio in 1:5 water extracts of soil and the values in saturated extracts of soil
- Liaise with current and ex-CSIRO staff to determine exact location of soil sampling sites in the 1990's and to access data derived from these samples
- Resample sites and determine changes in physio-chemical properties of soils

The slope of the relationship between EC_e and $EC_{1:5}$ had a value of 6.53 and values of $EC_{1:5}$ accounted for 92% of the variation in values of EC_e .

SARDI assessed the affect that a decade of saline irrigation had on soil physical and chemical properties by comparing a set of current measurements of these properties with those made a decade ago at the same site by CSIRO Plant Industry. Soils were sodic and saline in 1997 and again when measured in 2009; the salinity of soil in the top 0.6 m was 5.0 dS/m and the sodicity (ESP) was 13%. After, above average winter rain in 2011 the salinity of soils in top 0.6 m was 2.1 and the sodicity (ESP) was 7%. The sodic soils had been subject to annual cycles of saline high SAR irrigation in summer and non-saline low SAR rain in winter over the previous decade. The return to non-saline and non-sodic state in 2011 indicates that any change in soil structure wrought by a decade of these cycles was not a significant impediment to leaching of salts and displacement of sodium from the clay exchange sites.

Comparison between two set of soil moisture release characteristics determined at either end of the decade showed they were different, however there is an equal chance that the difference could be ascribed to slight differences in the soil composition (5% gravel content in earlier sample), rather than attributed to effects of saline irrigation.

We assessed whether a decade of annual cycles of saline high SAR irrigation in summer and non-saline low SAR rain in winter changed soil physical properties by comparing physical properties of soil determined on samples taken in 1999 and 2011. Comparison of soil moisture release data and the derived measures of pore size distribution showed that soils were different, however it is likely that these differences may be due to textural differences between samples taken in different years and due to mounding of soil under vine in 2002. As a consequence our results were inconclusive.

We recommend that the “paired site” approach of Murray and Burk (2010) be used in future assessments.

Output 4

In partnership with industry, establish a network of monitoring sites for soil salinity and grape juice quality in the Padthaway, Coonawarra, Wattonbully and Mt Benson/Robe districts.

Performance Targets:

- Assist industry to build a set of criteria for network membership which emphasised similarity of sites with regard to vine stocks, irrigation method and soil types; install soil solution monitoring at sites and train network members in their operation
- Support operation of the network by the provision of sampling consumables, analysis of collected samples and collation of data with associated weather and irrigation data

- Investigate the nature of the relationships between the salinity of water extracted from the soil and standard measures that are currently in use to assess vineyard salt status

A SE Salinity Monitoring Network was established in the winter of 2010. It had 14 sites spread across the Limestone Coast GI. All sites were located in own rooted Cabernet Sauvignon vineyards in which saline groundwater was applied by drip irrigation. The dominant soil type was a clay loam and no vineyards used overhead sprinklers for frost protection. The network operated for three seasons and all growers remained active in the network over the entire period of its operation.

SARDI supported the network by installing soil water extractors, providing training in their use and analysing soil water samples. Growers supported the network by regularly collecting samples and providing information on the salinity and volume of irrigation. SARDI collated this data and that on rainfall, and about once every four months provided each network participant with data from all 14 sites displayed in graphical form (sites were only identified by number).

SARDI also annually measured soil salinity and the concentrations of Na^+ and Cl^- in leaves and fruit. Levels of soil water salinity and soil salinity were all below values indicative of conditions which cause salinity damage in vines. Likewise concentrations of Na^+ and Cl^- in leaf petioles were below indicating the presence of salinity stress. Concentrations of Na^+ and Cl^- in juice were well below limits for these ions in overseas markets and below the level at which most consumers can detect an effect on the taste of wine.

Sodium concentrations in leaf and fruit were unrelated to variations in either the vineyard annual salt load (a product of irrigation depth and irrigation water salinity) or soil salinity. In contrast, variations in the chloride concentrations in leaves and fruit were positively related to variations in vineyard salt load and soil salinity.

Measures of the salinity of water extracted from the soil (EC_{sw}) could be indicative of the values of soil salinity (EC_e). At EC_{sw} above 7 dS/m, the EC_e was above the threshold for salinity damage to vines, but at values of EC_{sw} in between 7 and 3.5 dS/m, the values of EC_e could be either above or below the threshold level. At EC_{sw} below 3.5 dS/m, the EC_e was below the threshold for salinity damage to vines.

Average values of EC_{sw} before flowering predicted 57% of the variation in the concentration of Cl^- in the leaf petiole sampled at flowering. In the data set from the monitoring network, the concentration of Cl^- in juice was always less than 60 mg/L when its concentration in the leaf petiole at flowering was less than 0.55%.

Our field work in the SE of South Australia has shown that the measure of the salinity of water extracted from soil could be used as a guide for likely values of soil salinity (EC_e). It is unclear whether the guidance offered by this measure is location dependent.

We recommend that the relationship between the salinity of water extracted from soil and soil salinity (EC_e) be tested at other locations, and that such relationships also be developed for other soil water salinity devices such as the Fullstop™.

Output 5

Pro-actively communicate outputs.

Performance Targets:

- Establish a steering committee comprising funders, industry representatives from the Limestone Coast and researchers involved in the field of salinity management of grapevines. Provide the committee with project updates and the opportunity for consultation on at least three occasions during the project
- Use regional workshops and seminars to present project findings to Limestone Coast grower groups
- Use scientific and technical publications and presentations at national conferences to inform the national viticultural industry and other users of supplementary irrigation
- Summarise findings in a final report to NPSI

Over the life of the project, six meetings were held with a steering committee. Appendix One lists meeting dates and locations. Members of the committee and observers at meetings are listed in the acknowledgements section on the title page of this report. They represented: project funders; salinity, soil and water specialists from PIRSA and Flinders University; a rootstock and salinity specialist from CSIRO; technical support for the irrigation industry and SENRMB; and representatives from the Limestone Coast Wine Industry Technical Committee.

Appendix One gives details of workshops and seminars, scientific and technical publications and conferences presentations. Over 200 growers have attended our presentations at workshops and seminars. Presentations at conferences and steering committee meetings have reached over another 100 growers.

Our new findings on the potential role that rainfall re-direction can have in managing salinity have led a large corporate winery to committing about \$90,000 in in-kind as to pilot our technique with saline recycled water at two sites in SE Australia. This commitment forms part of a SARDI – University of Adelaide project bid to the Australian Water Recycling Centre of Excellence. The same group have also begun in-house work to pilot the technique with saline groundwater at another location.

The 14 growers in the salinity monitoring network developed new skills in salinity monitoring and these will continue to influence their practices after the close of this project.

Wider awareness of our new findings on the potential role that rainfall re-direction can have in managing salinity has also been promoted in rural Australia via a press release entitled "Precision rain for precision irrigation". It was circulated in January 2012 and by the end of February 2012 it had generated one radio interview (Adelaide), and 13 articles in SA regional papers. SARDI only monitors media in SA. The article was also distributed to viticultural regions across Australia and it is likely that the regional papers outside of SA also ran it.

Output 6

Develop guidelines

Performance Targets:

- Develop guidelines for minimising effect of soil salinity on wine quality based on outcome of field experiment, literature review and monitoring

Guidelines will summarise the findings of this project and those of the sister project supported by GWRDC which are immediately pertinent to managers of saline supplementary irrigation. The guidelines will be completed in early June 2012.

10. APPENDICES

10.1 Appendix 1: Communication

10.1.1 Scientific publications

Stevens, R.M., Pech, J.M., Gibberd, M.R., Walker, R.R., and Nicholas, P.R. (2010). Reduced irrigation and rootstock effects on vegetative growth, yield and its components, and leaf physiological response of Shiraz. *Australian Journal of Grape and Wine Research* 16:413-425.

Stevens R.M., Harvey, G., and Partington, D.L. (2011). Irrigation of grapevines with saline water at different growth stages. Effects on leaf, wood and juice composition. *Australian Journal of Grape and Wine Research* 17:239-248.

Stevens R.M., Harvey, G., Norton, S., and Frahn, W. (2011). Over-canopy saline sprinkler irrigation of grapevines during different growth stages. *Agricultural Water Management* 101:62-70.

Pech, J.M., Stevens, R.M., Gary J. Grigson, G.J., Schrale, G., and Cox, J.W. Screening the *Vitis* Genus for Tolerance to Boron with and without Salinity. Manuscript in preparation.

10.1.2 Conference papers/posters and final reports

Pitt, T.R., Stevens, R.M., Walker, R.R., Biswas, T.K. (2009). Managing Soil Salinity for Wine Quality in Groundwater Irrigated Vineyards (poster). 10th Irrigation Australia Ltd Conference, Swan Hill, Victoria, October 2009.

Pitt, T.R., Stevens, R.M., and Nicholas P. (2010). Sustaining perennial horticultural production under supplementary irrigation drawn from saline groundwater (poster). 11th Irrigation Australia Ltd Conference, Sydney, New South Wales, June 2010. pp 220-221.

Pitt, T., Stevens, R., Dyson C., and Chyvi, L. (2011) Redirecting rainfall to manage root zone salinity in groundwater irrigated viticulture (oral). 11th Irrigation Australia Ltd Conference, Launceston, Tasmania 22-25 August 2011.

Pitt, T., Stevens, R.M., Dyson, C., and Chyvi, L. (2011) Re-directing rainfall to manage root zone salinity (oral). CRUSH 2011, Adelaide South Australia, 29 September 2011.

Stevens, R.M., Pitt, T.R., Dyson, C., Pech, J.M., and Skewes, M. (2011) Salt tolerant rootstocks for long-term sustainability in the Limestone Coast. Final report to the Grape And Wine Research & Development Corporation. 55 pp.

Stevens, R.M., Pitt, T.R., and Dyson, C. (2011). Managing soil salinity in groundwater irrigated vineyards. Final report to National Program for Sustainable Irrigation 82 pp.

Stevens, R.M., and Pitt, T.R. (2012). Changing vineyard floor management to reduce root-zone salinity under supplementary saline drip irrigation (oral). 12th Irrigation Australia Ltd - 7th Asian Regional ICID Conferences, Adelaide, 26-28 June 2012.

10.1.3 Steering committee meetings

Pitt, T.R. and Stevens, R.M. (2009). Salt tolerant rootstocks for long-term sustainability in the Limestone Coast (Oral). Naracoorte, South Australia, September 2009.

Minutes distributed October 2010

Pitt, T.R. and Stevens, R.M. (2010). Managing Soil Salinity for Wine Quality in Groundwater Irrigated Vineyards (Oral). Padthaway, South Australia, May 2010.

Minutes distributed August 2010

Pitt, T.R. and Stevens, R.M. (2010). Salt tolerant rootstocks for long-term sustainability in the Limestone Coast (Oral). Coonawarra, South Australia, December 2010.

Minutes distributed May 2011

Pitt, T.R. and Stevens, R.M. (2011). Managing Soil Salinity for Wine Quality in Groundwater Irrigated Vineyards (Oral). Adelaide, South Australia, May 2011.

Minutes distributed August 2011

Pitt, T.R. and Stevens, R.M. (2011). Managing Soil Salinity for Wine Quality in Groundwater Irrigated Vineyards (Oral). Padthaway, South Australia, December 2011.

Minutes distributed January 2012

Pitt, T.R. and Stevens, R.M. (2011). Managing Soil Salinity for Wine Quality in Groundwater Irrigated Vineyards (Oral). Adelaide, South Australia, June 2012 (not yet held at time of writing).

Minutes distributed July 2012

10.1.4 Industry articles and fact sheets

Pitt, T.R. and Stevens, R.M., (2010). Sustaining perennial horticultural production under supplementary irrigation drawn from saline groundwater. National Program for Sustainable Irrigation Research Bulletin. NPSI, Narrabri NSW. 6 pp.

Pitt, T. and Stevens, R. (2011). Redirecting rainfall to manage salinity. Australian and New Zealand Grapegrower and Winemaker 575:18-19.

Stevens, R.M., Pitt, T.R., Dyson, C. and Nicholas, P. (2011) Long-term properties of rootstocks. GWRDC Fact sheet http://www.gwrdc.com.au/webdata/resources/files/Long-term_properties_of_rootstocks.pdf.

10.1.5 Workshops and seminars

Pitt, T.R. (2009). Introducing SARDI's upcoming salinity research in the South East. Limestone Coast Wine Industry Technical Sub-Committee 'Composting Workshop', Struan House, South Australia, April 2009.

Pitt, T.R. (2010). Managing soil salinity for wine quality in groundwater irrigated vineyards. Limestone Coast Wine Industry Technical Sub-Committee 'Salinity Workshop', Stonehaven Cellar Door, Padthaway, South Australia, June 2010.

Pitt, T.R. (2010). Managing root zone salinity in groundwater irrigated viticulture. About Science – Unlimited Research Discussion. Waite Campus, Urrbrae, South Australia, July 2010.

Pitt, T.R. (2010). Salt tolerant rootstocks for long-term sustainability in the Limestone Coast. Treasury Wines 'Technical Officers Meeting', Padthaway, South Australia, October 2010.

Pitt, T.R. (2010). Managing soil salinity for wine quality in groundwater irrigated vineyards. Barossa Grape and Wine Association - Viticulture Technical Group, 'Managing Saline Irrigation Water'. Yalumba Nursery, Nuriootpa, South Australia, November 2010.

Pitt, T.R. (2011). Managing soil salinity for wine quality in groundwater irrigated vineyards. Mudgee 'Future Leaders' SA Tour. Waite Campus, Urrbrae, South Australia, June 2011.

Pitt, T.R. (2011). SARDI Research in the Limestone Coast. SARDI Seminar Series. Waite Campus, Urrbrae, South Australia, August 2011.

10.1.6 Supporting SE Salinity Monitoring Network

Individual Grower South East Salinity Monitoring Network (SESMN) Feedback Reports:

Reports posted October 2009.

Reports posted December 2009.

Reports posted January 2010.

Reports posted March 2010.

Reports posted June 2010.

Reports posted October 2010.

Reports posted December 2010.

Reports posted July 2011.

Reports posted December 2011.

Three year SE Salinity Monitoring Network Summary Report, to be posted by the end of June 2012.

10.1.7 Press coverage – Newspapers & Radio

A press release entitled "Precision rain for precision irrigation" was circulated in January 2012. It acknowledged support from NPSI. By the end of February 2012 it had generated one radio interview (Adelaide), and 13 articles in SA regional papers. SARDI only monitors media in SA. The article was also distributed to viticultural regions across Australia and it is likely that the regional papers outside of SA also ran it. In May 2012, SARDI media also received a request from the American Society of Agricultural and Biological Engineers to run the press release in the Society's Resource Magazine.

10.1.8 Other Industry engagement

Rob Stevens chairs the program committee for the concurrent International Commission on Irrigation & Drainage (ICID) 7th Asian Regional and Irrigation Australia Limited conferences which will be held in Adelaide in June 2012.

10.2 Appendix 2: Intellectual property

Outputs of this research are in the public domain.

10.3 Appendix 3: Staff

Mr Rob Stevens,
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SARDI – Sustainable Systems, Adelaide

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10.4 Appendix 4: References

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