

Over-canopy saline sprinkler irrigation of grapevines during different growth stages

Rob M. Stevens^{a,*}, Gordon Harvey^{a,1}, Scott Norton^{b,2}, William Frahn^{a,3}

^a South Australian Research and Development Institute, PIRSA Loxton Centre, PO Box 411, Loxton 5333, Australia

^b Primary Industries SA, Loxton Centre, PO Box 411, Loxton 5333, Australia

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ABSTRACT

Wetting plant foliage with saline irrigation increases the uptake of toxic ions Na^+ and Cl^- . Over three consecutive seasons, Colombarid vines grafted on Ramsey rootstock were irrigated with saline water (EC 3.5 dS/m) by over-canopy sprinklers during any one of the first three of the four annual growth stages: bud burst to full bloom (treatment BB–FB), full bloom to veraison (treatment FB–V), and veraison to harvest (treatment V–H). At other times, vines received non-saline water (EC 0.5 dS/m) as did the control. Seasonal average soil salinities remained relatively constant over the trial. In contrast, the concentrations of Na^+ and Cl^- in one-year old wood and grape juice more than doubled. In treatments FB–V and V–H the average yield over the three seasons was reduced by up to 15%. Results were compared with those obtained in an earlier study which was undertaken in the same vineyard with the same treatments applied via dripper. With drippers, the maximum reduction in the average yield over three seasons was 2%. Saline sprinkling caused rises in Na^+ and Cl^- concentrations of fruit, leaf lamina and one-year-old wood that were at least 7-fold, 5-fold and 2-fold greater, respectively, than the rises caused by application of the same treatments with drip. Progressive seasonal rises in the concentrations of Na^+ and Cl^- in these tissues were due in part to carryover of salt added in previous seasons; with saline sprinkling the magnitude of these carryovers was 4-fold greater than those with saline drip irrigation. With saline water, vignerons can reduce losses by using irrigation systems which do not wet the foliage.

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1. Introduction

The deleterious effects of saline irrigation on plant growth have been attributed to an osmotic effect in which elevated concentrations of soluble salts in the soil causes a decline in plant water status and a toxic effect in which elevated concentrations Na^+ and Cl^- in plant tissue poison plant metabolism (Bernstein, 1975). Both effects are proportional to the concentration of salts in soil solution (Oertli and Richardson, 1968; Downton, 1977), however the relationship between the concentrations of Na^+ and Cl^- in plant tissue and those in soil solution can also be modified under saline conditions by other factors including irrigation method, rootstock and soil aeration (Bernstein and Francois, 1975; Downton, 1985; West and Taylor, 1984).

Bernstein and Francois (1975) and Benes et al. (1996) demonstrated the effect of irrigation method on yield in studies on bell peppers and barley. Applying moderately saline water directly to the soil surface did not cause yield loss or leaf damage. Sprinkling with the same water caused yield loss and leaf damage which were associated with higher concentrations of Na^+ and Cl^- in the leaves. Sprinkling the foliage of woody perennials and non-woody crops with moderately saline water increases concentrations of Na^+ and Cl^- in leaves (Ehlig and Bernstein, 1959; Maas et al., 1982).

Munns (1993) concluded that the deleterious effect of salinity on growth was due to leaf loss. Whilst many crops have been shown to suffer foliar damage and defoliation when sprinkled with saline waters (Maas, 1985), demonstration of a yield loss in addition to that expected from rises in soil salinity is limited to the studies of Bernstein and Francois (1975) and Benes et al. (1996).

Grapevines can tolerate a partial defoliation without suffering yield loss (May et al., 1969; Kliewer, 1970). In vines undergoing saline drip irrigation, the development of yield loss was associated with inter-seasonal rises in the concentrations of Na^+ and Cl^- in leaves (Prior et al., 1992a, 1992b). These rises were associated with rises in the concentrations of Na^+ and Cl^- in both the soil and the canes, a perennating plant organ (Stevens et al., 2011). Over a study of 2 seasons duration on saline sprinkled grapes, Francois and Clark

* Corresponding author. Present address: SARDI/PIRSA, GPO Box 397, Adelaide 5001, Australia. Tel.: +61 8 83039449; fax: +61 8 83039473.

E-mail address: rob.stevens@sa.gov.au (R.M. Stevens).

¹ Present address: Biological Services, PO Box 501, Loxton 5333, Australia.

² Present address: Philmac, 53–59 Deeds Rd., North Plympton 5037, Australia.

³ Present address: PO Box 1497, Renmark 5341, Australia.

(1979) found that foliar absorbed Na^+ and Cl^- did not increase the concentration of these ions in the canes. Given that partial defoliation does not necessarily lead to yield loss in vines and that foliar absorbed Na^+ and Cl^- has not been shown to affect the level of these ions in perennating tissue, then it is unclear whether saline sprinkling of grapevines over consecutive seasons will lead to the development of a yield loss above that to be expected from the effect that saline irrigation has on soil salinity.

Stevens et al. (1999) found that 3 consecutive seasons of drip irrigation with saline water in any one of the four seasonal growth stages caused a loss of 2% or less in the average yield over three seasons of Colombard grapevines on Ramsey rootstock. Widespread leaf damage did not emerge until the fourth season of this trial (Stevens, 2005). The current study was located in the same vineyard as the study of Stevens et al. (1999). It applied the same treatments, excepting that over-canopy sprinklers replaced drippers. In it we investigated the effects of saline sprinkling on yield and fruit composition, and on the concentrations of Na^+ and Cl^- in perennating and non-perennating tissues. Comparisons between this study and the previous study (Stevens et al., 1999, 2011) are used to distinguish the effects of saline sprinkling on production from those of saline drip irrigation.

2. Materials and methods

2.1. Experimental material and culture

The trial was located at Loxton, South Australia ($34^\circ 38'S$, $140^\circ 38'E$) in a vineyard which was replanted in 1977 to Colombard vines on Ramsey rootstocks. The vines were spaced at 3.5 m between rows and 2.5 m within rows, with rows aligned N–S. The vines were cane pruned and trained on a 1 m wide-T trellis. Nitrogen was applied as urea in the irrigation water at annual rates of 81 kg N/ha. A full cover herbicide program was applied throughout the growing season.

Vineyard soils were sandy, siliceous, thermic Xerollic Calciorthids. The soil textures were: 0–30 cm sand or sandy loam or sandy clay loam, 30–160 cm sandy clay loam or clay loam. A compact, class 3b, lime layer (Wetherby and Oades, 1975) was found between 85 and 90 cm.

2.2. Trial design, irrigation and treatments

The trial was imposed on vine rows which had not been part of the saline experiments described in Stevens et al. (1999, 2011). It was a randomised block design containing 5 replicates. A plot consisted of 3 adjacent rows of 6 vines per row (18 vines). Measurements were made on the middle 2 grapevines in the middle row. The outer rows acted as barrier rows. On the outside of each barrier row, midway between it and the adjacent row, a 1.7 m deep plastic sheet was inserted vertically to act as a soil barrier to the movement of salt between the rows and a 0.9 m high sheet of knitted high density polyethylene monofilament shade cloth was erected at 2.0 m above ground level to intercept sprinkler throw beyond the edge of the plot.

In September 1991, one year before treatments commenced, the irrigation system was converted from drip to over-canopy sprinklers. Inverted mini-sprinklers (Rondo, Plastro Gvat, Israel) were suspended at 2.4 m height above ground level along the trellis line and spaced at 2.5 m. Enclosed testing of this sprinkler arrangement, that is 2.5×3.5 m non-offset spacing, returned a sprinkler precipitation pattern with a coefficient of uniformity of 88% (Christiansen, 1942). During this season all vines were irrigated with non-saline water (electrical conductivity [EC] 0.5 dS/m).

Treatments commenced in September 1992. The vines were irrigated with saline water (EC 3.5 dS/m) during any one of the first three of the four annual growth stages. Saline irrigation was applied to treatment BB–FB from bud-burst until full-bloom, and to treatment FB–V from full-bloom until veraison and treatment V–H from veraison until harvest. In Colombard, veraison was signified by a change in the appearance of the outer surface of the grape skin from dull and waxy to clear and translucent. From harvest to leaf fall and at other times, they were irrigated with non-saline water (EC 0.5 dS/m) as was a control (CONT) which received non-saline water throughout the season. In this vineyard, bud burst occurred in September and leaf fall in May. The irrigations were scheduled to maintain the soil water content of a 1.6 m deep rootzone within 60 mm of field capacity. Irrigations commenced at 1800 h and were applied at a rate of 7 mm/h.

Non-saline water was drawn from the Murray River at Loxton and in the early 1990s in such water with an EC of 0.5 dS/m the average concentrations of Na^+ , Ca^{2+} , Mg^{2+} , K^+ , Cl^- were 2.5, 0.4, 0.5, 0.1, and 2.6 mmol/L. Saline water was generated by adding a sodium chloride brine to non-saline water to produce water with an EC of 3.5 dS/m. The brine was prepared by adding food grade salt to non-saline water. Two grades of salt were used. One was comprised of NaCl 99.8% by weight and Ca^{2+} and Mg^{2+} at concentrations of 300 and 45 ppm, respectively. The second grade was similar to the first, but also contained sodium aluminosilicate at 0.5% by weight. During irrigations the brine was continuously agitated.

2.3. Meteorological, water and soil measurements

Measurements of rainfall and data for calculation of reference evapotranspiration (ET_o) were sourced from an Australian Government Bureau of Meteorology station, which was located 100 m east of the experimental site (station number 024024). This site was surrounded by irrigated crops. The reference evapotranspiration for grass (ET_o) was calculated following the procedures of Allen et al. (1998).

Irrigation volumes were measured with an in-line flow meter. Water salinities (EC) were measured on samples collected by continuously bleeding the supply lines for each treatment through micro-capillary tubes into 4 L jars. Rainfall at a rate greater than 5 mm/d was considered to be effective. For each growth stage and for the entire season, the EC of water received by the grapevines (EC_w) was expressed as a volume-weighted average. For the purpose of this calculation both irrigation and effective rainfall were considered to be water additions with the EC of rainfall taken as 0.044 dS/m (Blackburn and McLeod, 1983).

Test wells with casing depths of 3.2 m were installed at 6 sites. A site was located in each treatment of the replicate located in the middle of the block and in the control treatments of the replicates located on the eastern and western edges of the block. The depth to the top of the perched watertable was read once weekly during the season.

Soil salinity was quantified as the EC of the saturated paste extract (EC_e). Soil samples were taken in 3 replicates just before bud-burst and at full-bloom, veraison, harvest and just after leaf fall. Soil was sampled at 0.05, 0.35, 0.75, 1.1 and 1.6 m depth. In order to aid in the interpretation of the soil salinity measure, at each sample time a single root-weighted value (RWECE) was calculated for each sample location. The calculation and the root length data used in it are described in Stevens and Douglas (1994).

2.4. Plant measurements

The concentrations of Na^+ and Cl^- were determined on leaf petioles and lamina and in one-year-old wood. Leaves opposite the basal bunch on shoots arising from canes were sampled in the

Table 1

Means (\pm s.e.) over three seasons in each of four growth periods for depths of irrigation (I), effective rainfall (R), the reference evapotranspiration (ETo) and the volume-weighted EC of received water (ECw) for treatments irrigated with non-saline and saline water.

Growth period	Depth (mm)			Volume-weighted ECw (dS/m)	
	I	R	ETo	Non-saline	Saline
Bud burst to full bloom	115 \pm 27	37 \pm 18	230 \pm 12	0.36 \pm 0.21	2.45 \pm 0.45
Full bloom to veraison	325 \pm 20	39 \pm 7	398 \pm 22	0.37 \pm 0.12	3.05 \pm 0.13
Veraison to harvest	301 \pm 35	10 \pm 6	361 \pm 5	0.55 \pm 0.06	3.46 \pm 0.16
Harvest to leaf fall	97 \pm 10	15 \pm 13	104 \pm 10	0.41 \pm 0.04	

middle of the first three of the four physiologically distinct annual growth stages and at harvest at the end of the third growth stage. The sample leaf was positioned at the 3rd node and unfolded at about the end of September. Segments of wood comprising the first two fully expanded basal internodes were sampled at pruning. In early March 1995, damaged and healthy mature primary leaves located on the exterior of the canopy were sampled from 3 replicates of vines undergoing saline irrigation and ranked according to the extent of damage. The ranking and associated damage were as follows: 1 - no necrosis or tissue darkening present; 2 - darkening of the lamina margin; 3 - brown necrotic lamina margin and tissue darkening extending inward; 4 - necrotic tissue present across the lamina.

After sampling the tissue was given three rinses to remove surface salt; the first rinse solution consisted of 5 L of distilled water containing 2 drops of P-free dishwashing detergent and 5 drops of 5 N nitric acid, and the second and third consisted of distilled water. Tissue was dried at 70 °C and ground to pass a 0.2 mm mesh. Cations were determined on either a hot nitric acid digestion, or on ash redissolved in hot 6 N HCl, by atomic absorption spectrophotometry, GBC model 906 (GBC, Melbourne, Australia). Chloride was determined on a cold water extract with a Buchler chloridometer (Labconco, Kansas City, MO).

Harvest samples were not taken in 1994 and the values of the Na⁺ and Cl⁻ concentration in leaf lamina were estimated from samples taken in February 1994. These estimates were based on the relationships between concentrations in the February and March samples in 1993 and 1995 (values of r^2 for linear regression of March on February were 0.93 for Cl⁻ and 0.92 for Na⁺).

The grapevines were harvested in late March (the exact dates were set by the winery which purchased the crop). The fruit yield per plot, the number of bunches and the weight of a random sample of 100 berries were measured at harvest. Measurements began in the season before treatments commenced. A bunch was defined as a structure arising from a shoot and bearing more than 5 berries. The number of berries per bunch was derived from these measurements. In each season, the one-year-old wood removed at pruning in August was weighed. Data collected in the season before treatments commenced, were used as a covariate in analysis of data collected during the trial.

Grape composition was determined on juice extracted by crushing the 100-berry samples with a hand press. Sample preparation and determination of °Brix, titratable acid, pH and concentrations of Cl⁻, K⁺, Na⁺, malate and tartrate followed procedures described in Stevens et al. (2011).

2.5. Data analysis

Data were analysed as a split plot ANOVA with treatment as the main factor and season the sub-plot factor. Analyses which involved the use of pre-treatment covariates were undertaken with Genstat 5 Release 3 (Lawes Agricultural Trust, Hampden, UK) and those without the use of covariate with Statistix (Analytical Software, Tallahassee, FL). Least significant differences were only calculated when the *F* tests for treatment and/or treatment by

season terms were significant. The assumption of normality was checked by inspection of the plot of fitted values against residuals.

3. Results

3.1. Water and soil salinity

For each of the four stages in the seasonal growth cycle of the vine, the three-seasons means for the depths of irrigation, effective rainfall, reference evapotranspiration, and the volume-weighted EC of received water (ECw) for both saline and non-saline treatments are presented in Table 1. The depths of water received in growth stages before flowering and after harvest were about one-third the depths received in each of the two growth stages between flowering and harvest. As a consequence the treatments salinised between flowering and harvest annually received about 3 times more salt than the treatment salinised before flowering. This caused large between-treatment differences in the means of the annual volume-weighted salinities of received water which for treatments CONT, BB-FB, FB-V and V-H were 0.4, 0.8, 1.5 and 1.4 dS/m, respectively. Treatments FB-V and V-H received high annual irrigation salt loads with annual ECw that were 1.1 and 1.0 dS/m higher than the control, as opposed to treatment BB-FB which received a low annual irrigation salt load with an annual ECw that was only 0.4 dS/m higher than the control.

The average depth to the perched watertable was greater than 2.5 m. In the 1st season the minimum, average and maximum depths to the perched watertable were 1.5, 2.6 and 3.2 m, respectively. In subsequent seasons at some sites, the water table was below the depth of the test well casing (3.2 m). In order to estimate an average value, these readings were set to a default value of 3.2 m depth. In the 2nd and 3rd seasons the average perched watertable depths were greater than 3.0 and 3.2 m, respectively, the minimum were 2.4 and 2.5 m, respectively, and the maxima were greater than 3.2 m in both seasons.

Soil salinity varied within the season. In the saline treatments, the minimum values generally occurred just prior to, and the maximum values at the end of, the growth stage in which the vines received saline irrigation. In all saline treatments, the minimum values (Fig. 1a) could be considered as non-saline as they were less than the threshold salinity of 1.5 dS/m for shoot growth decline in own-rooted vines where irrigation was applied directly to the soil surface (Ayers and Westcott, 1985). The maximum RWECe values (Fig. 1c) were below the threshold value for yield loss in surface irrigated Colombard vines on Ramsey rootstock of 3.3 dS/m (Zhang et al., 2002) except for the value of 3.4 dS/m in treatment FB-V in 1994. Seasonal mean soil salinity values did not increase over the trial (Fig. 1b).

3.2. Leaf, wood and fruit Na⁺ and Cl⁻ concentrations

By the 3rd season, leaf damage was prevalent in the saline treatments. Table 2 shows that Na⁺ concentrations in damaged leaves were higher than that in undamaged leaves ($P=0.006$), and that K⁺ and Cl⁻ concentrations in damaged leaves were equivalent to those in undamaged leaves.

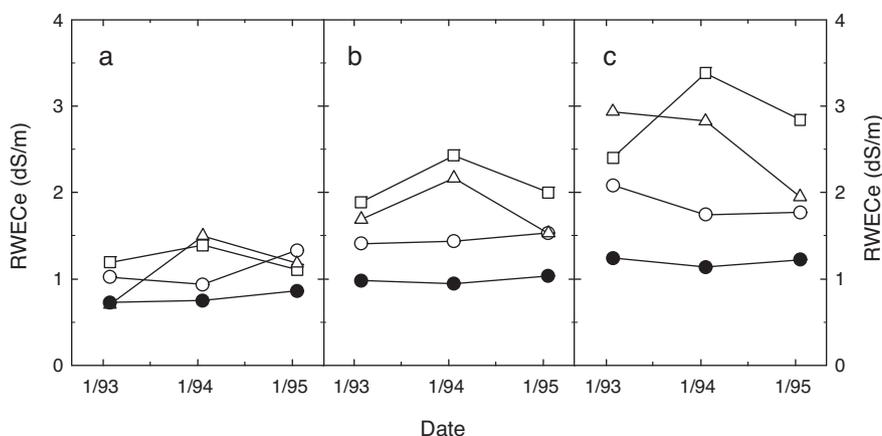


Fig. 1. The effects of irrigation treatment on the inter-seasonal variations in the seasonal minimum (a), mean (b), and maximum (c) values of root weighted ECe. CONT (●), BB-FB (○), FB-V (□), V-H (Δ).

Table 2
The concentrations (mmol/kg) of Na⁺, Cl⁻ and K⁺ in undamaged (rank 1) and damaged (ranks 2–4) leaf lamina sampled in the 3rd season (March 1995).

Parameter	Leaf damage ranking				LSD ^a
	1	2	3	4	
Na ⁺	103	326	299	291	101
Cl ⁻	200	287	269	266	NS ^b
K ⁺	88	107	100	79	20

^a LSD is least significant difference ($P=0.05$).

^b NS indicates that the treatment effect was not significant.

Saline irrigation increased the Na⁺ and Cl⁻ concentrations in the leaf lamina and petiole, one-year-old wood and juice (Figs. 2–4). The response to saline irrigation was modified by tissue type. These modifications displayed as differences between organs in the

sensitivity of the response to variations in the timing of saline irrigation and in the annual salt load, differences between organs in the time elapsing before the response emerged, and differences between organs in the proportion of the response that could be attributed to saline irrigation in seasons preceding that of sample collection.

In all seasons, saline irrigation increased the concentration of Na⁺ and Cl⁻ in the leaf lamina sampled at harvest (Fig. 2a and b). Saline irrigation late in the season (V-H) caused the greatest increase in Na⁺ and Cl⁻ concentrations. The Na⁺ and Cl⁻ concentrations in treatments receiving high annual salt loads (FB-V and V-H) were not always higher than the concentrations in the treatment receiving a low annual salt load (BB-FB) (Fig. 2a and b).

In the 2nd and 3rd seasons of the trial, the intra-season variations in leaf concentrations of Na⁺ and Cl⁻ may have been due

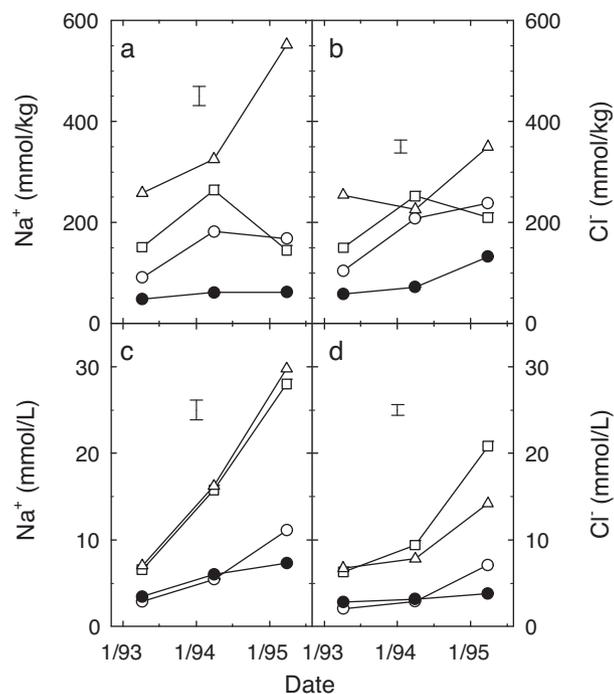


Fig. 2. The effects of irrigation treatment on the inter-seasonal variations in the concentrations of Na⁺ and Cl⁻ in the leaf lamina (a, b) and juice from fruit (c, d) sampled at harvest. CONT (●), BB-FB (○), FB-V (□), V-H (Δ). Bars indicate the least significant difference ($P=0.05$).

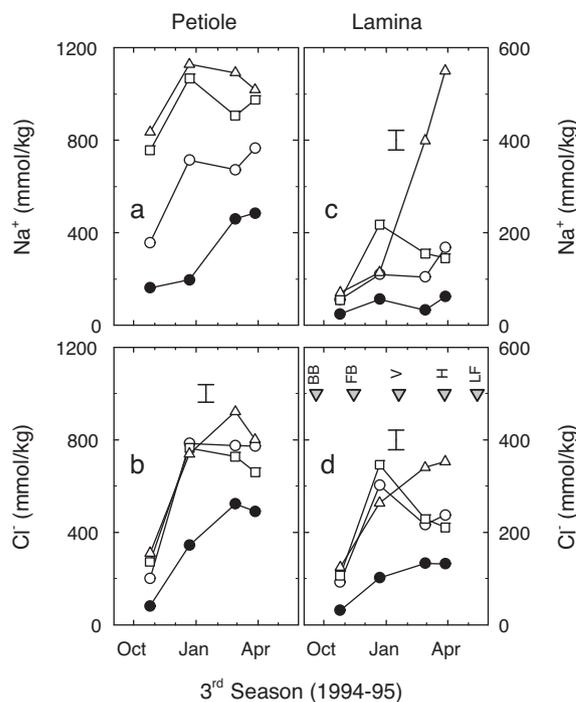


Fig. 3. The effects of irrigation treatment on the intra-seasonal variations in the concentrations of Na⁺ and Cl⁻ in the leaf petiole (a, b) and lamina (c, d) sampled in 1994–95 season. Labels in (d) indicate the dates corresponding to bud burst (BB), full bloom (FB), veraison (V), harvest (H) and leaf fall (LF). CONT (●), BB-FB (○), FB-V (□), V-H (Δ). Bars indicate the least significant difference ($P=0.05$).

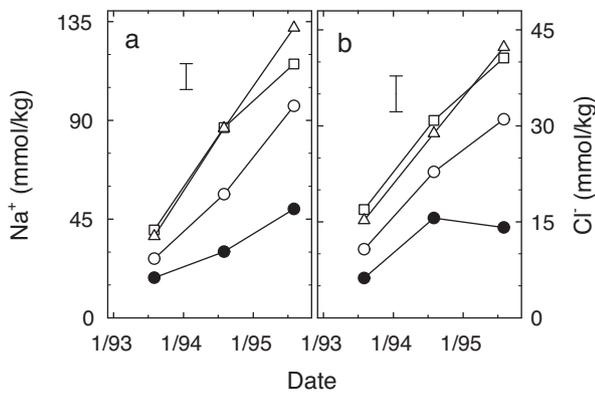


Fig. 4. The effects of irrigation treatment on the inter-seasonal variations in the concentrations of Na^+ and Cl^- in the one-year-old wood. CONT (●), BB-FB (○), FB-V (□), V-H (△). Bars indicate the least significant difference ($P=0.05$).

to both addition of salt within the season and the carryover of additions in previous seasons. Fig. 3 shows the intra-seasonal variations of the Na^+ and Cl^- concentrations in the leaf petiole and lamina during the 3rd season of the trial. The effects of treatment on the Na^+ concentrations in the petiole were not dependent on sampling date (Fig. 3a). The means of treatments FB-V and V-H (926 and 1018 mmol/kg, respectively) were equivalent and greater ($P<0.001$) than that of BB-FB (627 mmol/kg) which in turn was greater than that in the CONT (326 mmol/kg). Mean Na^+ concentrations in October samples were less ($P<0.001$) than those of later samples (December to March) which were equivalent to one another. In treatment V-H, the concentration of Na^+ in the December sample which was taken before commencement of saline irrigation was equivalent to that in the late March, after the saline irrigation had finished. Treatment effects on Cl^- concentrations in the petiole were dependent on the sampling date (Fig. 3b). In the saline irrigation treatments, most of the increase in petiole Cl^- concentrations occurred between October and December. In treatment V-H, the concentration of Cl^- in December was equivalent to that in late March. In treatment V-H, the carryover of salt added in the 1st and 2nd seasons accounted for the entire rise in petiole Na^+ and Cl^- concentrations in the 3rd season.

Treatment effects on the intra-seasonal variations in the leaf lamina concentrations of both Na^+ and Cl^- were dependent on the sampling date (Fig. 3c and d). Although October data showed that salt carryover from the preceding seasons elevated the concentrations of Na^+ in the lamina of FB-V and V-H to values above that in CONT, the major increases in the lamina concentration of this ion followed on from commencement of saline irrigation (Fig. 3c). That is, the major increases in treatments FB-V and V-H occurred after commencement of saline irrigation in November and January, respectively. This was not observed for Na^+ concentrations in the petiole. Salt carryover from the preceding seasons also elevated the Cl^- concentrations in October samples from saline treatments FB-V and V-H to above that in CONT (Fig. 3d). Unlike the temporal pattern of Na^+ concentration, the Cl^- concentration in treatment V-H underwent major increases both prior to commencement of saline irrigation, between October and December, and following commencement, between December and February.

In the 3rd season, the responses of concentrations of Na^+ and Cl^- in the leaf petiole to the carryover of salt added in previous seasons were greater than those in the leaf lamina (Fig. 3). In the lamina, carryover salt affected the Cl^- concentrations more than Na^+ concentrations (Fig. 3).

The leaf is not a perennial organ. The effects of exposure to salt in seasons preceding sample collection on the concentrations of Na^+ and Cl^- in tissue are exerted by reservoirs of salt in the soil and the

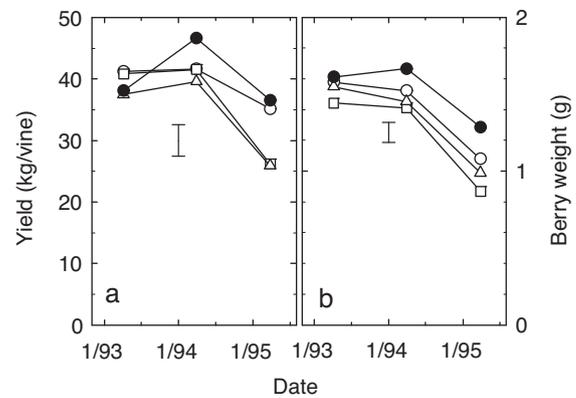


Fig. 5. The effects of irrigation treatment on the inter-seasonal variations in vine yield and berry weight. CONT (●), BB-FB (○), FB-V (□), V-H (△). Bars indicate the least significant difference ($P=0.05$).

perennating plant organs. Canes are perennial organs which are formed from the one-year-old wood that is retained at pruning. The concentrations of Na^+ and Cl^- in this organ during dormancy, at pruning in August, are indicative of the plant reservoir of salt. Fig. 4 shows that over the 3 seasons, the concentrations of Na^+ and Cl^- in one-year-old wood increased in all treatments. In the CONT, Na^+ increased in the 3rd season and Cl^- in the 2nd season. In the saline irrigation treatments with high annual salt loads, FB-V and V-H, the concentrations of Na^+ and Cl^- increased above those in the control in all 3 seasons, whereas in the saline irrigation treatment with a low annual salt load, BB-FB, the Na^+ and Cl^- concentrations only showed significant increases above CONT values in the 2nd and 3rd seasons. The concentrations of both ions in the treatments receiving high annual salt loads, FB-V and V-H, were similar and greater than those in the treatment receiving a low salt load, BB-FB.

Over the 3 seasons, concentrations of Na^+ in the juice increased in all treatments and the concentrations of Cl^- increased in the saline treatments (Fig. 2c and d). In the CONT, Na^+ concentration increased in the 2nd season. In saline irrigation treatments with high annual salt loads, FB-V and V-H, the concentrations of Na^+ and Cl^- increased above the values in the control in all 3 seasons, whereas in the saline irrigation treatment with a low annual salt load, BB-FB, the concentrations only increased above the control in the 3rd season. The concentrations of both ions in the treatments receiving high annual salt loads (FB-V and V-H) were greater than those in the treatment receiving a low salt load (BB-FB).

3.3. Vegetative growth, yield and fruit composition

Saline irrigation did not affect pruning weight. The pruning weights declined in each season ($P<0.001$); the values in the 1st, 2nd and 3rd seasons were 3.3, 2.8 and 2.3 kg/vine, respectively (data not shown).

Yield did not respond to saline irrigation until the 2nd season when its application between veraison and harvest reduced yield by 15% (Fig. 5a). In the 3rd season, yield was reduced by 28% and 29% in treatments FB-V and V-H. Saline irrigation reduced the weight of berries in all three seasons (Fig. 5b). In the 1st season, the berry weight in FB-V was 10% less than that in the CONT. In the 2nd and 3rd seasons, all saline irrigation treatments reduced berry weight. The effect was greatest in treatment FB-V and in the 3rd season the weight of berries in this treatment was 33% less than that in the control.

Saline irrigation did not affect the number of bunches per vine. In the 2nd season, there was 324 bunches per vine which was greater ($P<0.05$) than 287 in the 1st and 294 in the 3rd season which were

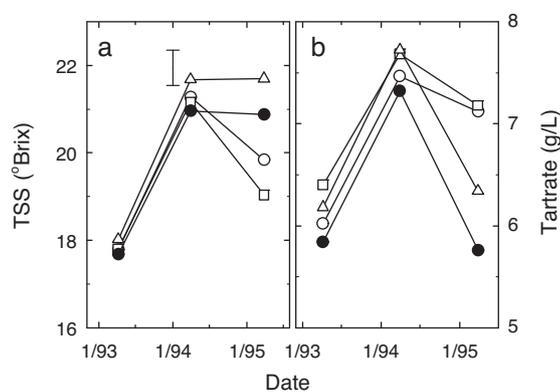


Fig. 6. The effects of irrigation treatment on the TSS and tartrate concentrations in juice. CONT (●), BB-FB (○), FB-V (□), V-H (△). Bars indicate the least significant difference ($P=0.05$).

equivalent. The number of berries per bunch was also not affected by saline irrigation. In the 3rd season, there was 101 berries per bunch which was greater ($P<0.01$) than 90 in the 1st and 87 in the 2nd season which were equivalent (data not shown).

Saline irrigation affected concentrations in juice of total soluble solids (TSS) and tartrate. It did not affect the pH or concentrations of titratable acid, potassium and malate in juice (data not shown). Salinity effects on TSS quantified as °Brix emerged in the 3rd season. In this season, TSS decreased in treatments BB-FB and FB-V and increased in treatment V-H (Fig. 6a). The effects of irrigation treatment on tartrate concentration were independent of season. The tartrate concentration of 7.2 g/L in treatment FB-V was equivalent to that of 6.9 g/L in treatment BB-FB which, in-turn, was equivalent to that of 6.8 g/L in treatment V-H and greater than that of 6.3 g/L in the control (Fig. 6b). The average tartrate concentration of 7.6 g/L in the 2nd season was greater than ($P<0.001$) those in the 1st and 3rd seasons (6.1 and 6.6 g/L, respectively) which were equivalent to one another.

4. Discussion

4.1. The effects of foliar wetting

By the 3rd season, saline sprinkling between either full bloom and veraison (treatment FB-V) or veraison and harvest (treatment V-H) reduced yields by about 30%. The three-season means were reduced by 10% and 15% for FB-V and V-H, respectively. In all instances of yield decline in sprinkler-irrigated vines, the maximum seasonal soil salinities were less than the threshold value of 3.3 dS/m for yield loss in drip-irrigated Colombard vines on Ramsey rootstocks (Zhang et al., 2002). A yield loss of this magnitude contrasts with the findings of Stevens et al. (1999) for the same vineyard with application of the same saline irrigation treatments, excepting that irrigation was applied via drip rather than over-canopy sprinklers. During the initial 3 seasons of saline irrigation, they found that the drip-treatment V-H did not lose yield and the drip-treatment FB-V lost yield only in the second season and then, by only 7%. In fact, the three-season mean yields for these drip treatments (FB-V and V-H) were reduced by 0% and 2%, respectively. The average soil salinities in the drip-treatments FB-V and V-H, both 2.0 dS/m, were similar to the respective averages of 2.1 and 1.8 dS/m for these treatments in the present study using sprinkler irrigation. Saline sprinkling between either full bloom and veraison or veraison and harvest caused a yield loss of at least 10% over three seasons, whereas yield loss with saline drip irrigation was 2% or less. The effect of irrigation type on the yield response could

not be attributed to the osmotic effect of salinity because irrigation type did not affect the values of soil salinity.

Yield is a product of bunches per vine, berries per bunch and berry weight. The present study found in common with Stevens et al. (1999), in which the same treatments were applied with drip-pers, that saline irrigation significantly reduced the berry weight, but did not affect the two other yield components. Likewise, Walker et al. (2002) working with Sultana vines on Ramsey rootstock also found that saline drip irrigation reduced berry weight, but did not affect bunch numbers. In the 3rd season of the present study and that of Stevens et al. (1999), the rates of berry weight reduction per unit salt load with over-canopy sprinkling were 0.45, 0.39, 0.34 g/(dS/m) for treatments BB-FB, FB-V and V-H, respectively, and those for drip were 0.21, 0.14, and 0.10 g/(dS/m) respectively. Sprinkling more than doubled the rate of loss of berry weight per unit annual salt load. Given that saline-sprinkled and saline drip-irrigated vines had similar soil salinities, the additional loss was probably due to the toxic effects of increased of Na^+ and Cl^- in the vine tissue due to foliar absorption of salt. Salts can enter the leaf through aqueous pores in the cuticle (Schonherr, 2006). Entry via this pathway is only active whilst the leaf is wet (Grattan et al., 1981). Wetting grapevine foliage with a saline solution for 10 h every 2 weeks caused a greater increase in leaf Na^+ and Cl^- concentrations than using the same solution to keep roots in a continuously well watered state (Stevens et al., 1996). Na^+ and Cl^- enter the leaf more readily via the cuticle than via the roots.

Treatment effects on the concentrations of the toxic ions Na^+ and Cl^- in tissue sampled in the first season of the trial are attributable to saline irrigation in this season, whereas for samples taken in subsequent seasons the effects are attributable to salt added by saline irrigation in both the season of sampling and the seasons preceding sampling. In the first season, the concentrations of Na^+ and Cl^- in the harvest sample of leaf lamina for treatment V-H were 210 and 196 mmol/kg above the respective control values. These increases were much higher than those seen with drip irrigation. For the harvest sample of leaf lamina from the drip-treatment V-H, Stevens et al. (2011) found that tissue Na^+ and Cl^- levels were 12 and 34 mmol/kg above the respective levels in the control. Increases in leaf lamina concentrations of Na^+ and Cl^- with saline foliar irrigation were at least 5-fold more than those recorded with the same irrigation treatments applied by drip.

In the 2nd and 3rd seasons, tissue samples taken before commencement of saline irrigation can be used to assess the effects that salt additions in previous seasons have on tissue Na^+ and Cl^- concentrations. Saline irrigation of treatment V-H commenced in January. The Na^+ and Cl^- levels of leaf lamina sampled in December of the 3rd season were 56 and 160 mmol/kg above the respective levels in the control. Carryover of salt applied in seasons preceding sampling caused a significant rise in tissue salinity; over 50% of the increase in the of Cl^- concentration in the harvest sample can be attributed to this carryover. Irrigation method affected the magnitude of the contribution made by saline irrigation in previous seasons. With drip-treatment V-H, Stevens et al. (2011) found that Na^+ and Cl^- in leaf lamina sampled in December of the 3rd season were 12 and 10 mmol/kg above the respective levels in the control. Increases in leaf lamina concentrations of Na^+ and Cl^- caused by sprinkling in the previous seasons were at least 4-fold more than those when the same salt loads were applied by drip.

The effect of exposure to salt in seasons preceding sampling can be exerted through reservoirs of salt in the soil and plant (West, 1986). Soil salinities in the current trial and that of Stevens et al. (1999, 2011) were similar. Therefore the increases associated with sprinkler irrigation are most likely associated with elevated values in the plant reservoirs of salt.

Canes are perennating organs and variations in their concentrations of Na^+ and Cl^- are indicative of inter-seasonal changes in

the plant reservoir of salt. At the end of the 3rd season, the Na⁺ and Cl⁻ concentrations in one-year-old wood in treatment V–H were 83 and 28 mmol/kg above the respective values in the control. Whereas under drip irrigation, Stevens et al. (2011) found that the Na⁺ and Cl⁻ concentrations in one-year-old wood of the V–H treatment were 37 and 5 mmol/kg, respectively, above the respective control levels. Increases in the Na⁺ and Cl⁻ in one-year-old wood caused by saline sprinkling were at least 2-fold more than those with the same irrigation applied by drip. In contrast to Francoise and Clark (1979), we found that saline sprinkling irrigation did increase the concentrations of Na⁺ and Cl⁻ in one-year-old wood. Wetting foliage with saline irrigation increases the size of the over-wintering plant reservoir of salt.

Foliar damage was also found in this vineyard with saline drip irrigation (Stevens, 2005), albeit not until the 4th season of saline irrigation. In common with the results in this trial, the Na⁺ concentration in damaged leaves was higher than that in undamaged leaves and the concentrations of K⁺ in the lamina of undamaged and damaged leaves were equivalent (Stevens and Harvey, unpublished data). In contrast with the present study, the Cl⁻ concentrations in damaged and undamaged leaves were equivalent. Further, with saline drip irrigation the Cl⁻ concentrations in damaged leaves were below 226 mmol/kg. Ehlig (1960), Bernstein et al. (1969) and Walker et al. (1997) found that grapevine leaves damaged by salinity had Cl⁻ concentrations above this value and all three studies attributed the damage to high Cl⁻ and not high Na⁺ concentrations. In the present study the mean Cl⁻ concentration in damaged leaves was greater than this value. With saline drip irrigation, Stevens et al. (2011) associated yield loss exclusively with elevated concentrations of Na⁺ in leaves sampled at harvest. In the present study neither leaf damage nor yield loss could be exclusively associated with elevated Na⁺ concentrations in the leaf.

Sharma et al. (2010) reported a black leaf symptom in vineyards irrigated with saline water. In Thompson Seedless vines on Dogridge rootstock they found that symptomatic leaves had higher Na⁺ and lower K⁺ concentrations than asymptomatic leaves. In our study significant differences in K⁺ concentrations in damaged and undamaged leaves were not found under either saline drip or sprinkler irrigation.

With non-saline water, over-canopy sprinklers may be the preferred system for irrigation enterprises located in a semi-arid climate at sites with a combination of light textured soil and undulating topography and, where water or power supply infrastructure is unable to support high frequency irrigation. Stevens et al. (1996) discuss other advantages. With saline water, the additional yield losses associated with the use of sprinklers may make enterprises at such sites economically unviable. Viability may require that water and power infrastructure be upgraded to enable the use of micro-irrigation and thereby avoid losses associated with foliar wetting.

4.2. Effects of timing

The effects of saline irrigation at different growth stages were due to variation in both the timing of saline irrigation and the annual irrigation salt load. The confounding effect of differences in the annual salt loads was removed by normalising the data. This consisted of calculating the quotient of the difference between the 3-season means of the parameter value in the saline and control treatments, and the difference between the 3-season means of the volume-weighted salinity of received water in the saline and control treatments. The resulting values indicate the rate of change in the parameter per unit increase in the annual salt load (Table 3). Normalised data shows that the timing of saline irrigation had strong effects on growth and tissue composition.

The decline in yield per unit annual salt load in treatment V–H was 1.5 fold greater than in treatment FB–V. This contrasts with

Table 3

The annual irrigation salt load in excess of that received by the control treatment ΔECW [$\Delta ECW = \Delta (\text{annual } ECW_i, \text{annual } ECW_{\text{CONT}})$ where $i = \text{BB-FB, FB-V, V-H}$] and response of selected parameters to saline irrigation at different growth stages normalised^a to remove inter-treatment variation in the annual salt load. Based on the mean values for three seasons of plant parameters and volume-weighted ECW.

Parameter	Treatment ^b		
	BB-FB	FB-V	V-H
ΔECW (dS/m)	0.34	1.03	0.97
Yield ((kg vine)/(dS/m))	– ^c	–4.1	–6.3
Berry weight (g/(dS/m))	–0.35	–0.26	–0.18
Lamina Cl ⁻ ((mmol/kg)/(dS/m)) ^d	282	114	191
Lamina Na ⁺ ((mmol/kg)/(dS/m)) ^d	265	126	320
1-year wood Cl ⁻ ((mmol/kg)/(dS/m))	28.1	17.0	17.4
1-year wood Na ⁺ ((mmol/kg)/(dS/m))	80.1	46.8	54.2
Juice Cl ⁻ ((mmol/L)/(dS/m))	2.3	8.7	6.5
Juice Na ⁺ ((mmol/L)/(dS/m))	2.7	10.8	12.5
Juice TSS (°Brix/(dS/m))	–0.62	–0.50	0.65
Juice tartrate ((g/L)/(dS/m))	1.65	0.76	0.45

^a Normalised response = $\Delta(\text{parameter}_i, \text{parameter}_{\text{CONT}}) / \Delta(\text{annual } ECW_i, \text{annual } ECW_{\text{CONT}})$ where $i = \text{BB-FB, FB-V, V-H}$.

^b Saline irrigation applied between bud burst and full bloom (BB–FB), between full bloom and veraison (FB–V), between veraison and harvest (V–H).

^c Data only displayed if treatment significantly differed ($P < 0.05$) from the non-saline control during the course of the experiment.

^d Leaf sampled at harvest.

the growth stage sensitivity under drip irrigation where over six seasons, Stevens et al. (1999) found that the yield decline in the drip-treatment FB–V was 3-fold greater than for that in the drip-treatment V–H. The decline in berry weight per unit annual salt load in treatment BB–FB was between 1.3- and 1.9-fold greater than in treatments FB–V and V–H, respectively. Likewise this also contrasts with growth stage sensitivity found with drip irrigation. Stevens et al. (1999) found that the decline in berry weight in drip-treatment FB–V was 2-fold greater than that in treatments receiving saline irrigation in other growth stages. Irrigation type determines when yield and berry growth are most sensitive to saline irrigation.

In leaf lamina and one-year-old wood, the increases in Cl⁻ concentrations per unit annual salt load in treatment BB–FB were 2.5–1.5-fold greater than the increases with applications of saline irrigation later in the season (Table 3). Likewise, the increase in juice Cl⁻ concentration in treatment FB–V was 1.3 fold greater than that in treatment V–H. With drip irrigation, Stevens et al. (2011) also found that Cl⁻ uptake per unit salt load was greater when saline irrigation was applied early in organ development.

In one-year-old wood, the increase in Na⁺ concentration per unit annual salt load in treatment BB–FB was 1.6 fold greater than those with applications of saline irrigation later in the season (Table 3). Again, this corresponds with Stevens et al. (2011) findings in one-year-old wood with saline drip irrigation that Na⁺ uptake per unit salt load was greater when saline irrigation was applied early in organ development.

In contrast, with leaf lamina and fruit the increases in the Na⁺ concentration per unit annual salt load were maximal when saline irrigation was applied late in the organ growth. In both organs, increases in Na⁺ concentrations were at least 1.2 fold greater when saline irrigation was applied after veraison (treatment V–H) rather than at earlier seasonal growth stages. These results contrast with the Stevens et al. (2011) study with saline drip irrigation that found Na⁺ uptake was either insensitive to the growth stage in which saline irrigation was applied or more sensitive to saline irrigation early in the season. The disparity between the current study and that with saline drip irrigation supports a proposition that under saline sprinkling, organ aging may enhance foliar and fruit uptake of sodium.

4.3. Fruit composition

The concentrations of Na^+ and Cl^- in white wine are similar to those in the juice (Rankine et al., 1971). The Australian and New Zealand food standard (FSANZ, 2010) specifies that the concentration of Cl^- in wine should not exceed 17 mmol/L. In the 3rd season, the juice Cl^- concentration in treatment FB–V of 20.8 mmol/L was in excess of the standard. Food standards in Switzerland, South Africa and some provinces in Canada specify maximum Na^+ concentrations in wine of 2.6, 4.3 and 21.7 mmol/L, respectively (Stockley, 2009). Juice Na^+ concentrations in the high salt load treatments, FB–V and V–H, exceeded all of these standards in at least one season. In the 2nd and 3rd seasons, the concentrations of Na^+ in the juice of the CONT exceeded the standards for Switzerland and South Africa.

In the non-saline control treatment, a comparison between concentrations of Na^+ and Cl^- in the 3rd season of the present study and those in the 3rd season of Stevens et al. (2011), in which the same treatments were applied with drip irrigation, shows that the concentrations of both ions were 10-fold higher with sprinkling. The EC's of the irrigation waters in the 3rd season of these studies were 0.6 dS/m with sprinkling and 0.4 dS/m with drip. It is unlikely that the higher EC in the 3rd season of the present study was the source of elevated juice concentrations of Na^+ and Cl^- in that season. In the 2nd season of these studies, the values for EC's were reversed, 0.6 dS/m for the drip and 0.4 dS/m for the sprinkling, yet the concentrations of both ions were still 5-fold higher with sprinkling. Under semi-arid climatic conditions with in-season rainfall of less than 150 mm and ETo of about 1100 mm, over canopy sprinkling with non-saline water will raise juice Na^+ concentrations above the levels that are acceptable in white wine in some overseas markets.

In the 3rd season, the juices of high salt load treatments FB–V and V–H had Na^+ and Cl^- concentrations that were at least 21 and 10 mmol/L, respectively, higher than the respective values in the control treatment. Drip-irrigated vines receiving the same treatments had Na^+ and Cl^- concentrations in the 3rd season that were at least 2.7 and 0.5 mmol/L, respectively, higher than the respective values in the control treatment (Stevens et al., 2011). Sprinkling saline irrigation caused increases in the concentrations of Na^+ and Cl^- in juice that were at least 7-fold and 19-fold more, respectively, than those with saline drip irrigation.

The control treatments in the present study and the study of Stevens et al. (2011) were both irrigated with non-saline water. In the 3rd season, the juice from fruit irrigated with over-canopy sprinklers had Na^+ and Cl^- concentrations of 7.3 and 3.8 mmol/L, respectively, whereas that in the drip-irrigated vines had Na^+ and Cl^- concentrations of 0.7 and 0.4 mmol/L, respectively. Sprinkling with non-saline irrigation caused 10-fold increases in both Na^+ and Cl^- concentrations.

With saline irrigation, the relative increases in Na^+ and Cl^- concentration in the fruit with a move from drip to over-canopy sprinkler are much larger than those in the leaf lamina and one-year-old wood. Levels of Na^+ and Cl^- in the fruit are more responsive to irrigation type than levels in vegetative organs.

The skins of the berries in treatments BB–FB and control were not wetted with saline irrigation. Therefore the potential sources of salt for uptake into the berry were non-saline sprinkled water and, in the case of treatment BB–FB, salt from saline irrigation which was stored in the soil and within the vine vegetative organs. Stevens et al. (2011) found that with the drip-treatment BB–FB, Na^+ and Cl^- concentrations in juice were respectively 1.6 and 0.6 mmol/L in excess of the values in the relevant non-saline control. In the present trial, the Na^+ and Cl^- concentration respectively were 3.8 and 3.3 mmol/L in excess of the values in the relevant non-saline control. The soil salinities in both the drip and sprinkled BB–FB

treatments were similar and thus the vines accessed similar soil stores of salt. The additional increases in Na^+ and Cl^- under saline sprinkling support a proposition that more salt was translocated out of vegetative organs into fruit under saline sprinkling than under saline drip.

5. Conclusions

Saline sprinkling reduced the average yield over the three seasons by up to 15%. These reductions occurred at soil salinities below the threshold of 3.3 dS/m for yield decline in drip-irrigated Colombar vines on Ramsey rootstock. Similar treatments applied via drip caused a maximum yield reduction of 2%. With sprinkler irrigation, vine yield was most sensitive to saline water between veraison and harvest whereas with drip, yield was most sensitive to saline water between full bloom and veraison. Saline sprinkling caused rises in Na^+ and Cl^- concentrations of fruit, leaf lamina and one-year-old wood that were at least 7-fold, 5-fold and 2-fold greater respectively than the rises caused by application of the same treatments with drip. Inter-seasonal rises in the concentrations of Na^+ and Cl^- were due in part to carryover of salt added in previous seasons and with saline sprinkling the magnitude of these carryovers was 4-fold greater than those with saline drip irrigation. Saline sprinkling between full bloom and veraison raised juice Cl^- concentration above the Australian standard for white wine. Even sprinkling with non-saline water (control treatment) raised juice Na^+ concentration above standards for white wine in some overseas markets. Drip irrigation for 3 seasons with the same water did not cause juice Na^+ and Cl^- concentrations to exceed the standards for these elements in wine. With saline water, vignerons should avoid irrigation systems which wet the foliage.

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