FINAL REPORT

THE USE OF SALINE WATER FOR IRRIGATION OF GRAPEVINES AND THE DEVELOPMENT OF CROP SALT TOLERANCE INDICES

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on the project

"Research on the use of saline water for irrigation purposes and an assessment of crop salt tolerance criteria"

Project Leader: **Prof. J.H. Moolman**

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Hulme Moolman: Project Leader

EXECUTIVE SUMMARY

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Supplementary to the Final Report to the Water Research Commission on the project

"Research on the use of saline water for irrigation purposes and an assessment of crop salt tolerance criteria"

Project Leader: **Prof. J.H. Moolman**

INTRODUCTION

As much as 80% of the water resources of the Western Cape Province water is used for irrigation. Virtually the entire fruit and wine industries of the region are dependent on irrigation (Dept. Water Affairs, 1986). According to various reports the quality of South Africa's water resources, with specific emphasis on the total salt content, is steadily, albeit slowly, increasing (Stander, 1987). This is especially true of rivers and storage dams situated in the semi-arid south-western and south-eastern parts of South Africa (Fourie, 1976).

Over the past 30 years an awareness of increasing salinity levels in the Breede River during summer months has grown considerably. During the period 1981 to 1990 the mean annual rate of increase in salinity of four of the principal tributaries of the Breede River between Worcester and Bonnievale ranged from 38 mg/L per year for the Kogmanskloof River to 145 mg/L per year for the Poesjesnels River (Kienzle, 1990). The Breede River Valley forms part of drainage region H (Dept. Water Affairs & Forestry, 1986) and is an important agricultural area for the production of high value crops under intensive irrigation. It plays an important role in the economy of the Western Cape and contributes significantly to South Africa's agricultural output. It has a wide and dynamic crop mix, but is primarily a wine-producing area, with 65% of the area under wine grapes. Other crops produced in the valley are peaches and apricots (13%), vegetables, mainly tomatoes (3%) and irrigated pastures (7%). The perception of an increase in salinity over time gave rise to concern about sustainability of using the water for the irrigation of these high- value salt- sensitive crops.

It is reasonable to assume that agriculture will in future not only have to bring about substantial water savings, but will also have to rely increasingly on water of a poorer quality than at present. However, international research has shown that salinity effects on the yield and quality of agricultural crops are of primary importance (Frenkel & Meiri, 1985, Shalhevet, 1994). Problems associated with salinity such as decreases in crop yield and quality) have already been encountered in a number of rivers and irrigation schemes in South Africa. A few examples are the Fish and Sundays River irrigation schemes in the Eastern Cape (Hall & Du Plessis, 1979; Tylcoat, 1985), the Riet River scheme in the Free State, and the Breede River in the Western Cape.

OBJECTIVES

The Department of Soil and Agricultural Water Science of the University of Stellenbosch (US) in April 1990 embarked on a five year research project, financed by the Water Research Commission (WRC), to do research on the use of saline water for irrigation purposes and an assessment of crop salt tolerance criteria. The objectives of this project were to:

a) To test the validity of the existing South African criteria for grapevine response to salinity as laid down in the officially recognised policy document GB/A/88/2* of the former Soil and Irrigation Research Institute (now the Institute of Soils Climate and Water, Agricultural Research Council). This was to be done by:

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* Document GB/A/88/2: "Hersiene kriteria vir besproeiingswater in die Breërivier", (*Revised criteria for irrigation water quality in the Breede River*, Soil and Irrigation Research Institute), 1988.

i) Investigating the salt tolerance of vines by using salinity related yield and growth indices.
ii) Investigating the effect of saline irrigation water on the quality of the yield (e.g. wine quality).

b) Evaluating the applicability of recommendations found in international literature based on criteria of crop response to saline conditions.
c) Investigating various indices which describe the way in which crops respond to soil salinity as opposed to water salinity.
d) Establishing a methodology, incorporating the effect of climate, by which irrigation water quality criteria can be evaluated.
e) Evaluating various methods of predicting salinity profiles from irrigation water quality variables and irrigation management practices (e.g. empirical methods and mathematical modelling).
f) Monitoring, at a low level of intensity, soil salinity, soil water content and drainage rates and volumes in two micro irrigated vineyards in order to establish and explain temporal and spatial patterns of salt buildup in typical conditions.

By achieving these objectives it was foreseen that the improved understanding of how grapevines respond to water and soil salinity can be used as the basis to improve the salinity management of the Breede River.

SUMMARY OF RESULTS AND CONCLUSIONS

i) The research was conducted at Robertson and Stellenbosch in experimental vineyards belonging to the Agricultural Research Council. Robertson (33° 46'S, 19° 46'E) and Stellenbosch (33° 58'S, 18° 50'E) are both located in the south-western part of South Africa. Robertson is situated in the Breede River Valley and has a drier climate than Stellenbosch which is situated closer to the sea. The two experimental vineyards vary with respect to soil, climate, cultivar, age and viticultural practices. The vineyard at Robertson was established in 1974 while that at Stellenbosch was planted in September 1989.

ii) Six salinity treatments, ranging in electrical conductivities from *ca.* 25 mS/m to 500 mS/m were used to investigate the long term effects of salinity on *Vitis vinifera* L. (Table 1). The rationale for the number of treatments and the range of salinities was two-fold. First, it was a prerequisite that the treatments should at least cover the range of salinities defined by the EC-operational curve used by the Department of Water Affairs for managing water releases from the Brandvlei dam. Secondly, some of the treatments had to exceed our first estimate of the threshold salinity value for *Vitis vinifera* L., i.e. 150 mS/m (Ayers & Westcott, 1989).

iii) Despite the modification of irrigation scheduling techniques in certain years, and differences in the irrigation water and soil salinities, the soil water regime in the Robertson vineyard during the course of this four year study remained stable (Table 2). The maximum inter-annual difference in the seasonal mean soil water content for any treatment was 29 mm distributed over a depth of 1.05 m.

Table 1 Salt content of the irrigation water expressed in terms of the electrical conductivity (ECi) of the six treatments that were used at the Robertson vineyard

Treatment	Target ECi (mS/m)		
	1991/92	1992/93 & 1993/94	1994/95
1 (control)	± 30 (control)	± 30 (control)	± 30 (control)
2	100	75	75
3	200	150	150
4	300	250	250
5	400	350	350
6	600	500	30

Table 2 Seasonal mean water content per salinity treatment for the 1991/92 to 1994/95 irrigation seasons at Robertson

Treatment	Soil water content (mm/1.05 m)			
	1991/92	1992/93	1993/94	1994/95
1	275	276	263	271
2	288	274	259	270
3	258	258	254	248
4	277	277	269	278
5	262	272	260	266
6	281	286	275	276

iv) Contrary to expectation, seasonal mean soil water content did not increase in accordance with the range of salinity treatments applied in any consistent or significant way as soil or irrigation water salinity increased (Table 2). This is probably due to the relatively high frequency of irrigation (once per week), good internal drainage properties of the soil and the way in which soil water balances were calculated. However, after extended periods of drying when no irrigation was applied (such as prior to harvest) water content did increase with increasing soil salinity and is indicative of reduced water uptake at the higher levels of salinity. This conclusion is confirmed by the soil water content measured outside the directly wetted zone (of the microsprinkler irrigation system) of treatments 1, 4 and 6 which increased as salinity increased.

v) Irrigation with the saline water led to a significant salt accumulation in the root zone during the irrigation season, reaching maximum levels just before harvest in March but the salt accumulation was not proportional to the salt load of the salinity treatments. This is explained in terms of accentuated leaching due to reduced soil water uptake at the higher levels of salinity (Tables 2 & 3).

vi) All treatments were irrigated during winter to leach the salt that accumulated in the soil profile during the previous irrigation season. At the Robertson vineyard it was found that it requires about 275-300 mm of water during winter to reduce the electrical conductivity of the soil solution (ECsw) of the topsoil (0-0.3 m) from 300 mS/m to 100 mS/m. To reach the same target ECsw of 100 mS/m at the 0.9 m

depth and for the same antecedent condition, about 700 mm of rain and irrigation is necessary.

Table 3 Treatment mean depth-weighted mean soil salinity (0-1.2 m) at the beginning (September) and end (March or April) and the associated volume-weighted seasonal mean rain and irrigation water salinities for the 1991/92 to 1994/95 irrigation seasons at Robertson

	Depth weighted mean soil salinity (0-1.0 m depth) and Volume weighted seasonal mean rain and irrigation water salinity (mS/m)					
Season	Treat. 1	Treat. 2	Treat. 3	Treat. 4	Treat. 5	Treat. 6
1991/92						
September	66	71	73	70	120	86
March	84	102	147	202	324	357
Irrig. Water	27	72	146	230	394	436
1992/93						
September	54	64	64	117	72	85
April	99	141	220	323	301	396
Irrig. Water	22	52	101	167	225	341
1993/94						
September	80	62	57	123	80	79
April	68	114	149	348	312	363
Irrig. Water	31	69	144	243	296	471
1994/95						
September	59	70	57	105	98	152
March	75	107	151	248	310	72
Irrig. Water	27	49	97	162	258	31

vii) Despite significant fluctuations in sodium adsorption ratio (SAR) of the soil solution from summer to winter, over the longer term there was a gradual increase in SAR with time and depth at Robertson. By April 1995 the SAR of all treatments and at all depths, including the control treatment, had increased to levels higher than the antecedent conditions of October 1991.

viii) The salt- and water balance, and all other inferences made from them, were strongly influenced by the positions of sampling sites in relation to positions of micro-sprinklers and assumptions concerning the size of, and redistribution of water and salt within the wetted area. Leaching fractions deduced from the salt balance were not always realistic. A study of spatial variability within the zone of influence of one microsprinkler showed that one sampling point per microsprinkler (or plant) is insufficient to obtain an accurate water and salt balance from which evapotranspiration and leaching can correctly be inferred. The leaching fractions calculated from the ratio of electrical conductivity of the irrigation water to that of the soil solution (ECi/ECsw) ranged from ca. 0.14 for the control (ECi = 30 mS/m) to 0.70 for treatment 6 (ECi=500 mS/m) with a general increase as salinity of treatment waters increased. These leaching fractions suggest substantial deep percolation losses, as much as 70% at the higher levels of irrigation water

salinity, compared to irrigation management strategies that are based on non-saline, non-stressed conditions for plant water uptake .

ix) Despite thorough leaching with low salinity water every winter, the effect of saline water treatments from the beginning of successive seasons caused the first noticeable effect of salinity on expansive growth of shoots and leaves to occur earlier every season. At Robertson this was on day 35 of the 1992/93 season, and day 20 of the 1993/94 season. Our data suggest that early in the spring, expansive growth is sensitive even to low soil salinity and that saline growth conditions in one season have a large influence on the growth during the following season.

x) Leaf specific fresh weights were not sensitive to salinity or leaf age while the internode fresh weights were smaller in the saline treatments. The specific dry weight of leaves increased with age more in the low than in the high salt treatments. From this it was inferred that salinity has a larger effect on the mass than on the sizes of these organs. Alternatively, it indicates an increase in metabolite deposition in the leaves and decreased metabolite transport to the internodes - a change that can be the result of salinity interference to the metabolite export from the leaves. The reduction in metabolite transport to the shoot under saline conditions, may also imply a reduced buildup of metabolite storage in the perennial plant organs.

xi) Leaf water potential (LWP) and stomatal conductance measurements in 1992/93 show that differences in LWP between salinity treatments are best shown early in the day before the stomata start to control transpiration. The 1992/93 data also show that stomatal closure occurs earlier in the day in the saline treatments than in non-saline treatments. This means salinity treatment effects on LWP will most likely only be detected with pre-dawn measurements.

xii) The minimum recorded LWP at Robertson was about -1100 kPa which is much higher than the minimum potentials reported from other irrigation studies. In spite of the relatively high leaf water potentials damage to growth and yield was significant. We speculate that salinity damage to grapevine leaves may be the result of accumulation of salts in the apoplast which means that the pressure chamber technique does not measure the total leaf water potential and perhaps also not the hydrostatic component of the xylem water potential of vines. Rather, it measures the difference between the vacuole water potential and the apoplast osmotic potential.

xiii) At Robertson the first full effect of the salinity treatments on the yield and berry growth was recorded in the third season. Even during the first two seasons however, the saline irrigation water, through the process of berry growth, ripening and must composition had a significant effect on yield.

xiv) An organoleptic evaluation of the wine did not reveal any salinity effect on wine quality, aroma or taste. In view of the substantial differences in, for example the Na and Cl content of the wine, this was a rather surprising result. However, there are so many factors in wine processing that determine wine quality, that a statistical quantification of the effect of salinity on wine quality, seems very

remote. At best, the effect of salinity on wine quality will have to be based on chemical analysis of the must.

xv) Salinity had a severe effect on yield with a yield decrease of 60% at the ECi 500 mS/m salinity level (Table 4). Yield was negatively influenced even at the intermediate ECi levels of 75 and 150 mS/m. However, a better understanding on the effect of salinity on the yield and reproductive growth of Colombar grapes is complicated by the fact that during the first four years of this study an irrigation water salinity of 250 mS/m seemingly had little effect on yield.[1] Quantifying the effect of salinity on yield was further hampered by the progressive decrease in the yield on the control treatment. It seems that plant vigour and size are key determinants that influence the response of Colombar grapes to salinity. Despite these two complicating factors, the results of this experiment indicate that grapevines are more sensitive to salinity than previously thought, and that the threshold salinity value of 150 mS/m as reported by Ayers and Westcott (1985) is too high. Our results are more in line with the limiting value of 100 mS/m reported by Prior *et al.* (1992 a, b, c).

Table 4 Results of an ANOVA on the effect of saline irrigation water on the yield of Colombar grapes over four years

Year	Salinity treatment (mS/m)						
	25	75	150	250	350	500	P
Arithmetic Mean Yield (fresh weight, kg/vine)							
1992	13.28a*	10.95ab	11.65ab	12.90ab	10.19ab	9.72b	0.137
1993	10.05a	7.86ab	7.56abc	8.78a	5.26bc	4.81bc	0.009
1994	7.83a	5.49ab	5.73ab	7.51a	3.54b	2.68b	0.019
1995	4.99ab	4.61ab	4.20abc	6.53a	2.69bc	1.91c	0.012
Geometric Mean Yield (fresh weight, kg/vine)							
1992	13.12a*	10.41ab	10.39a	12.35ab	9.63b	9.42b	0.146
1993	9.99a	7.41ab	6.33bc	8.14ab	4.95c	4.38c	0.068
1994	7.43a	4.80ab	4.08bc	6.43a	2.71bc	2.48c	0.009
1995	4.58ab	4.39ab	3.75bc	5.95a	2.55c	1.70d	0.001
Geometric Mean Yield with Shoot Mass (1991) as Covariate (fresh weight, kg/vine)							
1992	12.46a	10.40ab	10.60ab	11.60ab	10.43ab	9.59b	0.335
1993	9.52a	7.40ab	6.44bc	7.68ab	5.33bc	4.56c	0.012
1994	6.54a	4.78ab	4.27ab	5.51a	3.29bc	2.59c	0.010
1995	4.43a	4.38a	3.88ab	5.34a	2.93b	1.76c	<0.001

* Means separation within rows by LSD Multiple Range Test at the 5% level
P Probability level

xvi) Our data show no threshold salinity ECe value and yield decreased progressively above ECe = 75 mS/m at a rate of about 3% per 10 mS/m which is three times more than the rate of decrease reported by Maas & Hoffman (1977) as quoted by Ayers and Westcott (1985) which was used as a basis for criteria in document GB/A/88/2 (Figure 1). The minimum time integrated soil salinity of 75 mS/m was

[1] It is important to note that yield of Colombar in the fifth and sixth years of salinity exposure to irrigation water of 250 mS/m decreased by 12 and 33% respectively relative to the control irrigated with ECi of 30 mS/m.

attained by irrigating with the Robertson canal water with a electrical conductivity of 25-35 mS/m. If a lower soil salinity is to be achieved to avoid any yield loss, and if the existing salinity levels of the Robertson canal remain the same, leaching must be increased. This in turn will increase the irrigation return flow with the concomitant elevated levels of salinity in the Breede River. Any increase in the salinity of the Robertson canal will also lead to increased soil salinity values which in turn will reduce yields. The target ECi of 65 mS/m used by the Department of Water Affairs and Forestry to control water releases from the Brandvlei Dam is equivalent to treatment 2, which in our study, resulted in a volume weighted seasonal mean ECi that, depending also on rainfall, ranged from 58 mS/m (1994/95 season) to 78 mS/m (1991/92 season). Irrigation with this water was associated with yield losses that ranged from 10 to 30% during the course of this study. However, in this study irrigation water enriched with NaCl and $CaCl_2$ was used. Consequently the yield losses and salinity damage observed with Colombard at Robertson will be a combined result of osmotic and specific ion effects.

It is therefore possible that irrigation with water with a similar total salt content (i.e. 65 mS/m) but with a lower chloride content (e.g. more sulphate) will be less damaging to the crop.

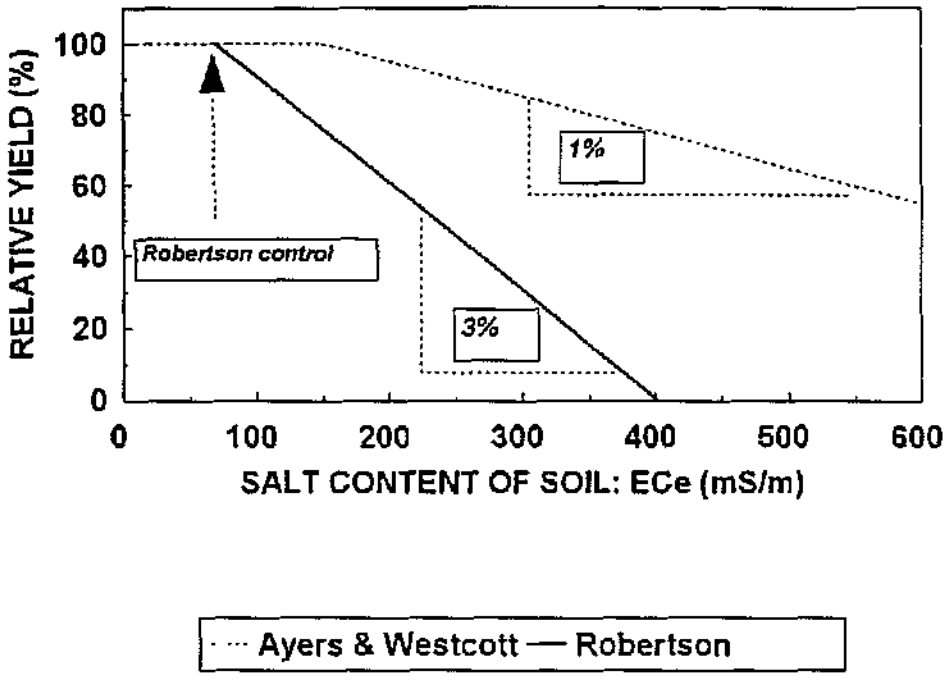

Figure 1 Salt tolerance of grapevine as given by Ayers & Westcott (1985) compared to the Robertson experimental data for Colombar winegrapes.

xvii) Chloride content in the leaves is a good index of salinity damage and we found that concentrations at harvest of 1.5 to 4 g/kg were associated with yield reductions of 10 to 20% respectively. Also, a chloride level of 1.5 g/kg in the leaves were

reached by irrigating with water with a chloride concentration as low as 40 mg/L. Consequently, our conclusion is that the existing ECi target levels set by the Department of Water Affairs for managing salinity in the lower reaches of the Breede River Irrigation scheme are too high to exclude reduction of yield. However the cost of attaining lower ECi levels may not be justified by the marginally higher yield attainable with fresher water.

xviii) Because of the need to establish a new vineyard, the research at Stellenbosch only started towards the end of the second last year (1993/94) of this five-year research project. Although yield and must composition of Weisser-Riesling grapes at Stellenbosch were not influenced by the limited amount of saline water applied in 1993/94 and 1994/95, soil salinity at the higher levels of saline irrigation water (ECi from 171 to 492 mS/m), was significantly increased. It is expected that the residual effects of the salinity exposure of 1994/95 on yield will materialise only during the 1995/96 and successive seasons.

xix) Contrary to the results of the Robertson experiment, the leaf water potential of Weisser-Riesling grapes at Stellenbosch showed a very strong treatment effect, in that leaf water potential decreased with increasing salinity.

xx) At Robertson production of wine grapes is fully dependent on irrigation and it was found that salinity effects are cumulative with time. Some negative effects were only manifested after two to three years of salinity exposure. At Stellenbosch supplemental irrigation is used to produce wine grapes which means that less salt is added to the soil during the irrigation season. It is reasonable to assume that salinity effects on grapevine performance under conditions of supplemental irrigation not only will be different to those observed under full scale, intensive irrigation, but also that the negative effects will take longer to become measurable and visible.

MEETING THE RESEARCH OBJECTIVES

All but one of the research objectives were successfully addressed. Time and manpower constraints prevented investigation on whether and how computer simulation models can be used to predict the dynamics of water and solute movement within the root zone of micro-irrigated vineyards. Furthermore, start of the study at Stellenbosch was delayed until 1993/94 because of vineyard establishment. Consequently insufficient data were available to investigate the role of climate (Robertson vs. Stellenbosch) on irrigation water quality criteria. The results from the Robertson experiment showed that at least three years are required to measure the full impact of salinity on grapevines. This suggests that at least one, but preferably two more years of data from Stellenbosch are needed to do an in-depth investigation of how climate alters the salt tolerance of winegrapes. All other objectives were addressed successfully and the attainment thereof contributed to a substantial improvement in our knowledge of salinity injury to winegrapes under field conditions.

The results contained in this report can be used by the Department of Water Affairs and Forestry to improve the salinity management of the Breede River and to better plan and manage irrigation expansion along the Breede River. The report can also be used locally

and internationally to provide improved guidelines for irrigation water salinity criteria under conditions of full-scale as well as supplemental irrigation of grapevines.

RECOMMENDATIONS FOR FURTHER RESEARCH

a) Determine the effect of saline water on the evapotranspiration rate and irrigation water requirements of grapevines, with specific emphasis on transpiration.
b) Evaluate alternative on-farm management strategies such as high frequency- and subsurface drip irrigation that can be used to enhance the use of saline water for the irrigation of perennial crops.
c) Investigate the interactions between plant growth, different growth stages and temporal and spatially changing salinity in the root zone and evaluate how this knowledge can be used to enhance the use of saline water to irrigate fruit and vine crops.
d) Determine the effect of alternating cycles of fresh and saline irrigation water on the surface properties of the soils of the Breede River Valley (e.g. soil crusting and infiltrability).
d) Investigate the role of climate on salinity damage to fruit and vine crops.
e) Use the six-year database of the Robertson experiment to evaluate how and whether hydrosalinity simulation models can be used to predict and manipulate salt accumulation in the root zone of vineyards irrigated with saline water.
f) Establish methodology to calculate the salt and water balance of vineyards under conditions of partial surface wetting, with specific emphasis on minimum data requirements.

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CHAPTER 1
INTRODUCTION

1.1 Background

South Africa is not richly endowed with water. The mean annual precipitation for the country as a whole is about 480 mm with a runoff coefficient only 9% (Dept. of Water Affairs, 1986). It follows that sustained food production in many parts of South Africa is only possible with irrigation. In the Western Province virtually the entire fruit and wine industries are dependent on irrigation. Agriculture, and specifically irrigated agriculture is the largest consumer of water. In 1980 irrigated agriculture accounted for 52% of the total water use in South Africa (Dept. Water Affairs, 1986). Although it will decrease to less than 50%, irrigated agriculture by the 2010 will still be the largest user of water. According to various reports published since 1975, the quality of South Africa's water resources, with specific emphasis on the total salt content, is steadily, albeit slowly, deteriorating (Stander, 1987). Alexander (1980) stated that "*there is no doubt that mineralisation (salinisation) is a serious problem in South Africa - and it can only get worse!*". This is especially true of rivers and storage dams situated in the PWV industrial area (Stander, 1987) and in the semi-arid south-western and south-eastern parts of South Africa (Fourie, 1976).

Over the past 30 years an awareness of salinity levels in the Breede River during summer months has grown considerably. During the period 1981 to 1990 the mean annual rate of increase in salinity of four of the principle tributaries of the Breede River between Worcester and Bonnievale ranged from 38 mg/L per year for the Kogmanskloof River to 145 mg/L per year for the Poesjesnel River (Kienzle, 1990). The Breede River Valley forms part of drainage region H (Dept. Water Affairs & Forestry, 1986) and is an important agricultural area for the production of high value crops under intensive irrigation. Irrigated agriculture accounts for more than 80% of the total water use in drainage region H. It plays an important role in the economy of the Western Cape and contributes significantly to South Africa's agricultural output. It has a wide and dynamic crop mix, but is primarily a wine-producing area, with 65% of the area under wine grapes. Other crops produced in the valley are peaches and apricots (13%), vegetables, mainly tomatoes (3%) and irrigated pastures (7%). The perception of an increase in salinity over time gave rise to concern about sustainability of using the water for the irrigation of these high value salt sensitive crops.

It is reasonable to assume that agriculture in future not only will have to bring about substantial water savings but will also have to rely increasingly on water of a poorer quality than at present. However, international research has proved that salinity effects on the yield and quality of agricultural crops are of primary importance (Frenkel & Meiri, 1985, Shalhevet, 1994). Problems associated with salinity (yield decrease, crop quality) have already been encountered in a number of rivers and irrigation schemes in South Africa. A few examples are the Fish/Sundays-River irrigation schemes in the Eastern Cape (Hall & Du Plessis, 1979; Tylcoat, 1985), the Riet River scheme in the Orange Free State, and the Breede River in the Western Cape.

1.2 Objectives

The Department of Soil and Agricultural Water Science of the University of Stellenbosch (US) in April 1990 embarked on a five year research project, financed by the Water Research Commission (WRC), to do research on the use of saline water for irrigation purposes and an assessment of crop salt tolerance criteria. The objectives of this project were to:

a) To test the validity of the existing South African criteria for grapevine response to salinity as laid down in the officially recognised policy document GB/A/88/2[1] of the former Soil and Irrigation Research Institute (now the Institute of Soils Climate and Water, Agricultural Research Council). The criteria for total salt content of the Breede River as measured in terms of the electrical conductivity of the irrigation water (ECi) is shown in Figure 1.1 and is defined as: *"At least 50% of the volume of irrigation water supplied to irrigators should have a electrical conduvctivity (ECi) not exceeding 70 mS/m. For up to 30% of the volume supplied, ECi would be allowed to fluctuate between 70 and 120 mS/m. The remaining 20% of the volume should have an ECi not exceeding 120 mS/m.* This objective was to be achieved by:
   i) Investigating the salt tolerance of vines by using salinity related yield and growth indices.
   ii) Investigating the effect of saline irrigation water on the quality of the yield (e.g. wine quality).

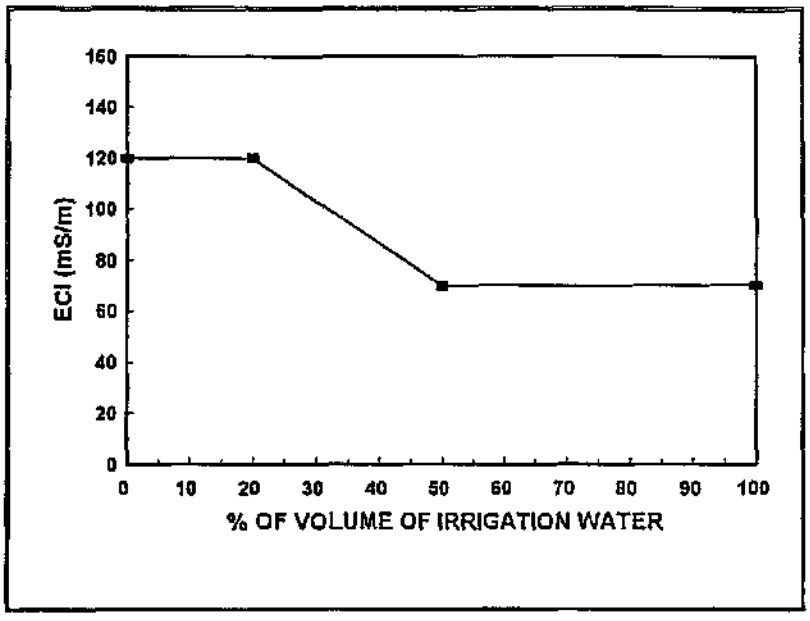

Figure 1.1 Operational curve used to control the salt content of the Breede River by manipulating the volume of water released from the Brandvlei Dam

b) Evaluating the applicability of recommendations found in international literature based on criteria of crop response to saline conditions.

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[1] Document GB/A/88/2: "Hersiene kriteria vir besproeiingswater in die Breërivier", (*Revised criteria for irrigation water quality in the Breede River*, Soil and Irrigation Research Institute), 1988.

c) Investigating various indices which describe the way in which crops respond to soil salinity as opposed to water salinity.
d) Establishing a methodology, incorporating the effect of climate, by which irrigation water quality criteria can be evaluated.
e) Evaluating various methods of predicting salinity profiles from irrigation water quality variables and irrigation management practices (e.g. empirical methods and mathematical modelling).
f) Monitoring, at a low level of intensity, soil salinity, soil water content and drainage rates and volumes in two micro irrigated vineyards in order to establish and explain temporal and spatial patterns of salt buildup in typical conditions.

By achieving these objectives it was foreseen that the improved understanding of how grapevines respond to water and soil salinity can be used as the basis to improve the salinity management of the Breede River.

1.3 Research team

The research team during the five years of this study consisted of the project leader, Prof. J.H. Moolman, Mr W.P. de Clercq (research officer) and Mr W.P.J. Wessels (senior research officer). Dr Avraham Meiri, on sabbatical leave from the Institute of Soils and Water, Volcani Center in Israel, joined the research team for the period September 1992 to August 1993 and again from February to April 1995. His presence greatly expanded and strengthened the plant physiology-related activities of the research team. Chemical analytical services were supplied by Mr. M.W. Gordon of the Department of Soil and Agricultural Water Science while Mrs. C.G. Moolman was responsible for chemical analytical services and data processing. Temporary assistants were also employed on an *ad hoc* basis. Several post-graduate students also participated in the research in pursuance of their M.Sc.Agric. degrees.

1.4 Scope of the report

The final report consists of nine chapters each dealing with a specific aspect of the research. No attempt was made to address specific research objectives individually as separate chapters. The extent to which we were successful in dealing with each objective, is dealt with in the last chapter of the report.

A review of literature on the effects of salinity on perennial crops and the environmental hazards associated with saline irrigation water is presented as Chapter 2. Chapter 3 gives a physical description of the two research facilities. Included is a description of the water salination system and the procedures used to maintain a constant salinity for the different treatments during the season. The temporal changes in the water and salt regimes of the vineyard at Robertson and the estimate of the water and salt balances are discussed in Chapter 4. The effects of saline irrigation water on the vegetative growth of Colombar grapevines at Robertson are presented in Chapter 5. In Chapter 6 we deal with the issue of how salinity influenced the reproductive growth and yield of Colombar grapes over a period of four seasons. Also presented in Chapter 6 is the effect of salinity on must and wine composition and quality. Chapter 7 presents the results of an investigation of various indices to describe the salt tolerance of Colombar grapes and a provisional assessment of the applicability of the water quality guidelines used to manage salinity in the Breede River Valley. In Chapter 8 we describe briefly the impact of two years of supplemental irrigation with saline water on soil conditions and the performance of

Weisser-Riesling grapes in a newly established vineyard at Stellenbosch. Little has been done in this regard and Chapter 8 is an overview of some aspects only. Finally, in Chapter 9 we document our summary of and conclusions from this research project. Also included in Chapter 9 are suggestions for the road ahead. The reports include five appendices. Appendices I and II describe results of two detailed studies indirectly related to the research objectives. Appendix I is a draft paper on our investigation of how potential salt response indices such as the canopy structure and light interception of a row crop like grapevine can be measured and quantified non-destructively using a ceptometer. Appendix II is a draft paper on how salinity influenced leaf water relations during the 1992/93 season at Robertson. Between 1986 and 1991 the Department of Soil and Agricultural Water Science monitored changes in soil salinity and deep percolation drainage rates of two micro-irrigated fields in the Breede River Valley. The long-term trends in the observations and our conclusions in this regard are presented as Appendix III of this report, while Appendix IV contains a list of all the data that were assembled during the course of this research project, all of which are available on CD-ROM. Appendix V list the technology transfer activities, including theses and dissertations, which emanated from this research.

CHAPTER 2
A LITERATURE REVIEW OF THE POTENTIAL OF USING SALINE WATER FOR IRRIGATION OF FRUIT AND VINE CROPS

2.1 Introduction

Supplies of good quality irrigation water are expected to decrease in future because the development of new water supplies will not keep pace with the increasing water needs of industries and municipalities (Oster, 1994). The forecast for South Africa is no different. The increasing demand for fresh water for industrial and urban use suggest that agriculture in future will probably have to use larger volumes of marginal quality such as saline water, industrial waste water and treated sewage effluent. In this regard irrigated agriculture are faced with two daunting challenges: a) using less water, in many cases of poorer quality, and b) maintain production of food and fibre for an expanding population. Expansion of the irrigated area furthermore will increase the volume of drainage water that must be disposed of. The drainage water from agricultural lands invariably is more saline than the irrigation water supplied to agriculture. Sustainable use of saline water for irrigation depends on three factors: the impact of salinity on the soil, the crop and the environment. Although interdependent, these three factors will be discussed separately.

Several reviews on the impact of salinity on soils and crops were published recently. In our review liberal use was made of the views of Francois and Maas (1993), Oster (1994), Shalhevet (1994) and Walker (1994). Our review however, focuses on fruit and vine crops.

2.2 Soil considerations

2.2.1 Leaching (internal drainage)

Use of saline water for irrigation increases the salt content of the soil and decreases the osmotic potential of soil water. This in turn reduces the amount of plant available soil water. Also, certain key physiological processes within the plant can be negatively influenced by the presence of a specific toxic ion(s). The net effect of these two factors is reduced yields and in some cases deterioration in fruit and wine quality. Each plant has a maximum salt level that can be tolerated without negatively influencing yield or crop quality. Irrigation with saline water add salt to the soil according to the relation Q (mass) = V (volume) x C (concentration). Q increases with each successive irrigation. To prevent accumulation of salt in the root zone to harmful levels, some of the salt must be removed. This is done by leaching.

In his review paper "*Irrigation with poor quality water*" Oster (1994) is of the opinion that the key to salinity control (when irrigating with saline water) is leaching, a net downward movement of soil water and salt through the root zone. The question is how often should leaching be done, and how much leaching is required? Oster (1994) argues that leaching need not occur with every irrigation. Normally at the end of the rainy season, which in the Mediterranean climate of the South-Western Cape of South Africa is towards the end of August or early September, soil salinity is low, especially in the upper part of the root zone. If this is true, Oster (1994) argues that it makes little sense to leach. Leaching only need to start once the level of soil salinities

approach hazardous levels. Shalhevet (1991) show that the rate of soil salinisation is in direct relation to the amount of saline water applied which should thus be kept to a desirable minimum. The salt content of the irrigation water and the salt sensitivity of the irrigated crop determine the amount of leaching that is required. Shalhevet (1994) describes the leaching requirement as the minimum fraction of total water applied (D_i) that must pass through the root zone in order to maintain the mean soil salinity below the threshold value, as determined by the salt sensitivity of the plant, i.e. LR (leaching requirement) = D_d/D_i. It can be shown that $D_d/D_i = C_i/C_d$, where C_i is the salinity of the irrigation water and C_d is tolerable level of salinity of the drainage water.

The greater the salinity of the irrigation water the greater the leaching. Leaching means applying more water than what can be stored in the root zone. This again implies that the extra water must be removed from the root zone by drainage, failing which will lead to the development of a water table. The presence of a water table near or in the root zone have a negative effect on soil aeration and hence plant growth. In order to ensure a continuous net downward movement of soil water at a rate sufficient to prevent temporary or permanent water logging, the soil must have good soil physical properties, specifically a good hydraulic conductivity.

2.2.2 Salinity and soil-physical properties

a) Clay swelling, dispersion and hydraulic conductivity

Clay swelling and dispersion are the two mechanisms which account for changes in hydraulic properties and soil structure (Quirk, 1986). Swelling reduces pore radii with the concomitant reduction in hydraulic conductivity. Swelling furthermore leads to aggregate breakdown and clay particle movement. This in turn leads to blockage of conducting pores especially in the subsoil (Frenkel et al., 1978). The salt content of irrigation water has a direct influence on clay swelling. Although it can be accepted that as a general rule, calcium clays swell less than sodium clays, swelling of both calcium and sodium clays increases as salinity decreases (Shainberg & Letey, 1984). In theory therefore, leaching will be more difficult to effect with non-saline water than with saline water especially on swelling soils.

b) Infiltration rate

Infiltration rate refers to the rate of entry of water into the soil at the soil-atmosphere interface. Infiltration rate is high during the initial stages but decreases asymptotically with time till a constant rate is reached. *(The physics of infiltration are described by Hillel (1982)*. One reason for the decrease in infiltration with time is the formation of a seal at the surface, especially in soils low in organic matter and with unstable structure. Seal formation is due to two processes: (1) physical disintegration of soil aggregates and their compaction caused by the impact of water drops, such as rain or sprinkler irrigated water, and (2) chemical dispersion and movement of clay particles and the resultant plugging of conducting pores (Oster, 1994). Infiltration rates are specifically sensitive to the ratio of sodium to calcium and magnesium (SAR) and the total salt content, quantified by the electrical conductivity (EC) of the irrigation water. Continued use of irrigation water with a high SAR tend to increase the exchangeable sodium content of the soil which in turn increases the swelling capacity and clay dispersion. In contrast, increases in the salt content of the water (EC) tend to suppress swelling and dispersion. Irrigation water with high SAR values will therefore in time lead to a reduction in infiltration rate, while those high in total salt will maintain a

stable infiltration rate. It follows that with certain irrigation methods too slow an infiltration rate will impact negatively on the leaching effort.

Because of the need for leaching, the most important soil property to consider when using saline water to irrigate fruit and vine crops is good internal drainage. A more complete description of how the chemical composition of the soil solution and irrigation water impacts on internal drainage is given by Shainberg & Letey, (1984).

2.3 Response of fruit trees and vine crops to salinity

2.3.1 Introduction

Much is known of the impact of salinity on irrigated crops. However, most of the studies aimed at understanding and quantifying salinity effects have been done on annual crops and attempted to find answers to questions like which crops to grow under saline conditions and how to use saline water for irrigation. The solution involves criteria for selecting the appropriate crops and guidelines for controlling soil salinity and hydraulic properties. It also requires improved knowledge of plant response to salinity, and of irrigation management and technology. The salt tolerance classification of agricultural crops in almost all cases used the growth or yield response to the depth-mean root zone salinity under one dimensional water flow. In many cases impractical high leaching fractions to rapidly reach desirable steady state salt content profiles were indicated (Maas & Hoffman, 1977; Ayers & Westcot, 1985; Maas, 1990; Francois & Maas, 1994). Better understanding of the interactions between plant growth, different phenological stages and the temporally and spatially changing salinity in most fields and orchards that use modern irrigation methods and management practices, may change the tolerance classification as well as the definition of the effective soil salinity. Studies on fruit tree and vine response to salinity, in pots or fields, in most cases measured the effects on growth of young seedlings and transplants of cultivars and rootstocks. Only a few studies were conducted on mature yielding fruit trees and vines (Bernstein *et al.*, 1956, Maas & Hoffman 1977, Maas 1990, Hoffman *et al.*, 1989, Prior *et al.*, 1992a and Boland *et al.*, 1993). In these studies the high sensitivity of most fruit trees and grapevines was evident and they were classified among the most sensitive crops. The recent increase in number of publications on the response of mature trees to salinity indicate the world wide trend of increased exposure of fruit trees and vines to salinity (Hoffman *et al.*, 1989; Catlin *et al.*, 1992; Boland *et al.*, 1993; Prior *et al.*, 1992a, 1992b, 1992c; Walker 1994).

Salinity can suppress growth and yield with no specific visual salt damage. This damage correlate with the soil solution osmotic potential, which for convenience of determination is usually replaced by the electrical conductivity of the saturated soil paste extract (EC_e). Visual damage symptoms, such as leaf burn followed by death of twigs and shoots, are the result of the accumulation of specific ions, mainly chloride and Na, to toxic levels in plant organs. Most fruit trees are sensitive to both osmotic and specific ion effects with increased importance of the toxic effect as exposure of the tree to salinity increases (Bernstein *et al.*, 1956, Hoffman *et al.*, 1989, Walker 1994, Catlin *et al.*, 1992, Prior *et al.*, 1992a, 1992b, 1992c). This section of the literature review focuses on the responses of fruit trees and vines to salinity and the implementation of this knowledge to minimise damage to crop production. Limited information from studies with fruit trees and vines and new approaches done under

transient conditions require extrapolation of information from similar studies with annual crops. Such extrapolation obviously needs additional experimental verification.

2.3.2 Osmotic vs. specific ion effects

Most fruit trees are relatively sensitive to salinity (Maas & Hoffman, 1977; Bernstein 1965, 1980, Maas 1990, Francois & Maas 1994). Growth inhibition and yield reduction may be the result of both total salinity and specific effects of toxic ions on key processes. In the case of toxic ion effects, visible symptoms of leaf and shoot damage may initially be absent. Stone fruits, citrus, avocado and grapes have shown growth reduction at salt concentrations that do not cause visible leaf damage (Francois & Maas 1994). For grapevines, growth reductions are observed at relatively low salinities, often before the appearance of visible symptoms (Downtown, 1977a, Walker *et al.*, 1981). Vegetative growth of Sultana cuttings decreased by 11% when NaCl salinity increased from 2 to 10 mM (Stevens & Harvey 1994). Grapes grafted on rootstocks with low chloride uptake will respond primarily to the osmotic effect (Bernstein *et al.*, 1969) and, consequently will then (incorrectly) be classified as moderately salt tolerant (Ehlig 1960). Growth and yield reduction of 50% with no visible leaf injury symptoms was reported for Valencia orange (Francois & Clark 1980). In the absence of visible toxic symptoms it was assumed that the response is to the soil solution osmotic potential and can be expressed as a function of the total salt concentration. However, once salts have accumulated to toxic levels the additive effects of osmotic stress and specific ion toxicities suppress growth and yield. The recognition of the need for greater clarity on tolerance levels for specific ion effects, yielded tables of tolerant levels of specific ions for selected cultivars and rootstocks for a limited number of fruit trees (Bernstein, 1980).

2.3.3 Factors that may modify salt tolerance

a) Steady state vs. transient soil salinity

Stable salinity profiles are obtained by uniform water application over the entire soil surface (flood or sprinkler irrigation) and heavy leaching. Under most field conditions salinity changes over time and space as a result of alternating rain and irrigation seasons, small or minimal leaching and non-uniform water application, mainly because of uneven wetting of the soil surface when using micro-irrigation methods. Differences in the distribution and activity of roots within the root zone have spatial and temporal dynamics that interact with changes in seasonal climatic conditions, soil characteristics, irrigation method and management, fertility and salinity. In order to compare the capacity of the mean profile salinity (expressed in terms of ECe with that of the weighted mean salinity of the absorbed water (ECw), Meiri (1984) analysed published data on how alfalfa and maize respond to spatially well defined salt distribution in the root zone. In case of maize, mean root zone soil salinity (ECr) was obtained using root weight per depth as the weighing factor, while root length was the weighing factor for alfalfa. For both crops ECr, or ECe, describe better the plant response to salinity than ECw, which reflect a lesser quantity of water that were absorbed from the more saline soil zone. The disagreement between the spatial salinity effect (ECr) on the water uptake and the effective salinity (ECe) may firstly be the result of the stress level that develops in the plant when it is forced to absorb more water through the less saline root fraction. Secondly a possible signal transmitted by the roots that sense stress with no measurable change in the plant water potential or water uptake.

Fruit trees and vines have permanent non-active thick roots and temporally dynamic and active fine roots. In grapevine (var. Chenin Blanc) dry mass of the fine roots is about 30% of the total root system dry mass (Saayman & Van Huyssteen 1980). The interaction between the dynamics of the soil water content and salt distributions and the growth and activity of the thin roots should determine the effective salinity. Meiri (1984) explained the large differences, from no effect of saline volume on water uptake and growth of tomatoes (Lunin & Gallatin, 1965) to the relatively larger effect of such volume than its contribution to water uptake (Shalhevet & Bernstein, 1967; Bingham & Garber, 1970), by considering the timing of the actual exposure to salinity, given their past and present activity. In the first case roots did not develop in the highly saline volume. The extent of root growth in different parts of a variably established salt profile will depend on the absolute salinities and their distribution. In the second case the salinity was imposed on a developed root system. The effect of salt distribution in the root zone on chloride transport to the shoots of young grapevines also depended largely on the fraction of roots exposed to salinity and whether the salinity was imposed on established root system or whether the roots grew into the salinised zone (Sykes 1985). In both cases however, chloride accumulation was not transferred to other roots. Roots established in salinised zones transported more chloride to shoots than roots growing into a saline zone. The difference depends on interactions with unmeasured factors.

The effect of spatial and temporal variations in the root zone salinity on distribution and activity of roots of fruit trees and vine crops and how temporally changing soil salinity influences salt tolerance, need experimental evaluation under field conditions.

b) Irrigation method

Irrigation method might alter salt tolerance in three principal ways: wetting of foliage, changing salt and water distribution in the soil and applying water at a high frequency (Shalhevet, 1994). The main problem encountered with sprinkler irrigation when saline water is used, is wetting of the foliage. Ehlig & Bernstein (1959) showed in a greenhouse study that the extent of injury depended on the frequency and duration of sprinkling. Intermittent wetting was more detrimental than continuous wetting. Injury was crop specific: vegetable and forage crops were insensitive to water of up to -0.4 MPa solute potential, while tree crops like citrus, almond, apricot and plum were sensitive. Leaf injury was positively correlated with frequency of irrigation and with temperature: the more frequent the irrigation and the higher the temperature, the greater the leaf injury. Walker (1992) also reports that the results of Johnston *et al.*, (1992) suggest that sprinkler irrigation with saline water (140-200 mS/m) leads to higher grapejuice chloride and sodium concentrations than does drip irrigation. Normally, leaf injury can be reduced by irrigating during the night when saline water does not evaporate from the leaves leaving a deposit on the leaf surface, or by applying non-saline water at the end of each irrigation cycle in order to wash off accumulated salts (Shalhevet, 1994).

The advantage of drip irrigation when using saline water is twofold. Firstly, leaf contact is avoided and for sensitive crops this may mean the difference between success and failure (Shalhevet, 1994). For example, a yield difference of 50% was found for bell pepper between drip and sprinkler irrigation when the salinity was 440 mS/m, but no difference was observed when good water was used (Bernstein &

Francois, 1973). It is uncertain whether these results (obtained with annual crops) can be extrapolated to fruit and vine crops.

The second advantage of drip irrigation lies in the pattern of salt distribution under the drippers and the maintenance of constantly high matric potentials. The typical pattern is one of low salt accumulation under the drippers due to high leaching and marked accumulation of salt at the wetting front and between the laterals (Yaron *et al.*, 1973, Moolman & De Clercq, 1989). The distribution of water content is reversed, with a decrease away from the point source. This results in a root pattern in which most of the roots are typically found in the highly leached zone beneath drippers (Moolman & De Clercq, 1989). Shalhevet (1994) concludes that drip irrigation is the best possible way of applying saline water to crops, avoiding leaf injury and at the same time providing optimum soil water conditions. However, the limited volume of wetted soil might pose problems for fruit and vine crops with larger root systems. Using more than one dripper (emitter) per tree and/or using micro-sprinkler irrigation can overcome this problem.

Other forms of irrigation, e.g. furrow irrigation (flood) are often less adaptable in terms of frequency of application and because of the longer intervals between irrigation permit build-up of salt in the soil, exacerbating the impact of salinity. Uniformity of application over the irrigated field is also more difficult with furrow than with drip irrigation (Walker, 1994).

c) Soil properties and waterlogging

Soil properties that may alter the salt tolerance of plants are fertility, texture and structure (Shalhevet, 1994). In a generalised statement Shalhevet (1994) says that at high fertility levels, there will be a larger yield reduction per unit increase in salinity than under low fertility, meaning that plants are more sensitive to salinity when conditions are conducive to high absolute yields. At extremely low fertility levels, when yields are low, increase in salinity may have very little additional damaging effect on yield. The effects of soil texture and structure are revealed through influence on the infiltration capacity, water-holding capacity and ratio of saturation water content to field capacity.

The water-holding capacity of a sandy soil is lower than that of a medium textured soil, which in turn is lower than fine textured soils. For the same evapotranspiration rate a sandy soil will lose proportionally more water than a clay soil, resulting in more rapid increase in the soil solution concentration (Shalhevet, 1994). However, if sound irrigation practices are followed, the sandy soil will be irrigated more frequently, thereby reducing the damage caused by increased concentration.

Salt concentration in soil is normally reported for the saturated soil paste water content (SP). Plants respond to the salt concentrations according to field water conditions (Avnimelech & Eden, 1970). When the hydraulic characteristics of the soil are not reported, it is customary to assume that SP is double that of FC and four times that of the wilting percentage (Richards, 1954). Since the water content ratio SP/FC actually ranges between 1.76 and 3.00 for different soils, discrepancies from the general rule of thumb may result in as much as 50% error in transforming SP data to field conditions for comparing data from various sources. Hoffman *et al.*, (1989) used the relationship ECe=0.3 + 0.6ECsw to convert electrical conductivity of soil water sampled with suction cups (ECsw) to equivalent saturated paste conductivities (ECe) determined *in*

situ. This factor, although having no effect on the salt tolerance of plants *per se*, or on the salinity response function, may profoundly influence the interpretation of the results (Shalhevet, 1994).

The studies of Prior *et al.*, (1992c) demonstrate the need to consider soil properties, specifically texture, when predicting the effects of saline water on grapevine productivity. In their study, irrigation with saline-sodic water caused more damage to sultana grapes in heavier than in lighter soils. Root zone depth and root density were lower in the heavier soils. The textural effect on yield was the result of reduced leaching and increased salinity in the more clayey soils with no effect in the yield response to soil salinity (Prior *et al.*, 1992c).

The combination of high salinity and low soil oxygen for grapevines results in greater uptake and transport of chloride and sodium ions to shoots compared with high salinity and well drained, aerated conditions (West & Taylor, 1984). If applied long enough, these combined factors can have a severe effect on the vine crops.

d) Specific ion effects

Stone fruits, citrus, avocado and grapevines have all showed specific sensitivity to foliar accumulation of Cl^- and Na^+. The initial symptoms of excess Cl^- accumulation in fruit crops is leaf tip necrosis developing into marginal necrosis, premature leaf drop, complete defoliation, twig and shoot dieback, and in extreme cases death of the tree or the vine (Bernstein, 1980). Chloride is absorbed and transported by the roots and deposited in the leaves of fruit and vine crops more rapidly than Na. Therefore chloride toxicity generally shows up earlier, is more severe and is observed on a wider range of species than Na^+ toxicity (Bernstein, 1980; Hoffman *et al.*, 1989; Maas, 1990; Francois & Maas 1994, Walker 1994). Chloride content in grape leaves increased more with time of exposure of the plant to salinity than with leaf age. In grapes (Bernstein *et al.*, 1969) and other fruit and nut crops (Bernstein & Hayward, 1958), chloride was higher and increased more than sodium with water salinity. There was no correlation between severity of burn and leaf-chloride level, the severity apparently being determined more by duration of harmful levels than by actual level at the time of sampling. In some cases non-damaged young leaves had higher chloride content than old damaged ones.

Injury by Na^+ can occur at concentrations as low as 5 mmol L^{-1} in the soil solution (Maas 1990). However, injury symptoms caused by specific ions may not appear for a considerable time after exposure to salinity. Time is needed to load the perennial organs or to cause change in the capacity to retard the transport of ions to the leaves. Some of the more sensitive fruit crops may accumulate toxic levels of Na^+ and /or Cl^- over a period of years from soils that would otherwise be classified as non saline and non sodic (Ayers *et al.*, 1951; Bernstein 1980). Initially it is thought that Na^+ is retained in the sapwood of the tree and with the conversion of the sapwood to heartwood is released and then translocated to the leaves causing leaf burn (Bernstein *et al.*, (1956); Francois & Maas, (1993)). With succeeding years, the Cl^- and Na^+ accumulate more rapidly in the leaves, causing leaf burn to develop earlier and with increasing severity (Hoffman *et al.*, 1989). The results of the latter study also showed that Na^+ accumulation in plum leaves did not significantly increase until the leaves were already severely damaged by chloride accumulation. This suggests that high Cl^- level probably damage leaf cell membranes.

Catlin *et al.*, (1993) found chloride content in plum leaves to increase rapidly between years and reaching a maximum level after four years of irrigation (if ECi is 200 mS/m or less), while sodium content (which increases much more slowly) was still increasing in the sixth season of saline irrigation. For peach trees a higher proportion of sodium to chloride was found in both fruit and wood compared with the leaves (Boland *et al.*, 1993). This is explained by different mechanisms involved in the transport of these ions. The results of Boland *et al.*, (1993) indicate that sodium is primarily translocated in the phloem, while chloride is also transported to the leaves via the xylem. Other workers have shown similar results, the transport of ions to the leaves generally being via the transpiration stream (Flowers & Yeo, 1986) while transport to the fruit is normally being via the phloem (Greenway & Munns, 1980).

In view of published data it can be inferred that osmotic effects influence the salt tolerance of fruit and vine crops, but in many cases the specific ion effects seem to be more damaging than the osmotic effect. Therefore in cases where NaCl is the principal salt in the irrigation water, it will be rather difficult to distinguish between osmotic and specific ion effects.

e) Rootstocks

In grafted plants the rootstock determines to a large extent the salt uptake and hence the salt tolerance. Bernstein *et al.*, (1969) evaluated the chloride content in grapes grafted on 6 rootstocks and report a range of 1:16 between the minimum and maximum chloride concentrations found in the grapes. Different cultivars and rootstocks absorb chloride and sodium at different rates, and prevent or retard the accumulation of ions in the aboveground organs of plants to different levels. This lead to considerable differences in tolerance to specific ion effects within a species. Grapevine cultivar and rootstocks differ widely in levels of Cl- transported to the leaves (Ehlig, 1960; Sauer, 1968; Bernstein *et al.*, 1969; Downton 1977b; Downton, 1985; Alexander & Groot Obbink 1971, Alexander & Woodham, 1968; Groot Obbink & Alexander, 1973; Antcliff *et al.*, 1983). For example, berries of own-rooted vines of Cabernet sauvignon, Sultana and Shiraz contain up to three times more chloride than berries from vine grafted to chloride excluding rootstocks such as Ramsey and Harmony (Downton, 1977b). According to Walker (1994) there is less information on the effects of rootstocks on yields. Stevens & Harvey (1989) have shown that Colombar on Ramsey rootstock experienced no decrease in vine vegetative growth or yield when irrigated with saline water (ECi=350 mS/m) for two month periods over two consecutive spring-summer seasons.

f) Chemical composition of the irrigation water

According to Walker (1994) a comparison by Kishore *et al.*, (1985) of the effects on grapevine growth of a range of different salts (viz. chloride, sulphate and carbonate salts of magnesium, calcium, potassium and sodium) demonstrated that chloride salts caused more leaf damage than sulphate or carbonate salts at the same concentrations. Sodium and potassium caused greater growth reductions than calcium and magnesium.

g) Climate

Shalhevet (1994) reports that three elements of climate, namely temperature, humidity and rainfall, may influence salt tolerance and salinity response, with temperature being the most critical one. High temperatures increase the stress level to which a crop is exposed, either because of increased transpiration rate or because of the effect of

temperature on the biochemical transformations in the leaf. High atmospheric humidity tends to decrease the crop stress level to some extent, thus reducing salinity damage as demonstrated for bean (Hoffman *et al.*, 1978). Regarding grapevines, Walker (1994) is of the opinion that prolonged periods of cool wet weather during spring-summer will have an ameliorating effect on vine response to salinity through lower evaporative demand and potential minimisation of salt build-up in the soil and consequent lower rates of salt uptake by roots and transport to leaves. Conversely, extensive periods of heat and high evaporative demand may have a compounding effect on vine response to salinity. Prior *et al.*, (1992b) in Australia found that symptoms of leaf damage that appeared in December or January was more related to climatic stress than to particular chloride or sodium levels.

Shalhevet (1994) concludes that under harsh environmental conditions of high temperatures and low humidity, the salt tolerance of plants may change so that the threshold salinity decreases and the slope increases, making the crop more sensitive to salinity.

h) Timing of salt application and intra-seasonal effects

Adjusting the salinity level of irrigation water to the temporal changes of salt tolerance of annual crops, and using integrated crop and water quality rotations based on the differences in tolerance among growth stages and crops, are powerful tools to reduce salinity damage to crops and soils. Relative to steady state conditions, this practice can result in an increased use of saline water for irrigation and reductions both in leaching volume and other ameliorating amendments (Grattan *et al.*, 1987; Meiri *et al.*, 1986; Oster, 1994; Shalhevet, 1994).

Use of this approach to manage the salt tolerance of fruit trees and grapevines started only recently. Reduced water application to fruit trees by adjusting temporal deficit irrigation and water stresses to periods that restrict vegetative growth but not yield, save water during the stress period as well as during the post stress period because of the smaller plant canopy (Boland *et al.*, 1993; Mitchell *et al.*, 1989). This suggests the occurrence of luxury vegetative growth under irrigation when stress is absent. Reports on the response of fruit trees and vines to temporally variable salinity are limited. In a study conducted for three years, Stevens *et al.*, (1993) found for the Colombar grapevine cultivar that overall the greatest salinity effect of saline irrigation water on the plants (in terms of must composition and berry size) was manifested when the saline water was applied between anthesis and veriason. The effects on sodium and pH took two seasons to become noticeable with the more saline treatments, and more than three years with the less saline treatments. As soil EC did not increase between seasons the increase in sodium in the must during the second season was probably due to mobilisation of sodium accumulated within the permanent vine organs during the first season. The changes in pH, acids and cations were not of commercial significance and salinity did not reduce yield. Thus, by synchronising application of the saline irrigation water with the less sensitive growth stages of grapevine, as much as 40% of the annual water requirements of the vine could be met with saline water (ECi=350 mS/m) without financial loss (Stevens *et al.*, 1994).

Intra-seasonal carry-over effects when using saline irrigation water also impact on the interpretation of salt tolerance of fruit and vine crops. The storage of water and salt in the soil cause a phase lag in, and attenuated the magnitude of crop responses to changing soil conditions when changing the salinity level of the irrigation water.

Modelling of alfalfa response to seasonal changes in water quality predicted that this lag would cause larger yields than expected during saline seasons, and lower yields than expected during non-saline seasons (Bradford & Letey 1993a). The magnitude of this phase lag depends on the size of the water storage capacity of the soil and the prevailing irrigation management. To avoid the residual high salt effect, there is a need to leach when changing to low salt water. It might be sufficient to reduce soil salinity by leaching with the saline water and then changing to the less saline water.

The growth season of annuals starts and terminates in a small seed with a limited interseasonal transfer of the effects of saline periods by way of metabolites or salts. In fruit trees and vines, deciduous or evergreen, the temporal growth of the root, shoot and leaf depend on metabolite and mineral reserves in the perennial organs as well as salts stored in these organs. Therefore, the carry over of salinity effects in the plants is large. In plum trees, even before the first irrigation of the season with 400 mS/m water was applied, leaf damage and flower deformation were already evident, and is indicative of a significant inter-seasonal carry over of salt and salinity effects (Catlin *et al.*, 1993).

i) Water stress and high frequency irrigation

In his analysis of international literature on the possibility of using poor quality water for irrigation, Shalhevet (1994) came to the conclusion that there is a clear relationship between yield reduction due to salinity increase and water consumption. What is less clear is whether this relationship is identical to the effect of water stress on yield and water consumption under similar conditions. Shalhevet (1994) reports that the bulk of evidence leads to the conclusion that it is and that a unified function may be applied to both water and salinity stress. This implies that salinity and water stress are additive in their effect on transpiration and yield. However, Shalhevet (1994) shows that the quantitative effects of these two stresses are not identical. One MPa increase in water stress may not have the same detrimental effect of one MPa increase in salt stress. Meiri's (1984) analysis of international literature showed that water stress has a greater weight than salt stress in suppressing growth. From this, one can infer that in times of water shortage, it would be better to irrigate with saline water rather than to let the crop suffer from water stress. But, this managerial option to alleviate drought stress by using saline water to irrigate still has to be evaluated more thoroughly under experimental conditions. Shalhevet (1994) is of the opinion that actual transpiration and yield are reduced by salinity in accordance with the production function, which relates relative yield to relative evapotranspiration, and the evapotranspiration - salinity response function. However, it is still unresolved whether reduction in water uptake with increasing salinity is the cause or the result of a reduction in growth.

Because water and salinity stress are additive, it has been argued that high frequency irrigation can be used to offset some of the negative effects of decreasing osmotic potential with decreasing water content (Kafkafi, 1984). Shalhevet (1994) maintains that there are few concrete data to support this recommendation. As the soil dries out between irrigations, matric potential and osmotic potential decrease and consequently, the shorter the irrigation interval, the lower would be the pre-irrigation salt concentration. However, it has been found that increased irrigation frequency results in an upward shift of the peak of salt concentration distribution with depth (Bernstein & Francois, 1973b). Furthermore, Shalhevet (1994) argues that salinity reduces evapotranspiration (ET), resulting in a slower soil drying than under non-saline

conditions. Thus, for the same irrigation interval, the total preirrigation soil water potential may be lower under non-saline than under saline conditions (because of the lower matric potential), resulting in a greater damage to the crop. Also, as irrigation becomes more frequent, the evaporation component of ET increases, leading to additional water application and an increase in salt load. The net result of these two processes is difficult to predict and conflicting reports on the advantages of high frequency irrigation are found in literature. Shalhevet (1994) concludes that the bulk of evidence in the literature shows no advantage to increasing irrigation frequency when irrigating with saline water. There is evidence that increased irrigation frequency with saline water, might even increase salinity damage. However, under excessive leaching this may be reversed.

2.3.4 Effective soil salinity

An index of "effective root zone salinity" is required when evaluating the effects of soil salinity on crop performance. As discussed earlier, salt tolerance is normally expressed in terms of the electrical conductivity of the extract of a water-saturated soil paste. However, this is not the salinity that the plant responds to. Also, salinity within the root zone varies in time and in space. *In situ* sensors or soil solution collecting devices can be used to follow local temporal changes in salinity at field water content. It would be good to have sufficient observation points to follow also the spatial changes or, to have user-friendly models of water and salt dynamics to provide the spatially distributed salinity from the temporal monitoring of a limited number of points. Temporal integration of the data of a single profile of suctions cups served as the root zone salinity in a study of the response of a plum orchard to soil salinity under mini-sprinkler irrigation (Hoffman *et al.*, 1989, Catlin *et al.*, 1993). Prior *et al.*, 1992c) report that the soil solution extract of a single suction cup showed good correlation with the spatial average salinity of a drip irrigated vineyard. This single value was used to quantify the soil salinity and to calculate the water balance. But to characterise the temporal and spatial changes in soil salinity at a microscale (i.e. within the root zone), will require continuous monitoring of soil salinity at a number of sites within and outside the wetted zone. As soil heterogeneity increases on the mesoscale (i.e. irrigated field scale), the number of monitoring sites increases (Moolman & De Clercq, 1989).

2.3.5 Indices to describe salinity hazard to fruit and vine crops

Two factors need to be considered when evaluating response functions to describe the effects of salinity on fruit and vine crops: firstly, what is the minimum time scale for studies involving perennial crops, and secondly is total salinity the correct (or only) variable that should be considered in response functions.

a) Consideration of the time scale

For annuals, temporal integration of salinity can be over one season only, because there generally is little transfer of salinity effects between seasons. However, there is growing evidence that damaging effects of salinity on perennial crops are cumulative and might take several years before the real effects become visible (or measurable). Hoffman *et al.*, (1989) in their study with plum trees showed that three years of saline irrigation, and a two year time integration, excluding the dormant period, is the minimum time scale to correctly quantify the impact of salinity on plum yield. After five years of saline irrigation water Catlin *et al.*, (1992) found that a three year time

integration of soil salinity, even better describes the effects of salinity on plum trees. The explanation was that two or three years of averaging accounted for the influence of salinity on bud formation and shoot growth in the years prior to yield year. Five years of saline irrigation and three years of time integrated mean soil salinity did not change that much the salt tolerance values inferred after three years of study. The interpretation may be that no change occurred in the response of plums to total salinity or, to the combined effects of total salinity and specific ion effects (possibly with no visible leaf damage). If there is a worsening salinity effect with time it could be the result of important metabolic processes that are impaired between seasons. One such process is a decrease in carbohydrate reserves in the perennial organs at the end of the growing season, as shown for grapes by Prior *et al.*, 1992b). The most severe salinity effect on plums was leaf damage that almost killed the trees after two, three and four years of irrigation with water of ECi of 800, 600 and 400 mS/m respectively. This visual damage was considered a specific ion effect, which showed up when the Cl^- reached toxic levels in the leaves. Limited leaf damage showed up towards the end of the first season in all treatments with ECi higher than 300 mS/m. Leaf damage worsened in proportion to water salinity and was visible earlier in following seasons. Increased disorders in flowers with the increase in salinity and number of seasons of saline irrigation were also considered toxic effects. Since the soil was leached every winter the increased salinity damages in time suggest a salt carry over in the perennial organs of the tree. It was previously documented that build up of toxic levels of chloride and sodium in plant organs on soils with relatively low salinity and sodicity can take several years (Bernstein *et al.*, 1956, Francois & Maas, 1994). Initially, sodium was thought to be retained in the sapwood of the tree. With the conversion of sapwood to heartwood, sodium is released and then translocated to the leaves, causing leaf burn. This may partly explain why stone fruits and grapes appear to be more sensitive to salinity as the plants grow older (Francois & Maas, 1994).

Growth and final fruit size of peach trees subjected to irrigation water salinity levels from 25 to 100 mS/m, in conjunction with restricted irrigation volumes (i.e. deficit irrigation), showed a strong negative linear response to salinity during the second year of salinity exposure (Boland *et al.*, 1993). Leaf chloride levels increased over time and with treatment levels to a maximum of 3% for the 100 mS/m treatment at the end of the second year with no increase in leaf Na. In the woody plant organs salinity increased both sodium and chloride (Boland *et al.*, 1993). In this particular experiment with peach trees, there was one-year delay between imposing salinity and the first visual symptoms of leaf damage, a result that is probably also related to salt deposition in the wood. Sodium and chloride also accumulated in the fruit, which is similar to results reported by Downton (1977b) for grapes.

In a long term study of the effects of saline irrigation water on mature pear trees, Myers *et al.*, (1995) report that trees irrigated with 210 mS/m water continued to yield well up to six years after the soil profile became salinised and before yield declined suddenly. In the eighth and ninth year yield of this treatment had decreased to about 60% and 50% of the control respectively. Forty percent of the trees were dead in the ninth year. The sudden yield decline was not associated with further increases in soil salinity.

Response functions that consider total salt content only may therefore not be adequate to quantify the impact of salinity on fruit and vine crops. The examples above and other studies showed that for many fruit trees the response to specific ions is more

important than the response to total salinity. Consequently it can be argued that the tolerance classification and response functions must use the concentrations of the toxic elements also. Furthermore, economic aspects should also be considered when evaluating saline water for crop production purposes. With plum trees (Catlin *et al.*, 1993) the 200 mS/m irrigation water caused limited leaf burn, that did not increase over years, with no reduction in yield. Apparently, for Cl, the trees reached long-term steady-state with annual balance zero. The annual balance is the difference between the ion uptake and its removal through leaves, yield and pruned shoots. Consequently for plum trees it can be argued that the proposed salt tolerance criteria should be zero annual salt gain with an acceptable level of yield reduction. This conclusion is similar to that of Oster (1994) who states that some leaf damage with no yield reduction, or some yield reduction as a result of the total salinity or specific ion effects, may be acceptable or even profitable.

b) The response function

Fruit trees and vine crops were included in the general model (Maas & Hoffman 1977) that describes the response to total salinity as a two piece response function where the threshold salinity (EC_t) is the maximum salinity without yield reduction, and S is the slope of the curve determining the fractional decline per unit increase in salinity beyond the threshold. For generality the data is normalised by relating the yield to the non saline treatment yield (RY) and uses the depth mean salinity of the saturated paste extract (EC_e) assuming stable and one dimensional salt profile.

$$RY = 1-(EC_e - EC_t)*S \quad \text{.....(2.1)}$$

Hoffman *et al.*, (1989) applied the two-piece model to the data of their plum experiment with reasonable success but that the response function correlates better with the mean root zone salinity to a depth of 120 cm for a two year time integration, excluding the dormant period, than with the mean salinity of the yield year (Hoffman *et al.*, 1989). In the case of a six year study on salinity effects on grapevine (Prior *et al.*, 1992a), yield was affected by the salinity of current and preceding seasons. The salinity effects were described better by a logistic function than by the two-piece response model. The logistic function was of the form:

$$y = D\left[1+\left(\frac{EC_i}{EC_{ih}}\right)^{\alpha}\right]^{-1} \quad \text{.....[2.2]}$$

where y is yield, EC_i is salinity of irrigation water, D is the theoretical yield at ECi = 0, EC_{ih} is the half-effect EC_i and α is the shape parameter. This model has no threshold value and shows a reduced marginal effect with increasing salinity. The ECih value for pruning weight in the Prior model was lower than for yield which suggest that salinity has a larger effect on pruning weight than on yield. Larger salinity effects on shoot growth than on yield was reported also for plum trees (Catlin *et al.*, 1993).

Other indices of salinity hazard included water salinity, soil salinity and the ionic composition of selected plant organs. Leaf chloride was the most convenient and reliable method of measuring yield response to salinity for peach (Boland *et al.*, 1993). For grapes high Cl^- in petioles (Christensen *et al.*, 1978) and petioles and laminae (Walker *et al.*, 1981) indicate whether plants have been subjected to salinity. The

petiole chloride predicted the yield response slightly better than the laminae chloride in a long term field study (Prior *et al.*, 1992b).

2.3.6 Physiological response to salinity

Potted Sultana vines treated with NaCl (up to 125 mol/m^3) in a glasshouse study showed decreasing rates of CO_2 fixation with increasing levels of Cl^- in the leaves (Downton, 1977a), Walker *et al.*, 1981). Field grown Sultana vines subjected to salinity experience similar reductions in stomatal conductance and photosynthesis, with the reduction also strongly correlated with leaf chloride (rather than sodium) (Prior *et al.*, 1992b). Leaves on salt-treated plants showing reduced photosynthetic rates have lower sucrose and starch concentrations, but increased reducing sugar concentrations (Downton, 1977a). Salt-stressed Sultana vines in the field showing reduced photosynthetic rates, also have lower starch concentrations in shoots (Prior *et al.*, 1992b). The photosynthetic reduction has been shown to be due to increased stomatal resistance (Walker, 1994) which in turn might be related to internal disturbances at higher leaf chloride levels (Walker *et al.*, 1981).

Similar results were reported by Boland *et al.*, (1993) for peach trees. Photosynthesis of peach trees was reduced at high levels of salinity in the irrigation water with decreased stomatal conductance and likely chloride toxicity in the leaves.

Boland *et al.*, (1993) demonstrated that saline irrigation on peach trees resulted in less negative leaf water potential after two years of salinity exposure. This is contrary to results of Lloyd *et al.*, (1987) (citrus), Lloyd & Howie, (1989) (citrus), Myers & West, 1989) (pears) who found either more negative or similar leaf water potentials under saline irrigation.

2.3.7 Recovery from salt damage

Under certain circumstances salt stress might be beneficial, e.g. to improve fruit or wine quality. The economic benefits from such temporary stress depend on the crop recovery on the release of the stress. Changes in metabolite partition from vegetative to reproductive growth as a direct effect of the stress, or by induced changes in development, like flowering, may increase commercial yield. Recovery from stress depends on the magnitude and duration of salinity stress, the processes that were affected and the carry-over effect. Reduced growth during accelerated rate stages will be sustained longer than reduced growth (due to salinity) during linear or diminishing rate stages.

Walker *et al.*, (1981) reported that recovery of grapevines exposed to saline conditions is possible on changing from 80 days in 90 mol/m^3 NaCl, to a salt free nutrient solution. One year of fresh water substantially ameliorated damage to leaves and flowers of plum trees, with additional improvement on the second year of fresh water irrigation (Catlin *et al.*, 1993). Fresh water reduced the leaf Cl- and Na+ content and increased the Na/Cl ratio as supply from soils stopped and supply from storage in the plant reflected the slower release of stored sodium and Cl. Salts from the first year were removed with leaf, fruit and pruned material.

2.3.8 Impact of salinity on fruit and wine quality

Only a few references on salinity effects on fruit and wine quality were found in international literature. Also, comparison among different studies is not easy because

different indices of quality are used, depending on the crop. Hoffman et al., (1989) using fruit size as an index of quality, reports that plum size was reduced by salinity. However no mention is made of how salinity influenced another quality parameter namely the sugar content of the plums. Saline irrigation reduced fruit size of peaches and increased the Na and Cl content of the fruit (Boland et al., 1993). The relationship between peach quality and Na and Cl levels in the fruit however, is not mentioned. In a long term study on the effects of saline irrigation water on the yield and growth of mature Williams pear trees, Myers *et al.*, (1995) found that saline irrigation in general caused an increase in the proportion of fruit in the smallest size class.

Prior *et al.*, 1992a used sugar levels in sultana berries as the index of quality. There was little consistent effect of salt treatment on sugar levels of the juice in the early years of their salinity experiment but in years 5 and 6, grapes from salinised vines contained less sugar. Dried fruit quality was high, except where yields were severely reduced by salinity.

Downton (1977d) found that accumulation of Na and Cl in Cabernet Sauvignon fruit was reflected in the concentrations of these ions in wine. Both experimental and commercial red wines from Australia contained about five times more chloride than those of European origin. White wines differed threefold. Routine use of rootstocks in European viticulture to overcome phylloxera problems (some nematode and phylloxera resistant rootstocks are also chloride excluders) probably partly accounts for the lower chloride content in wines of European origin. The lower levels of Cl in the white wines can be partly ascribed to the winemaking procedure since those wines are not usually fermented on their skins. The chloride concentrations of the wine may depend upon the extent to which extraction of components in the skins occurs during the fermentation process since about half of the chloride in grape berries is located in the skin. Thus the wine maker may have some scope for limiting wine Cl by controlling the amount of skin contact early in the fermentation (McCarthy & Downton, 1981). However no data could be found on how, and whether Na and Cl effect wine quality in terms of aroma and taste.

2.4 Environmental considerations

Notwithstanding the fact that irrigation in many climate zones is essential for crop production, it can be argued that the introduction of irrigation in an area is one of the most drastic ways in which human activities impact on the environment. Soil genesis is a slow process and the age of soils is mostly measured using geological time scales. One consequence of the slow rate of soil formation is that soil is in equilibrium with the prevailing climate. For example, in arid or semi-arid regions the chemical composition of the soil is the result of weathering processes which reflect a shortage of soil water (relative to the potential evaporation), and high temperatures. In most cases such soils contain unweathered minerals and large quantities of soluble salt. Introduction of irrigation disturbs this equilibrium and weathering of soil minerals is accelerated. Rhoades *et al.*, (1968) have shown that increases in salt concentration of 200 mg/L to 300 mg/L are common when arid-land soil solutions remain in contact with relatively unweathered soil minerals for substantial periods of time. Also, some, or most of the soluble salt is mobilised and transported down the soil profile. Under irrigation, the mobilised salt ends up in receiving rivers as return flow where it impacts on the ecology of the river. Prior to the onset of irrigation the ecology of the river was in equilibrium with the composition of the natural seepage of soils typical of the semi-

arid climate. The environmental impact of irrigation and return flows on river ecology can be minimised by intercepting the return flow and disposing of it elsewhere with specially constructed drainage canals or pipelines. However, because of the additional need to leach when irrigating with saline water, the amount of return flow that must be disposed of is greater than for non-saline water. This furthermore implies that the infrastructure required to utilise saline water for irrigation such as drainage canals, interceptor drains, pipelines, evaporation ponds, etc., will be more expensive in comparison with the non-saline case.

2.5 Conclusion

The key for sustainable use of saline water for irrigation is to avoid salt input due to unnecessary irrigation, and to prevent the rapid build-up of salinity by means of effective leaching at the appropriate time. That will result in maximal drainage water concentration and minimal leaching volume with acceptable damage to the crops. Oster (1994) concludes that the use of poor quality water requires three changes from standard irrigation practices: (1) selection of appropriate salt tolerant crops; (2) improvements in water management, and in some cases the adoption of advanced irrigation technology; and (3) maintenance of soil-physical properties to assure soil tilth and adequate soil permeability to meet crop water and leaching requirements. In this regard our conclusions are in accordance with those of Ayers & Westcott, (1985) and Francois & Maas, (1993), namely that fruit trees and vine crops must be considered as sensitive to very sensitive to salinity. Furthermore, high frequency irrigation, which requires advanced irrigation technology, apparently is not necessarily the key to successful use of saline water. There is evidence that water stress might be more damaging to crop growth and yield than salt stress. This suggests that in times of water shortage (drought) it might be better to irrigate with saline water than to expose the crop to prolonged water stress. However, little information on this practise as applied to fruit and vine crops are available in literature.

CHAPTER 3
DESCRIPTION OF THE RESEARCH INFRASTRUCTURE AT ROBERTSON AND STELLENBOSCH

3.1 General

Six salinity treatments, ranging in electrical conductivities from *ca.* 25 mS/m to 500 mS/m were used to investigate the long-term effects of salinity on *Vitis vinifera* L. The rationale for the number of treatments and the range of salinities was two-fold. First, it was a prerequisite that the treatments should at least cover the range of salinities defined by the EC-operational curve used by the Department of Water Affairs for managing water releases from the Brandvlei dam (Figure 3.1). Secondly, some of the treatments had to exceed our first estimate of the threshold salinity value for *Vitis vinifera* L., i.e. 150 mS/m (Ayers & Westcott, 1989). For a sound mathematical description of the response of grapevine to salinity and assuming that the piecewise linear response function of Van Genuchten and Hoffman (1984) is applicable[2], the minimum number of salinity treatments that can be used is five, i.e. two treatments below and two treatments above the threshold value respectively. We decided to use six salinity treatments.

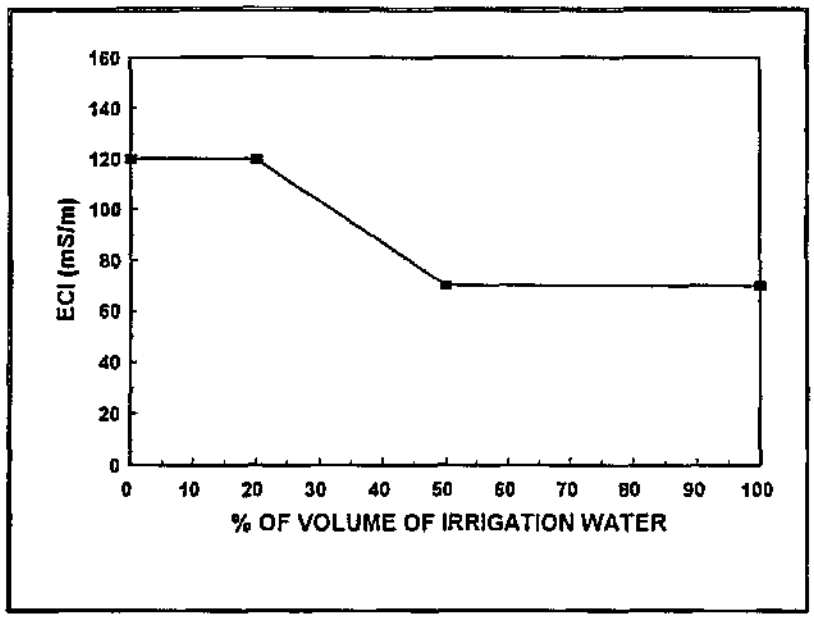


Figure 3.1 Operational curve used to control the salt content of the Breede River by manipulating the volume of water released from the Brandvlei Dam

The research was conducted at Robertson and Stellenbosch in experimental vineyards belonging to the Agricultural Research Council. Robertson (33° 46'S, 19° 46'E) and Stellenbosch (33° 58'S, 18° 50'E) are both located in the south-western part of South Africa. Robertson is situated in the Breede River Valley and has a drier climate than Stellenbosch, which is, situated closer to the sea. The two experimental vineyards vary with respect to soil, climate, cultivar, age and viticultural practices. The vineyard at

[2]The piecewise response function contains two independent parameters: the salinity threshold, being the maximum soil salinity without yield reduction, and the slope of the curve determining the fractional decline per unit increase in salinity beyond the threshold.

Robertson was established in 1974 while that at Stellenbosch was planted in September 1989. Because of these differences, each research facility will be described separately.

3.2 Robertson research site

3.2.1 Climate, viticultural practices and general instrumentation

The experimental farm at Robertson is located 156 m above sea level and the climate can be described as semi-arid with a Mediterranean rainfall pattern. The experimental farm has a long term (1954-1989) mean annual precipitation and mean annual class A-pan evaporation of 280 and 1790 mm/a respectively (Anon., 1989). The monthly distribution of precipitation, temperature, class A-pan evaporation and sunshine hours are summarised in Table 3.1. It should be noted that potential evaporation at all times exceeds the rainfall, especially during summer which means that viticulture is only possible under full-scale irrigation.

Table 3.1 Climatic means for the Robertson experimental farm, 1954-1989 (Anon. 1989)

Month	Mean Max. Temperature (°C)	Mean Min. Temperature (°C)	Rainfall (mm/month)	Evaporation (mm/d)	Sunshine (h/d)
1	30.7	15.6	12.2	8.4	9.8
2	30.2	15.8	16.1	7.2	9.0
3	28.5	14.4	15.7	5.6	8.0
4	25.4	11.4	30.4	3.7	6.9
5	22.0	8.2	32.5	2.4	6.3
6	19.4	5.9	31.9	1.8	6.1
7	18.9	5.2	26.9	2.0	6.6
8	19.5	6.1	41.8	2.7	6.9
9	21.7	8.1	19.8	4.0	7.2
10	24.6	10.4	21.5	5.7	8.2
11	27.2	12.8	18.4	7.2	8.9
12	29.5	14.5	12.2	8.3	9.6

The 1.2 ha experimental vineyard was established in 1974 and is planted to Colombar grafted on 99 Richter rootstock. The vines are trained on a factory trellising system (Saayman, 1988). Between 1976 and 1984 the vineyard was used in an irrigation experiment evaluating the effect of different irrigation systems (flood, sprinkler, microsprinkler and drip) and soil water regimes on vine performance (Van Zyl, 1984). The vineyard is divided into four blocks of six plots each, giving a total of 24 plots (Figure 3.2). The borders and original plot sizes of Van Zyl (1984) were retained for the present study. Each plot consists of an experimental row bounded by two border rows on each side. The row and plant spacing is 3 m x 1.5 m respectively. Blocks 1 and 4 have 24 plants per row while blocks 2 and 3 have 23 plants per row. In the experimental row, ten vines were used for research purposes.

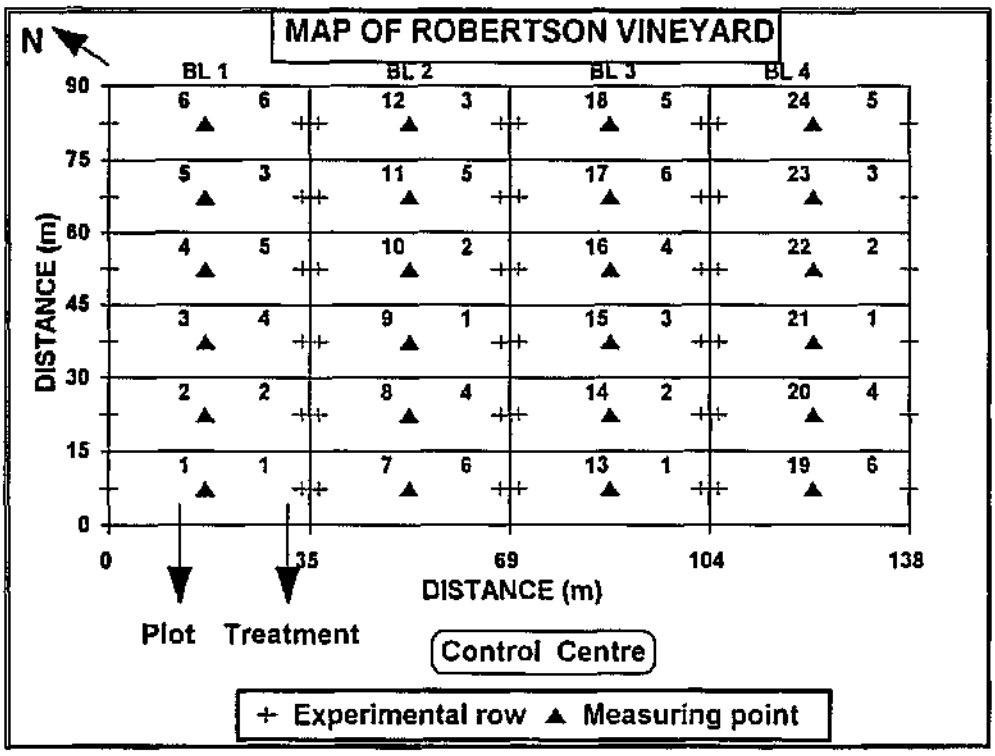


Figure 3.2 Schematic diagram of the experimental vineyard at Robertson showing 24 plots arranged according to a randomised block design consisting of four blocks (replicates) and six treatments (the triangles indicate the centre of each plot where the soil water content and soil solution was monitored).

Each plot is equipped with a neutron probe access tube installed in the experimental row 0.5 m from a vine trunk, to a depth of 1.4 m, which allows the profile water content to be determined to a depth of 1.2 m. Because of a very hard duripan in the subsurface the access tubes on two sites could be installed to a depth of 1 m only. In February 1993 additional access tubes were installed on all the plots of treatments 1, 4 and 6. These tubes were placed midway between two neighbouring rows, at a distance 1.5 m from a vine. During the 1993/94 season a further seven access tubes per 4.5 m^2 were installed in plots 7, 8 and 9. This was done to conduct detailed, short-term surveys of the water balance of the vineyard. The vineyard is situated on a flat terrain and because lateral flow is unlikely, no provision was made for subsurface drainage.

Soil water samplers, also referred to as suction cups, are installed on each plot, 0.2 m from the middle of the experimental row at depths of 0.15, 0.30, 0.60, 0.90 and 1.20 m. The suction cups are connected to a vacuum pump at the control centre, and samples of the soil solution can be collected using a remotely controlled sampling technique developed by the research team (De Clercq *et al.*, 1994). The soil water samplers were assembled locally from 50 mm diameter ceramic cups and PVC tubes in lengths of 150, 300, 600, 900 and 1200 mm. A removable rubber stopper with a vacuum inlet is placed at the top of the PVC tube. A 25 mL bottle with a special watertight stopper, consisting of a rubber grommet through which a thin capillary polypropylene tube is fed, is placed inside the cup sampler. The capillary tube extends 10 mm outside and 50 mm to the inside of the bottle. The bottle is placed upside down at the base of the cup sampler with the 10 mm capillary tube extension touching the bottom of the ceramic cup. Any water that collects at the base of the soil water

sampler will therefore be in contact with the small bottle. The suction cup sampler was installed by augering a hole to the required depth and by ensuring that the ceramic cup makes good contact with the soil matrix. The rubber stopper and air inlet of the cup sampler protrude about 50 mm above the soil surface. When the vacuum pump is switched on, the negative pressure inside the cup samplers directs flow of the soil solution to the inside of the ceramic cup. Soil water (when present) will flow from the soil matrix, through the porous ceramic cup into the sampler where it collects at the base of the cup sampler. Under normal circumstances, when the vacuum pump is switched off the suction is released and the suction gradient reverses in favour of the soil matrix. If the sample of the soil solution that accumulated at the bottom of the ceramic base is not quickly removed from the soil water sampler, it will permeate back into the soil. However, with our set-up, the sample bottle and its capillary tube act as a liquid trap. As soon as the vacuum inside the soil water sampler is released, water, which accumulated at the base of the ceramic cup, will flow to the lower pressure inside the 25 mL sample bottle. The 25 mL sample container inside the cup sampler is attached to the rubber stopper at the top of the cup sampler by means of a string. When the stopper is removed from the sampler (PVC tube), the small sample bottle at the base of the tube is simultaneously pulled out of the assembly for easy retrieval.

The experimental vineyard is also equipped with a Class A-evaporation pan and a standard (cumulative recording) rain gauge. From November 1991 up to April 1994, the class A-pan and rain gauge were read daily. During the summer of 1992/93 an automatic recording weather station was installed. Wet and dry bulb air temperature, incoming solar radiation, wind speed and rain were recorded on an hourly basis.

3.2.2 Soil properties

Van Zyl (1984) describes the soil as a Hutton fine sandy loam, but according to the current South African soil classification system (Soil Classification Working Group, 1991) the soil is classified as a Trawal 2210 fine sandy loam (Typic Durochrepts) with a duripan at approximately 1.2 m. Prior to the start of the study (in April 1990), 49 soil samples were taken and analysed for a range of physical and chemical properties to document the antecedent conditions. When the samples were taken in April 1990, the plot sizes and boundaries had not yet been finalised. It was then not realised that if the 15 m x 15 m sampling grid were to be superimposed on the final experimental layout, most of the sampling positions would coincide exactly with the borders between adjacent plots. The analytical results can therefore only be summarised in terms of mean values per block (replicate). The results are shown in Table 3.2.

The depth of the duripan below the soil surface was surveyed in 1993 using an automatic recording penetrometer and a 5 m x 11 m sampling grid. The maximum depth that could be recorded with the penetrometer probe is 1.4 m. The depth to the duripan varied between a minimum of 0.8 m and a maximum of >1.4 m. The results are shown as a contour map in Figure 3.3.

3.2.3 Irrigation system

In 1990/91 the previous irrigation system was replaced with a computerised, remote controlled micro-irrigation system. The irrigation system is controlled on site by a *Gulf Irrigation Controller* which is linked via a modem and personal computer to the control centre at Stellenbosch.

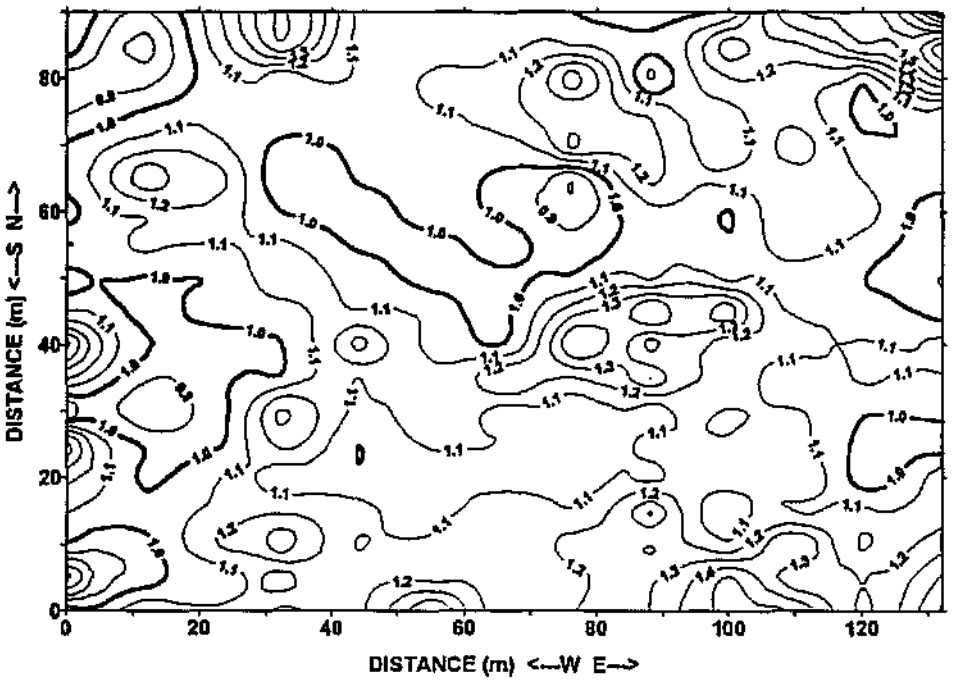


Figure 3.3 Spatial distribution of the depth (meters) to the duripan (below the soil surface) in the Robertson experimental vineyard

Table 3.2 Mean soluble salt content (in terms of the electrical conductivity of a saturated paste extract), extractable cation concentration, cation exchange capacity and clay content per depth for each block (replicate) of the experimental vineyard at Robertson as determined in April 1990

Block	Depth (m)	ECe* (mS/m)	Ca (cmol/kg)	Mg (cmol/kg)	Na (cmol/kg)	CEC** (cmol/kg)	Clay (%)
1	0.15	84	11.9	3.5	0.3	10.9	21.3
	0.30	75	12.7	3.6	0.3	11.3	28.5
	0.60	92	14.2	4.6	0.5	12.4	20.7
	0.90	93	15.4	6.1	0.6	14.3	17.1
	1.20	76	13.4	6.4	0.6	12.7	14.2
2	0.15	123	10.5	3.1	0.3	11.1	21.8
	0.30	120	11.6	3.7	0.4	11.5	19.4
	0.60	152	13.6	4.8	0.4	13.1	17.5
	0.90	187	15.0	6.4	0.7	14.2	15.4
	1.20	185	14.0	7.3	0.8	13.5	15.0
3	0.15	84	10.3	3.4	0.3	10.7	20.5
	0.30	79	10.7	3.6	0.3	11.2	25.2
	0.60	93	16.9	4.6	0.4	11.7	26.2
	0.90	122	14.8	6.3	0.6	14.2	18.7
	1.20	146	14.3	6.6	0.6	14.1	16.6
4	0.15	77	12.8	3.7	0.3	11.2	21.1
	0.30	74	12.9	3.9	0.3	10.7	28.6
	0.60	67	13.9	5.3	0.5	12.3	28.0
	0.90	85	14.9	6.9	0.6	13.8	25.7
	1.20	98	14.9	7.9	0.8	14.0	16.2

*ECe=electrical conductivity of a saturated paste extract, **CEC=cation exchange capacity

The irrigation controller has a number of safety features which can terminate an irrigation event when, for example, the pressure and water flow rate changes suddenly. The water is applied with mini-sprinklers that wet 66% of the surface area per vine. The sprinklers are located beneath the plant canopy, at 1.5 m intervals and are placed halfway between two adjacent vines, wetting the trunk but not the foliage. Water is applied in a 280° arc at a rate of 7.3 mm/h (based on a full surface wetted area of 4.5 m^2 per vine).

The total amount of water that the vineyard receives per irrigation event is recorded with an electronic flow meter. Each plot is equipped with a manually adjustable pressure valve and it was assumed that by adjusting the supply pressure at each plot to 50 kPa, each plot would receive the same amount of water, i.e. 1/24th of the total amount of applied water. In February 1993 a pressure regulating emitter (dripper) was installed on the inlet side of each sub-lateral irrigation line serving an experimental row. Each emitter was connected to a closed (but not airtight) 20 L plastic container which collects all the water discharged by the emitter during an irrigation event. At the end of an irrigation event, the mass of water in each can was determined by weighing. These weights were used to calculate on a pro rata basis how much irrigation water each of the 24 plots received and whether the assumption of a uniform application at a fixed supply pressure is valid (*see also section 3.2.4*).

3.2.4 Irrigation water salinity control system

The electrical conductivities of the six different salinity treatments used during the course of this experiment are given in Table 3.3.

Table 3.3 Salt content of the irrigation water expressed in terms of specific electrical conductivity (ECi) of the six treatments that were used at the Robertson vineyard

Treatment	Target ECi (mS/m)		
	1991/92	1992/93 & 1993/94	1994/95
1	± 30 (control)	± 30 (control)	± 30 (control)
2	100	75	75
3	200	150	150
4	300	250	250
5	400	350	350
6	600	500	30

The control treatment (±30 mS/m) is the local irrigation water from the Robertson canal serving the experimental farm. The other five salinity treatments were obtained by blending a *ca.* 30% stock solution consisting of a 1:1 molar mixture of $CaCl_2$ and NaCl with the control water. In 1991/92 a 1:2 Ca:Na ratio was used. The stock solution of $CaCl_2$ and NaCl was prepared and stored in a 10 m^3 tank located next to the main water supply line. During the first season (1991/92) the mixing of the stock solution with the control (canal) water was done by adjusting the outlet pressures of the main water supply pump and salt injection pump. The required volume of the stock

solution mixed with the canal water to give the necessary EC levels, was controlled by means of five manual taps with adjustable needle valves. This turned out to be a very cumbersome technique because the final EC of the irrigation water was very sensitive to changes in the pressure of the main water supply line. On a number of occasions in 1991/92, the supply pressure dropped appreciably during the irrigation application (because the filters became blocked), with the result that the initial EC (set using a portable EC-meter) tended to drift towards a higher value. This was especially noticeable for treatment 5 (400 mS/m). In order to minimise this effect, the EC at the start of an irrigation was set slightly below the target EC of each treatment.

Because of the problems experienced with the salt mixing system during the first season, a computerised electronic EC-control system (Wessels *et al.*, 1995) was installed. This electronic system is based on in-line EC sensors in real time communication with a computer which in turn controls the operation of five solenoid valves. The solenoid valves control the volume of the stock solution injected into the supply line and respond to commands received from the computer. One of the features of the system is that a continuous record of the electrical conductivity of the irrigation water is kept. The system was installed in September 1992 and was fully operational by November 1992. The water and salt control system was further improved by installing a self-flushing filter station in the main supply line. The combination of the EC-controller and new filter system proved to be successful and since November 1992, the actual EC values during an irrigation were much more stable than previously.

An example of the EC-time series recorded by the salt control system during a particular irrigation event is given in Figure 3.4. The spikes indicated in the graph are the result of the backwashing of the automatic filters every 20 minutes. During backwashing the water supply pressure drops but the pressure from the salt injection pump remains constant with the effect that the ECi immediately increases.

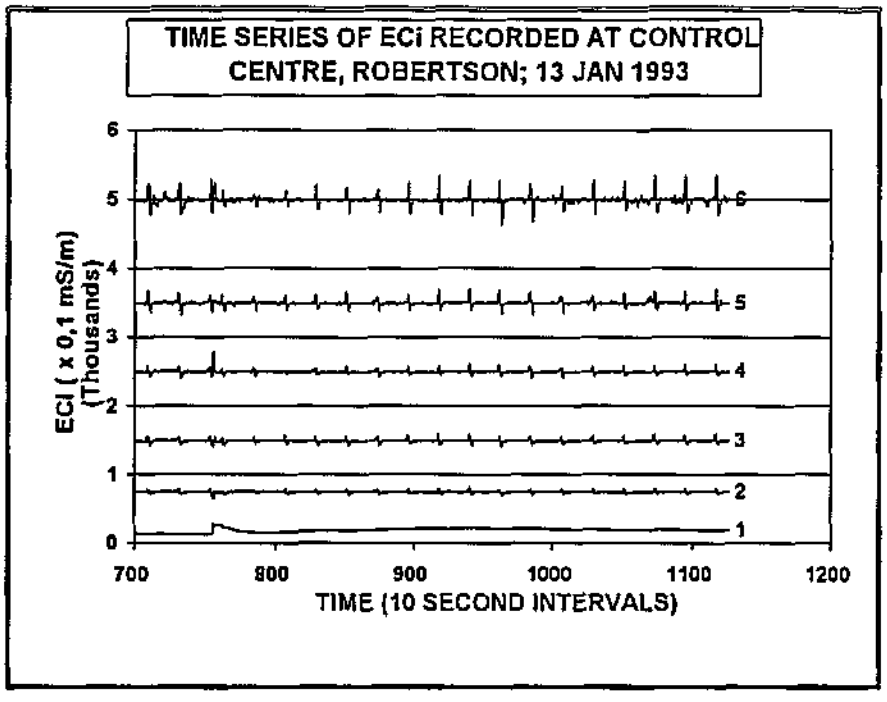


Figure 3.4 Example of the time series of ECi electronically recorded every ten seconds for at the control centre during the irrigation event of 13 January 1993

The computer however responds by closing the solenoid valves which decreases the flow of salt into the supply line, resulting in a decrease in ECi. The outcome is that the temporal mean ECi remains stable throughout the event.

3.3 The Stellenbosch research facility

3.3.1 Climate, viticultural description and general instrumentation

The climate of Stellenbosch is Mediterranean with wet winters and mild to cold temperatures and a dry summer. The research at Stellenbosch is conducted at the Nietvoorbij experimental farm of the Institute for Viticulture and Oenology, Agricultural Research Council. Long term climatic data for Nietvoorbij could not be found but it is assumed that the climatic record is not substantially different from that of the nearby Welgevallen weather station (experimental farm of the University of Stellenbosch). The latter weather station is situated 119 m above sea level and has a long term (1942-1988) mean annual precipitation and mean annual Class A-pan evaporation of 827 and 1870 mm/a respectively (Anon., 1989). The monthly distribution of precipitation, temperature, Class A-pan evaporation and sunshine hours are summarised in Table 3.4. Viticulture in the Stellenbosch region is generally practised under rainfed conditions or using supplemental irrigation, i.e. only a a few irrigation applications at critical phenological stages are used.

The experimental vineyard at Stellenbosch was specifically established for this study. The virgin soil was deep ploughed in 1989 and the required amount of lime and fertilizer applied. After soil preparation, the Weiser-Riesling cultivar grafted on Richter 99 rootstock was planted using a three-wire hedge trellising system (Saayman, 1988).

Table 3.4 Climatic data for Stellenbosch as measured at the Welgevallen weather station, 1944-1988 (Anon. 1989)

Month	Mean Max. Temperature (°C)	Mean Min. Temperature (°C)	Rainfall (mm/month)	Evaporation (mm/d)	Sunshine (h/d)
1	26.8	13.3	19.7	8.3	10.0
2	30.8	15.9	20.8	8.3	9.7
3	26.8	14.4	29.8	6.2	8.4
4	23.2	11.2	77.2	4.3	7.2
5	22.3	10.6	114.4	2.5	6.0
6	18.6	7.0	130.5	2.1	5.3
7	16.7	7.2	120.9	2.0	5.6
8	19.2	8.4	121.2	2.4	5.8
9	19.7	8.4	72.3	3.6	6.8
10	20.8	9.3	57.0	5.7	7.6
11	26.3	12.6	41.1	8.2	9.6
12	28.3	14.3	21.8	8.2	9.8

The vineyard is arranged into 24 plots according to a randomised block design of six treatments and four replicates (blocks). Each plot consists of six rows with ten vines per row. Plant spacing is 1.2 m x 2.75 m and two experimental rows were used, bounded on each side by two border rows. Ten plants, five in the centre of each of the

two experimental rows were used in this study. The schematic layout of the 24 plots, replicates and treatments are shown in Figure 3.5.

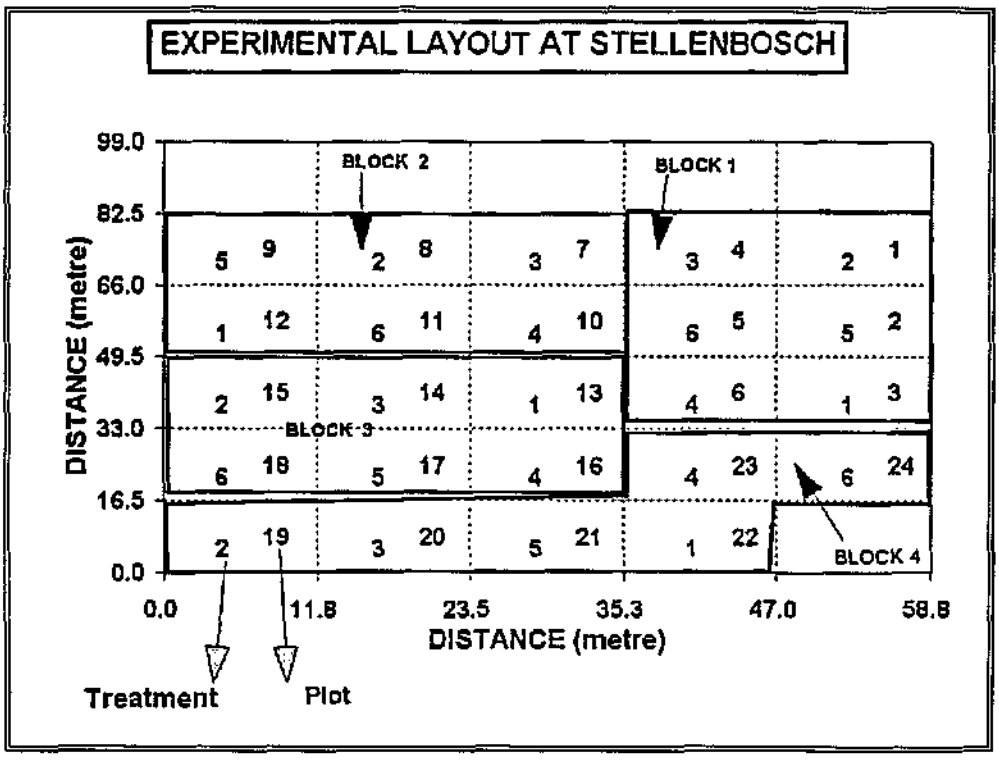


Figure 3.5 Schematic diagram of the experimental vineyard at Stellenbosch showing the randomised block design of the 24 plots arranged into six treatments and four blocks (replicates)

The vineyard is situated on a steep slope which mean that saline seepage from the higher lying plots irrigated with saline water, will possibly contaminate the lower areas downslope. In order to prevent this a complex subsurface drainage network was installed in 1990/91, i.e. a year after the vines were planted. Each of the 24 plots are drained individually using two drain pipes buried at 1.5 m depth on the two downslope sides of the plot. In addition to the drain pipes, each plot is bounded on the two downslope sides with plastic sheeting buried vertically to a depth of 1.5 m. The drainage system is designed such that the deep percolate of each plot can be collected individually.

One of the experimental rows per plot has a neutron probe access tube, located within the vine row directly below the plant canopy. Because of underlying rock and a high stone content, the access tubes could be installed to a depth of approximately 1 m only. This means that soil water measurements are restricted to a maximum depth of 0.9 m. All 24 plots are also instrumented with suction cups at 0.15, 0.3, 0.6, and 0.9 m depths. On some plots a depth of 1.2 m could be reached. One vacuum pump is used to service all of the suction cups simultaneously. The automatic sampling and sample retrieval system is similar to the one used at Robertson. However, sampling of the soil solution with the suction cups was not as successful as at Robertson, probably due to a poor contact between the suction cup and the soil caused by the larger coarse fraction.

An automatic recording weather station with a radio link to the University campus was installed in 1993. The weather station has the potential to monitor temperature, wind speed, rain and incoming solar radiation. Unfortunately, repeated problems were experienced with some of the sensors and the communication link, and consequently the weather data of this station were not used.

3.3.2 Soil properties

The soil is classified as a combination of Clovelly and Glenrosa (Soil Classification Working Group, 1991) derived from granite and shale. Each plot was sampled in April 1990 and the chemical and physical properties prior to the start of the study are shown in Table 3.5. The results are summarised in terms of means per treatment prior to the start of the study and differ from the Robertson data where the antecedent conditions could only be presented as means per block. The cation exchange capacity varies between approximately 4.5 and 8.8 cmol/kg and is indicative of kaolinitic clay.

Table 3.5 Soluble salt content, given in terms of the electrical conductivity of a saturated paste extract, extractable cation concentration, cation exchange capacity and clay content of the experimental vineyard at Stellenbosch, as sampled in April 1990 summarised in terms of means per treatment

Treat-ment	Depth (m)	ECe* (mS/m)	Ca (cmol/kg)	Mg (cmol/kg)	Na (cmol/kg)	CEC** (cmol/kg)	Clay (%)
1	0.15	64.52	3.35	1.71	0.18	5.12	28.5
	0.30	51.07	2.25	1.92	0.15	4.81	27.2
	0.60	39.91	1.20	3.03	0.18	5.61	31.1
	0.90	32.81	0.78	3.93	0.36	5.96	27.2
	1.20	32.06	0.48	5.07	0.59	6.46	21.9
2	0.15	69.55	3.32	1.35	0.15	5.03	22.2
	0.30	52.08	2.52	1.66	0.10	5.07	23.0
	0.60	38.92	1.46	2.65	0.12	5.50	22.9
	0.90	36.33	1.22	3.24	0.21	5.94	26.8
	1.20	28.36	0.69	3.32	0.27	4.89	17.6
3	0.15	50.78	3.55	1.54	0.12	5.24	24.3
	0.30	46.16	3.18	1.53	0.09	5.05	22.2
	0.60	42.97	2.93	2.17	0.08	4.76	17.3
	0.90	38.22	2.79	3.31	0.18	6.69	20.2
	1.20	30.12	2.33	3.78	0.26	5.95	15.8
4	0.15	73.41	3.13	1.28	0.12	5.55	17.7
	0.30	54.53	2.58	1.49	0.09	5.61	20.8
	0.60	41.93	1.92	2.10	0.09	5.51	22.1
	0.90	35.87	1.48	2.70	0.16	6.36	20.4
	1.20	24.00	0.59	3.71	0.23	6.31	23.2
5	0.15	66.98	3.13	1.20	0.05	4.51	24.2
	0.30	44.25	1.95	1.58	0.05	4.55	25.5
	0.60	34.67	1.15	2.11	0.07	4.41	27.5
	0.90	33.43	0.83	2.86	0.08	5.18	30.0
	1.20	26.88	0.39	4.13	0.17	6.13	31.0
6	0.15	83.02	3.39	1.48	0.12	5.57	23.7
	0.30	55.08	2.78	1.86	0.07	5.67	25.4
	0.60	47.28	2.45	2.29	0.09	5.87	26.6
	0.90	40.15	1.54	3.19	0.29	6.72	25.3
	1.20	32.15	0.84	5.05	0.44	8.62	29.1

*ECe=electrical conductivity of a saturated paste extract, **CEC=cation exchange capacity

3.3.3 Irrigation system

A manually controlled micro-sprinkler system was installed in 1990. The micro-sprinklers distribute water in a 280° arc, i.e. the soil surface is not wetted uniformly. Within the row the sprinklers are spaced at 1.2 m and in a mature vineyard the system will wet the trunk of the vine but not the foliage. Each plot has a manually adjustable pressure valve and at 50 kPa the design application rate is 6.85 mm/h. The system is operated without a flow meter and applications are based on the design specifications only.

3.3.4 Water salinity control system

The salinity treatments as well as the Ca:Na ratio used at Stellenbosch are identical to those used at Robertson in 1992/93 and 1993/94 (see Table 3.3). Mixing the 30% stock solution of $CaCl_2$ and NaCl with the control water is achieved using the same manual technique that was used at Robertson in 1991/92, i.e. the required salinity is obtained by using manually controlled needle valves and by adjusting the pressures of the main water supply and a salt injection pump. As mentioned in section 3.2.4, this is a rather cumbersome and time-consuming technique and the salt injection valves had continuously to be adjusted to maintain a stable EC.

The first irrigation with saline water was applied in January 1994. The irrigation water sampling network was not as extensive and detailed as at Robertson. For the January 1994 irrigation event, samples of the irrigation water were taken a short distance away from the point where the stock solution was mixed with the control water, i.e. one sample per treatment (total = 6) instead of a sample at each plot (total = 24) was taken. During the 1994/95 season one plot per treatment was selected where a sampling system similar to the one used at Robertson was installed, i.e. a system consisting of a pressure regulating emitter in a sub-lateral irrigation line connected to a 20 L container. This differed from the previous system in that samples were collected at the plots and not at the control centre, but still only one sample per treatment was collected. These samples were retrieved and the ECi and chemical composition determined in the laboratory.

CHAPTER 4
EFFECT OF SALINE IRRIGATION WATER ON THE WATER AND SALINITY REGIMES OF THE SOIL IN A COLOMBAR VINEYARD UNDER SEMI-ARID CLIMATIC CONDITIONS AT ROBERTSON

4.1 Introduction

The uptake of water by plants is controlled by several factors, one of which is the water potential. The soil water potential again is a function of matric- and osmotic potentials. The first can be manipulated by irrigation while the second is influenced by the soluble salt content of the soil solution. It is reasonable to assume that if crops are exposed to different levels of salinity, soil water potential, and therefore water uptake, will vary. This in turn will lead to variable soil water and soil salinity regimes. In this chapter the effects of the different salinity treatments and chemical compositions of the irrigation water on the soil water content and root zone soil salinity as observed from 1991 to 1995 at Robertson are presented. Different approaches to estimate the water balance, salt balance and leaching fraction are also described.

4.2 Methods

4.2.1 Salinity of the irrigation water

The electrical conductivities of the six different salinity treatments used during the course of this experiment are shown in Table 4.1.

Table 4.1 Salt content of the irrigation water expressed in terms of electrical conductivity (ECi) of the six treatments that were used at the Robertson vineyard

Treatment	Target ECi (mS/m)		
	1991/92	1992/93 & 1993/94	1994/95
1	± 30 (control)	± 30 (control)	± 30 (control)
2	100	75	75
3	200	150	150
4	300	250	250
5	400	350	350
6	600	500	30

The first irrigation with saline water was applied on 13 December 1991. At the end of the 1991/92 season the salinities of all treatments except the control, were reduced to the lower levels shown in Table 4.1. This was done to comply with the recommendation of the Steering Committee that the salinity treatments must be adjusted downwards to overlap better with the three break points of the EC-operational curve used for managing the water releases from the Brandvlei Dam (Fig. 3.1). Treatment 6 was discontinued in 1994/95 and the four plots of this treatment were subsequently irrigated with the control water.

In addition to the electronic record of the ECi values recorded on site, samples of the irrigation water were also collected and analysed. Initially, rain gauges placed at strategic points below the leaf canopy, were used. At the end of every irrigation the rain gauges were emptied and the irrigation water samples taken to the laboratory at Stellenbosch where the electrical conductivity of each sample was determined. A full chemical analysis was done at selected times only. In 1991/92 only the 12 plots of blocks 1 and 4 were equipped with rain gauges. During the 1992/93 season the collection system was expanded and an additional twelve rain gauges were installed in blocks two and three, i.e. we were able to collect samples of the irrigation water from all 24 plots.

In February 1993 the water sampling system was improved by installing a trickle (drip) emitter in the water supply lines serving the 24 experimental rows. The outlet of each emitter was connected to a closed 20 L plastic container, which collects a cumulative, integrated sample of the water, discharged during the course of an irrigation. At the end of each irrigation event the containers were weighed and the mass of water recorded. From each plot a sample of the water was kept for further chemical analyses in the laboratory. This sampling system served two purposes. The main function of the sampling system was to obtain a better record of the chemical composition of the irrigation water. Instead of collecting the water samples immediately after an irrigation event (which was not always possible) to prevent changes in the salt concentration due to evaporation, the "new" system allowed us to leave the samples in the containers longer before being removed for chemical analysis. With the initial system (i.e. the rain gauges) it was found that evaporation during and after an irrigation event, resulted in significant increases in the salt concentration of the irrigation water samples with time. The chemical composition of the water sample that was analysed in the laboratory therefore did not reflect the composition of the irrigation water to which the plants were exposed. The sampling system also created the opportunity to calculate the amount of water that each of the 24 plots received per irrigation event. It was too expensive to service each of the 24 plots with a flow meter and only one water meter was used to record the total amount of water applied per irrigation event. Initially it was assumed that, by adjusting the water pressure at each plot to the same value, the applied water would be distributed uniformly over the whole of the 12 150 m^2 study area. By determining the amount of irrigation water in the 20 L containers, which after each event should be equal, this assumption could be verified.

4.2.2 Irrigation management and irrigation scheduling

During the course of this study, scheduling of irrigation applications was done using two different approaches. During the first season, i.e. 1991/92, irrigation amounts and the frequency of applications were based on calculated estimates of evapotranspiration. During the following three seasons, from 1992/93 to 1994/95, irrigation scheduling was based on *in situ* measurements of the soil water deficit. However, the reference value for calculating the soil water deficit, namely the field water capacity, as well as the soil depth on which the deficit was based, changed slightly from season to season. In order to understand the soil water regime better, the soil water management applicable to each season is described separately. Throughout the experiment all treatments received the same amount of water and no special provision was made for leaching. Furthermore, all seasons have it in common that during winter, the salinity treatments were replaced with the non-saline control water. The saline water was replaced with low salinity canal water

on 1 April 1992, 1 May 1993, 1 May 1994 and 1 April 1995, respectively, for each of the four irrigation seasons.

i) Irrigation scheduling in 1991/92

In 1991/92 irrigation applications were based on a 70% soil water regime, which is similar to the T3 treatment of Van Zyl (1984). This meant that the vineyard was irrigated at a 30% depletion of the total *plant available water*. Evapotranspiration, further on referred to as ET, was estimated from daily Class A-pan data and the crop coefficients of Van Zyl (1984): October 0.31; November 0.47; December 0.50; January and February 0.48 and March 0.45. The calculation of ET did not distinguish between different evapotranspiration rates as affected by the various treatments, i.e. the effect of a lower osmotic potential of the soil solution on crop water uptake was not accounted for. In practice this meant that the vineyard was irrigated according to the assumed evapotranspiration in the non-stressed control treatment. Van Zyl (1984) reports an *in situ* determined mean field water capacity of 263 mm/m for this vineyard, with associated total plant available water content of 151 mm/m. This value was used as the basis for irrigation applications during 1991/92 with a 30% depletion corresponding to 45 mm of soil water. The mean interval between successive irrigation applications for the period 13/12/91 (when the salinity treatments started) and 26/03/92 (end of harvest), was 8.5 days. Conversion of the calculated ET value from mm to a volume of irrigation water was based on a fully wetted area per plant, i.e. 4.5 m^2 per plant or 12 150 m^2 per vineyard, and an irrigation system efficiency of 85%.

Although the water content was not used in deciding when to irrigate, soil water content was monitored with a CPN neutron soil moisture meter throughout the season. Measurements were made twice weekly at depths of 0.15, 0.30, 0.60, 0.90 and 1.2 m. The measurements were taken on fixed days of the week and not relative to an irrigation (which could have been any day of the week as dictated by the rate of evapotranspiration). Inspection of the depth distribution of soil water content and more specifically, the soil salinity profiles at the end of the season suggested a significant leaching within the vineyard rows. We consequently decided to switch to a different scheduling technique.

ii) Irrigation scheduling in 1992/93

From the beginning of the 1992/93 season, the applications were based on measured soil water deficits and not on estimated evapotranspiration. This was done by measuring the soil water content at the normal monitoring position in the plant row on Tuesdays (using the CPN neutron probe) and by calculating the deficit relative to the apparent maximum water storage capacity, for a soil profile of 1.2 m depth. The mean deficit of the four control plots and a total wetted area of 12 150 m^2 were then used to convert mm of deficit to the volume of irrigation water that was applied the next day, i.e. Wednesday. Following the irrigation, the soil water content was measured again on Fridays, which allowed a crude water balance to be obtained. Because of this sequence of events, the irrigation interval for most of the season was seven days.

A survey of the spatial distribution of irrigation water around four microsprinklers conducted in November 1992 revealed that most of the applied water falls on as little as 39% of the total area (4.5 m^2) per plant. In the field it was observed that a strip approximately 0.5 m wide between two adjacent rows is dry, i.e. 1/3 of the total area receives very little or no water at all. The conversion from mm to m^3 of irrigation water

therefore meant that the soil water deficit of an area equivalent to 12 150 m^2 is applied to 8 150 m^2. It is speculated that this is one of the causes for the high leaching fraction inferred from the salinity profiles observed at the end of the 1991/92 season. Based on these results, we decided that the conversion from mm to m^3 of applied water in future should be based on 8 100 m^2 rather than 12 150 m^2. This change was implemented on 1 December 1992.

In his thesis, Van Zyl (1984) mentions mean values for field capacity for each of the different treatments that he used, without specifying where in the 3.6 ha vineyard (original size) the actual field measurements were made. Less than half the area of the original vineyard were used. Because of the uncertainty about exactly where in the vineyard the field capacity measurements were made, it was decided to use the maximum soil water content of the four control plots observed during the 1991/92 season as indices of the apparent maximum storage capacities, rather than the values published by Van Zyl (1984). Only data pertaining to measurements made two days after an irrigation event were used to identify the maximum soil water contents. These reference soil water contents for the four control plots are summarised in Table 4.2 in units of mm/1.20 m as well as mm/1.05 m.

Table 4.2 Soil water contents used as indices of the upper limit of plant available soil water content (field capacity) for the calculation of irrigation applications for the 1992/93, 1993/94 and 1994/95 seasons at Robertson

Plot number Control treatment	1992/93			1993/94 & 1994/95
	Max. H_2O 91/92 N-Probe Calibration 1 (mm/1.20 m)	Max. H_2O 91/92 N-Probe Calibration 1 (mm/1.05 m)	Max. H_2O 91/92 N-Probe Calibration 2 (mm/1.05 m)	Field capacity N-Probe Calibration 2 (mm/1.05 m)
1	333	288	299	287
9	348	291	298	283
13	355	312	326	298
21	358	295	305	282
Mean	348	297	305	287

In 1991/92 and 1992/93 the raw data of the neutron probe soil moisture meter (i.e. the count ratios), were converted to soil water contents using a set of calibration equations developed in 1991 when the neutron access tubes were installed. The neutron probe was calibrated for each of the five depths where water was measured. At that time (1991), only a few measurements of bulk density, measured using the core method were available. Missing values were interpolated using a nearest neighbour approach. *(Bulk density is required to convert gravimetric water to volumetric units).* Soil water deficits and irrigation applications in 1992/93 were calculated using this set of calibration equations. Furthermore, the deficit was based on a rooting depth of 1.20 m with a mean water content of 348 mm as shown in Table 4.2 under the heading "calibration 1". In May 1993 the bulk density of the five depth layers of each plot was measured again, using a gamma probe. Because the bulk density of each plot was now measured rather

than inferred from nearest neighbours and also because the gamma probe measures a larger (more representative) volume of soil than the traditional core method, it was felt that the first calibration of the neutron probe could be improved upon. This recalibration was completed in May 1993 and all the water contents of the previous two years were subsequently recalculated. It is assumed that the recalibration of the neutron probe would not have affected the irrigation applications in any significant way (if at all). This assumption is warranted because the new calibration equation was essentially an adjustment of the intercept of a linear equation without influencing the slope of the line. The maximum storage capacities of the four control plots recalculated with the improved calibration equations are given in Table 4.2 (calibration 2) in units of mm/1.05 m.

iii) Irrigation scheduling in 1993/94 and 1994/95

The irrigation scheduling technique used in 1993/94 and 1994/95 was similar to that of 1992/93, i.e. applications based on the measured soil water deficit. However, *in situ* determined field capacity values were now used to calculate the soil water deficit. Field capacity (or drained upper limit) of the 12 plots of treatments 1, 4 and 6 were determined in the winter of 1993, when the vines were dormant. Instead of continuous ponding, water was applied using the micro-irrigation system described in Chapter 3. In each of the 12 plots, soil water content was monitored continuously at two positions in the plot using a neutron probe moisture meter until satiation was reached (i.e. maximum attainable water content under field conditions). An area of approximately 10 m^2 of the soil surface was then covered with plastic sheeting and the drying curve followed for a prolonged period. The field capacity of each depth layer (0.0-0.15 m, 0.15-0.30 m, 0.30-0.60 m, 0.60-0.90 m, and 0.90-1.20 m) was determined separately. The water contents at field capacity of the four control plots expressed for a root zone of 1.05 m soil depth are listed in Table 4.2. The experimentally determined mean field capacity of 287 mm/1.05 m is equivalent to 273 mm/m which is slightly more than the 263 mm/m reported by Van Zyl (1984) for the same vineyard.

All other procedures concerning soil water monitoring and irrigation scheduling were the same as in 1992/93. Logistical problems (mostly related to the availability of labour) in 1994/95 prevented us from being consistent with regard to the timing of the post-irrigation water content measurement. On a number of occasions the measurement was done on a Saturday.

The different approaches used in scheduling irrigations and the reference water contents applicable to the calculation of the soil water deficit, during the course of this study, can be summarised in chronological sequence as follows:

Time	Scheduling method	Area used to convert depth to volume	Reference water content
1/9/91-30/4/92	Calculated ET using A-pan data; 30% depletion of plant available water; 151 mm/m	12 150 m^2	263 mm/m
1/9/92-1/12/92	*In situ* measured soil water deficit	12 150 m^2	348 mm/1.20 m
1/12/92-30/4/93	*In situ* measured soil water deficit	8 100 m^2	348 mm/1.20 m
1/9/93-30/4/94	*In situ* measured soil water deficit	8 100 m^2	287 mm/1.05 m
1/9/94-30/4/95	*In situ* measured soil water deficit	8 100 m^2	287 mm/1.05 m

Unless stated otherwise, all water contents presented in this report, are based on the May 1993 calibration equations and are expressed as mm per 1.05 m soil depth.

4.2.1.3 Monitoring soil salinity

Soil samples were taken with an auger at each of the 24 plots at the beginning (September) and end (March or April) of the 1991/92, 1992/93, 1993/94 and 1994/95 irrigation seasons. Samples of the 0-0.15 m, 0.15-0.3 m, 0.3-0.6 m, 0.6-0.9 m and 0.9-1.2 m depths were collected, dried, sieved and saturated paste extracts made using the method of Longenecker and Lyerly (1964). The saturation percentage, pH (of the paste), EC_e (mS/m), Ca, Na, K, Mg, NO_3, Cl, SO_4, PO_4 and HCO_3 (all in mg/L) were determined. Cation concentrations were determined using an atomic absorption spectrophotometer (*Varian AA 1275 and Varian AA 250+*). With the exception of HCO_3, all anion analyses were done with an ion chromatograph (*Dionex 200-SP*). The sum of carbonate and bicarbonate concentrations were determined by difference, (i.e. $CO_3 + HCO_3$ = sum of cations - sum of anions). For the sake of brevity, the results pertaining to the EC_e and SAR only are presented in this report.

The method of Longenecker and Lyerly (1964) is based on the principle that if a soil sample is in contact with a water-saturated sand, it will saturate itself by capillary action. Because of the large differences in the salt content of some the samples and that of the distilled water in the sand bath, the effect of contact time on dilution of the soil solution (due to diffusion from the soil to the sand bath) was evaluated. Twenty samples of a saline soil were placed on the sand bath. After contact times of 1, 3, 6, 12 and 15 hours two samples (per time) were removed and the pH of the paste, water content and electrical conductivity of the extract determined. A saturated paste was also prepared in duplicate by adding and mixing distilled water with samples of the same soil (i.e. according to the standard hand method of Richards, 1954). The results are summarised in Table 4.3. From 1 to 15 hours the water content of the soil increased by 1.5%, the pH by 0.23 while the ECe decreased by 70 mS/m. The water content, pH and ECe after 15 hours compared favourably with the standard hand method. Based on these results we concluded that 15 hours is the minimum contact time necessary to obtain results comparable to the standard hand method, and that in this period, dilution will be negligible. Throughout the course of this study, a contact time of 18 hours was used.

Table 4.3 Effect of time in contact with a water-saturated sand bath on the water content, pH and electrical conductivity of saline soil samples from the Robertson vineyard

Contact time (h)	Water content (kg/100kg)	pH	ECe (mS/m)
1	29.2	7.03	663
3	30.6	7.02	640
6	30.7	7.10	627
12	30.2	7.28	629
15	30.9	7.26	593
Hand method	33.0	7.00	610

The soil solution was sampled using the porous cup soil water samplers and the sampling technique described in Chapter 3. The samplers were installed in phases between

February and August 1992 with the result that only limited information on the salinity of the soil solution of 1991/92 is available. Samples of the soil solution were always taken approximately 36 hours after the cessation of an irrigation event. It was found that a 12 hour cycle of intermittent suction, with 1 hour breaks in-between, gave the best results in terms of the overall success rate, i.e. whether a sample could be collected or not as well as the volume of sample collected. A maximum of 120 samples can be collected at any time (24 x 5), but between 1992 and 1995 we were never able to collect more than 115 samples out of the possible 120. On average between 80 and 100 samples per event could be collected. The soil water samples were retrieved before the next irrigation event, normally on a Tuesday, and the electrical conductivity determined (EC_{sw}). At selected times during the season a more complete chemical analysis was performed. Samples were also collected during winter.

4.3 Results

4.3.2 Seasonal mean electrical conductivity and chemical composition of irrigation water

Irrigation with saline water in the four seasons started on the following dates:

1991/92	19 December 1991	1992/93	11 November 1992
1993/94	22 September 1993	1994/95	5 October 1994

In spite of the seemingly good control over ECi recorded electronically during an irrigation event (i.e. short term stability as illustrated in Figure 3.4), the laboratory measured ECi values of the irrigation water samples at times deviated substantially from the target values. This is illustrated in Figure 4.1 which is the time series of the treatment mean ECi of water samples collected during the 1993/94 season. The cause for this deviation was the salinity sensors in the water supply system which gradually became clogged with dirt and consequently, increasingly less sensitive with time. We therefore had to regularly clean and recalibrate the sensors.

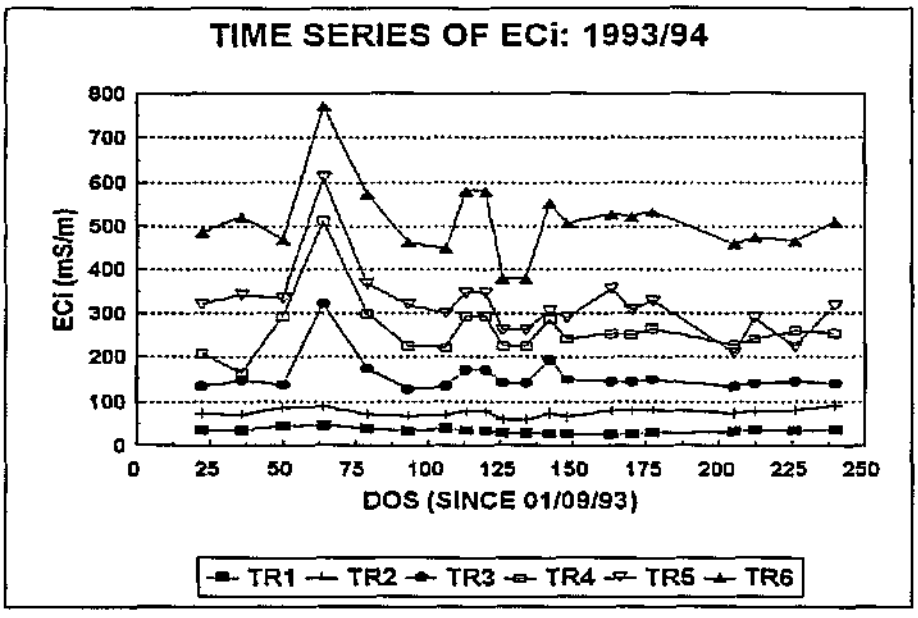


Figure 4.1 The 1993/94 time series of mean ECi per treatment calculated from the irrigation water samples collected *in situ* in the 24 L containers at each of the 24 plots of the Robertson vineyard

Based on the volumes of applied water and the ECi's per event, a volume-weighted seasonal mean ECi value for each treatment could be calculated (Table 4.4). A complete chemical analysis of the irrigation water was conducted on 24 occasions, i.e. eleven events in 1991/92, seven events in 1992/93, four events in 1993/94 and two events in 1994/9. The results of the 1992/93 to 1994/95 seasons were combined and the relationship between ECi and each of Ca, Na, Cl and the total salt content, referred to here as TDS, were determined using regression analysis. Similar relationships were determined for the 1991/92 season but, because of the different Ca:Na ratio that was used during the first season, the 1991/92 data set was treated separately. It is important to note that in the regression analysis (Table 4.5) the Y-intercept value was not calculated but was forced through zero. Consequently, in Table 4.5 all the intercept values are shown as 0. Using the volume-weighted seasonal mean ECi values and the appropriate regression coefficients (Table 4.5), the volume weighted mean Ca, Na, and Cl content of the irrigation water for each treatment and season could be reconstructed (Table 4.4). It should be stressed that the ECi values and chemical compositions shown in Table 4.4 represent the whole period 1 September to 30 April and include the effect of the low salt canal water that was sometimes used early in the season (September to October).

4.3.2 Irrigation quantities

The gross volume of water used for irrigation and the calculated potential evapotranspiration (PET) using class A-pan data for the period 1 September to 30 April for each of the four seasons are shown in Table 4.6. For the 1994/95 season Class A-pan data were not available and PET was calculated using the Penman-Van Bavel equation (Van Bavel, 1966). The PET data of 1994/95 therefore cannot be compared with the data of the previous three seasons. The volume of irrigation water used in 1991/92 was considerably more than for any of the subsequent seasons. This can be explained by the way in which the soil water deficit (in mm) was converted to volume (m^3). Between September 1991 and December 1992, the conversion was based on the total area of the vineyard (12150 m^2) in contrast to the smaller wetted area (8100 m^2) that have been used since December 1992. The less water that was used in 1993/94 compared to 1992/93 is attributed mainly to the fact that irrigation during the first three months of 1992/93 was also based on the assumption of a fully wetted surface area, i.e. 12 150 m^2.

The information in Table 4.6 also highlights an irrigation management problem that has considerable practical implications and for which no solution was found in this study. If the A-pan data and crop factors are correct and our assumption is wrong that the plants exploit only 2/3 of the available soil volume to meet its water demand, the vineyard since 1992/93 could have been under-irrigated by a considerable amount. For example, for the 1993/94 season the volume of water applied is equivalent to 566 mm per 12 150 m^2 and 849 mm per 8 100 m^2. Compared to the A-pan calculated ET of 702 mm the former value represents an under-irrigation of 136 mm while the second approach represents an over-irrigation of 147 mm. Similar comparisons can be made for the other years. As will be seen in a following section, the salinity profiles suggest that considerable leaching occurred within the wetted zone in 1991/92, which is indicative of over-irrigation.

The volumes of irrigation water applied from May to August, using the non-saline canal water, are also shown in Table 4.6. Between May and August 1993, the irrigation system on three occasions was used in the field experiment to determine the *in situ* field capacity

of the soil. This accounts for the large amount (4741 m^3) of water that was applied during the winter of 1993.

Table 4.4 Volume-weighted mean ECi and chemical composition of irrigation water for the period September to April of the following year for 1991/92 to 1994/95 seasons at the Robertson vineyard

Target (mS/m)	EC_i (mS/m)	Ca (mmol/L)	Na (mmol/L)	Ca:Na (molar)	SAR*	Cl (mmol/L)	$EC_{i\text{-}rain}$** (mS/m)
1991/92* **							
30 (control)	29	0.69	1.51	0.45	1.82	2.85	27
100	78	1.83	4.02	0.45	2.97	7.58	72
200	159	3.75	8.24	0.45	4.26	15.55	146
300	251	5.90	12.99	0.45	5.34	24.51	230
400	429	10.10	22.22	0.45	6.99	41.94	394
600	475	11.18	24.59	0.45	7.35	46.40	436
1992/93* **							
30 (control)	26	0.85	0.88	0.96	0.95	2.58	22
75	65	1.92	1.81	0.96	1.33	5.27	52
150	128	3.94	3.13	0.96	1.68	9.08	101
250	212	7.06	5.46	0.96	2.12	15.61	167
350	285	9.78	7.67	0.96	2.46	21.87	225
500	433	16.20	11.66	0.96	2.90	33.30	341
1993/94							
30 (control)	34	1.09	1.14	0.96	1.09	3.33	31
75	75	2.44	2.54	0.96	1.63	7.41	69
150	158	5.12	5.34	0.96	2.36	15.56	144
250	263	8.54	8.91	0.96	3.05	25.98	243
350	323	10.51	10.96	0.96	3.38	31.95	296
500	509	16.54	17.25	0.96	4.24	50.29	471
1994/95							
30 (control)	32	1.04	1.08	0.96	1.06	3.16	27
75	58	1.90	1.98	0.96	1.44	5.77	49
150	121	3.94	4.11	0.96	2.07	11.98	97
250	196	6.35	6.62	0.96	2.63	19.31	162
350	318	10.34	10.78	0.96	3.35	31.44	258
25	35	1.15	1.20	0.96	1.12	3.50	31

* SAR = sodium adsorption ratio = $Na/(Ca+Mg)^{0.5}$ with concentrations in mmol/L

** $EC_{i\text{-}rain}$: ECi adjusted for rain during season, with EC_{rain} = 5 mS/m

*** Treatments 2 to 6 include 1871 m^3 of canal water applied between 1/09/91 and 19/12/91 and 208 m^3 of canal water applied between 2/10/92 and 11/11/92

4.3.3 Soil water regime

The time series of soil water content for treatments 1, 2, 4 and 6 from September to April for 1991/92, 1992/93 and 1993/94 are shown in Figure 4.2. The water fluctuations of 1992/93 and 1993/94 have a higher frequency than 1991/92 because of the shorter irrigation interval that was used.

Table 4.5 Linear regression statistics of the relationship between ECi (in mS/m) and the total salt content (TDS, mg/L) and ionic composition (mg/L) of the irrigation water for 1991/92 and the combined data set for the 1992/93 to 1994/95 seasons, where Y (mg/L) = $a + bECi$ (mS/m)

Y	1991/92 (n=66)			1992-1995 (n=308)		
	a	b	r^2	a	b	r^2
TDS (mg/L)	0	5.639	0.983	0	5.584	0.986
Cl (mg/L)	0	3.508	0.982	0	3.506	0.986
Ca (mg/L)	0	0.941	0.955	0	1.299	0.975
Na (mg/L)	0	1.190	0.983	0	0.779	0.974

Table 4.6 Gross volume of water used for irrigation, A-pan evaporation and evapotranspiration calculated using the the crop factors of Van Zyl (1984) for the period September to April

September to April	1991/92	1992/93	1993/94	1994/95
Irrigation, gross volume applied (m^3)	11251	7452	6877	7347
Irrigation (mm)				
per 12150 m^2	926	613	566	604
per 8100 m^2	1389	920	849	907
Rainfall (mm)	126	252	113	201
PET = A-pan data (mm)	1794	1967	1678	1607* 1647**
AET=PET x crop factor (mm)	782	823	702	ND
May to August	**1992**	**1993**	**1994**	**1995**
Irrigation, gross volume (m^3)	2991	4741	1312	NA
Irrigation (mm)				
per 12150 m^2	246	390	108	
per 8100 m^2	369	585	162	
Rainfall (mm)	155	142	117	

* = Reconstructed A-pan record

** = Based on Penman-Van Bavel equation

The marked decrease in soil water content observed between day 90 and 120 of 1992/93 as well as the wetter soil water regime of 1991/92 is attributed to a change in the water management that was implemented in December 1992. Since December 1992 irrigation applications were based on a wetted area of 8 100 m^2 which is 30% less than the total area of the vineyard, i.e. 12 150 m^2.

In all four years the soil water content during the season fluctuated in response to irrigation and evapotranspiration without any clear and consistent trend between treatments (Fig. 4.2). For each of the four seasons the soil water content measured the day after the grapes were harvested are shown in Figure 4.3. With the possible exception of 1994/95, the general trend was for soil water content to increase with ECi, which can

be attributed to a reduced water uptake at the higher salinities. However, this trend became visible only after an extended period of drying during which time the vineyard was not irrigated. We conclude that in this well drained soil, the high frequency of irrigation applications tended to mask the negative effect of salinity on water uptake.

The seasonal mean water content per treatment for the four years are shown in Table 4.7. The differences in treatment mean water content between the seasons were minor with the maximum difference being 29 mm (treatment 2, 1991/92 and 1993/94). In most cases the differences were less than 15 mm. The data show that for all treatments the soil water regime of 1993/94 was drier than any of the other seasons. This is consistent with the smaller amount of irrigation water that was applied in 1993/94 (Table 4.6). Within any particular year, the seasonal mean soil water content also does not show an increase as salinity increases. Treatment 3 was consistently drier than any of the other treatments. This could have been caused by a number of factors, but the most likely explanation is that treatment 3 received less water than the other treatments. This possibility was evaluated by using the 1993/94 and 1994/95 data of the weight of the water collected in the 20 L containers per irrigation event, to calculate the fraction of the seasonal total of water used (Table 4.6) that each treatment received. According to this analysis treatment 3 in 1994/95 did receive less water than the other treatments. However, in 1993/94 it was treatment 2, which received the least amount of water. The difference between the maximum (treatment 6) and minimum (treatment 2) in 1993/94 was 33 m^3 per plot, which is equivalent to 98 mm per wetted area or 65 mm per total area. The difference between maximum and minimum in 1994/95 was of the same order of magnitude. The sequence from the minimum to maximum amount of water applied is not consistent with the sequence from low to high seasonal mean soil water content (Table 4.7) and suggests that unequal water distribution among the different plots and treatments is not the main cause of the differences in the seasonal mean water contents.

The volume of irrigation water per plot was calculated from the weights of water in the 20 L containers that were connected to the trickle emitters. Consequently, it is possible that the inferred differences between plots could be the result of variations in the flow rates of the 24 emitters. In 1994 this was investigated by checking the flow rate of each emitter individually under controlled laboratory conditions (at a pressure of 50 kPa). A coefficient of uniformity (U_s) of 0.942 was achieved ($Us = 1 - S_q/q$; S_q = *standard deviation of emitter flow*, q = *mean emitter flow rate*, Bralts & Edwards, 1987). The relationship between the individual emitter flow rates and, as an example, the total volume of water that each plot received in 1993/94 is shown in Figure 4.4.

Despite the relatively high coefficient of uniformity, there seems to be a weak (but noticeable) relationship between the flow rate and volume per plot. However, the differences in the flow rate of the emitters cannot explain all the variability in the soil water contents of the salinity treatments shown in Table 4.7. It is therefore concluded that:

i) the differences in the treatment mean soil water contents were not caused by non-uniform irrigation water applications, and

ii) that these differences must be soil and plant related (i.e. the differences are caused by natural spatial variability of soil physical properties, the treatment-imposed differences in soil salinity and differences in plant size) which in combination led to variable evapotranspiration rates and therefore different soil water regimes.

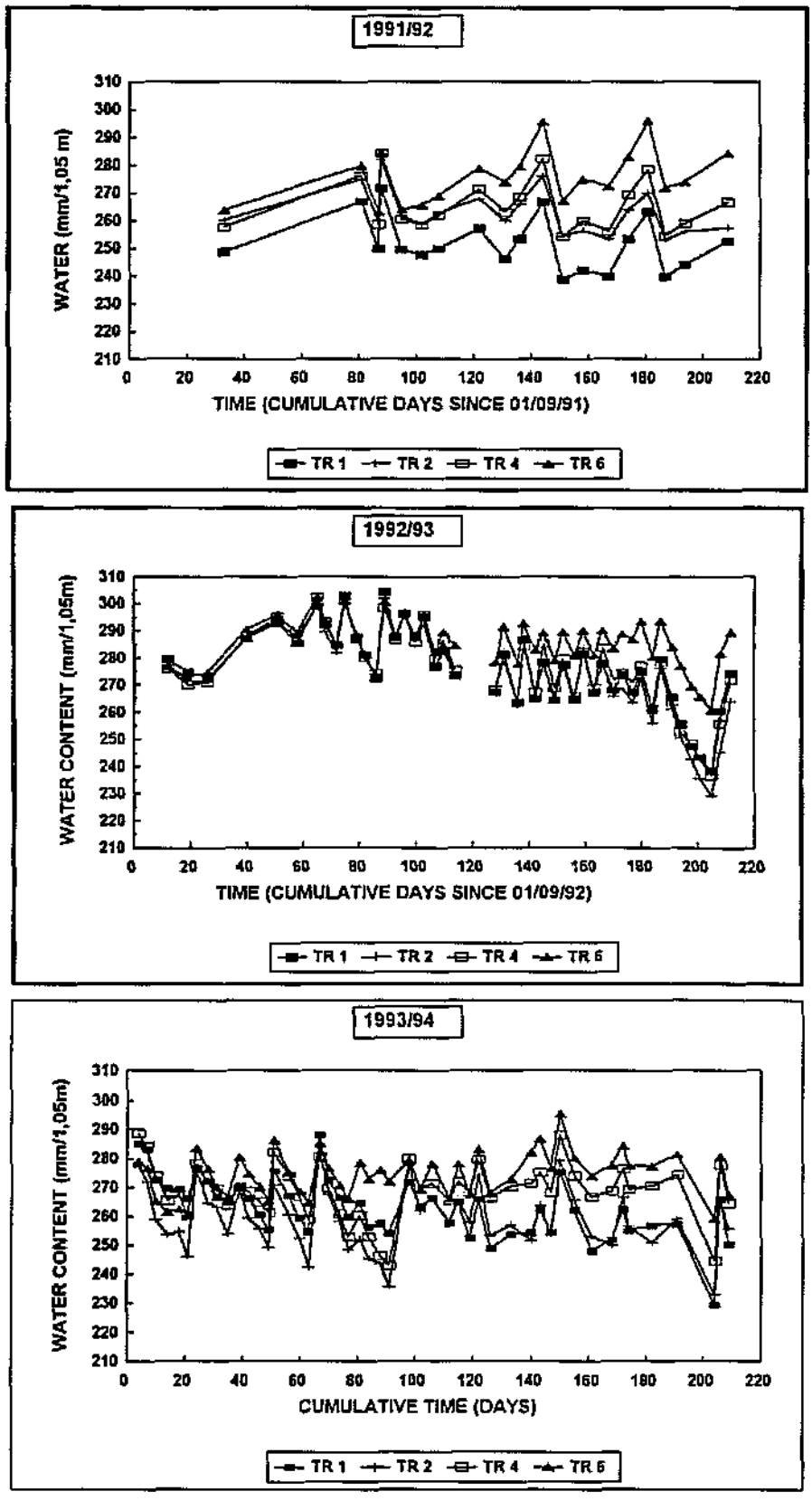


Figure 4.2 Time series of the treatment mean soil water content of treatments 1, 2 4 and 6 for the 1991/92, 1992/93 and 1993/94 irrigation seasons at Robertson

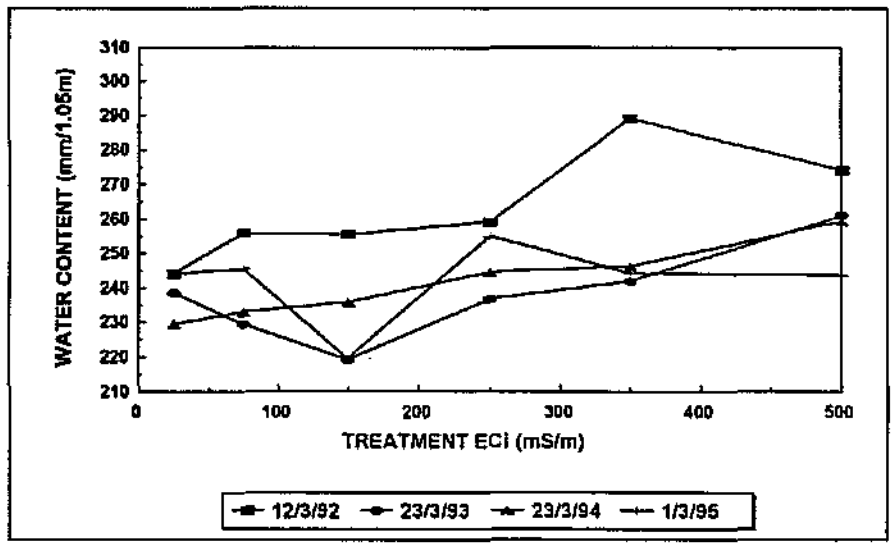


Figure 4.3 Relationship between irrigation water salinity (ECi) and treatment mean soil water content measured after an extended period of drying during which no water was applied

Table 4.7 Seasonal mean water content per salinity treatment for the 1991/92 to 1994/95 irrigation seasons

Treatment	Soil water content (mm/1.05 m)			
	1991/92	1992/93	1993/94	1994/95
1	275	276	263	271
2	288	274	259	270
3	258	258	254	248
4	277	277	269	278
5	262	272	260	266
6	281	286	275	276

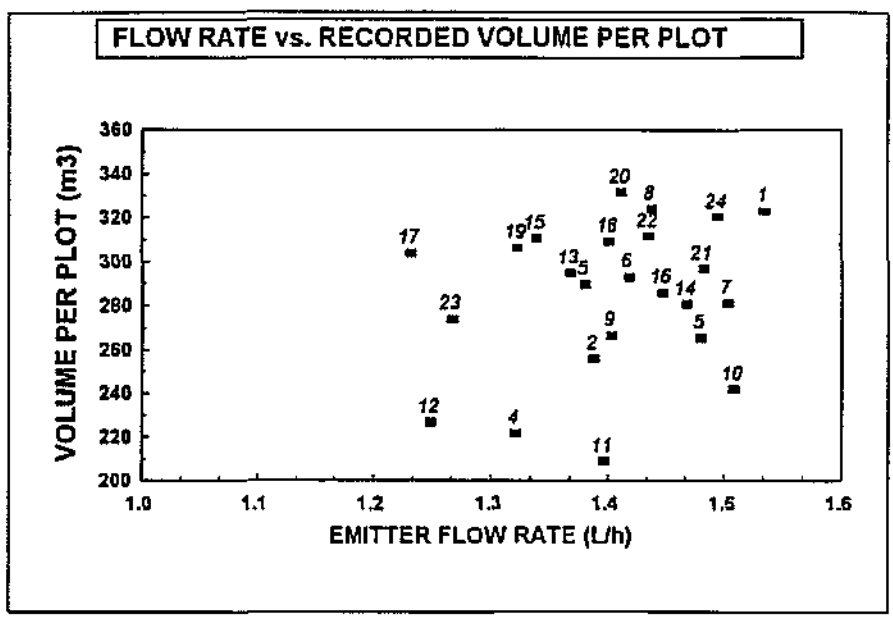


Figure 4.4 Relationship between the flow rate of a reference emitter in each plot at a pressure of 50 kPa, and the volume of irrigation water (calculated proportional to the flow rate of the reference emitter) that each plot received during the 1993/94 season (the labels indicate the plot numbers)

Since 26 January 1993, the soil water content of treatments 1, 4 and 6 were routinely measured at two positions within each plot. The first measuring point is the normal position situated within the row midway between two neighbouring micro sprinklers (0.75 m from the sprinkler). The second measuring position is in the middle of two adjacent vineyard rows (1.5 m from the sprinkler). These two positions are referred to as the A *(within)* and B *(between)* row positions. The B position lies outside the wetted area of the micro-sprinklers and should in theory be drier than the A position. The difference in the soil water content of these two positions, calculated as A *(within)* minus B *(between)* for the 1993/94 season is shown in Figure 4.5.

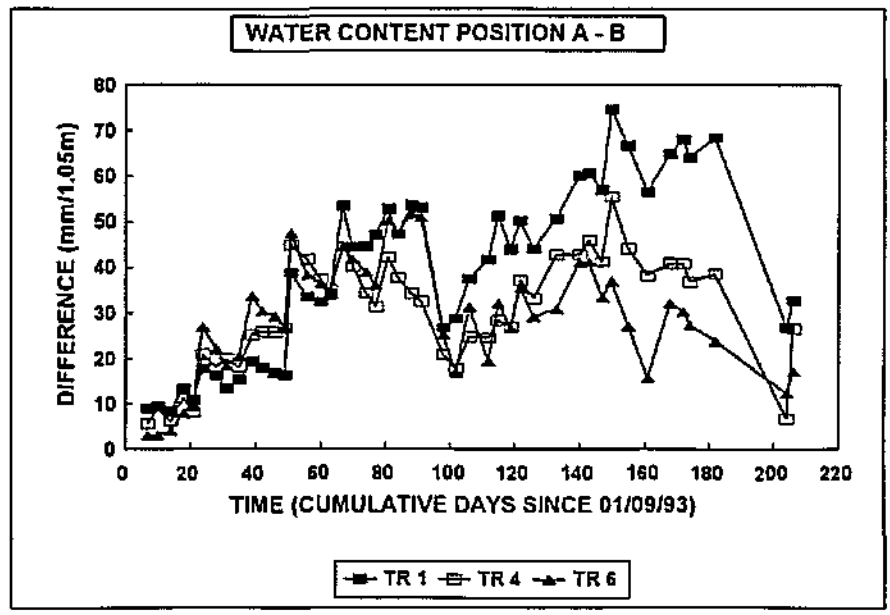


Figure 4.5 Difference in the total soil water content measured at two positions in the Robertson vineyard (expressed as treatment means) during the 1993/94 season: A=measured within the row, B=measured between adjacent rows

At the start of the irrigation season (September) position B was only slightly (<10 mm) drier than position A. The differences between the three salinity treatments were also small. As the season progressed the difference between A and B gradually increased to approximately 40 to 50 mm. Between day 90 and day 100 of the 1993/94 season, the automatic irrigation control system erroneously applied irrigation water for two consecutive days. This over- irrigation had a marked effect on the difference in water content between A and B (Fig. 4.5). From day 100 a significant treatment effect started to emerge with the difference between A and B of treatment 1 > treatment 4 > treatment 6. This sequence suggests that the rate of water uptake in the 4.5 m^2 area per plant decreased with an increase in salinity. Because treatment 4 and 6 received the same amount of water as the control treatment, the soil within the wetted zone gradually became wetter with a concomitant increase in the water content due to lateral redistribution to the non-wetted zone (position B). The difference in water content between positions A and B therefore decreased towards the end of the season. After harvest, the vineyard was deliberately over-irrigated which, even in the case of treatment 1, resulted in a substantial increase in the water content at position B. This explains the marked reduction in the difference in water content of positions A and B that can be seen from about day 180 to 210 (Fig. 4.5).

4.3.4 Soil salinity

a) Annual trends in electrical conductivity (ECe) and sodium adsorption ratio (SAR) of the saturated paste extract

The salinity profiles of the different treatments, presented as bar graphs of the treatment mean electrical conductivities (ECe) and sodium adsorption ratios (SAR) of the saturated paste extracts, at the beginning and end of each irrigation season are shown in Figures 4.6 and 4.7. Also indicated in Figure 4.6 are the associated volume-weighted seasonal mean salinities of the irrigation water. With the exception of the control (treatment 1), there was a significant build-up of salt in the soil profile during the irrigation season with the salt accumulation increasing with the salinity treatments. The relatively uniform salt profiles of 1991/92 suggest high leaching fractions. The soil samples used to monitor temporal changes in soil salinity were collected midway between two adjacent vines in the experimental row directly below a microsprinkler at a position where the water distribution of two neighbouring microsprinklers overlap. Because of the unequal wetting of the soil surface, the surface water flux and therefore deep percolation, will be considerably more at the sampling point than at a position further away. Although lower irrigation water salinity was used, the salt content at the end of the second (1992/93) season was, with the exception of treatments 5 and 6, higher than during the previous year. This indicates an improved irrigation management with less deep percolation losses and a more pronounced salt accumulation with depth in 1992/93 compared to 1991/92. The reduced leaching within the vineyard row is attributed to the fact that since December 1992/93, irrigation quantities were based on wetting only 2/3 of the total area per plant.

The results and temporal trends of the treatment mean SAR can be summarised as follows (Fig. 4.7):

i) SAR increases with the salt content of the different treatments, which is in accordance with the chemical composition of the water (see Table 4.4).

ii) There was a significant increase in the SAR from October 1991 to March 1992. The SAR at the end of the summer in March 1993 is lower than that of March 1992. This is a direct consequence of the change in the Ca:Na ratio from 1:1 equivalent (1991/92) to a 1:1 molar (1992/93) ratio.

iii) After the initial decrease in SAR from March 1992 to September 1992, and with the exception of treatment 6 where the downward trend continued till April 1993, all treatments show a progressive increase in SAR with time in the subsoil. This is especially noticeable at the 0.9 m and 1.2 m depth. This eventually might impact negatively on the internal drainage characteristics of the soil.

The salinity profiles of treatments 1, 4 and 6 are shown in a different format in Figure 4.8. Salinities at the 0.6 m and 0.9 m depths of treatment 4 have increased progressively since 1991/92. At the end of the 1993/94 season there were only minor differences in the salt concentration of treatments 4 and 6 at the 0.6 and 0.9 m depths. In spite of this and as will be shown in a following chapter, the yield of treatment 4 (ECi = 250 mS/m) was not statistically different from the control treatment, whereas treatment 6 experienced a severe yield decrease. This might be interpreted as an indication that grapes respond more to irrigation water salinity than to soil salinity. However, as will be shown in a following chapter, yield correlated better with soil salinity than with irrigation water salinity. Furthermore, in view of the progressive increase of salinity during the course of

this study, and judging from the effect that the other salinity treatments had on yield, it seems reasonable to predict that an irrigation water with a salt content similar to that of treatment 4 will eventually have a negative impact on yield.

The depth weighted mean soil-, and the volume-weighted rain- and irrigation water salinities at the beginning and end of the four irrigation seasons are summarised as treatment means in Table 4.8. Despite large differences in the irrigation water salinities, the salinity profiles (Fig. 4.8) as well as depth-weighted mean salinities (Table 4.8) of treatments 4, 5 and 6 in 1992/93 and 1993/94 were more or less similar. This is indicative of large differences in soil water uptake by the plants of these three treatments. In the case of treatment 4 the plants in 1992/93 and 1993/94 were able to use the 250 mS/m irrigation water to a greater extent than was the case with the higher salinity waters of treatments 5 and 6. This led to a greater evapoconcentration of salts and less leaching within the 0 to 0.9 m deep root zone of treatment 4 compared to treatments 5 and 6. Apparently, due to the low osmotic potential of the soil water and/or irrigation water, plant water uptake was severely influenced at the 350 and 500 mS/m levels. The situation changed somewhat in 1994/95 with treatment 5 being considerably more saline than treatment 4. This might serve as an indication that after three years the salinity of treatment 4 was starting to affect plant water uptake. This led to an increase in leaching and therefore a reduction in salt accumulation with depth.

b) Spatial variability of soil salinity

The treatment mean salinity data reported in the previous sections are based on one sample per plot, always taken at the same position relative to a microsprinkler *(see section "a" above)*. Logistical and financial constraints prevented us from taking more than one sample per plot on a routine basis. Consequently, the extent and effect of within-plot spatial variability could be investigated on a limited scale only. In March 1994 five samples per plot were collected (to a depth of 1.2 m) on the four replicates of treatment 4. All sampling positions were located within the row, directly below a microsprinkler as shown schematically in Figure 4.9a. The effect of within-plot as well as within-treatment spatial variability can be inferred from the depth weighted mean ECe's of treatment 4 summarised in Table 4.10. Considerable variability within a plot is evident, e.g. in plot 16 the depth-weighted mean ECe ranged from 143 to 277 mS/m. The treatment mean ECe and standard deviation for this particular sampling date is 258 mS/m ± 70 mS/m. The effect of sampling position on ECe was further investigated in September 1994 and March 1995 by sampling five positions per plot (to a depth of 1.2 m) but this time at different positions and distances relative to the microsprinkler. The study was limited to blocks 1 and 2 of treatments 1, 4 and 5. The different sampling positions were the normal position (directly below a microsprinkler), and at four additional positions perpendicular to the row, at distances 0.5 m and 1.0 m either side of a microsprinkler (Figure 4.9b). Although salinity to the north and south of the rows differed substantially, the results of each treatment, for the sake of brevity, were reduced to a mean per distance. Reasons for the differences to the northern and southern sides of a vine row were not investigated in greater detail. The depth and spatial distribution of soil salinity of treatment 4 at the beginning (September) and end (March) of the 1994/95 season are shown in Figure 4.10. The general trend at similar depths is for salinity to increase with distance from the row, but the increase is less than expected. For example, the depth-weighted means, minimum and maximum ECe's of treatment 4 at distances 0,

0.5 and 1.0 m from the microsprinkler in March 1995 was 248 (237-259) mS/m, 250 (232-288) mS/m and 265 (219-297) mS/m respectively.

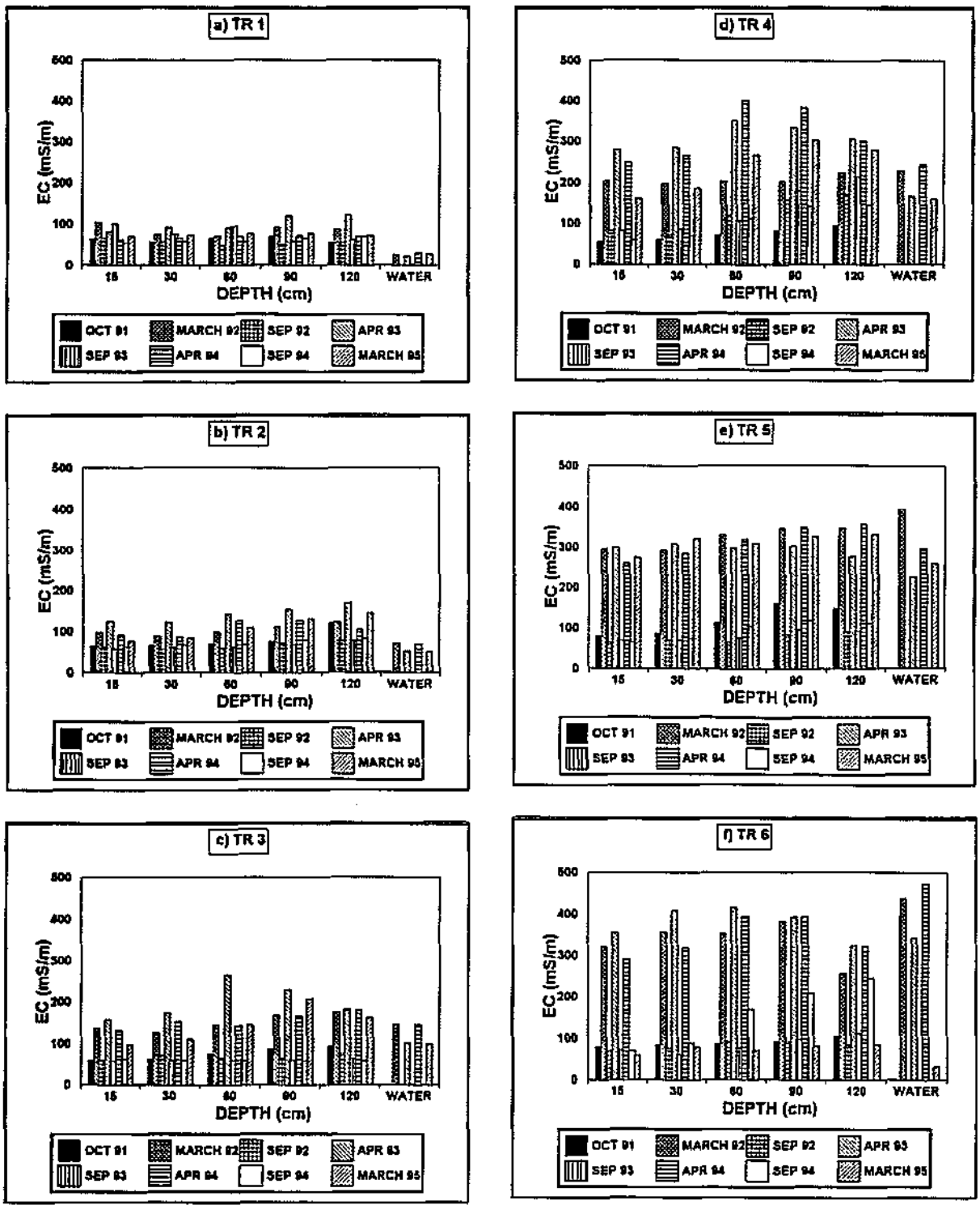


Figure 4.6 Salt content, expressed in terms of ECe at the beginning (September) and end (March or April) of the irrigation season at Robertson, for the period 1991 to 1995, and the associated volume-weighted seasonal mean electrical conductivity of the irrigation water

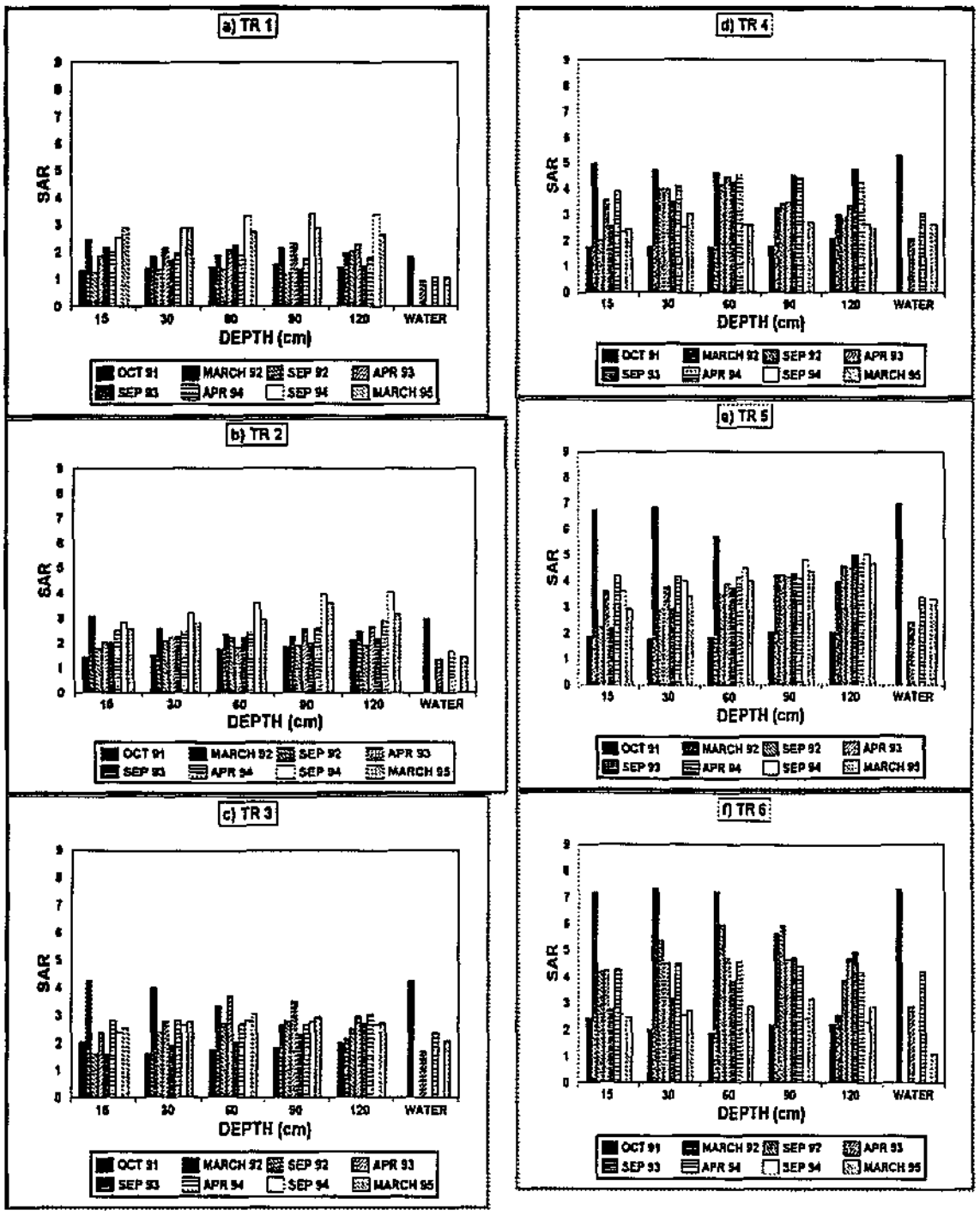


Figure 4.7 SAR of the saturated paste extract at the beginning (September) and end (March or April) of the irrigation season at Robertson for the period 1991 to 1995, and the associated volume-weighted seasonal mean SAR of the irrigation water

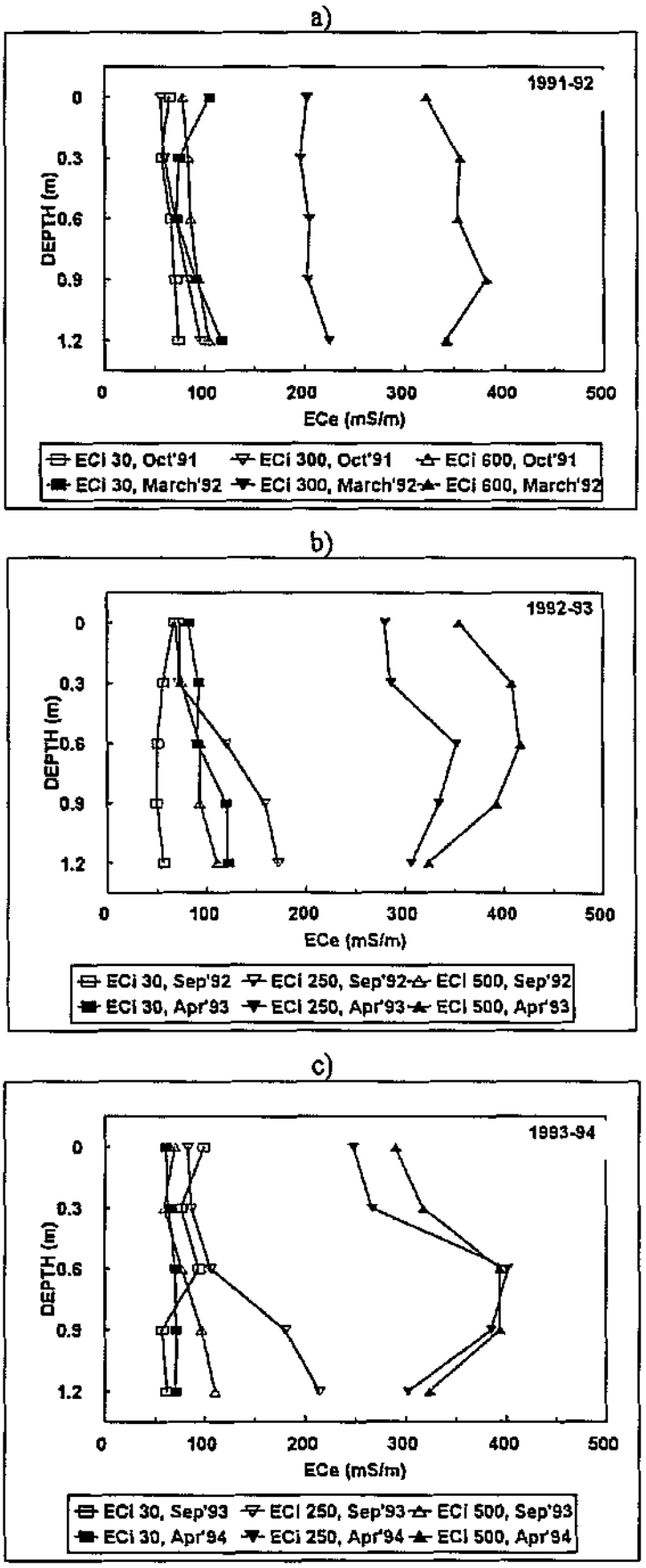


Figure 4.8 Soil salinity profiles of treatments 1, 4 and 6 at the beginning and end of the first three seasons: a) 1991/92, b) 1992/93, c) 1993/94

Table 4.8 Treatment mean depth-weighted mean soil salinity (0-1.2 m) at the beginning (September) and end (March or April) and the associated volume-weighted seasonal mean rain and irrigation water salinities for the 1991/92 to 1994/95 irrigation seasons at Robertson

	Depth weighted mean soil salinity (0-1.0 m depth) and Volume weighted seasonal mean rain and irrigation water salinity (mS/m)					
Season	**Treat. 1**	**Treat. 2**	**Treat. 3**	**Treat. 4**	**Treat. 5**	**Treat. 6**
1991/92						
September	66	71	73	70	120	86
March	84	102	147	202	324	357
Irrig. Water	27	72	146	230	394	436
1992/93						
September	54	64	64	117	72	85
April	99	141	220	323	301	396
Irrig. Water	22	52	101	167	225	341
1993/94						
September	80	62	57	123	80	79
April	68	114	149	348	312	363
Irrig. Water	31	69	144	243	296	471
1994/95						
September	59	70	57	105	98	152
March	75	107	151	248	310	72
Irrig. Water	27	49	97	162	258	31

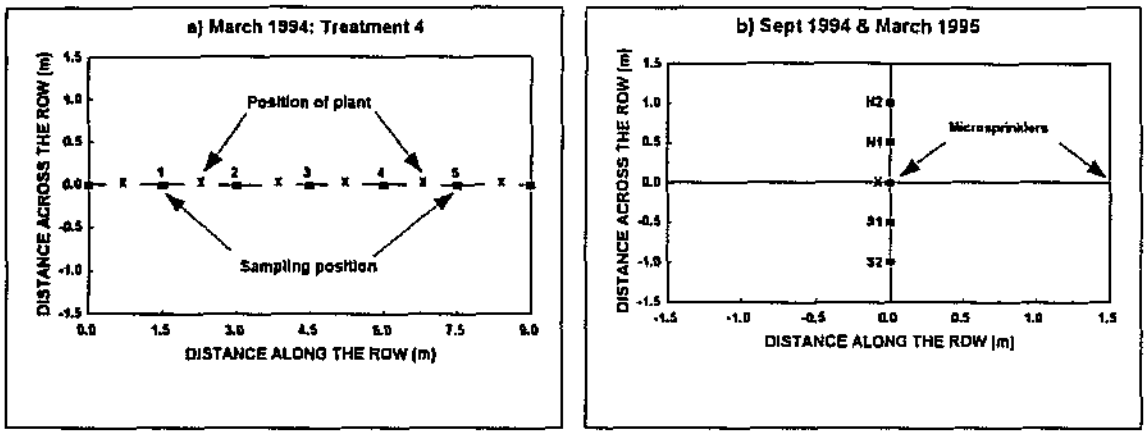


Figure 4.9 Diagram showing the positions where soil samples were collected to determine the spatial distribution of soil salinity: a) March 1994, all replicates of treatment 4; b) September 1994 and March 1995, blocks 1 and 2 of treatments 1, 4 and 5

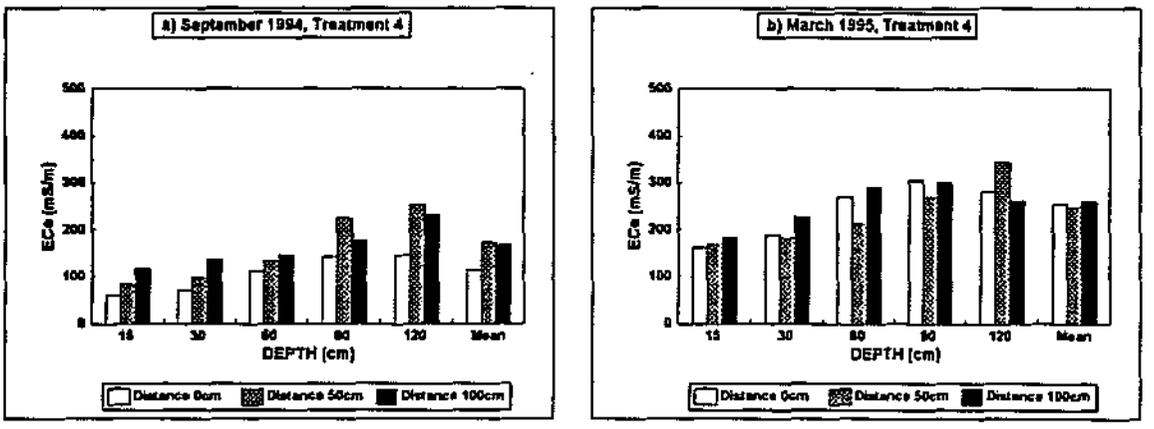


Figure 4.10 Treatment mean ECe of blocks 1 and 4 of treatment 4 as a function of distance from a microsprinkler in a) September 1994 and b) March 1995

Table 4.9 Depth weighted mean ECe and summary statistics of five samples per plot taken at identical positions relative to a microsprinkler, from the four replicates of treatment 4 sampled in March 1994

Depth weighted mean ECe (mS/m)				
Sample	Plot (replicate)			
	3	8	16	20
1	314	210	270	256
2	331	219	277	432
3	238	179	177	328
4	301	262	143	237
5	367	204	210	202
Plot mean	310	215	215	291
Standard Deviation	42	27	52	82
Coef.Variation	0.14	0.13	0.24	0.28
Treatment mean	258			
Standard Deviation	70			
Coef.Variation	0.27			

c) Seasonal changes in electrical conductivity of the soil solution (ECsw)

Since February 1992 the rate of salt accumulation in the root zone during the irrigation season was monitored using suction cup samplers. There were 19 successful sampling events per season in 1992/93 and 1993/94 and 21 in 1994/95. The data were reduced to mean values per treatment and the results were used i) to monitor the rate of change in the salt concentration of the soil solution, ii) to obtain depth weighted mean values for the salt content of the root zone, and iii) to obtain time integrated seasonal mean salinity data for each of the irrigation seasons.

The differences in the salt content per depth and treatment immediately after harvest for the 1992/93, 1993/94 and 1994/95 seasons are presented in Figure 4.11a-c. It is important to distinguish between the salt concentration of the *in situ* soil water (EC_{sw}) shown in Figure 4.11 and that of the saturated paste extracts (EC_e) shown in Figures 4.6

and 4.8. Because of a lower water content the EC_{sw} values are all higher, and represent a higher salt concentration than the EC_e data which reflect conditions of a saturated paste. As expected, the differences in the salt concentration per treatment and depth are substantial. For a particular treatment, each year ended at more or less the same salinity level, e.g. ECsw at the 0.6 m depth for treatment 3 was approximately 400 mS/m for each of the 1992/93, 1993/94 and 1994/95 seasons. The exception is treatment 6 which was irrigated with the control water in 1994/95. The slightly higher ECsw values at the end of the 1992/93 season observed at the 0.15 and 0.3 m depths of treatments 2, 3 and 4 compared to the next two seasons, might be attributed to reduced water uptake and increased leaching with time.

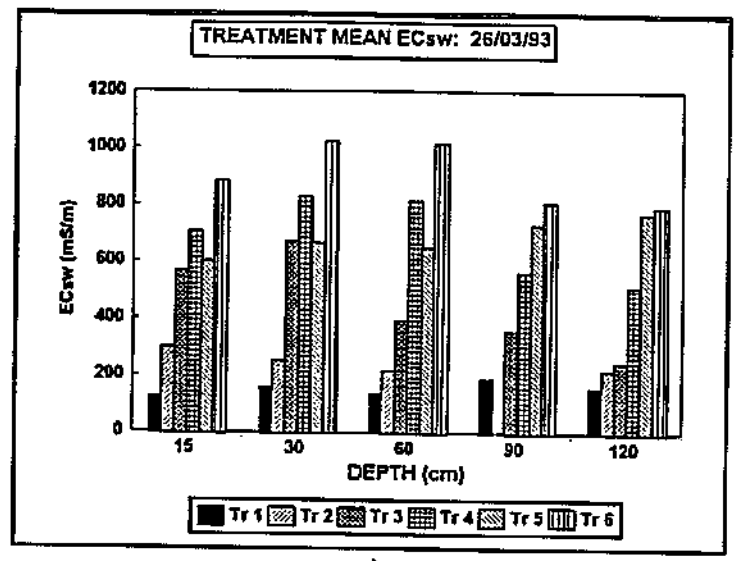
The weekly measurements of soil water content and ECsw were used to monitor the time rate of change in the salt content of the root zone, weighed according to the depth and water content of the respective soil layers. The results of the 1992/93 season, representing three different scenarios, are shown in Figure 4.12a-c. In Figure 4.12a the depth weighted EC_{sw} for the 0-0.3 m topsoil is given while Figures 4.12b & c refer to the subsoil (0.6-1.0 m) and total root zone (0-1.0 m) respectively. An interesting feature seen in Figure 4.12 is the phase lag in the build-up of salt in the subsoil in response to a wave, or front, of low salinity water moving through the profile. At the beginning of the season, the salt content of, for example treatment 6, increased with depth (see Figure 4.6 and 4.8). From the first irrigation with the saline water, applied on day 45 (15/10/92), the salt content of the 0.15 m depth started to increase. This was observed for all the salinity treatments, but was more accentuated in treatments 4, 5 and 6 (Fig. 4.12a). However, as the less saline water of the topsoil moved through the profile the salt content of the deeper layers decreased continuously with time. It was only after a cumulative total of 351 mm per 4.5 m^2, (equivalent to 527 mm per wetted area) of water had been applied (day 110), that the salinities of the subsoil (0.6-1.0 m) started to increase. Similar observations were made in 1993/94 and 1994/95.

d) Long term time course of soil salinity

The long term time course of soil salinity as well as the seasonal mean soil salinities were calculated by combining the electrical conductivities of the saturated soil extracts (ECe) and conductivities of the *in situ* soil water sampled with the suction cups (ECsw). The ECsw values were converted to equivalent ECe values using the equation:

$$ECe = 43.77 + 0.34ECsw \quad (n = 389, R^2 = 0.71, P = 0.001)$$

This relationship was established by linear regression using the data of those dates when both soil samples (ECe) and soil water extracts (with the suction cups) were collected. The slope of the relationship between ECe and ECsw differ considerably from that reported by Ayers & Westcot (1989) *(ECe = 0.50ECsw)* and Hoffman *et al* (1989) *(ECe = 0.6ECsw)*. The time course of soil salinity from October 1991 to March 1995 for the different treatments was expressed in terms of depth-weighted mean values (0-1.0 m). The results for treatments 1, 2, 4 and 6 are presented in Figure 4.13. For the 1991/92 season only ECe data of October 1991 and March 1992 were available. The salinity build-up during summer and the effect of the winter leaching programme are clearly visible. By March 1994, treatments 4 (250 mS/m) and 6 (500 mS/m) had resulted in nearly identical ECe values. Furthermore, although the salt concentration of treatment 6 was nearly double that of treatment 4 (see Table 4.4), the difference in the ensuing soil salinity was much less.



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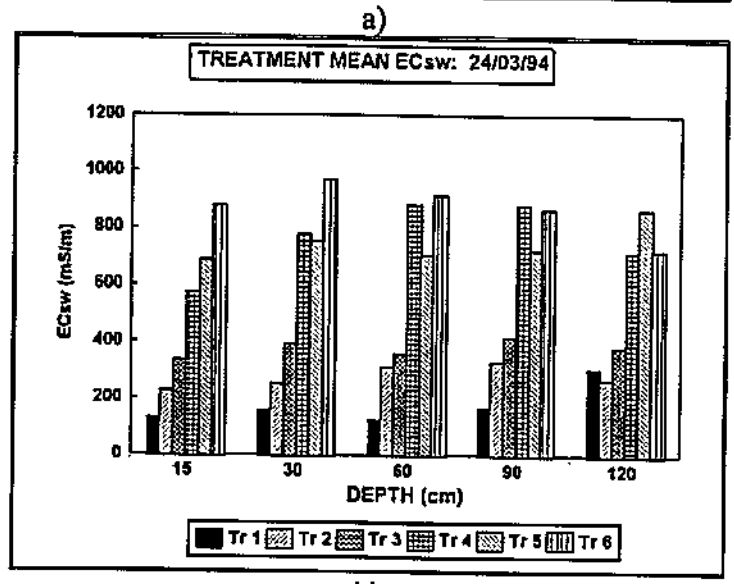

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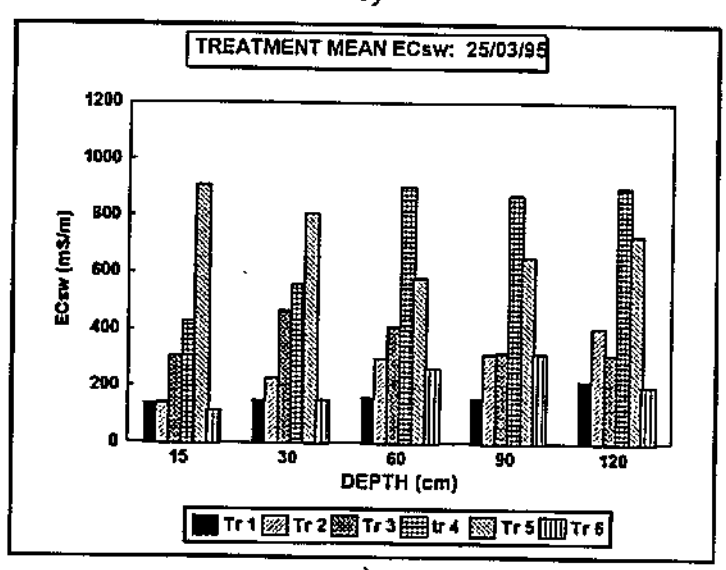
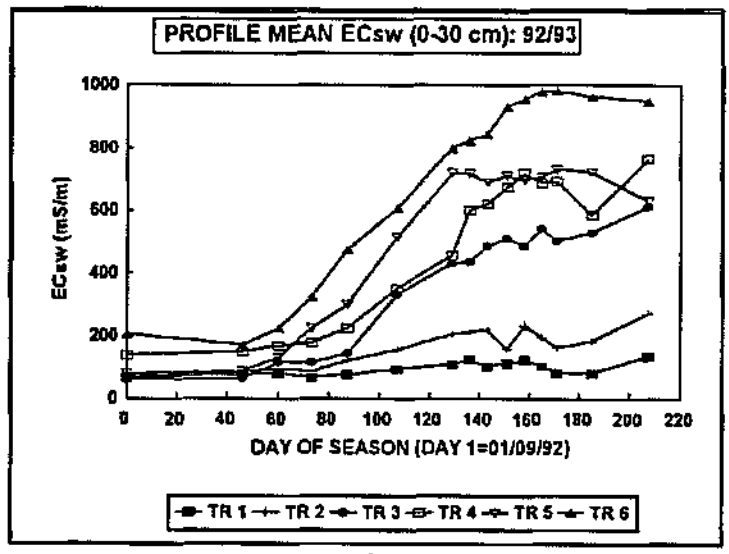
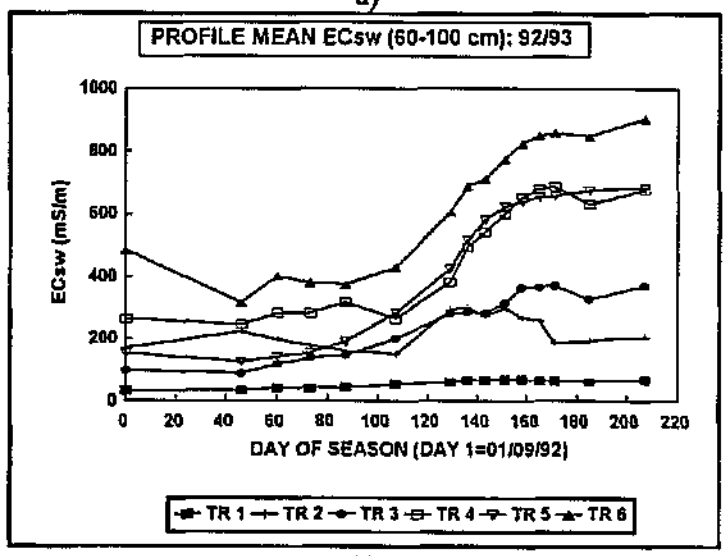


c)

Figure 4.11 Electrical conductivity of the soil solution at field soil water content per depth and treatment in a) March 1993, b) March 1994 and c) March 1995



a)



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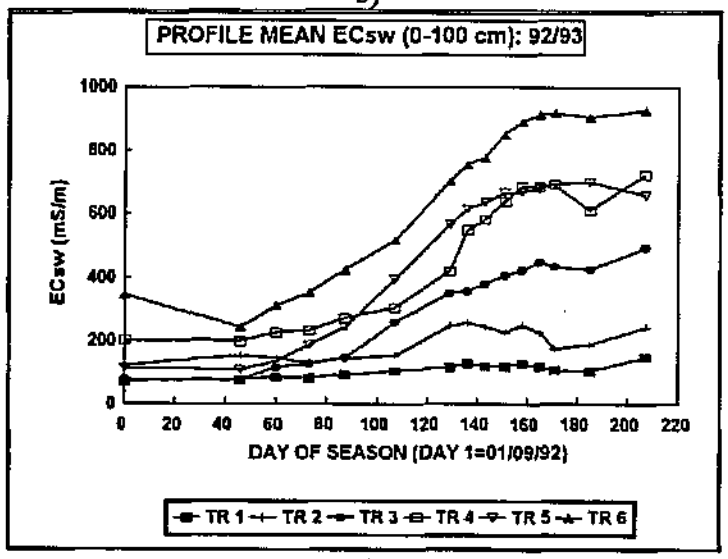

c)

Figure 4.12 Time rate of change in the depth- and water-content weighted salinity of the soil solution during 1992/93 for a) the topsoil (0-0.3 m), b) subsoil (0.6-1.0 m) and c) total root zone (0-1.0 m)

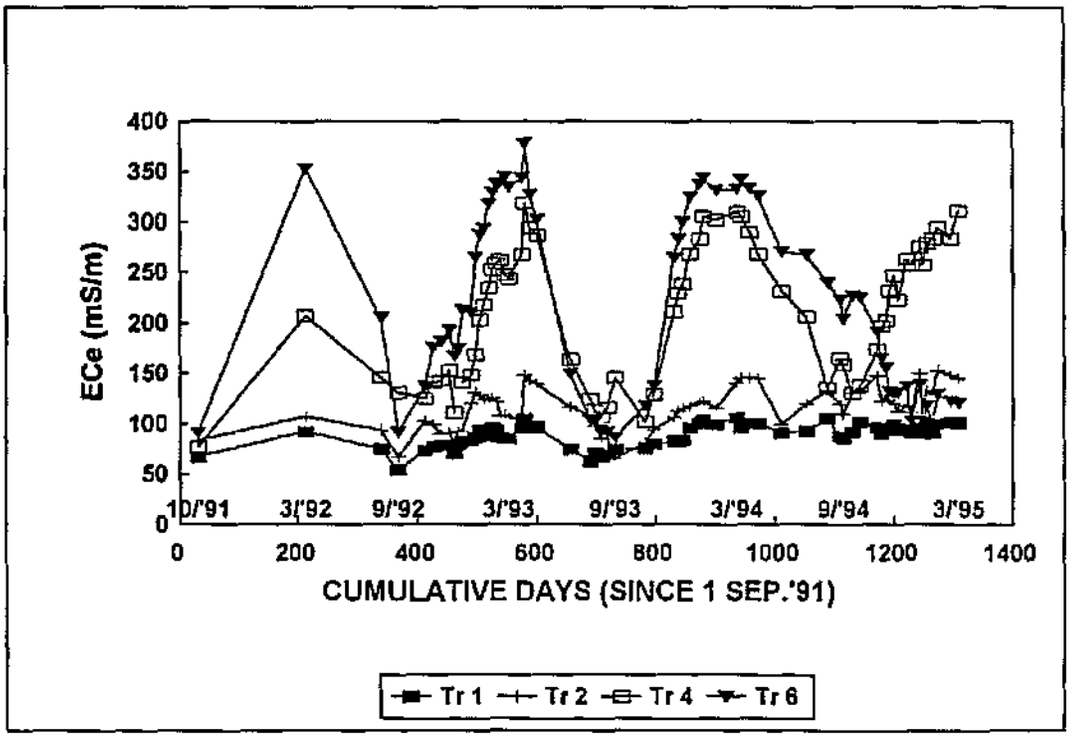

Figure 4.13 Time course of the depth-weighted mean root zone (0-1.0 m) salinity for treatments 1, 2, 4 and 6 expressed in terms ECe

e) Time integrated seasonal mean soil salinity

The time interval between sampling events and the depth-weighted mean soil salinities were used to obtain a time integrated seasonal mean value of the root zone soil salinity for each of the four irrigation seasons. The time integrated ECe was calculated as follows:

$$EC_{(int)} = \frac{\sum_{j=1}^{j=n} (EC_{d_j} . \Delta t_{j,j+1})}{t_{totl}}$$

where

$EC_{(int)}$	= time integrated ECe
EC_{dj}	= depth weighted mean ECe at time j
t_j	= time of sampling, day of season
n	= number of sampling events
$\Delta t_{j,j+1}$	= time interval between sampling event j and j+1
t_{totl}	= total number of days per season(s)

The results are summarised in Table 4.10 and include the 0-0.3 m and 0-1.2 m depth mean as well as two scenarios for the time integration, i.e. a one year and a two year time integration. These salinities were used to evaluate the salt tolerance of the Colombar cultivar, presented in a separate chapter. The slightly higher salinity value of treatment 5 compared to treatment 6 in 1991/92 can be explained by the higher subsoil

salinity of treatment 5 at the start of the experiment in October 1991 (see also Figure 4.6 e & f).

Table 4.10 One- and two year time integrated depth-weighted seasonal mean soil salinities (ECe in mS/m) of the Robertson vineyard for the period 1991/92 to 1994/95

		One year time integration				Two year time integration		
Treatm	Depth (m)	1991/92	1992/93	1993/94	1994/95	1991/93	1992/94	1993/95
1	0-1.2	74	80	91	94	77	86	93
	0-0.3	68	74	81	78	71	78	79
2	0-1.2	89	101	109	129	95	105	119
	0-0.3	72	93	98	92	83	96	95
3	0-1.2	96	114	132	128	105	123	130
	0-0.3	77	137	139	133	107	138	136
4	0-1.2	109	178	226	215	143	202	221
	0-0.3	92	169	206	187	130	188	196
5	0-1.2	176	166	208	226	171	187	217
	0-0.3	135	180	226	243	157	203	234
6	0-1.2	155	224	249	160	189	237	205
	0-0.3	143	233	278	98	188	255	188

f) Winter leaching

The data shown in Figures 4.6 and 4.8 and Table 4.8 also indicate the extent to which salt accumulated during summer could be leached the following winter. For example, the ECe's of even the two highest salinity treatments could be reduced by leaching to values less than 100 mS/m at the start of the following season. For some unknown reason, treatment 4 responded differently to winter leaching. With all the other salinity treatments and with the exception of treatment 6 in September 1994, the salt content at the beginning of a new irrigation season, was always less or similar to the values of October 1991. In the case of treatment 4, this never was the case and by September 1994 the salt content at all depths was considerably more saline than when the experiment started in October 1991 (Fig. 4.6). This is specifically true for the subsoil (>0.6 m). The results shown in Figure 4.6 are the means of four replicates per treatment. The variation in salt content between the four replicates at the end of the 1994 winter leaching period is shown in Table 4.10. The data show that the variation (expressed in terms of the coefficient of variation) between treatments are more or less similar, i.e. the mean of, for example, treatment 4 was not subject to a greater (or smaller amount of spatial variability than treatments 1, 2, 3, 5 and 6. The four replicates of each treatment therefore behaved consistently with regard to salt accumulation in summer and leaching in winter.

The time rate of decrease in the treatment mean ECe due to leaching during the winter of 1993 and 1994 is shown in Figure 4.14 as a function of cumulative total of rain plus irrigation. It is important to note that the depth of irrigation (mm) is based on the wetted area per plant. In 1993 the irrigation system was used to determine the field capacity of the soil and on three occasions irrigation quantities in excess of 90 mm per event were applied to the whole vineyard. This accounts for the big difference in the amount of irrigation water used during the winter of 1993 compared to 1994.

There are a number of factors that will dictate how much low-salinity water will be required to affect leaching during winter, e.g. soil type and texture, salt content at the end of summer and crop type. For conditions similar to the Robertson vineyard, the data shown in Figure 4.14 can be used as a first estimate of the amount of water required. For example, if the ECe at the end of the irrigation season (summer) is 300 mS/m and it is to be reduced to a value of 100 mS/m at the 0.3 m depth during winter, approximately 275 to 300 mm of irrigation and rain will be required (Fig. 4.14 a & d). However, for a target ECe of 100 mS/m at the 0.9 m depth and for the same antecedent condition, about 700 mm of rain and irrigation is necessary (Fig. 4.14 c & f). The results of Figure 4.14c also indicate that if the ECe at the end of summer is 325 mS/m a cumulative total of 275 mm of rain and irrigation water during winter, will have very little effect on the ECe at 0.9 m depth.

Table 4.11 Coefficient of variation in the salt content (ECe in mS/m) at the end of the 1994 winter leaching season (20/9/94) per depth and treatment

Depth (cm)	Treat 1	Treat 2	Treat 3	Treat 4	Treat 5	Treat 6
15	0.145	0.086	0.143	0.369	0.692	0.374
30	0.342	0.278	0.261	0.296	0.280	0.759
60	0.359	0.484	0.129	0.403	0.330	0.507
90	0.402	0.350	0.361	0.532	0.358	0.576
120	0.252	0.371	0.384	0.519	0.617	0.387

4.3.5 Estimating evapotranspiration and the leaching fraction from water- and salt balances, and salinity profiles

a) Water balance

The decrease in soil water content during the uninterrupted drying cycles of 1992/93 and 1993/94 (mostly from Fridays to Tuesdays) were used as a first estimate of how the different salinity regimes influenced evapotranspiration. Due to reasons given in a following paragraph, the soil water data of 1994/95 were not included in this calculation. It was assumed that the decrease in water content is due to evapotranspiration alone and that the effect of deep drainage (from Friday to Tuesday) on the water balance is negligible. The greater the difference in water content from Friday to Tuesday, the higher the assumed crop water uptake and therefore, evapotranspiration will be. The seasonal totals per treatment are shown in Figure 4.15.

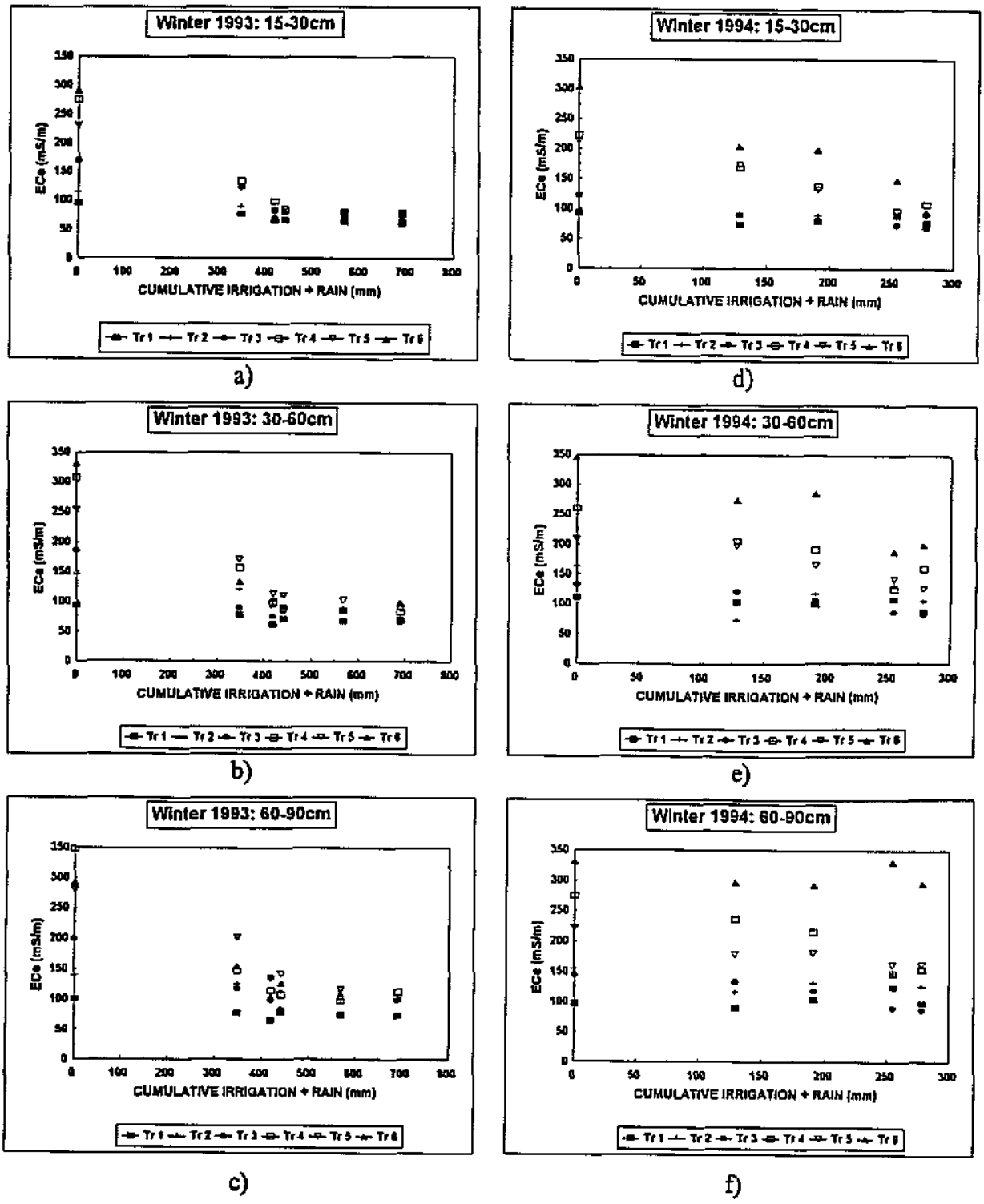

Figure 4.14 Decrease in treatment mean ECe of the 0.15-0.3 m, 0.3-0.6 m and 0.6-0.9 m depths of the Robertson vineyard during the winter of 1993 and 1994 as a function of cumulative total of rain plus irrigation

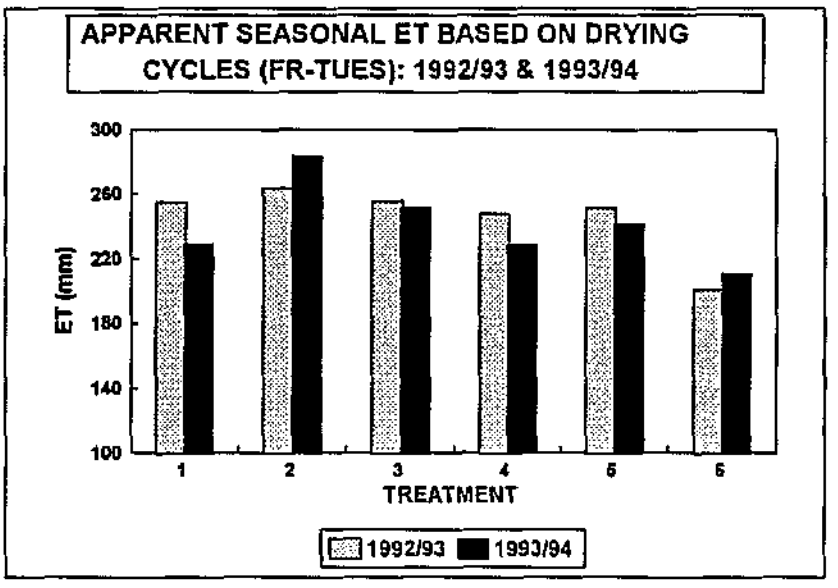

Figure 4.15 Differences in the apparent evapotranspiration of the salinity treatments based on the Friday to Tuesday drying cycles of 1992/93 and 1993/94

Trends for the different treatments were similar in 1992/3 and 1993/94 with a progressive decrease in crop water uptake, albeit erratic and small, as salinity increases. The cumulative totals of the decrease in soil water content represent all the uninterrupted drying cycles totalling 93 and 111 days for the 1992/93 and 1993/94 seasons respectively. By adjusting these totals for the period 1 September to 31 March, i.e. 212 days, an apparent seasonal evapotranspiration could be obtained (Table 4.12). In all cases the apparent ET of 1993/94 was between 10% and 25% less than the 1992/93 data. However, no treatment effect in this seasonal decrease seems to be evident. The absence of a treatment-, and therefore salinity effect, is probably related to the fact that this calculation of ET is based on only one monitoring point per plot, located within the wetted zone. Water used from the interrows were not considered.

Table 4.12 Apparent evapotranspiration of the different salinity treatments at the Robertson vineyard for the 1992/93 and 1993/94 seasons, calculated from the decrease in soil water content during drying cycles over 2/3 of the land area, adjusted for the total number of days from September to March

Treat-ment	1992/93		1993/94	
	mm	Relative*	mm	Relative*
1	581	(1.00)	438	(1.00)
2	601	(1.03)	541	(1.24)
3	583	(1.00)	480	(1.10)
4	565	(0.97)	437	(1.00)
5	573	(0.99)	462	(1.05)
6	458	(0.79)	403	(0.92)

* Relative to treatment 1

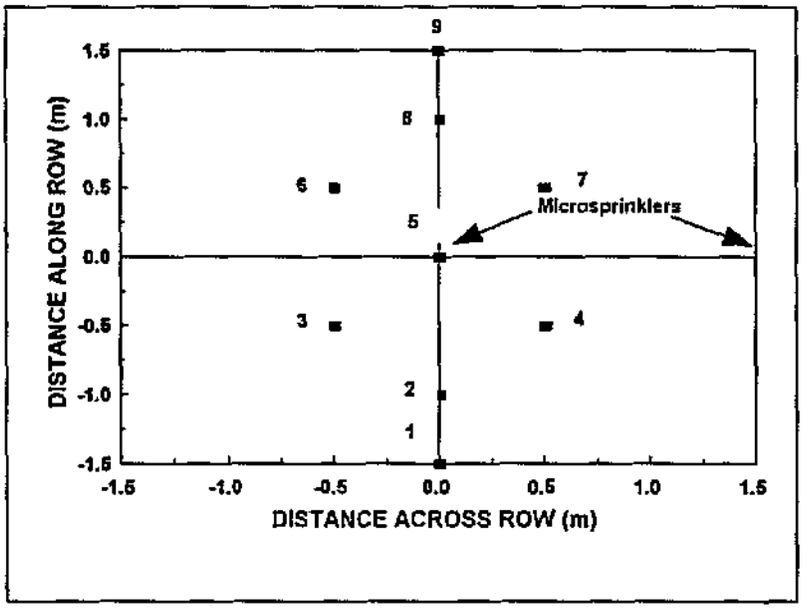

Figure 4.16 Diagram indicating the positions where neutron probe access tubes were installed for a detailed study of the water balance of plots 7 (treatment 6), 8 (treatment 4) and 9 (control)

The effect of the position and number of soil water monitoring points per plot on the estimate of evapotranspiration and deep drainage (i.e. leaching fraction) was investigated by conducting a detailed study of the water balance. On plots 7, 8 and 9, an additional eight neutron access tubes were installed in the 4.5 m^2 area served by a microsprinkler, i.e. total of nine monitoring points were used. On all three plots the same spatial pattern and distances from, and directions relative to, the microsprinkler were used. The schematic layout of the monitoring points is shown in Figure 4.16. (Position 5, directly underneath a microsprinkler, is where water content was measured on a routine basis). The water balance was obtained by measuring soil water with the neutron probe immediately before the start, and again 24 hours after the cessation of randomly chosen irrigation events in March 1994, December 1994 and February 1995. The amount of water applied per plot was calculated from the volume of water registered at the flow meter and by assuming a uniform application per plot. The volume of water applied per emitter was obtained by dividing the volume of water per plot by the number of microsprinklers on that particular plot. The water content at each sampling position was reduced to a mean value for positions at similar distances and directions relative to the emitter, i.e. symmetry at similar points across and along the row was assumed. The results from three sampling dates in the 1993/94 season for treatment 6 (plot 7) and the control (plot 9) are shown in Figure 4.17. The water content measured on 25/02/94 and 24/03/94 represent conditions 24 hours after an irrigation event, while the data of 23/03/94 represent the water distribution after a drying cycle of 28 days (from 25/02/94 to 23/03/94). The spatial distribution of water is shown as contour lines and is expressed in units of mm/1.05 m with a contour interval of 5 mm/1.05 m. The contour lines were constructed using geostatistical techniques calculated with the SURFER for Windows (*Golden Software, Inc.*) contouring programme and using Kriging and a linear model for the semivariogram. Also indicated in Figure 4.17 are the actual data measured at each of the sampling positions shown in Figure 4.16.

Evapotranspiration (ET) and the leaching fraction (LF) were calculated using the following equations:

$$ET = \left(\sum_{j=1}^{j=9} SWC_{j(t)}.A\right) - \left(\sum_{j=1}^{j=9} SWC_{j(t+1)}.A\right) \; m^3$$

$$LF = \frac{I - \left(\left(\sum_{j=1}^{j=9} SWC_{j(t)}.A\right) - \left(\sum_{j=1}^{j=9} SWC_{j(t-1)}.A\right)\right)}{I}$$

where

$SWC_{j(t)}$ is the soil water content *(m/1.05 m)* in the surface area A, (m^2) measured at point j, with $j = 1, 9$, measured at time t;

$SWC_{(t-1)}$ is the soil water content immediately before, $SWC_{(t)}$ the soil water content 24 hours after an irrigation event, and $SWC_{(t+1)}$ is the soil water content before the next irrigation event; and

I is the volume of irrigation water applied (m^3).

The areas represented by positions 1 to 9 (Fig. 4.16) were calculated using Thiesen polygons and were:

1 & 9 = 0.375 m^2	2 & 8 = 0.5625 m^2
3, 4, 6 & 7 = 0.53125 m^2	5 = 0.5 m^2

which sum to a total of 4.5 m^2 per microsprinkler. It follows that the product of $SWC.A$ will be determined by the value of A (area) allocated to a particular measuring point j. It also follows that A will be a function of the number of measuring points within the 4.5 m^2 area per microsprinkler. If, for example, only one measuring point is used, which may be any one of positions 1 to 9 indicated in Figure 4.16, the area represented by that measuring point in theory should be 4.5 m^2.

The spatial distribution of water content and its effect on estimates of the water balance can be summarised as follows:

i) The spatial variability in water content is more accentuated across the row than along the row.

ii) Maximum water content is recorded at a distance 0.75 m diagonally from the micro-sprinkler and the minimum values at a distance 1.5 m perpendicular to the sprinkler.

iii) The water content in plot 7, irrigated with saline water (500 mS/m), at all positions and times represents substantially wetter conditions than at similar positions in plot 9, irrigated with the control water.

iv) Because of the significant and non-linear nature in the spatial variability of water content, different estimates of evapotranspiration and leaching will be obtained depending where measurements are made and how many measuring points are used in the water balance. This is especially true for the control treatment where the gradient across the row is much steeper than it is for treatment 6.

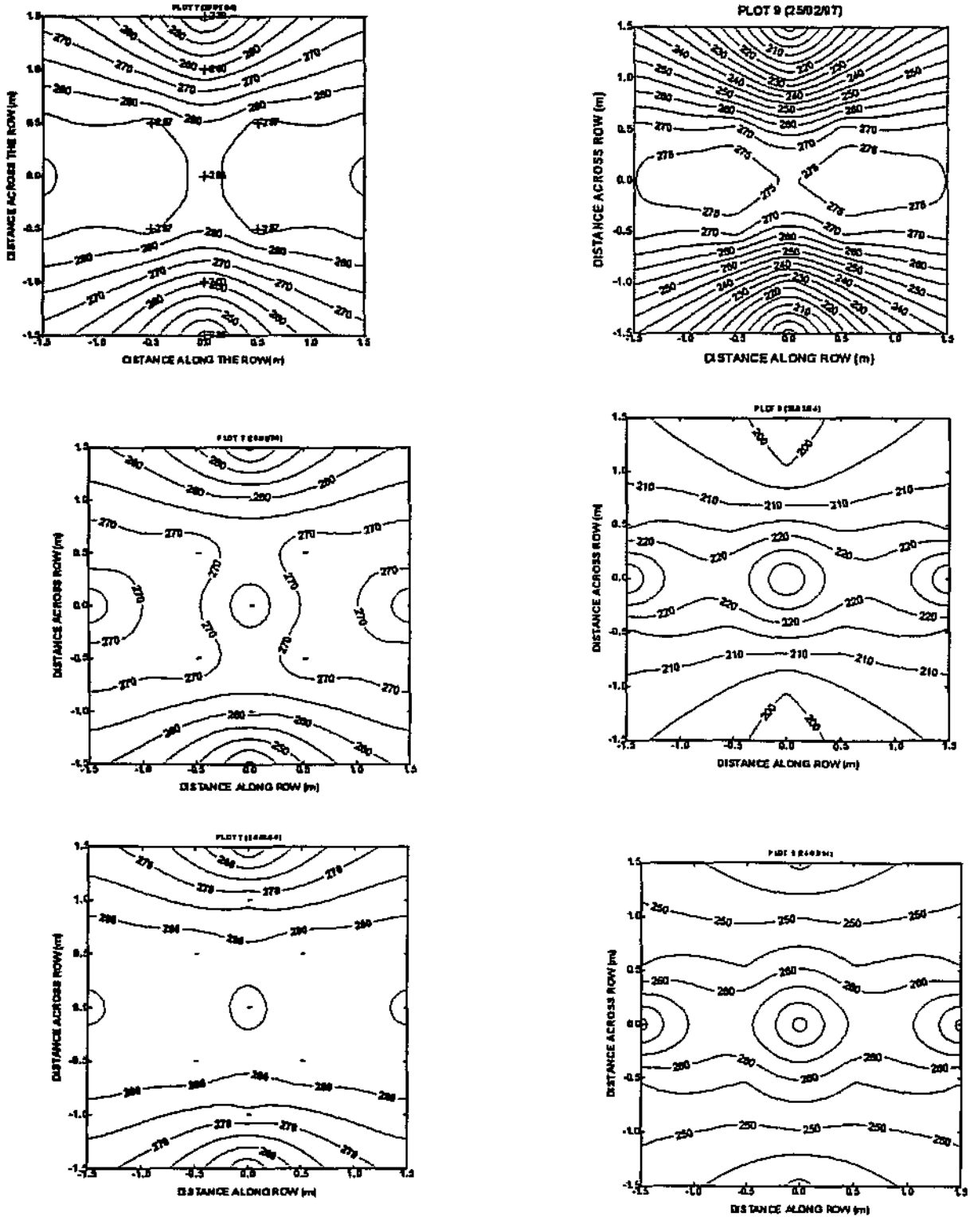

Figure 4.17 Spatial distribution of soil water (mm/1.05 m) at plots 7 (treatment 6) and 9 (control) at three different dates in 1993/94

The effect of the number of measuring points and the distance from and direction relative to the microsprinkler on the water balance is illustrated in Table 4.13, which is a summary of the water balance of a 28 day drying cycle from 25/2/94 to 23/3/94 and the mean leaching fraction of four irrigation events during the 1994/95 season (30/11/94, 7/12/94, 14/12/94 and 08/02/95). Soil water depletion during the drying period was assumed to be the result of evapotranspiration, while the leaching fractions were based on soil water losses that could not be accounted for 24 hours after an irrigation event. Although different combinations of measuring positions and areas per position are possible, the results shown in Table 4.13 represent two extreme cases:

a) the "100%" correct (or true) area-weighted mean evapotranspiration and LF, based on nine measuring points per microsprinkler, with different areas allocated to each position,

b) the incorrect (or spurious) evapotranspiration and LF based on only one measuring point per microsprinkler, and an area of 4.5 m^2 per measuring point. The effect of four different distances from the microsprinkler is shown.

Table 4.13 Effect of soil water sample number (*n*) and the orientation of the sampling points relative to the microsprinkler, on the water balance of a 26 day drying cycle and four 24-hour wetting cycles

Plot and treatment	*n=9* Weighted mean (true)	*N=1* at 1.5 m (pos. 1 & 9)	*n=1* at 1.0 m (pos. 2 & 8)	*n=1* at 0 m (pos. 5)	*n=1* at 0.75 m (pos. 3,4,6 & 7)
	A: (Drying cycle) Evapotranspiration (mm per 4.5 m^2) for the period 25/02/94 to 23/03/94				
7 (Tr 6)	8.3	-0.5	-1.1	23.1	12.9
8 (Tr 4)	28.4	15.0	12.1	42.9	38.3
9 (Tr 1)	36.5	-6.7	22.5	38.9	58.6
	B: (Wetting cycle), Mean leaching fraction for an area of 4.5 m^2 based on the irrigation events of 30/11/94, 07/12/94, 14/12/94 and 08/02/95				
7 (Tr 6)	0.443	0.516	0.730	0.000	0.371
8 (Tr 4)	0.399	0.767	0.782	0.030	0.154
9 (Tr 1)	0.198	0.863	0.763	0.000	0.000

By using the data of all nine measuring points, ET for the period 25/02/94 to 23/03/94 is calculated to be 36.5 mm, 28.4 mm and 8.3 mm for treatments 1, 4 and 6 respectively. This is equivalent to a ratio of 1 : 0.78 : 0.23 which is markedly different from the ratio of 1 : 1 : 0.92 shown in Table 4.12. The most plausible reason for this marked difference between the two sets of data is that the results listed in Table 4.12 were calculated using the data of one measuring position only, similar in distance and direction from the microsprinkler to position 5 (Figure 4.16). According to the soil water content measured at position 5, ET for the period 25/2/94 to 23/3/94 for treatments 1, 4 and 6 will respectively be 38.9 mm, 42.9 mm and 23.1 mm. This overestimates the "true" ET by 6.6% (treatment 1), 51.1% (treatment 4) and 178.3% (treatment 6). This suggests that the apparent ET shown in Table 4.12 is not a true reflection of the effect of salinity on soil water uptake by vines and that the influence of salinity is considerably more severe than what can be inferred from the results shown in Table 4.12. However, it should be noted that the results of Tables 4.12 and 4.13 refer to two different time scales

representing different salinity regimes. The information of Table 4.12 cover the period 1 September (i.e. low salinity) to 31 March (i.e. high salinity), with a progressive increase in salinity between the two dates as indicated in Figures 4.6, 4.8 and 4.11. The ET calculated for the period 25/2/94 to 23/3/94 (Table 4.13) reflect conditions when soil salinity of treatments 4 and 6 were at their maximum which should have a greater impact on soil water uptake (relative to treatment 1) than earlier during the season.

The effect of spatial variability on the calculation of deep percolation (leaching losses) of soil water within the area served by one microsprinkler, is equally dramatic. For example, if leaching is calculated using the area-weighted mean approach, the mean LF for plot 7 is 0.443 (Table 4.13b). However, for the four respective irrigation events summarised in Table 4.13 the soil water fluctuations observed at position 5, suggest negligible leaching: the mean of four irrigations being 0.00. The actual values for these four events (data not shown) at position 5 ranged from -0.20 (i.e. under-irrigation) to 0.12. The same spurious result applies to treatments 1 and 4.

The effect of salinity on the true, area-weighted LF seems to be smaller than the effect on ET. For example, the LF of treatment 6 is 2.24 times greater than LF of treatment 1 while ET of treatment 1 (36.5 mm) is 4.40 times more than the ET of treatment 6 (8.3 mm, Table 4.13). This can be explained by the different processes that are operative during water uptake by plant roots (i.e. biological and biochemical processes controlled by osmotic forces) and soil water movement (i.e. physical processes controlled by soil properties and hydraulic gradients).

The detailed study of the water balance therefore suggests that a single, and possibly even two, measuring positions per plot (or area served by a microsprinkler) is not sufficient to quantify the effect of salinity on water uptake and deep drainage.

b) The salt balance

An indication of deep percolation losses and the associated treatment mean leaching fraction (LF) were calculated using three different approaches. The first approach was based on the the change in the salt content of the soil over the season (September to April) and the amount of salt added with the irrigation water. The second approach was similar to the first one except that it used the changes in NaCl and $CaCl_2$ only (as opposed to total salt content). The third approach used the volume weighted, rainfall adjusted seasonal mean ECi data of the irrigation water and the ECsw of the soil solution at the end of the season, to calculate the ratio ECi/ECsw.

The total amounts of salt added to the vineyard per treatment for each of the seasons from 1991/92 to 1994/95 are listed in Table 4.14. The salt input is based on the period September to April and includes the salt added to the soil by the salinity treatments as well as the salt added when the low-salinity canal water was used for irrigation early in the season (September). The analytical data of the soil samples collected at the beginning and end of each season were used to calculate the increase in the salt content of each plot (to a depth of 1.0 m) and were expressed as a mass per unit area. However, the outcome of a salt balance of an irrigated field, where only part of the soil surface is wetted, is influenced by the area used in the calculation, i.e. the total area of 12150 m^2 (or 4.5 m^2 per plant) or the wetted area of 8100 m^2 (or 3.0 m^2 per plant). Consequently, the salt balance and leaching fraction were calculated for both the total area as well as the wetted area. The increase in salt content and leaching fraction of each plot was determined individually and the results were reduced to treatment means and standard

deviations (Table 4.14). It is important to note that the salt balance is based on one soil sample per plot, always taken at the same position within the wetted area. Spatial variability within and outside the wetted area could therefore not be accounted for. The following procedure was used to calculate the salt balance and leaching fraction:

$$M_{(n)} = \sum_{j=1}^{j=5} \left[\frac{Sat\%_j \times BD_j \times \Delta D_j \times ECe_j \times 5.51}{100 \times 1000 \times 1000} \right]$$

$$LF = \left[\frac{\left(M_{(n)} + \frac{IL}{A} \right) - M_{(n+1)}}{\left(\frac{IL}{A} \right)} \right]$$

where:

M_n = Mass of salt *(kg)* in 1 m of soil per m^2 of surface area at the beginning of the irrigation season (1 September)

M_{n+1} = Mass salt in soil at the end of the irrigation season (30 April)

j = depth layer, with j=1 the 0.15 m depth and j=5 the 0.9 m depth

Sat% = water content (percentage by mass) of the saturated soil paste

BD = bulk density *(kg/m^3)*

ΔD = depth increment from depth j to j+1 *(m)*

ECe = electrical conductivity of the saturated paste extract *(mS/m)*

5.51 = factor to convert *mS/m* to *mg/L*, obtained by establishing the relationship between TDS and ECe (r^2=0.963, n=117)

IL = total mass of salt added to the soil per microsprinkler from September to April *(kg)*, obtained by converting ECi (mS/m) to TDS (mg/L) using a conversion factor of 5.584, (r^2=0.986, n=309)

A = area, *(m^2)*; being either the total area per plant (≡ microsprinkler, 4.5 m^2), or wetted area per plant (= 2/3 x 4.5 m^2 = 3 m^2)

The leaching fraction is defined as Qd/(Qi+Qr), where Qd is the deep percolation quantity and Qi and Qr the irrigation and rainfall quantities respectively. It is important to note that in the calculation of the salt balance as described above, deep percolation of water is inferred from the salt loads of the irrigation water and the soil solution. In the case of the ECi/ECsw ratio the basic premise is one of steady state conditions (Oster, 1984) which in the absence of rain means that:

$$QiCi = QdCd \qquad \text{and,} \quad Qd/Qi = Ci/Cd = LF$$

where Q is the amount of water, C is the salt concentration, i is irrigation and d is drainage. C can be substituted with ECsw. However, the ratio of Qd/Qi is not measured or calculated but assumed to be equal to ECi/ECsw. Prior et al (1992c) describes a procedure whereby Qd can be calculated from changes in the root zone salt storage, i.e. Qd is not inferred from the ratio of Ci/Cd. However, we have not applied this technique to our data.

For the following reasons the results of the salt balance, shown in Table 4.14, were rather disappointing :

i) Contrary to expectation, there is no consistent trend for leaching to increase with salinity.
ii) The leaching fraction based on the total area is consistently less than that of the wetted area (as expected).
iii) There is significant variation between replicates of a specific treatment, e.g. the mean and standard deviation of LF for treatment 4 in 1992/93 was 0.294 and 0.394 respectively.
iv) The treatment mean LF varies from year to year, without any consistent trend, e.g. for treatment 3 the LF for the total area ranged from a minimum of 0.007 (±0.466) in 1992/93 to a maximum of 0.717 (±0.053) in 1991/92.
v) The LF of treatment 1 is unrealistically high, especially as the irrigation applications (since 1992/93) were calculated relative to the measured (as opposed to estimated) soil water deficit of this treatment.

It is concluded that the leaching fraction according to the salt balance is not a true reflection of the real field processes, and is probably an artefact of substantial spatial variability within the plot and between replicates of the same treatment.

Du Toit (1995) adapted the salt balance to consider only NaCl and $CaCl_2$, in the irrigation water and soil solution. The procedure differed from the previous one because analytical results were used throughout and no assumptions concerning TDS were made, neither was it necessary to establish the relationship between ECe, ECi and TDS. In our first approach, TDS was calculated by summing the anion and cation contents (determined by chemical analysis, see sections 4.2.2.1 and 4.2.1.3) to obtain an estimate of the "total dissolved salt content". The carbonate and bicarbonate content was not analytically determined but assumed to be equal to the difference between cation and anion contents on a charge equivalent molar basis. For the 1993/94 season the method of Du Toit (1995) yielded the following leaching fractions:

treatment 1 = 0.19; treatment 2 = 0.22; treatment 3 = 0.44;
treatment 4 = 0.39; treatment 5 = 0.41; treatment 6 = 0.57

The third approach to estimate deep percolation, assumed steady state conditions at the end of the season which means the ratio of ECi/ECsw or Cl(i)/Cl(sw) is equal to the leaching fraction (Oster, 1984). In the present study the ECsw data of the 0.9-1.2 m depth layer (obtained with the suction cup apparatus) at the end of the 1992/93, 1993/94 and 1994/95 seasons were used and the ratio of ECi/ECsw calculated for each plot with ECi equal to the volume weighted seasonal mean values of the different treatments (Table 4.4). The results were reduced to treatment means and standard deviations and are presented in Table 4.15. The general trend is for the ratio of ECi/ECsw to increase with salinity treatment. The LF of treatment 4 was consistently lower than treatment 3, which accords with the salinity profiles and yield (presented in next chapter). Leaching fractions obtained by calculating ECi/ECsw are not only smaller than those calculated using the salt balance (Table 4.13), but the variability among replicates of the same treatment is also less. Figure 4.17 presents the leaching fractions of 1992/93, 1993/94 and 1994/95 as a function of the volume weighted ECi.

Table 4.14 Seasonal salt load of the irrigation water expressed as a mass per unit area for the total area (4.5 m^2) and wetted area (3 m^2) per plant and the associated treatment mean leaching fraction (and standard deviation) based on the increase in the salt content of the soil during the irrigation season (September to April) from 1991/92 to 1994/95

Treatment	Increase in Soil Salinity (kg/m^2)	Salt Load of Irrigation water (kg/m^2)		Mean LF (±STD) for the Total Area	Mean LF (±STD) for the Wetted Area
		Total Area*	Wetted Area		
1991/92					
1	0.059	0.131	0.196	0.552 (0.758)	0.701 (0.505)
2	0.091	0.348	0.522	0.740 (0.258)	0.826 (0.172)
3	0.202	0.714	1.071	0.717 (0.053)	0.811 (0.035)
4	0.379	1.125	1.687	0.663 (0.033)	0.775 (0.022)
5	0.608	1.925	2.887	0.684 (0.117)	0.789 (0.078)
6	0.830	2.129	3.194	0.610 (0.040)	0.740 (0.027)
1992/93					
1	0.127	0.089	0.133	-0.438 (0.469)	0.041 (0.312)
2	0.222	0.222	0.333	0.002 (0.531)	0.334 (0.354)
3	0.431	0.434	0.651	0.007 (0.466)	0.338 (0.311)
4	0.508	0.720	1.080	0.294 (0.394)	0.529 (0.263)
5	0.594	0.969	1.454	0.386 (0.189)	0.591 (0.126)
6	0.879	1.473	2.210	0.403 (0.065)	0.602 (0.044)
1993/94					
1	0.032	0.110	0.165	0.700 (0.189)	0.800 (0.126)
2	0.165	0.226	0.339	0.268 (0.404)	0.512 (0.270)
3	0.265	0.479	0.718	0.446 (0.264)	0.630 (0.176)
4	0.627	0.877	1.315	0.285 (0.094)	0.523 (0.063)
5	0.627	0.947	1.420	0.337 (0.204)	0.558 (0.136)
6	0.816	1.721	2.581	0.526 (0.120)	0.684 (0.080)
1994/95					
1	0.050	0.116	0.174	0.6221 (0.479)	0.747 (0.320)
2	0.122	0.197	0.296	0.381 (0.807)	0.587 (0.538)
3	0.276	0.339	0.508	0.182 (0.639)	0.455 (0.426)
4	0.486	0.683	1.024	0.289 (0.429)	0.526 (0.286)
5	0.626	0.986	1.480	0.365 (0.197)	0.577 (0.131)
6	-0.244	0.137	0.206	NA	NA

It is uncertain why the three methods used to estimate leaching fractions yield such divergent results. The soil and soil solution samples represent conditions at a specific point in the vineyard. In the previous sections the extent of within-plot and within-treatment variability was demonstrated. The salt balance essentially is a mass balance approach for which surface areas are required. Spatial variability and uncertainties concerning the actual size of the wetted area, more specifically the volume of wetted soil, will therefore have a greater influence on the results of the salt balance than on the ECi/ECsw ratio approach, which does not require knowledge of areas represented by the point sample. The salt balance furthermore requires conversion of electrical conductivity to total salt content, e.g. mass per volume. The accuracy of such a conversion again is a function of experimental errors made during the chemical analyses. In contrast, determination of electrical conductivity is relatively simple and error free. For these reasons, the leaching fractions based on the ECi/ECsw ratios are accepted to be more representative of the actual field conditions than those based on the salt balance.

Table 4.15 Treatment mean and standard deviations of the leaching fractions according to the electrical conductivity of the irrigation water and the soil solution at the 0.9 to 1.2 m depth layer

Treatment	1992/93		1993/94		1994/95	
	Mean	STD	Mean	STD	Mean	STD
	LF=ECi/ECsw					
1	0.139	0.014	0.111	0.000	0.152	0.078
2	0.232	0.058	0.278	0.000	0.170	0.053
3	0.469	0.000	0.448	0.136	0.395	0.066
4	0.398	0.043	0.375	0.056	0.239	0.123
5	0.389	0.003	0.377	0.044	0.473	0.028
6	0.519	0.039	0.704	0.036	0.180	0.000

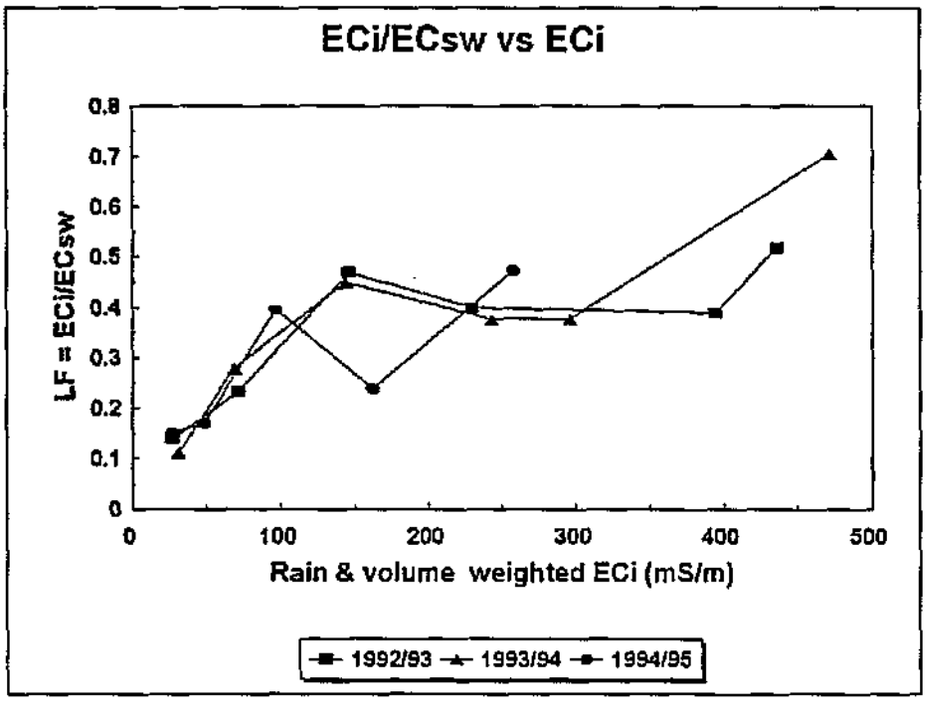

Figure 4.18 The effect of salinity treatment on ECi/ECsw calculated leaching fractions for the Robertson vineyard for the period 1992/93 to 1994/95 (ECi is volume weighted seasonal mean values adjusted for rainfall)

The treatment mean leaching fractions for the respective years from 1992/93 to 1994/95 (Table 4.14) were combined with the irrigation and rain quantities (Table 4.6) and the treatment mean measured soil water contents of September and April to estimate the amount of evapotranspiration for the period 1 September to 30 April. Evapotranspiration was calculated on a volume basis using the following mass balance approach:

$$ET = SW(Sept) + Qi + Qr - Qd - Qsr - SW(Apr)$$

where

ET = evapotranspiration (m^3 from 12150 m^3 of soil)
SW(Sept) = volume (m^3) of soilwater to a depth of 1.05 m in 12150 m^2 at the beginning of the growing season
SW(Apr) = volume of soilwater at the end of the growing season
Qi = irrigation quantity (m^3 per 12150 m^2)
Qr = rain (m^3 per 12150 m^2)
Qd = drainage (m^3) below the 1.05 m root zone
= LF.Qi
Qsr = surface runoff, assumed to be negligible

ET was expressed both as volume and a depth per unit area for the total area of the vineyard (12150 m^2). The results are shown in Figure 4.19. Evapotranspiration of treatment 1 ranged from 640 mm to 825 mm for the period September to April. This is more than the ca. 600 mm nett irrigation requirement found by Van Zyl (1984). However, his results refer to the period September to March, while our data include the post-harvest irrigation and soil water uptake as well. There is a general trend for ET to decrease as the salt content of the irrigation water increased. For example the difference in ET of treatments 1 (825 mm) and 6 (451 mm) was 374 mm in 1991/92 and 359 mm (=650-291 mm) in 1993/94.

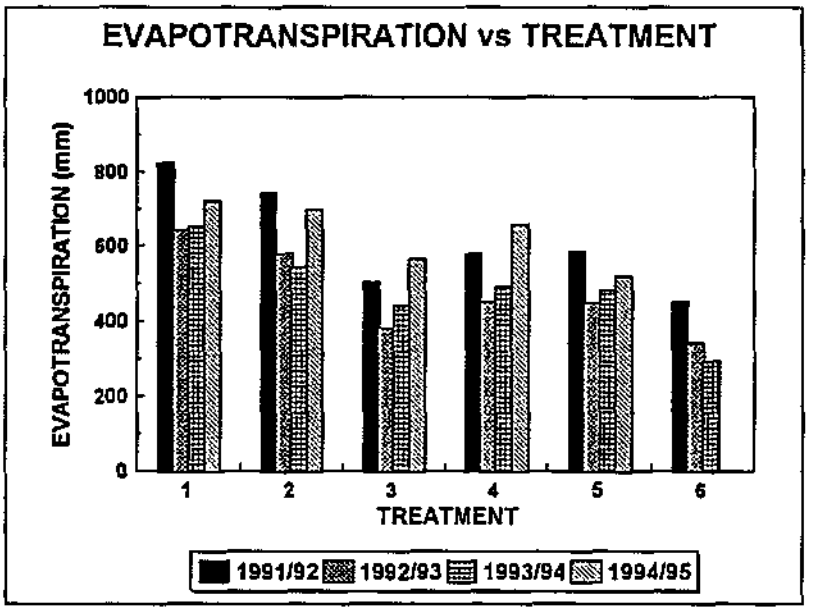

Figure 4.19 Treatment mean seasonal evapotranspiration of the Robertson vineyard from 1991/92 to 1994/95 for the period September to April, calculated from the leaching fraction, irrigation and rain quantities

4.4 Summary and conclusions

i) With the exception of the first season (1991/92), the volume weighted seasonal mean salt contents of the different irrigation salinity treatments accorded well with the target salinities. This was mainly due to a locally designed computerised salt injection and salinity control system that was commissioned in 1992/93. Notwithstanding the good control over salinity levels during an irrigation event, the system is not fail-safe and the salinity sensors had to be cleaned and recalibrated on a regular basis.

ii) Despite different irrigation scheduling techniques that were used between the different years, the soil water regime during the course of this four-year study period was very similar. The maximum inter-annual difference in the seasonal mean soil water content for any treatment was 29 mm/1.05 m.

iii) During the irrigation season, differences in soil water content between the six salinity treatments were minor. Contrary to expectation, seasonal mean soil water content did not increase in any consistent or significant way as soil- or irrigation water salinity increased. This is probably due to the relatively high frequency of irrigation (once per week) and good internal drainage properties of the soil. However, differences were observed after extended periods of drying during which time no irrigation was applied (such as prior to harvest). On these occasions, water content did increase with increasing soil salinity and is indicative of reduced water uptake at the higher levels of salinity. This conclusion is confirmed by the soil water content measured outside the directly wetted zone (of the microsprinkler irrigation system) of treatments 1, 4 and 6 which increased as salinity increased. The soil water content outside the wetted zone of treatment 1 was significantly less than that of treatment 6. The difference increased as the season progressed and

after 160 days in 1993/94 the soil water content of treatment 1 outside the wetted zone was as much as 40 mm/1.05 m less than that of treatment 6.

iv) Irrigation with the saline water led to a significant salt accumulation in the root zone during the irrigation season, reaching maximum levels just before harvest in March. Salt accumulation was not proportional to the amount of salt load of the salinity treatments. Treatment 4, with an ECi of 250 mS/m for example resulted in similar salinity profiles as treatments 5 (350 mS/m) and 6 (500 mS/m). This is explained in terms of accentuated leaching due to reduced soil water uptake at the two higher salinities.

v) For this combination of soil and irrigation water (i.e. Robertson canal water) it requires about 275-300 mm of water during winter to reduce ECsw of the topsoil (0-0.3 m) from 300 mS/m to 100 mS/m. To reach the same target ECsw of 100 mS/m at the 0.9 m depth and for the same antecedent condition, about 700 mm of rain and irrigation is necessary.

vi) Despite significant fluctuations in SAR of the soil solution from summer to winter, over the longer term there was a gradual increase in SAR with time and depth. By April 1995 the SAR of all treatments and at all depths, including the control treatment, had increased to levels higher than the antecedent conditions of October 1991.

vii) The salt- and water balance, and all other inferences made from them are strongly influenced by the choice of sampling sites and assumptions concerning the size of, and redistribution of water and salt within the wetted area. Leaching fractions according to the salt balance were disappointing. A study of spatial variability within the zone of influence of one microsprinkler showed that one sampling point per microsprinkler (or plant) is insufficient to obtain a water and salt balance from which evapotranspiration and leaching can be inferred. The leaching fractions calculated from the ratio of ECi/ECsw ranged from ca. 0.14 for the control to 0.70 for treatment 6 with a general increase as salinity increased. These values were accepted as more representative of the true field conditions. The leaching fractions suggest that deep percolation losses are substantial, as much as 70% at the higher levels of irrigation water salinity, compared to irrigation management strategies that are based on non-saline, non-stressed conditions for plant water uptake.

CHAPTER 5
EFFECT OF SALINITY ON THE GROWTH AND ION COMPOSITION OF THE VEGETATIVE ORGANS OF COLOMBAR GRAPES

5.1 Introduction

Rain provides part of the water used in evapotranspiration and leaching of vineyards irrigated with saline water in semiarid regions. At Robertson irrigation with low salinity water supplements the limited winter rainfall for leaching. The result is minimal soil salinity at the end of the winter, at about the time of bud brake, and increase in soil salinity over the irrigation season (this report Chapter 4). The traditional approach to quantify the effect of salinity on crop production is to relate the yield of annuals to the seasonal mean soil salinity (Maas and Hoffman, 1977). In a salt tolerance experiment with mature plum trees, i.e. deciduous and perennial, yield was related to the mean soil salinity of two successive irrigation seasons (Hoffman *et al.*, 1989, Catlin *et al.*, 1993). The seasonal averaging assumes no interactions in time for all the effects of soil salinity on the processes that determine growth and development. If there are such interactions, different weightings should be given to sensitive and tolerant stages. For perennial deciduous grapes, plant phenological stages are used to manipulate and manage the plant (Van Zyl 1984, Williams, 1987). However, the time scales for many processes that determine the final plant response may be different, and the magnitude of the response at a given stage may be affected by processes at previous stages. Leaf and shoot growth can continue during the reproductive growth stage. Metabolite availability for fruits is influenced by the canopy size as determined during the vegetative stage (Bowen and Kliewer, 1990, Hunter and Visser, 1990). Metabolite reserves stored in perennial organs during one season influence growth and production during following seasons. Salt stored in perennial organs can become toxic to new growth (Hoffman *et al.*, 1989, Bernstein *et al.*, 1956). Differentiation of bud primordia during the vegetative stage of one season determine the potential number of berries in the following season (Pratt 1971, Srinivasan and Mullins, 1981). Relating plant response to soil salinity is therefore not simple and requires short term scaling of the differential responses rather than averaging the responses and salinities over long periods.

In this chapter the effect of salinity on the vegetative growth, salt accumulation, volume expansion, and metabolite and ionic deposition in the vegetative plant organs of the Colombar grapevine from 1991/92 to 1994/95 seasons are discussed. The measurements and level of monitoring differed slightly between the seasons. During the first season, only shoot mass was measured. Much more detailed measurements were made in 1992/93 and 1994/95.

5.2 Methods and Materials

During the first season (1991/92) vegetative growth measurements were restricted to measurements of shoot mass at pruning. In all subsequent seasons, vegetative growth was monitored using the plants of the border rows. Two types of measurements were used, viz. non-destructive and destructive. The only vegetative growth parameters conducted in the experimental row were *ad hoc* measurements of trunk circumference and shoot mass at pruning. The time scale that was used in this study is the day of season (DOS) which starts on September 1st.

Main shoot lengths were measured in all treatments. A more detailed characterizing of the vegetative growth in treatments 1, 4 and 6 (25, 250 and 500 mS/m irrigation water salinities respectively) was done, using non-destructive measurements up to about day 100 of each season (DOS) and destructive measurements from about day 77 to 220 (DOS). The methodology of the destructive and non-destructive measurements will be described separately.

5.2.1 Non-destructive measurements

In 1992/93 three plants per plot which had a minimum of four cordons with four spurs per cordon, were pruned before bud brake (BB) to four spurs per cordon and 16 spurs per plant. The same plants were used in the following two seasons but standard pruning techniques were applied. Trunk circumferences of the three plants were measured 9 times during the 1992/93 season and 3 times in 1994/95 using a tape measure and a fixed position per trunk. The trunk circumferences of the ten experimental plants per plot were measured once each year from 1992 to 1995, just before harvest. Standard shoots from two plants were selected for weekly shoot and leaf elongation measurements. These shoots were from the upper bud on the 1st spur from the trunk on the north east cordon. Measurements started on DOS 27 in 1992/93 and 1994/95 measurements on DOS 8 and in 1993/94. Initially the total length of the shoots from the base to tip were measured with a tape measure. As the shoots became too long, the measuring technique was changed and only the elongation of the apical 200 mm sections of the shoot was monitored. The 200 mm position was marked weekly and therefore the distance between old and new markings implied the weekly elongation rate. In a preliminary study, this mark, 200 mm from the tip, was found to be beyond the shoot elongation zone which is in accordance with reported data (Winkler *et al.*, 1974). This method is faster and involves less handling of the shoots. Some shoot tips were broken by handling or by wind action. Broken shoots were replaced by similar ones on the north west cordons. Since cumulative growth was studied, the elongation of the new shoots and leaves were calculated and added to the elongation data of the old shoots. Shoot and leaf length measurements in treatments 25, 250 and 500 mS/m were conducted over the days 27-93 (DOS). The practice of topping vigorous growing shoots to arrest abundant growth was unfortunately also done to some of our shoots. Consequently the non-destructive measurements were discontinued after DOS 100.

The shoot length data were then used to estimate shoot elongation rates and day of bud break (1992/93 only). The leaf length data served to estimate leaf elongation rates and leaf initiation timing (Erickson & Michelini, 1957; Freeman & Kliewer, 1984). The leaf length data of 1992/93 were also converted to leaf area to estimate the development of the leaf area index (LAI). At this early stage of the season, lateral leaves (which were few and small) were ignored. The conversion used an empirical fitted curve:

$$A_{lt} = a * L_{lt}^{b} \qquad [5.1]$$

(A=area L=length lt=leaf number and time, a=0.136 and b=1.962 curve fitting parameters obtained by linear regression analysis with Statgraphics)

$$LAI_t = A_{lt} * N_{sp} / SA_p \qquad [5.2]$$

(N_{sp} = number of shoots per plant, SA_p = soil area per plant).

A leaf scoring technique assessed salinity damage to the leaves. Leaf scoring was done on all 24 plots on both sides of the experimental rows (i.e. on the Northwest and Southeast sides, Fig. 3.2). All ten experimental plants per plot were included (10 plants x 24 plots). Plants with healthy, good looking leaves were ranked 1 and a completely defoliated plant was ranked 5. In 1992/93 scoring was done four times during the season, on DOS 164, 211, 239 and 274. In 1993/94 leaf damage was assessed three times, on DOS 90, 120 and 217 while only one survey was conducted in 1994/95, on DOS 189.

Leaf area of the ten experimental plants per plot in 1992/93, 1993/94 and 1994/95 was determined using a *Decagon Sunfleck Ceptometer*. During the last two seasons, 1993/94 and 1994/95, leaf area was also measured with a *LICOR 2000* plant canopy analyser.

5.2.2 Destructive measurements

Total pruned shoot mass per vine was determined at the end of the growing season when the vines were dormant, i.e. during winter (August) by pruning according to the spur-pruning method. This particular method of pruning result in the growth of two shoots per spur and about two bunches per shoot. The pruning mass was determined by weighing the pruned shoots of each experimental plant individually.

To monitor the effect of salinity on shoot growth (mass and length) along the season, destructive sampling of shoots was also conducted seven times in 1992/93 and five times in each of 1993/94 and 1994/95 The seven sampling events of 1992/93 were done between early November (full bloom) and late March (harvest). The five sampling events in 1993/94 and 1994/95 more or less coincided with full bloom (27/10/93 & 1/11/94), pea-size stage of bunches (24/11/93 & 29/11/94), veraison (4/1/94 & 10/1/95), harvest (10/3/94 & 28/2/95) and post harvest (3/5/94 & 3/5/95). Two shoots per plot were sampled to study growth in treatments 1 (25 mS/m), 4 (250 mS/m) and 6 (500 mS/m). In 1994/95, destructive sampling was done on all treatments. In all years an upper shoot on a middle spur on a south cordon and a lower shoot on a middle spur on a north cordon were sampled. It was assumed that these two shoots would best represent the mean shoot, considering the larger shoots on the northern cordons and the larger shoots from the upper buds on a spur. The bunches were separated from the shoots and both were stored in plastic bags at low temperature for 24-48 hours until further analysis. The following shoot measurements were made:

i) shoot length;
ii) number of internodes, leaves on main shoots, and leaves on lateral shoots;
iii) fresh and dry mass of main shoots, leaf blades and petioles;
iv) total area of leaves on main shoots or lateral shoots (with a *Licor* area meter), and
v) on three samplings in 1992/93 the lengths of the leaf laminae were measured to obtain the leaf area/length ratio.

The latter ratio was needed to estimate leaf area from non destructive measurement of leaf lengths. When a significant area of the leaf became necrotic, fresh weight measurements became meaningless and large errors in area determinations could be expected. Only dry mass was consequently determined and the area was estimated using the parameters of a fitted curve that describes the area/dry weight ratio in

previous sampling. In the 25 and 500 mS/m treatments, half the number of shoots were used to get the above mentioned information for individual internodes and leaves.

From the measured plant parameters the following additional estimates were obtained.

vi) Dry matter (DMC) and water (WC) content as.
DMC = DW/FW. [5.3]
WC = 1-DMC. [5.4]

vii) Specific leaf dry- (SLDW) or fresh mass (SLFW) obtained by dividing the dry (LDW) or fresh mass (LFW) of the leaves by their area (LA).
SLDW = LDW/LA [5.5]
SLFW = LFW/LA [5.6]

viii) Leaf area/length ratio. - see eq 5.1.

ix) Leaf area index (LAI) as:
$LAI = LA_S * N_{sp}/SA_p$ [5.7]
LA_S = leaf area of shoot; Nsp = number of shoots per plant.
SA_p = soil surface area per plant (4.5 m^2).

x) Leaf ion content.
Leaves from the destructive samples were analysed for Cl, Na and K content. Dry grounded leaf samples of 200 mg were extracted over 24 hours in 10 mL acidic solution (900 mL H_2O + 100 mL acetic acid + 6.4 ml HNO_3). The extracts were analysed for content of Cl by potentiometric titration (*Metrohm - 702 SM Titrino*) with $AgNO_3$ and of Na and K by atomic absorption (*Varian - AA-1275*). Comparison of the extract method with dry ashing gave satisfactory results for Na and K.

5.2.3 Leaf water relations

Monitoring stomatal conductance and leaf water potential measured the effects of salinity on the water status of the leaves. In 1992/93 a more detailed study was conducted by measuring also the total organic solute content and the osmotic potential of the leaf sap. The results of this in-depth study are presented as Appendix II of this report.

Leaf water potential was measured on 19 occasions in 1992/93, concentrating mostly on treatments 1 (25 mS/m), 4 (250 mS/m) and 6 (500 mS/m). The majority of the measurements were made during midday (11h00-14h00). A full diurnal cycle, from pre-dawn till early evening, was measured on 08/12/92 (DOS 92) and again on 25/03/93 (DOS 207). A pre-dawn till midday and midday till sunset cycle of measurements were made on 05/01/93 (DOS 127) and 02/02/93 (DOS 155) respectively. In 1993/94 we had to scale down on the frequency of measurements and leaf water potential was measured on five dates only. The first measurement on 26/10/93 (DOS 55) included a midday measurement, while a full diurnal set of measurements was made on 25/11/93 (DOS 85) and on 14/03/94 (DOS 194). Predawn measurements were made on 06/01/94 (DOS 127) and again on 20/01/94 (DOS 141). During the last season, 1994/95, measurement of leaf water potential was restricted to 03/11/94 (midday) and 29/11/94 (pre-dawn). Except for 1992/93, when measurements of stomatal conductance started on 08/12/92, all measurements of leaf water potential were always preceded with a measurement of stomatal conductance on the same leaves used for leaf water potential.

A fully developed, apparently healthy leaf that was about the 12th leaf from the main shoot tip, and in full exposure to the sun, was used throughout for the study of leaf

water relations. In the case of treatments 5 (350 mS/m) and 6 (500 mS/m) this was not always possible because as the season progressed these leaves (12th position on main shoot) in these treatments started to show necrotic symptoms and stopped growing. The procedure was then to select any fully developed healthy leaf exposed to the sun.

Stomatal conductances were measured with a steady state continuous flow porometer with adjustable inlet air flow rate and air humidity (*PP systems*). The cuvette has a 2 cm^2 leaf exposure opening and can be clipped comfortably over any leaf. The instrument was held in such a way as not to disturb the natural orientation of the leaf. A suitable leaf for this measurement was defined as a leaf with a standard size, unscathed, fully developed, with full sun exposure and more or less in the twelfth position from the tip of the shoot but not lower or opposite the bunch. In most instances three leaves were measured with the median leaf being used for other measurements. A light sensor attached to the probe provides the light radiation intensity parallel to the leaf surface in the PAR range (photosynthetic active radiation). A temperature sensor in the probe provides an equilibrium temperature of the cuvette and the leaf which is the ambient temperature. A microprocessor calculate the GS using the airflow air temperature and change in air relative humidity between inflowing and outflowing air.

5.3 Results

5.3.1 Non-destructive sampling

a) Trunk circumference

Trunk circumference measurements in 1992/93 started on day 16 (DOS). In all six treatments the seasonal changes were similar (Fig 5.1). A temporal decrease early in the spring was followed by a rapid recovery towards day 50. After this day changes in circumferences were small. The mean seasonal increase in trunks circumferences for all treatments was 1.6 mm. The large variability shown by the large standard error (Fig 5.1) resulted mainly from differences between plots.

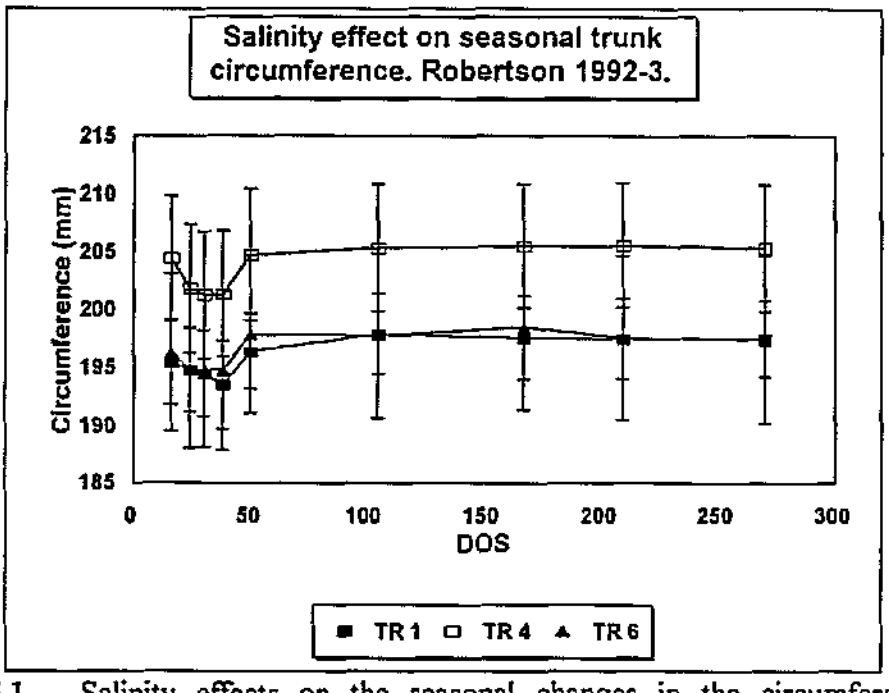

Figure 5.1 Salinity effects on the seasonal changes in the circumferences of Colombar grapevine trunks of treatments 1, 4 and 6 in 1992/93

The seasonal trend in the trunk circumference data of 1994/95 is inconsistent, probably because of measurement errors, and is not shown here. The annual changes in the trunk circumference of the ten experimental plants of all treatments, measured just before harvest, are listed in Table 5.1. Also shown are the standard errors associated with each treatment mean. Although the difference are not statistically significant, treatment 4 had the largest plants and treatment 6 the smallest. We do not believe this to be a salinity effect, but rather an artefact of the previous history of this vineyard. The coefficient of variation (not shown) varied between a minimum of 0.02 and a maximum of 0.08. The annual changes were minor and were consequently not investigated any further. However, the size of the individual experimental plants as manifested by trunk circumference, were used in the statistical analysis of yield.

Table 5.1 Treatment mean and standard deviation of trunk circumference of the 240 experimental Colombar grapevine plants at the Robertson vineyard: 1992/93 to 1994/95

	Stem circumference (mm)					
Treatment	**1992/93**		**1993/94**		**1994/95**	
	Mean	STD	Mean	STD	Mean	STD
1	188	4	188	5	188	6
2	183	14	184	14	182	13
3	181	7	184	7	182	7
4	189	11	191	11	189	13
5	180	8	183	9	180	10
6	169	14	171	14	169	12

STD = standard deviation

b) Shoot elongation and leaf growth

The mean shoot length of three treatments during the initial 80 to 100 days of the season are shown in Figure 5.2. Total shoot length decreased with the increase in salinity. Treatment 4 was an exception where, during 1994/95, growth reduction was less than expected from the salinity effect in the other salt levels (Fig. 5.2c). During the early part of the season, i.e. till about day 40, the historical effect of the previous season's salinity was obscured in the increase of shoot length, i.e. treatments 4, 5 and 6 had longer shoots than treatment 1. This was observed during all seasons, but was especially noticeable in 1993/94 when measurements started in the first week of September 1993 (Fig. 5.2b). Later during the season, shoot elongation seemingly responds to the current season's salinity with shoot elongation rate decreasing with increasing salinity (Figure 5.3). Consequently, from about DOS 40, i.e. early in October, the situation reverses with the shoots of treatment 1 now being longer than that of the salinity treatments. Our results are consistent with Downton and Crompton (1979) who reported that one irrigation season with saline water reduced growth rate but brought forward bud burst in the following spring by approximately 4 days. At Robertson the 500 mS/m saline irrigation water of treatment 6 was replaced in 1994/95 with the low salinity water of the control treatment. However, the growth response of treatment 6 in 1994/95 (Fig. 5.2c) was only slightly better than that of treatment 5, i.e. it did not respond to the current year's low saline water. This indicates that the salinity

of the previous seasons also had an effect of shoot elongation and not only on bud burst.

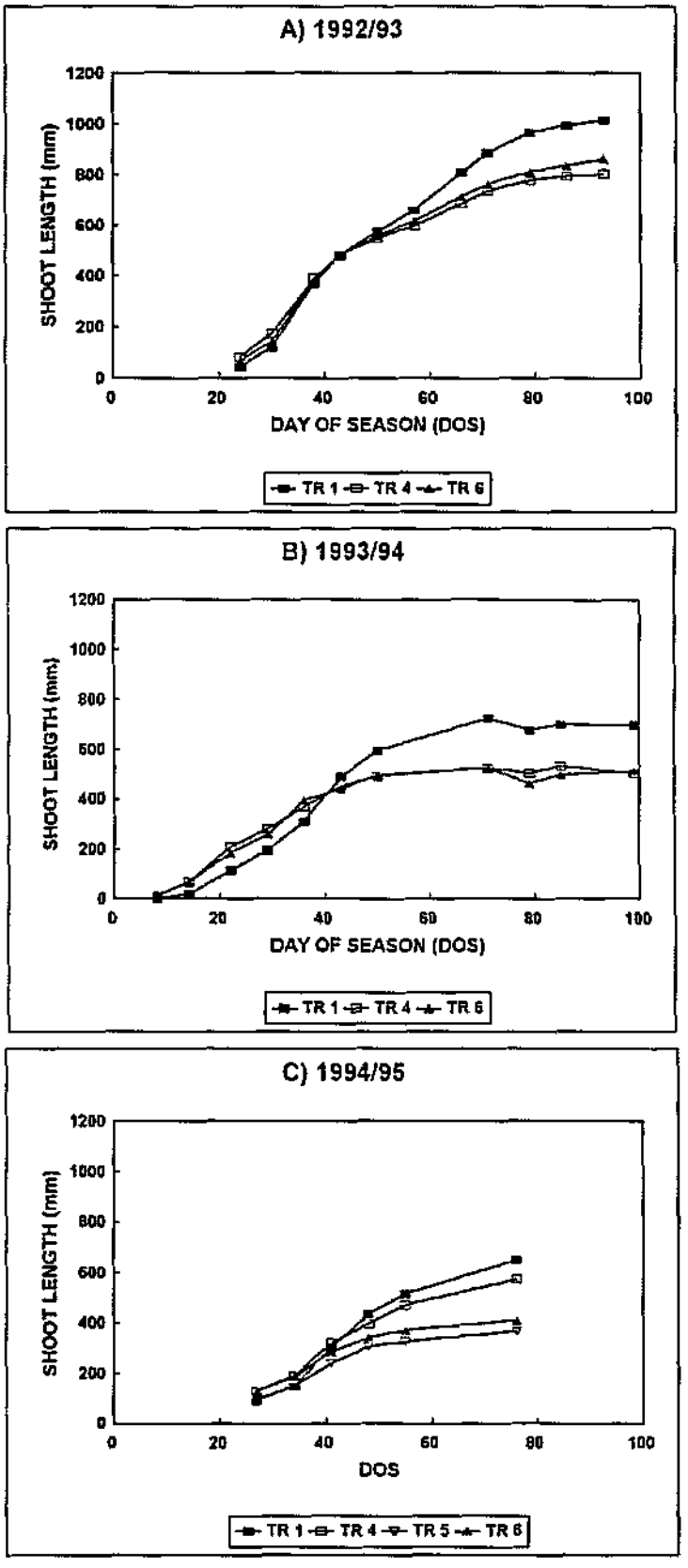

Figure 5.2 Salinity effect on the treatment mean shoot length of Colombar grapes at Robertson during the early part of the season: a) 1992/93, b) 1993/94 and c) 1994/95

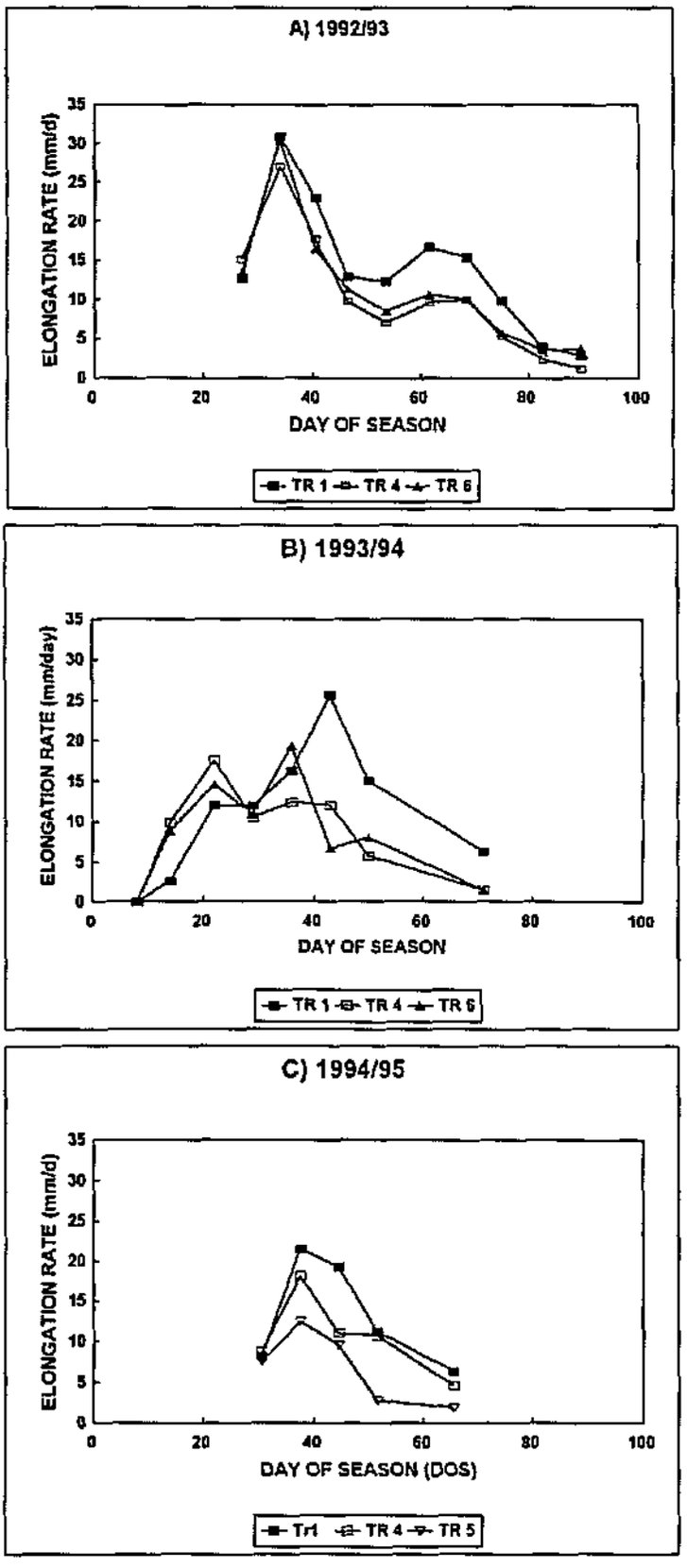

Figure 5.3 Salinity effect on the shoot elongation rate of Colombar grapes at Robertson during the early part of the season: a) 1992/93, b) 1993/94 and c) 1994/95

The effect of salinity on internode elongation for the 1994/95 season is shown in two figures. Figure 5.4 show that on DOS 76 the internodes of the upper shoot were slightly longer than the lower shoot's internodes for all salt levels. On both shoots salinity reduced the internode length and number. This is different to the results of 1992/93 when it was found that salinity reduced the lengths of only the internodes with a larger serial number than 5 (data not shown). In 1994/95 the salinity effect was clear already in internode 2. This indicate that as the exposure to salinity increases and in spite of winter leaching and low salinity conditions at the beginning of the growing season, the negative effect of the previous season's salinity manifest itself progressively earlier the following season. In Figure 5.5 the mean internode lengths of both shoots (upper and lower) of treatments 1, 4 are shown for DOS 27, 48 and 76 of the 1994/95 season. Close inspection of the salinity effect on internode length and number show clear differences over the season. On DOS 27 the saline treatments had more internodes than the control treatment. Internode length was maximal in treatment 4 (ECi=250 mS/m) and minimal in treatment 5 (ECi=350 mS/m). On DOS 48 internode length decreased with the increase in salinity and on DOS 76 also the internodes number decreased with increasing salinity.

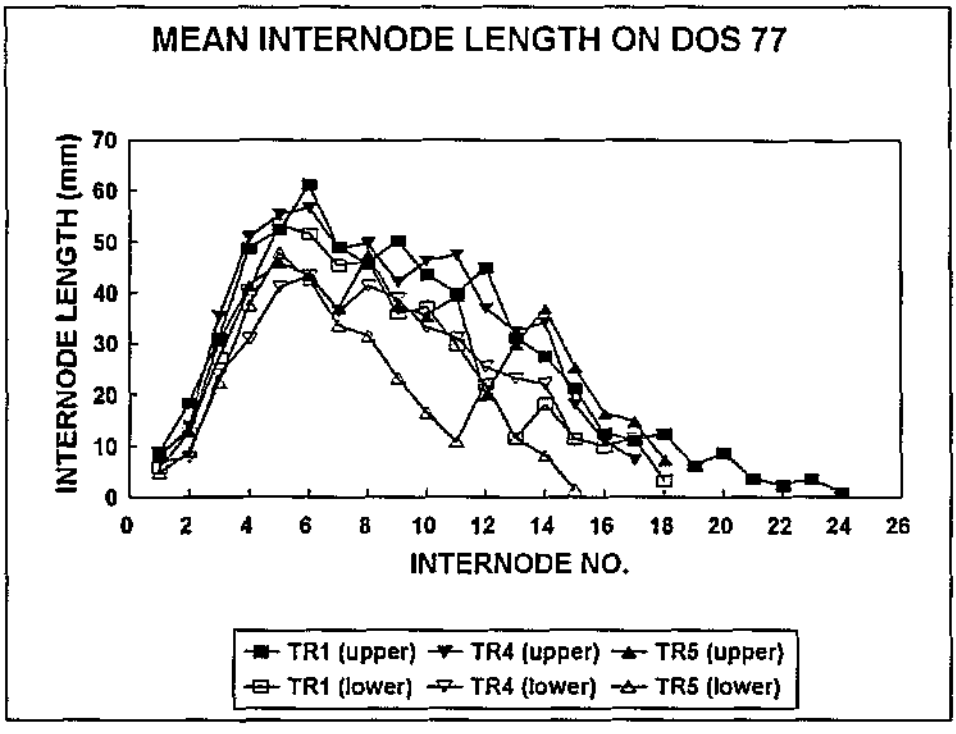

Figure 5.4 Mean internode length of the upper and lower shoots of treatments 1, 4 and 5 during the 1994/95 season

From about day 90 the shoot elongation in all years and for all treatments became very slow. This pattern is similar to the reported growth pattern of grapes (Van Zyl, 1984; Williams and Matthews, 1990; Winkler *et al.*, 1974).

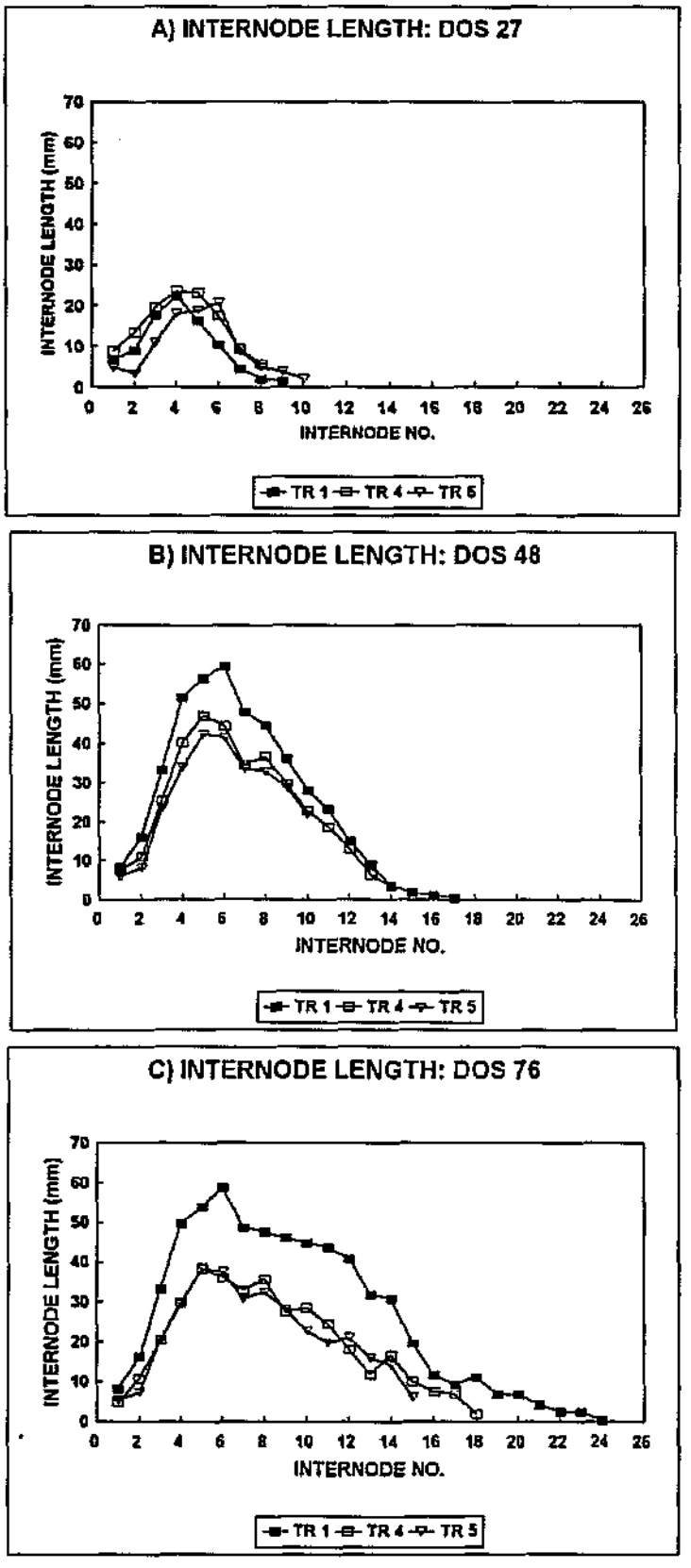

Figure 5.5 Mean internode length of Colombar grapes in treatments 1, 4 and 5 at three different dates along the 1994/95 season

Leaf area per shoot for treatments 1, 4 and 6 in 1992/93 and 1993/94 are shown in Figure 5.6. Leaf area per shoot for all treatments in 1993/94 were considerably less

than during the previous year. As expected, leaf area per shoot (Fig. 5.6a), leaf area index (LAI) calculated from leaf length measurements (Fig. 5.7a) and new leaf initiation (Fig. 5.7b) in 1992/93 followed similar patterns. (Similar observations were made in 1993/94, data not shown). The salt treatment effect on leaf area, was larger than the effect on leaf number, since mean leaf area also decreased.

To find out when salinity started to reduce leaf area, the individual leaf areas of 1992/93 and 1994/95 were compared (Fig 5.8). The data of 1992/93 show smaller leaves in the saline treatments from leaf no. 6, a leaf that started to grow on about day 33. In 1993/94 this was noticed on leaf no. 5 which in the case of treatment 4 developed between day 14 and 22, and between day 8 and day 22 for treatment 6. These and other growth measurements show a salinity effect very early in the season (e.g. before the first irrigation with saline water was applied in the 1992-3 growth season), which point to a possible residual salinity effect. It could also be a change in plant factors produced in one season and needed in the following spring. Such factors can be reduced metabolite and nutrient reserves, toxic salt levels or change in hormone balance. The aggravation of salinity damage over seasons was also reported for plums (Hoffman *et al.*, 1989; Bernstein *et al.*, 1956).

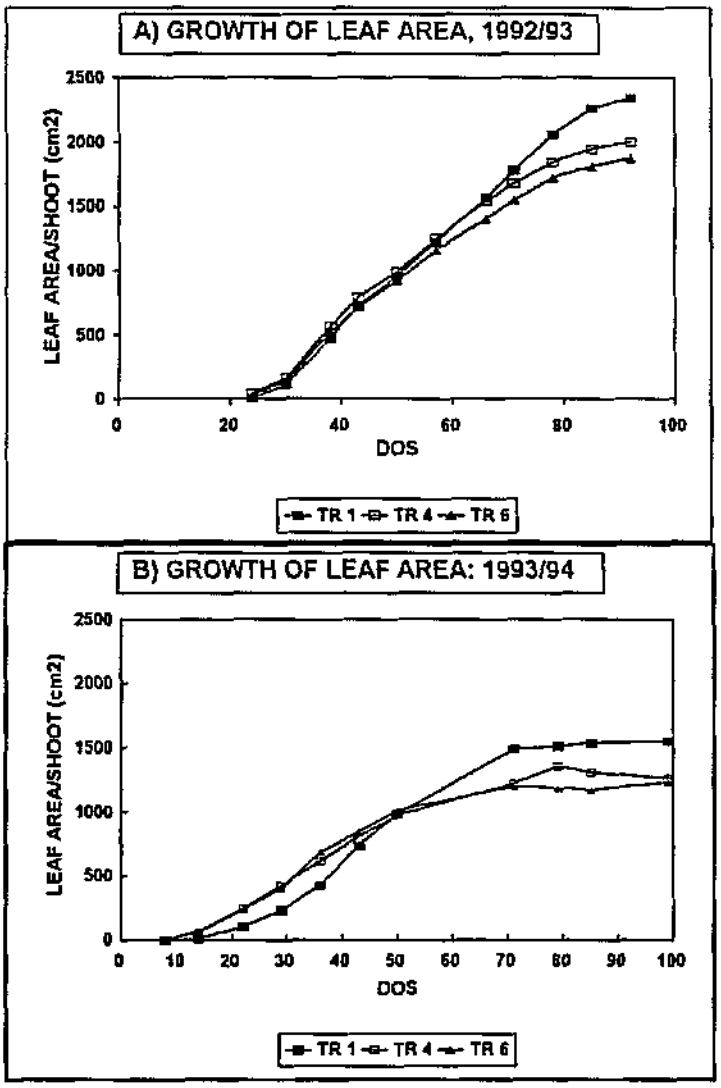

Figure 5.6 Growth of leaf area per shoot for treatments 1, 4 and 6 in a) 1992/93 and b) 1993/94

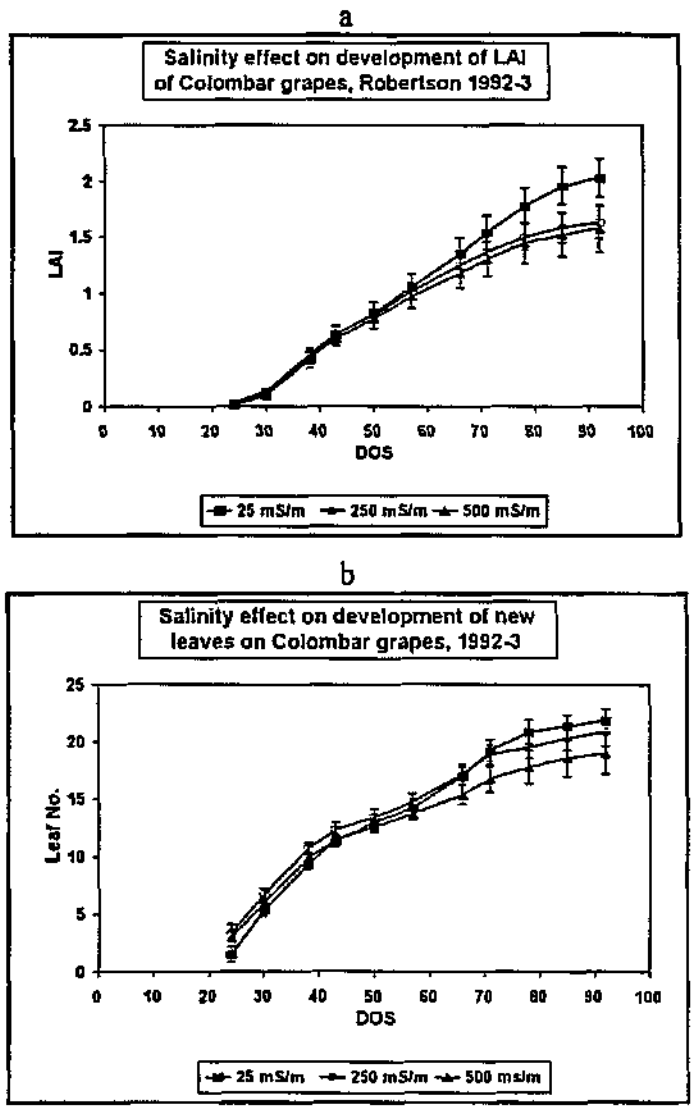

Figure 5.7 Salinity effect on a) leaf area index and b) the development of new leaves on the main shoot of treatments 1, 4 and 6 between day 23 and day 93 of the 1992/93 season

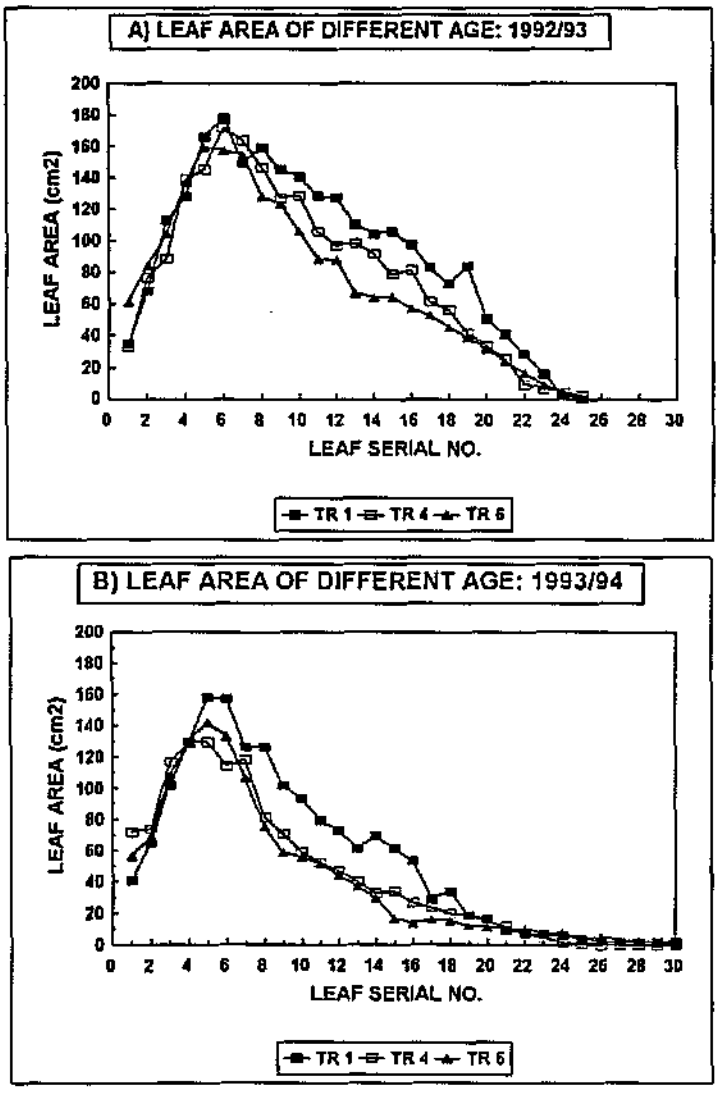

Figure 5.8 Salinity effect on the area of Colombar leaves of different age (serial number)

c) Leaf degradation score

Leaf score, taken at different times during the season quantified the salinity damage to the leaves. As mentioned previously, the leaf scoring was done on both sides of the row on all experimental vines (10 plants * 24 plots). The deterioration in treatments was in the sequence 6 > 5 > 4 = 3 > 2 = 1. For treatments 3 to 5, the score of 1992/93 gave a linear increase for all measurements over time.

For the 1992/93 data we assumed a linear model for all treatments and calculated the time (T_0) when the damage started by extrapolation of the equation

$$D=a+bT \qquad [5.8]$$

to $D=1=T_0$ (D=damage level). The predicted time of first damage for treatments 6 and 5 were days 132 and 151 (Table 5.2) while veraison started on day 127. Leaf damage at this period of maximal sugar accumulation in the fruit (Winkler *et al.*, 1974) can be detrimental for yield quantity and quality.

Table 5.2 Salinity effect on the estimated date of leaf damage initiation during the 1992/93 season (To is T when S=1 in S=a+bT; 1 is the lowest score; b = rate of increase in damage (score/day))

Treatment	EC_{iw} (mS/m)	b (score/day)	T_0 (DOS)	n
1	25	0.06	230	2
2	75	0.07	230	2
3	150	0.05	203	3*
4	250	0.05	202	3*
5	350	0.03	151	4*
6	500	0.04	132	2

* data used to calculate the linear regression equation [5.8].

The long-term effect of salinity damage to the leaves of treatments 3 and 5 are shown in Figure 5.9. During the 1993/94 season leaves of treatments 3, 5 an 6 (150, 350 and 500 mS/m respectively) show damage on DOS 120 with the first symptoms of damage (T0) being visible on about day 90. This was earlier than the T0 of 203, 151, and 132 DOS for these treatment in 1992/93. Also, the damage score on day 210 was larger in 1993/94 than in 1992/93. Treatment 4 (250 mS/m) show only slightly larger damage than treatment 1 and about the same damage as treatment 2. This observation is in agreement with all the other observations that this treatment is affected less by salinity. To date we explain it by the plants being more vigorous from the beginning of the study for unexplained reasons. Plant size, or the growing conditions responsible for it (e.g. edaphic and environmental factors) seem to interact with the salinity effects. Prior *et al.*, (1992) showed that soil structure is such a factor.

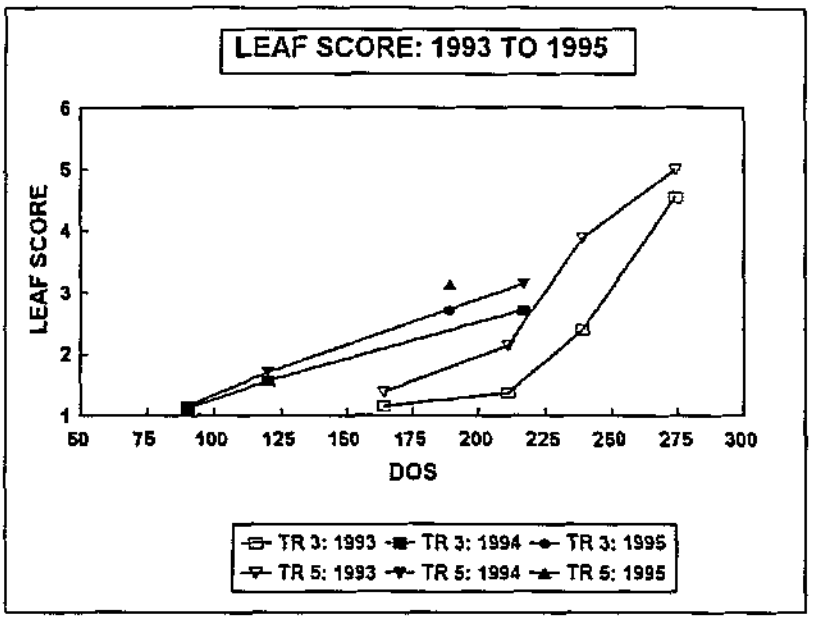

Figure 5.9 Long term salinity effect on leaf damage of Colombar grapes according to a leaf score: treatments 3 and 5

During all seasons, leaf damage was more severe on the lower cordon on the north side of the vineyard rows (Fig. 5.10). These cordons carry less vigorous shoots than the south side cordons. They absorb more sun radiation at the later hours of the day when air temperatures are higher and air relative humidity lower and the stomates are less

open resulting in less evaporative cooling. All these three factors can lead to earlier and more severe leaf damage.

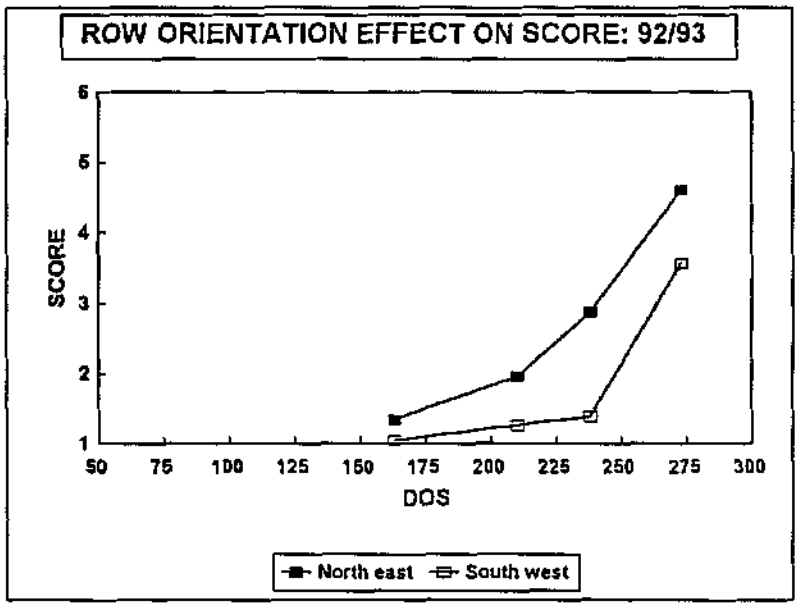

Figure 5.10 Row orientation effect on visible salinity damage symptoms of Colombar grapevine leaves: means of combined data (irrespective of treatment) of 1992/93

5.3.2 Destructive measurements of vegetative plant organs

Between 1992 and 1995 a wealth of data were gathered on the effects of salinity on the vegetative organs of Colombar grapes. As mentioned in section 5.2, vegetative organs were sampled at different growth stages along each of the three seasons. In this section, only a selection of some of the data are presented. Because of the destructive nature of the sampling, different shoots were sampled each time. It is to be expected that this will increase the within treatment variability. Trends along the season, differences among three treatments and within treatment variability are illustrated visually using the results of 1992/93. The data of 1993/94 for all treatments are summarised in tabular form as treatment means.

a) Internode length and mass

Elongation of the internodes is most sensitive to stress, including water stress. Comparing the internode length and mass in the 25 and 500 mS/m treatments, Figure 5.11 show that the internode mass during 1992/93 were more sensitive to salinity than the internodal lengths. Also shown is the magnitude of the within treatment variability. Similar observations concerning the variability were made during the other seasons. The deposition of dry matter in the shoots after the cessation of their elongation is well documented (Winkler *et al.*, 1974, Williams and Matthews, 1990).

The time span over which a given internode elongates, can be defined accurately with marking experiments. Therefore, the internode with the lowest serial number that show salinity effects, can indicate the earliest salinity effect. The similar length of the first 4-5 internodes and shorter internodes with larger serial number (and reduced mass of all internodes in the saline treatment) indicate a salinity effect when internode 5 was at the final elongation stage and internode 1 still in stage of biomass deposition. The distance

of node 5 from the base of the shoot is 150 mm and the length of the elongation zone is 120 mm. When these two lengths are added (i.e. 270 mm) and plotted against shoot elongation (Fig. 5.2a), it gives the latest possible time for a salinity effect on shoot elongation during the 1992/93 season. The salinity effect could have started before, but not later than the stage when node 5 reached its final distance from the base. This calculation show that the salinity effect in treatment 6 started before day 33 of 1992/93, an estimate which is in accordance with the conclusions from non-destructive measurements of shoot elongation and growth of leaf area. This effect must surely reflect a residual effect of the previous season.

Statistics of the eight shoots per treatment sampled at harvest in March 1994 are shown in Table 5.3. Similar data are available for the other sampling dates and years, but are not shown here. The number of nodes per shoot, as well as the fresh and dry mass per internode decrease with increasing salinity. The internodes of treatment 1 are longer than those of the salinity treatments, but differences between the five salinity treatments are small and inconsistent. These results are all in accordance with observations made during 1992/93.

Table 5.3 Summary of the shoot and internode number, length and mass responses of Colombar grapes to salinity in 1993/94 in terms of the arithmetic means of eight shoots per treatment sampled in March 1994

Parameter	Tr 1 25 mS/m	Tr 2 75 mS/m	Tr 3 150 mS/m	Tr 4 250 mS/m	Tr 5 350 mS/m	Tr 6 500 mS/m
Number of nodes per shoot	21.9	20.1	21.4	18.4	18.5	17.0
Length per node (mm)	33.5	28.8	32.0	29.2	27.3	28.5
Fresh mass per shoot (g)	22.89	14.98	18.43	14.41	12.17	10.21
Dry mass per shoot (g)	11.23	7.46	9.38	7.14	5.88	4.94
Dry mass fraction	0.49	0.50	0.51	0.50	0.48	0.48

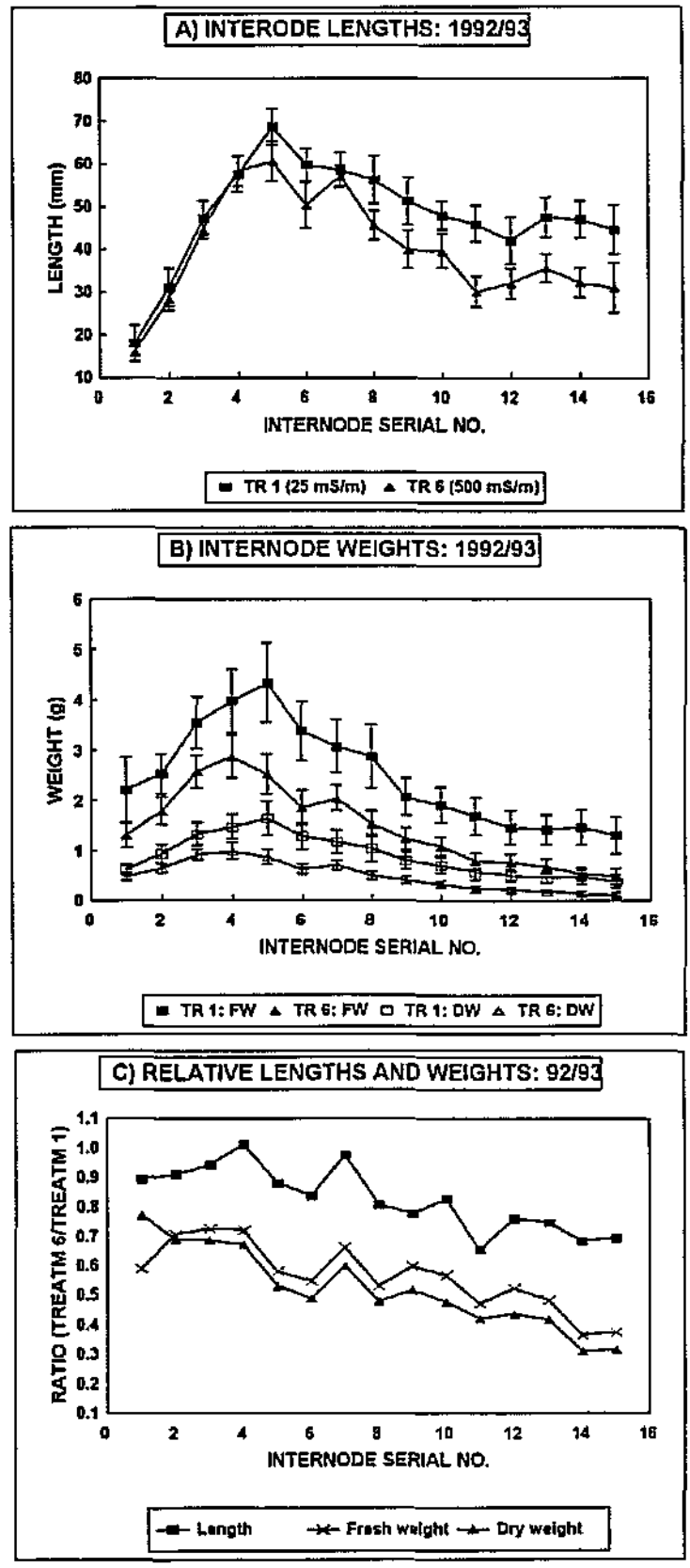

Figure 5.11 Salinity effect on the a) length, b) fresh and dry mass and c) normalised length and mass (relative to treatment 1) of the internodes on the main shoots of Colombar grapes: 1992/93 season

b) Leaf and petiole mass

Leaves that were used in the evaluation of the area to length ratio, also served to determine the effect of salinity and age on the specific weight of the leaf. The fresh and dry mass of the leaves were determined and the weight per unit area (mg/cm^2) were calculated. The specific fresh weight is a parameter for leaf growth in thickness. The specific dry weight represent mainly deposition of metabolites. Salinity had only a marginal effect on the specific weight of leaves, even in the high salt treatment. Figure 5.12, which summarises treatment means and standard errors of five sampling days, presents the effects of two of the main variables during the 1992/93 season, namely salinity (treatments 1 and 6) and leaf serial number (i.e. short term age effect), while Figure 5.13 presents the main effect of the third variable, leaf age over the season, on the specific fresh and dry weights as well as dry matter content of the Colombar leaves. The age differences between leaves with different serial numbers on a shoot is constant over all five sampling days. This enabled us to infer the short term age effect from the data in Figure 5.12. The constant values of the specific weights and dry matter content for a wide range of leaf serial numbers in the two salinities, indicate that age did not affect these parameters within a sampling day. This is in contrast to Freeman & Kliewer (1984) who showed a linear increase in dry matter density with age for Cabernet Sauvignon sampled on one day. Dry matter content was higher in all, except the very young leaves in the saline treatment.

The large standard errors (SE's) in Fig. 5.12 are the result of large differences in dry matter content between the sampling dates. The mean values of the three parameters for all leaves within a given day show the seasonal time effects (Fig 5.13). This figure shows a large increase over time in specific dry weight and with little and inconsistent change in the thickness of the leaves in the high and low salt treatments. Throughout the period, day 78-169 of 1992/93, the saline leaves had larger dry matter content. The small differences between leaves of different age within a sampling date and the large differences between days indicate that the dry matter deposition rate is mainly a seasonal change, which occurred under high or low salinity and was not related to the individual leaf age. The sugar content of leaf sap increased by 5% over this period (data not shown), and can account for about 30% of this dry matter deposition.

Similar calculations were made in 1993/94 and 1994/95 but for the sake of brevity, the effect of age during the season and leaf position on the shoot on specific fresh and dry weight are not presented here. The salinity effect on specific fresh- and dry weights and dry matter content of leaves and the fresh and dry weights of the petioles at harvest (March 1994) are summarised as treatment means for all treatments in Table 5.4. Specific fresh weight decreased and specific dry weight increased with salinity. Relative to the control, salinity apparently increases the dry matter fraction of leaves by between 8% (treatment 2) and 13% (treatment 4). This observation is in accordance with the data of 1992/93 (see DOS 172, Figure 5.13c). Treatment 1 has a higher fresh and dry mass per petiole than any of the salinity treatments, but within the five salinity treatments no consistent trend is apparent.

The relative contribution of the shoots, leaves and petioles to the total dry mass of these three vegetative plant organs at different phenological growth stages of the 1993/94 season is shown in Table 5.5. The purpose of this investigation was to differentiate between the concentration and quantity of salt in these three organs (see next section). At harvest (DOS 191) leaves contributed between 54% and 62%, the

shoots 33% to 41% and petioles about 5% to the total dry mass of the vegetative organs. Salinity apparently decreases the contribution of shoots, but increases the contribution of leaves to the total vegetative organ mass which indicate that salinity had a greater negative effect on shoot growth than on leaf growth. The effect of salinity on the petiole's contribution to the vegetative mass is not clear. At full bloom salinity seemingly increases the contribution of petioles to the total mass, while at pea size stage, the opposite occurs. At the other two dates, no consistent trend with salinity is apparent. No clear explanation for this differential effect of salinity on the vegetative organs has been found yet, but the increase in dry specific mass of the leaves with salinity might be related to this observation (Table 5.3). The relationship between photosynthetic activity of leaves with decreasing leaf area is currently being investigated by the Viticultural and Oenological Research Institute as part of a bigger leaf defoliation research programme. An increase in photosynthetic activity per unit area might lead to greater ion and metabolite deposition in smaller leaves compared to larger leaves. Prior *et al.*, (1992b) found that salinity decreased pruning mass more than losses of yield. However, they also report a decrease in photosynthesis with increasing salinity which contradicts some of our explanations above. They report a lower total seasonal carbon fixation of salinised vines, which was reflected in the decreased levels of starch and total carbohydrate in shoots as well as lower pruning mass. At this stage we cannot offer any firm explanations for the results shown in Table 5.5.

Table 5.4 Summary of the specific fresh and dry weight of leaves, and petiole fresh and dry weight responses of Colombar grapes to salinity in 1993/94 in terms of the arithmetic means of eight shoots per treatment sampled in March 1994

Parameter	Tr 1 25 mS/m	Tr 2 75 mS/m	Tr 3 150 mS/m	Tr 4 250 mS/m	Tr 5 350 mS/m	Tr 6 500 mS/m
Specific fresh weight per leaf (mg/cm^2)	20.25	19.01	18.54	19.04	18.18	17.06
Specific dry weight per leaf (mg/cm^2)	10.71	13.07	11.71	13.48	12.75	14.09
Leaf dry matter content (fraction)	0.608	0.648	0.676	0.689	0.634	0.659
Fresh weight per petiole (mg)	103.8	69.7	88.3	80.3	62.6	64.9
Dry weight per petiole (mg)	61.7	47.8	60.6	51.9	42.9	43.1
Petiole dry matter content	0.622	0.692	0.694	0.671	0.689	0.674

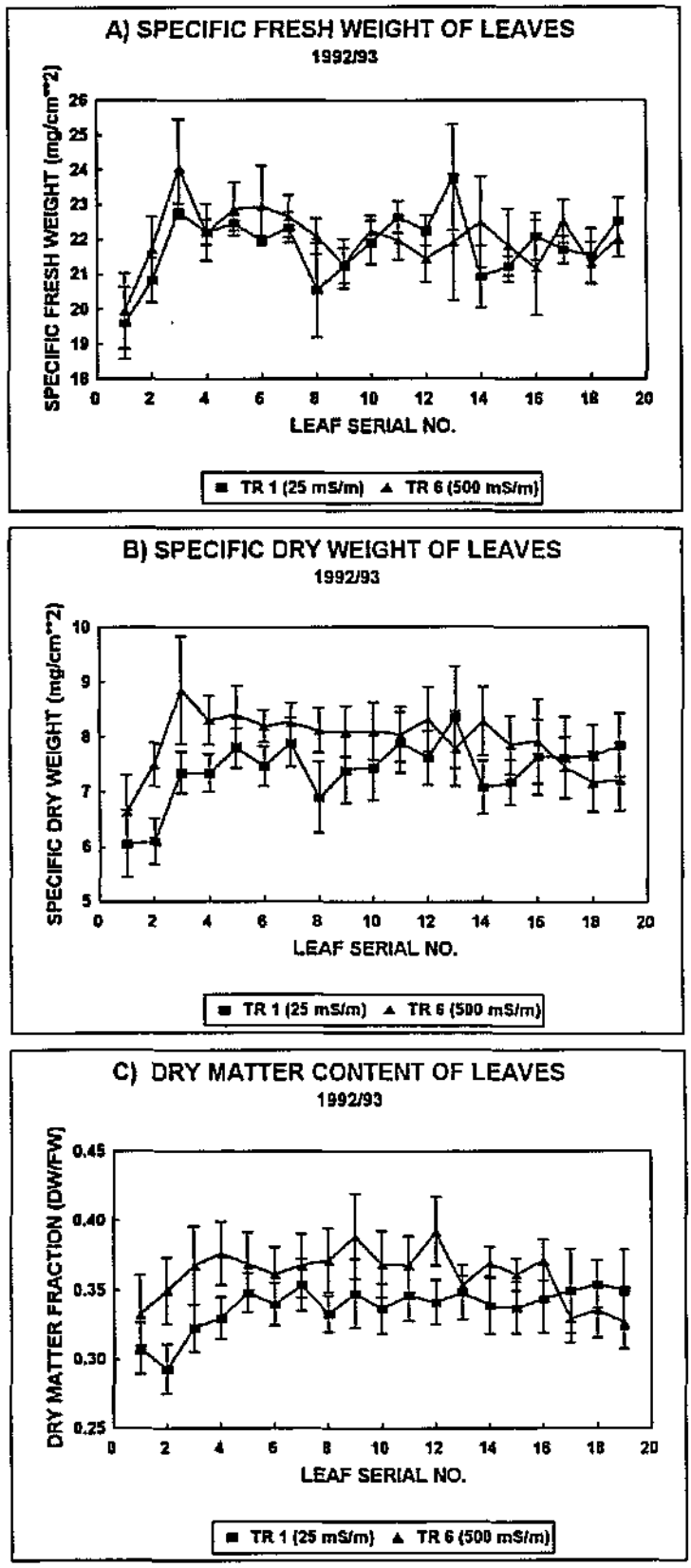

Figure 5.12 Salinity effects on a) the specific fresh weights, b) the specific dry weights and c) dry matter content of Colombar leaves of different serial number (means of five sampling days)

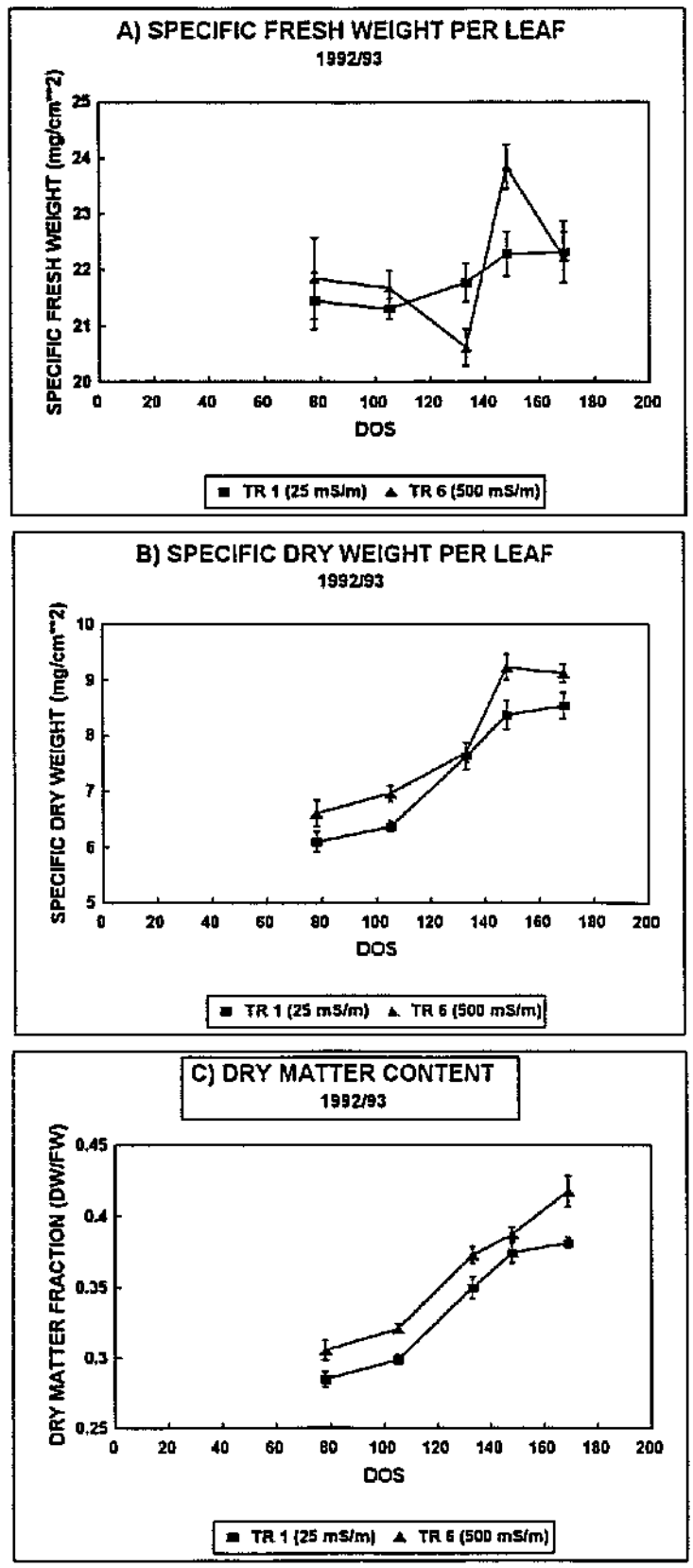

Figure 5.13 Salinity and age effects on a) the specific fresh-, b) specific dry weight and c) dry matter content of leaves during the 1992/93 season

Table 5.5 The effect of salinity on the relative contribution of the different plant organs to the total vegetative dry mass of Colombar grapes at different phenological growth stages in the 1993/94 season summarised in terms of the arithmetic means of eight shoots per treatment

Treatment	Full bloom DOS 57	Pea size stage DOS 85	Veraison DOS 126	Harvest DOS 191
Fraction of dry mass in shoot				
1 (25 mS/m)	0.322	0.279	0.483	0.411
2 (75 mS/m)	0.374	0.258	0.387	0.359
3 (150 mS/m)	0.344	0.278	0.398	0.356
4 (250 mS/m)	0.326	0.253	0.471	0.335
5 (350 mS/m)	0.283	0.222	0.392	0.345
6 (500 mS/m)	0.269	0.180	0.348	0.336
Fraction of dry mass in leaf blade				
1 (25 mS/m)	0.612	0.670	0.460	0.542
2 (75 mS/m)	0.559	0.695	0.558	0.593
3 (150 mS/m)	0.589	0.673	0.541	0.596
4 (250 mS/m)	0.605	0.698	0.481	0.616
5 (350 mS/m)	0.644	0.735	0.554	0.608
6 (500 mS/m)	0.661	0.777	0.593	0.618
Fraction of dry mass in petiole				
1 (25 mS/m)	0.066	0.051	0.057	0.047
2 (75 mS/m)	0.066	0.047	0.055	0.048
3 (150 mS/m)	0.068	0.049	0.061	0.048
4 (250 mS/m)	0.069	0.049	0.048	0.049
5 (350 mS/m)	0.074	0.043	0.054	0.048
6 (500 mS/m)	0.070	0.043	0.059	0.046

c) Pruning mass

The arithmetic mean mass per salinity treatment of the shoots pruned during the winter (August) of each year is presented in Table 5.6. The results of 1991 represent the variability in plant size and growth vigour before the start of the salinity treatments in December 1991. Plant size varied considerably with treatment 4 having the biggest plants (see the results of trunk circumference measurements Table 5.1). Pruning mass (and other plant parameters) furthermore had a log-normal frequency distribution. In view of the historical differences in plant size and log-normal distribution, the ANOVA of the pruning mass was done on log-transformed data using the untransformed shoot

mass of 1991 as a covariate. The results of the ANOVA are shown in Table 5.6. Since 1992, pruning mass of all treatments, including treatment 1, have declined progressively, especially at the higher salinity levels. The difference between the control and the salinity treatments increased from 1992 to 1993, but in 1994 and 1995 this difference was much reduced. In spite of the substantial decline in the pruning mass of treatment 1 from 1992 to 1995, the salinity effect within a year increases. In 1992, the only statistically significant difference in shoot mass was between treatment 1 (25 mS/m) and 6 (500 mS/m). In 1993 treatment 6 and 5 both showed a statistically significant shoot mass reduction, and by 1995 treatments 6, 5 and 3 were statistically significant different to treatment 1. This is indicative that the salinity effect on shoot growth increases with time.

Table 5.6 Influence of the salinity treatments on the arithmetic and geometric mean pruning mass of Colombar grapevine

Year	Salinity treatment (mS/m)						
	25	75	150	250	350	500	P
*Arithmetic Mean Pruning Mass (no covariate) (fresh mass, kg/plant)**							
1991	0.98	0.88	0.84	1.00	0.71	0.84	
1992	1.34	1.04	0.97	1.22	0.89	0.87	
1993	1.08	0.77	0.65	0.91	0.60	0.50	
1994	0.67	0.44	0.38	0.59	0.30	0.22	
1995	0.55	0.34	0.24	0.41	0.19	0.17	
(1991-1995)	0.43	0.53	0.60	0.61	0.52	0.67	NS
Geometric Mean Pruning Mass with Pruning Mass of 1991 as Covariate (fresh mass, kg/plant)							
1992	1.17a**	1.03ab	0.87b	1.05ab	1.01ab	0.89b	0.338
1993	0.97a	0.76ab	0.62bc	0.78ab	0.67bc	0.51c	0.009
1994	0.54a	0.43ab	0.35b	0.46ab	0.34bc	0.23c	0.009
1995	0.43a	0.35a	0.22bc	0.31ab	0.22bc	0.18c	0.002

* Not statistically analysed
** Means separation within rows by LSD Multiple Range Test at the 5% level
P Probability level

The reason for the continuous and substantial decline in pruning mass of treatment 1, could not be resolved. It is quite possible that because of the age of the vines (>20 years) they are progressively losing growth vigour, but it is unlikely that a 58% reduction (based on arithmetic means) in pruning mass between 1992 and 1995 can be attributed to loss of vigour alone. There are two further possible explanations for the response of treatment 1. The first is related to the fact that, in order to reduce unintentional leaching losses we have continuously adjusted downward the reference soil water content on which the irrigation quantities were based (see Chapter 4, section 4.2.2). It could be that, even in treatment 1, these changes resulted also in higher water and/or salt stress in the root zone which lead to a continuous decline in shoot growth and mass. The other possible reason is related to the practice of winter leaching. It is standard viticultural practice in the Breede River Valley to establish a cover crop in vineyards during winter. This is normally done by sowing a crop like barley, oats or rye

early in April and to apply a top-dressing of nitrogen at the same time. The nitrogen served to get a well established cover crop and to act as a N-resource during the important post-harvest period when the vines are establishing reserves necessary for the following spring. In our case we have deliberately tried to leach as much of the accumulated salt in winter, but obviously with a concomitant loss of the applied nitrogen. Although a light application of nitrogen fertiliser was applied early each season to supplement the post-harvest application, it could be that the vineyard has since the winter of 1992 experienced a nitrogen deficiency.

d) Ionic composition of vegetative plant organs

The leaves sampled for destructive growth analysis, were analysed for ion content also. In 1992/93 only leaves from treatments 1, 4 and 6 were analysed, while all treatments were included in the analyses of 1993/94 and 1994/95. Two types of leaf samples were prepared for the ion analysis namely combined samples of all leaves on the main shoots or on laterals of the main shoots, and individual leaves along the main shoots of selected treatments (1992/93 and 1994/95 only). The combined samples from the different samplings during the season were used to follow the seasonal changes in leaf salt content. The individual leaves sampled on, for example days 148 and 169 of 1992/93, served to evaluate the age and location effects on the leaf ion content.

Absolute ion levels varied substantially from year to year as well as within a season. The seasonal changes in the ionic content of leaves on the main shoots are shown in Figures 5.14 to 5.16. Chloride (Fig. 5.14) and sodium (Fig. 5.15) during all three seasons were stable and low in treatment 1 but increased with increasing irrigation water salinity. The increase in Cl and Na along all three seasons seems to be linear. For both elements the rate of increase was faster at the higher levels of salinity, i.e. treatments 5 and 6, and was faster for Cl than for Na. In 1994/95, the saline water of treatment 6 was replaced with low salinity canal water (25 mS/m). Initially in 1994/95, Cl and Na were maximal in treatment 6, but from about DOS 130 up to the end of the season, treatment 5 had the highest concentrations. The relatively high ionic content of the leaves of treatment 6 must be a residual effect of Cl and Na accumulated in the plant organs during the first three years of salinity exposure. The temporal trend in the K content of the leaves during 1993/94 are shown in Figure 5.16. The initial K content that was highest in treatment 1 in all years, decreased over the season in all treatments. This decrease was faster with the increase in salinity. Similar observations were made in 1992/39 and 1994/95 (data not shown).

Relating the leaf damage score to the leaf salt content in treatment 6, show that in 1992/93 on day 132 when damage started, the Na and Cl content levels were about 1.7 g/kg (0.17%) and 6 g/kg (0.6%) - values that were not reached in the leaves of treatment 4 when leaf damage started on about day 202. The first salinity damage to the leaves of treatment 6 in 1993/94 were visible on about day 90, when the chloride concentration was also about 6 g/kg (Fig. 5.14b, and assuming that the increase between day 60 and day 193 is linear, i.e. ignoring the inflection that occurred between day 60 and 90). This observation concerning chloride damage to the leaves accords remarkably well with that of 1992/93. However, at this same stage (DOS 90, 1993/94) the sodium content in treatment 6 were 2 g/kg, which is slightly higher than when damaged started in 1992/93.

Profiles of the ion content in leaves along the main shoots (Fig 5.17) on days 148 and 169 in treatment 1 of 1992/93 show similar low content of Cl and Na in all leaves and

increase in K content (data not shown) in leaves younger than serial number 24. In treatment 6 the Cl and Na levels were higher and K levels lower than in treatment 1, on the two days. Within treatment 6, Cl and Na levels were higher and K levels were lower on day 169. In this treatment the salt content was similar in all leaves older than serial number 16 to 20 and decreased sharply in younger leaves. The K content of treatment 6, that was lower than in treatment 1, did not increase in the young leaves. Also in individual leaves, as in the composite samples, the Cl content was five times larger than the Na content. The small differences between older leaves are interesting. Assuming transpiration as the main salt import system there are two ways to explain this uniformity. The first possibility is a control mechanism that include recycling of salts that were imported into the leaves. The second possibility assumes a similar seasonal integrated salt import to the different leaves. This reflects seasonal changes in the transpiration of different leaves and in the salt content in the xylem fluid. The older leaves which transpire over longer periods imported lower salt concentration early in the season. Later in the season, when xylem salt content increased, they were shaded and had lower transpiration.

The differences between days 148 and 169 of 1992/93 support this explanation. The sharp decrease in salt content in the young leaves on both days can be the result of lower transpiration rates, shorter transpiration period, and growth dilution. The large differences between the two days in shoot length are the result of the large heterogeneity in the vine shoots and the sample size. This differences between leaves diminishes if the comparison of the two dates use the serial number from the tip rather than the distance from the base. Such a change bring leaves of similar serial number on the upper shoot, closer on a time scale.

In 1993/94 the ionic composition of the shoot segments, leaf petioles, trunk and roots was also determined. Differences in the chloride concentration and content per organ for shoots, leaves and petioles at harvest in 1993/94 are summarised in Figure 5.18. Chloride concentration on a dry mass basis was highest in the petioles at all stages along the season. This was also reported by Prior *et al.*, (1992b). However, when expressed in terms of mass per organ, the leaf blades have the highest chloride content.

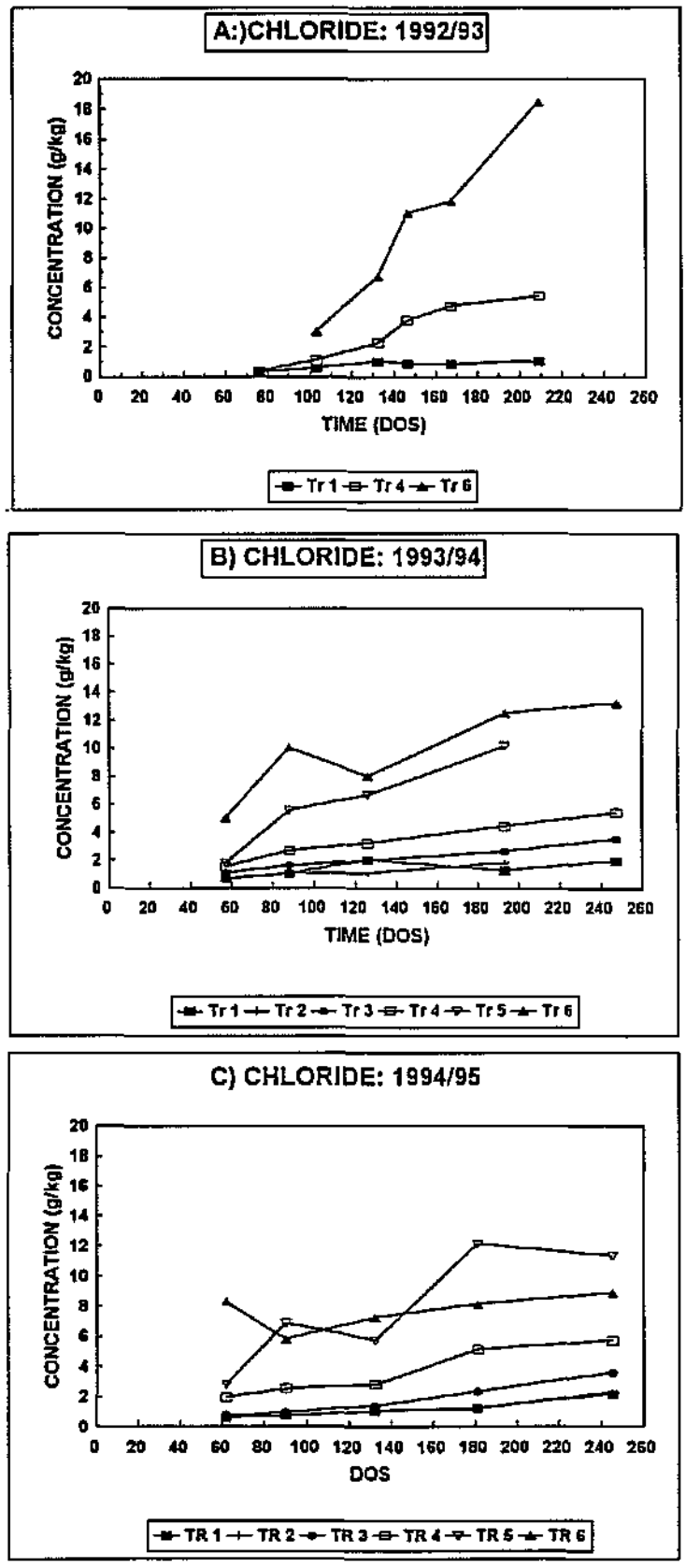

Figure 5.14 Seasonal changes in the chloride content of leaves of Colombar grapes irrigated with saline water: a) 1992/93, b) 1993/94 and c) 1994/95

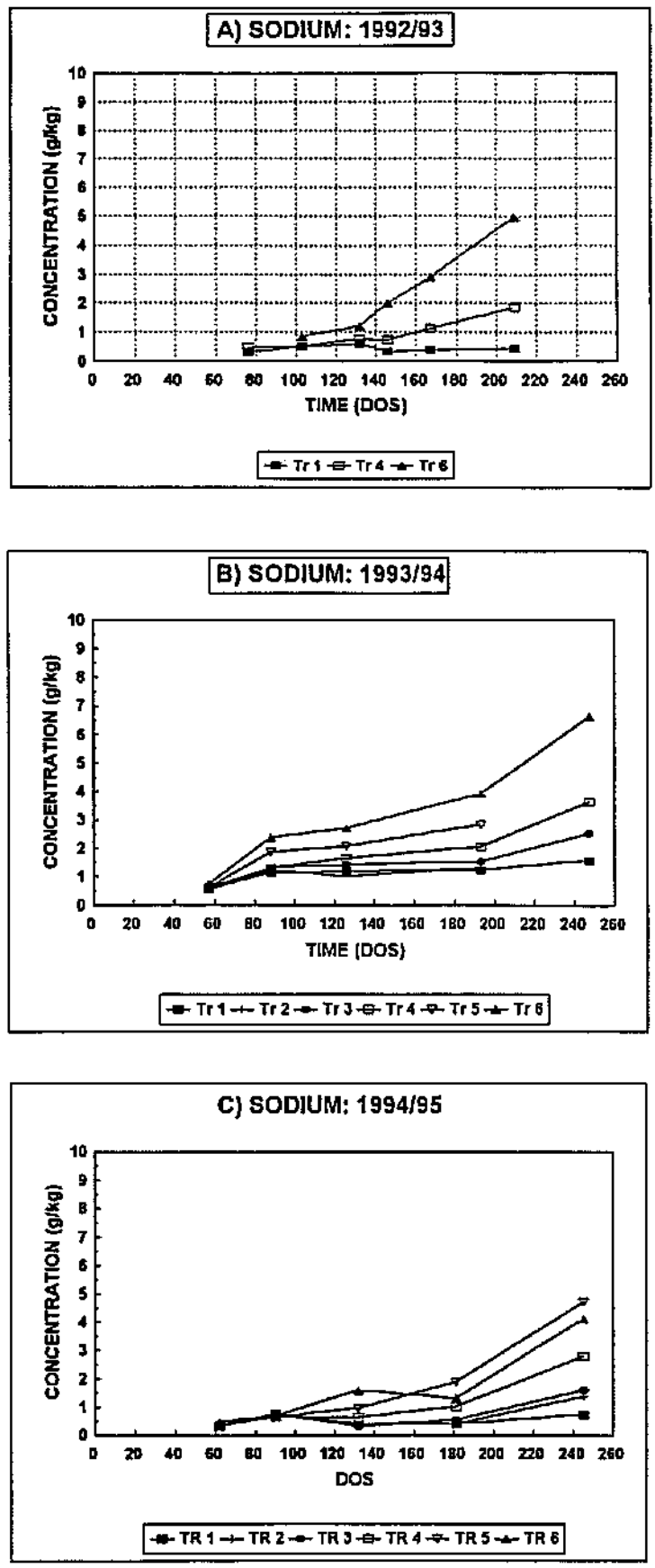

Figure 5.15 Seasonal changes in the sodium content of leaves of Colombar grapes irrigated with saline water: a) 1992/93, b) 1993/94 and c) 1994/95

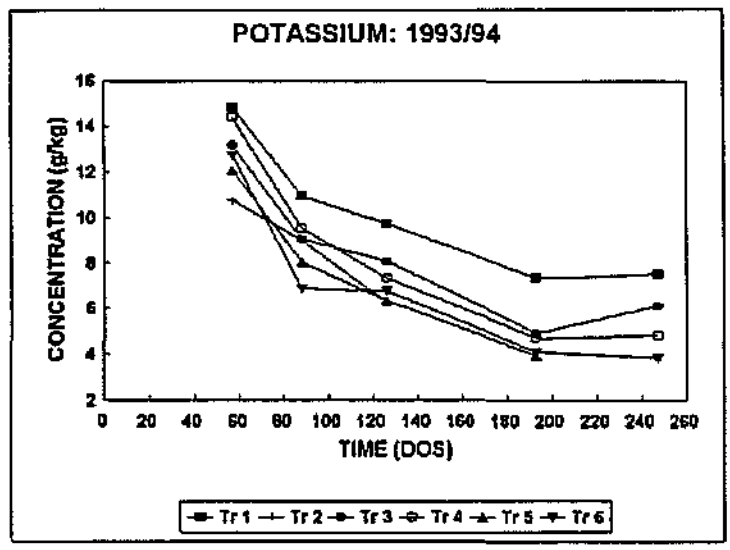

Figure 5.16 Seasonal changes during the 1993/94 season in the potassium content of leaves of Colombar grapes irrigated with saline water

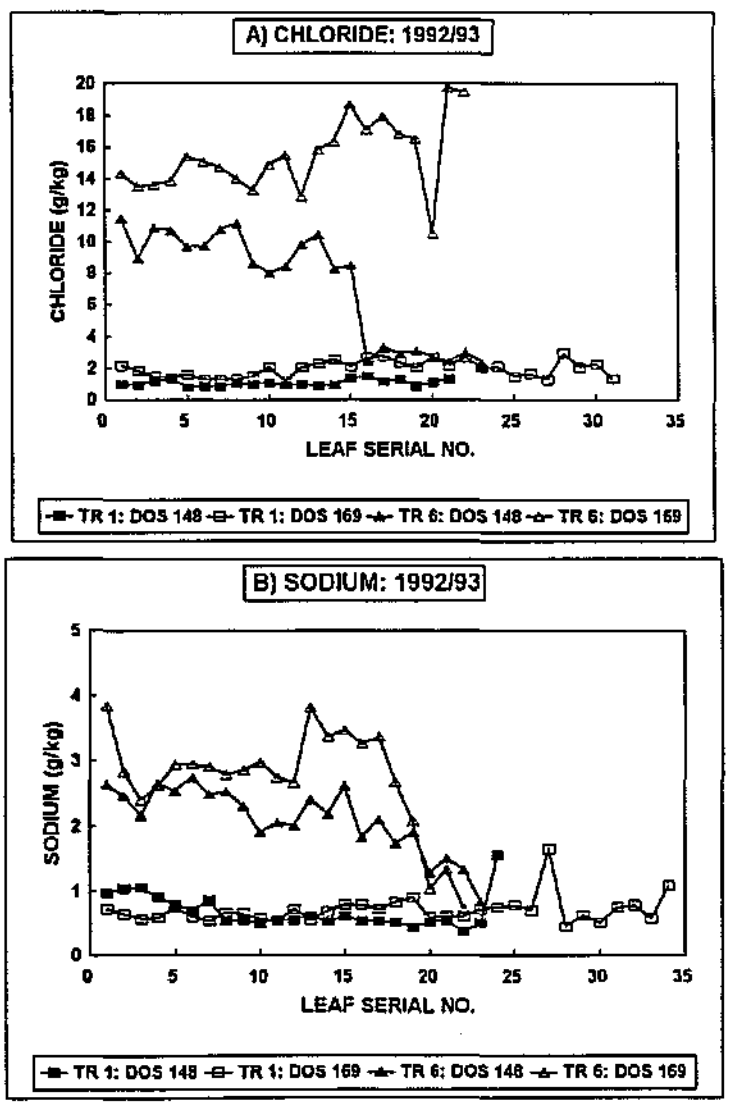

Figure 5.17 Effect of salinity during 1992/93 on a) chloride and b) sodium content of Colombar grapevine leaves with different serial numbers on the main shoot

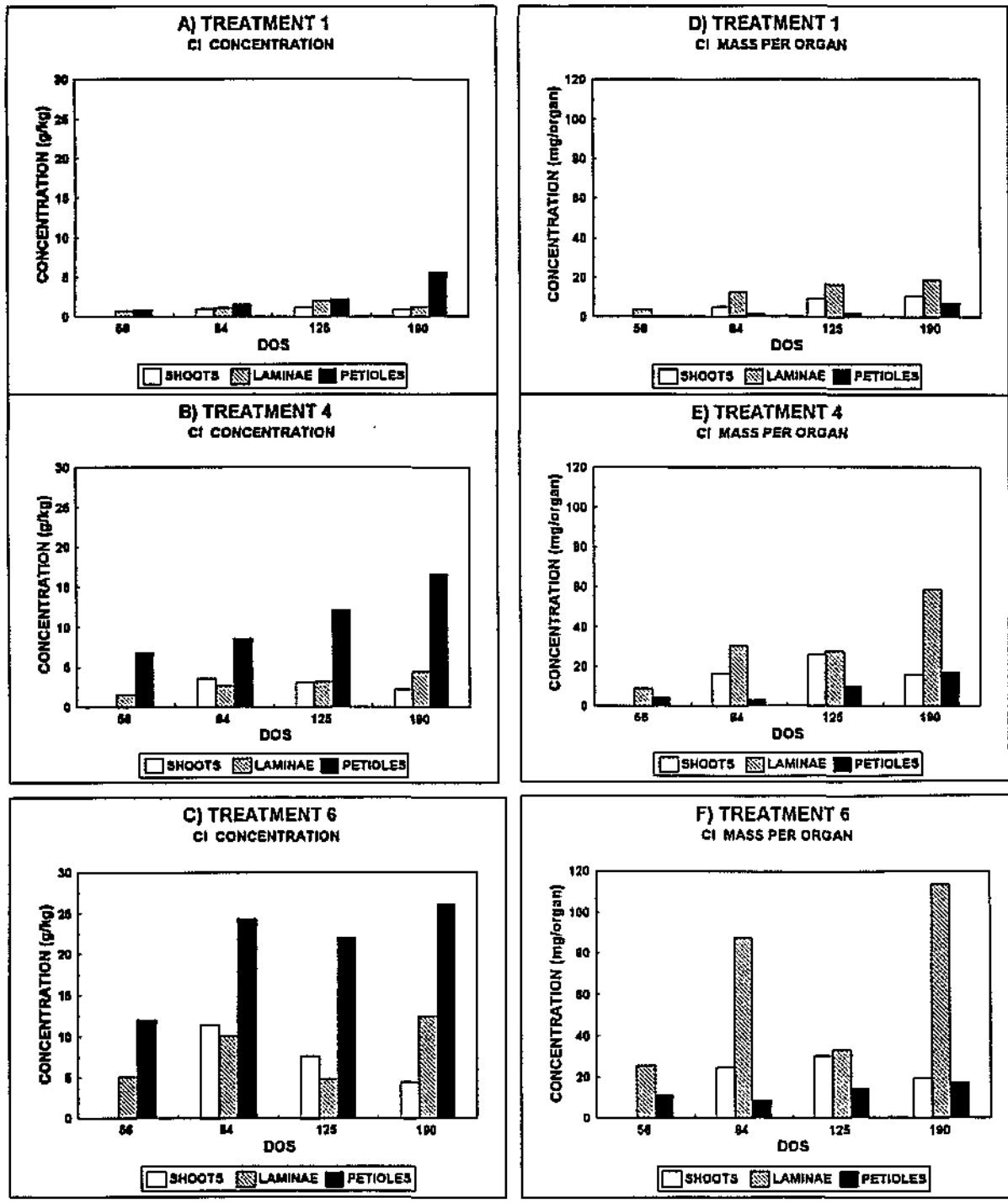

Figure 5.18 Chloride concentration and mass in the vegetative organs of Colombar grapes at different times during the 1993/94 season: treatments 1 (a & d), treatment 4 (b & e) and treatment 6 (c & f)

e) Mass balance of salt accumulation and redistribution in organs of the Colombar grapevine[3]

During the 1994/95 season the Ca, Mg, Na, K, and Cl content of different plant organs were determined at selected growth stages. The stages were before bud burst (18/08/94), at full bloom (01/11/94), pea size stage of the berries (29/11/94), veraison (10/01/95), harvest (28/02/94) and post harvest (03/05/95). The ionic composition of the berries and must (grape juice) were determined at veraison and harvest. The roots and trunk were sampled before bud-burst and again at post-harvest. All four replicates of treatments 1, 4 and 5 were included in this study. For the shoot, petiole and leaf analysis two shoots per plot were sampled. Duplicate samples per plot of the roots (sampled with a soil auger) and trunk (sampled with a stem corer) were taken. The concentrations of the different ions (in g/kg) (*analytical procedure described in section 5.2.2 (x)*) were multiplied with the dry mass per plant of each organ (see 5.2.2 (iii)) and the data used to calculate the distribution of the various ions, with specific emphasis on Na and Cl, in each of the organs. The distribution of Na and Cl in the plant was expressed in terms of percentage share of the total amount of Na and Cl in the plant found in the different organs at different phenological stages (Table 5.7).

In interpreting Table 5.7 it is important to note that not all plant organs were sampled at each of the growth stages. Consequently the percentages will sum to 100% only at those stages when all organs were sampled, e.g. veraison. With regards to Na and Cl the following general comments can be made (Table 5.7):

i) Most of the salt within the plant are found in the roots. For example, for treatment 1 (25 mS/m) at veraison 52.4% of the chloride are in the roots with 16.5% in the leaves. The equivalent percentages for sodium are 63.55 and 10.48%.

ii) The percentage share of Na and Cl in the roots decrease along the season, from 74.3% at full bloom to 40.1% at post harvest (treatment 1) with a concomitant increase the share of the leaves (due to translocation from the roots to leaves).

iii) At most of the phenological stages the percentage share of Na and Cl in the plant increase with salinity in the non-perennial parts (leaves, petioles, berries), but decrease with salinity in the perennial parts (roots and trunk).

Grapevines are perennial plants that store nutrient and metabolite reserves in roots and trunks. Consequently another approach to the mass balance is to calculate the amount of salt removed from the plant system by different processes and to calculate how much of a specific ion accumulates in the permanent organs. This approach was followed using the data of the 25 (control), 250 (treatment 4) and 350 (treatment 5) mS/m treatments of the 1994/95 season. In this case the salt balance refers to two aspects. First, it refers to the absolute amount (g/vine) or percentage of the total of each element at the end of the season, that were either lost through harvest, leaf fall or pruning, or remained in the permanent parts, i.e. roots and trunks.

In the study at Robertson whole plants were not removed. Therefore, the actual mass of the permanent parts of Colombar had to be determined indirectly and for this purpose we used the data of Saayman & Van Huyssteen (1980). They sampled whole plants of Chenin blanc/101-14 Mgt vines and determined the total dry mass of plants as well as the relative contribution of shoots, trunk and roots to the total plant mass. Using their data we could estimate the absolute amount of Ca, Mg, Na, K and Cl in the different plant organs at the different growth stages,

[3] This part of the project was the theme of a M.Sc. Agric. study at the University of Stellenbosch by E. van Zyl whose thesis is titled "Seasonal distribution of salts in the plant organs of *Vitis Vinifera* L. (cv. Colombar) irrigated with saline water)

but with specific emphasis on the information pertaining to the beginning and end of the season (Table 5.8).

Mullins (1992) and Bernstein (1975) suggested that there is a *"carry-over effect of accumulated salts in roots and trunks"* of fruit trees. Our attempt at the salt balance therefore also includes a calculation of the amount of each element that accumulated in the permanent parts during the season (Table 5.8). This was done by subtracting the amount of a specific ion in the roots and trunk at the beginning of the season from the amount of that element at the end of the season (Table 5.8). Negative numbers suggest a loss of the specific ion from the permanent parts. For example, 0.77 g Cl per vine (25 mS/m treatment) was lost, but 2.56 g K per vine (25 mS/m treatment) accumulated in the permanent parts during the 1994/95 season (Table 5.8).

At the end of the 1994/95 season the largest part of the total amount of Cl for all the treatments were either lost through leaf fall, 43,5% (25 mS/m treatment) or remained in the permanent parts, 43.9% (25 mS/m treatment). The rest were lost through harvest and pruning. It is important to note that as shown earlier, the mass of the different organs decreased with salinity, but in spite of this decrease the mass of Cl per vine removed through the harvest and leaf fall increased with salinity. All the treatments showed a loss of Cl in the permanent parts during the 1994/95 season. For example the 25 mS/m treatment lost 0.77 g/vine; 250 mS/m treatment lost 0.11 g/vine and 350 mS/m treatment lost 0.17 g/vine (Table 5.8). The fact that the vines of the higher salinity treatments did not accumulate any Cl was surprising and the reason is not quite clear. It can either be that the permanent parts were already saturated with Cl taken up during the previous four years *(1994/95 was the fourth season of irrigation with saline water)*. It can also mean that the vines got rid of some of the Cl present at the beginning of the season by other unknown and unmeasured means. The correct explanation is probably a combination of these two factors. Respectively 43.8%, 45.0% and 38.9% of the Cl that was in the vines of the 25 , 250 and 350 mS/m treatments at the beginning of the 1994/95 season remained in the permanent parts at the end of the season.

The control (25 mS/m) treatment had a loss of Na in the permanent parts (0.47 g/vine), but in the case of the 250 mS/m and 350 mS/m treatments Na accumulated to the amount of the 0.18 g/vine and 0.11 g/vine respectively. Myers *et al.*, (1995) also found for pear trees that the Na in the wood of the trees, irrigated with 210 mS/m water, increased significantly towards the end of the season. The percentage of Na that remained in the permanent parts at the end of the season was 64.4% and 37.9% for the 25 mS/m and 350 mS/m treatments respectively. Downton (1977) and Garcia & Charbaji (1993) reported that Na accumulated preferentially in the root system of grapevines. In our study this seems to be true for the 25 mS/m treatment, but for the 350 mS/m treatment the combination of Na lost through leaf fall (39.0 %) and removed by harvest (17.3%) and pruning (5.8%) were larger than the percentage of Na that remained in the permanent parts. Element retention by abscising leaves indicates that substantial quantities of Na were lost from the plant at the end of the season through leaf fall, with the amounts increasing with salinity. This suggests that the Na in the higher salinity treatments is moving more easily to the grapes (bunches) and leaves where it is then removed from the plant.

Table 5.7 Chloride and sodium distribution within the different plant organs of Colombar, expressed as percentages of the total within the plant, at selected growth stages of the 1994/95 season

a) Chloride

Plant organ	Treatment	Full bloom 01/11/94 DOS 62	Harvest 28/02/95 DOS 181	Post harvest 03/05/95 DOS 245
Laminae	1(25 mS/m)	3.12	20.69	33.96
	4(250 mS/m)	7.33	32.16	26.76
	5(350 mS/m)	10.06	38.79	30.88
Petioles	1(25 mS/m)	0.39	5.85	8.64
	4(250 mS/m)	1.95	8.83	5.90
	5(350 mS/m)	3.11	5.68	3.83
Shoots	1(25 mS/m)	1.85	7.39	6.58
	4(250 mS/m)	4.56	6.50	2.95
	5(350 mS/m)	6.12	4.82	3.87
Trunk	1(25 mS/m)	20.27	15.76	3.89
	4(250 mS/m)	8.91	5.47	3.11
	5(350 mS/m)	8.76	5.41	4.30
Roots	1(25 mS/m)	74.37	44.32	40.05
	4(250 mS/m)	77.24	38.88	41.94
	5(350 mS/m)	71.96	33.63	34.41
Berries	1(25 mS/m)		5.98	
	4(250 mS/m)		8.16	
	5(350 mS/m)		11.65	

b) Sodium

Laminae	1(25 mS/m)	1.82	9.63	19.96
	4(250 mS/m)	3.27	19.21	33.63
	5(350 mS/m)	3.94	15.04	28.29
Petioles	1(25 mS/m)	1.66	2.93	4.89
	4(250 mS/m)	1.49	10.07	2.93
	5(350 mS/m)	0.98	9.24	7.52
Shoots	1(25 mS/m)	0.72	6.40	6.08
	4(250 mS/m)	1.89	8.69	4.48
	5(350 mS/m)	2.19	6.51	6.24
Trunk	1(25 mS/m)	18.70	19.06	15.62
	4(250 mS/m)	22.43	14.08	12.32
	5(350 mS/m)	27.99	14.72	11.99
Roots	1(25 mS/m)	77.10	57.38	49.06
	4(250 mS/m)	70.92	38.91	37.88
	5(350 mS/m)	64.91	33.44	27.69
Berries	1(25 mS/m)	0.00	4.60	
	4(250 mS/m)	0.00	9.04	
	5(350 mS/m)	0.00	21.05	

Table 5.8 Salt balance at the end of the 1994/95 season, (Robertson) of Colombar/99R grapevine irrigated with 25, 250 and 350 mS/m water

Element	g/vine and % of total amount of element removed by									
	Harvest		leaf fall		pruning		Remained in permanent parts		Total	Seasonal accumulation in permanent parts
	g/vine	%	g/vine	%	g/vine	%	g/vine	%	g/vine	g/vine
25 mS/m										
Cl	0.24	5.9	1.77	43.5	0.27	6.6	1.79	43.9	4.07	-0.77
Na	0.13	4.6	0.71	25.0	0.17	6.0	1.83	64.4	2.84	-0.47
K	8.79	37.1	4.26	18.0	2.49	10.5	8.13	34.5	23.67	2.56
Ca	0.69	1.8	18.74	49.7	2.64	7.0	15.67	41.5	37.74	1.41
Mg	1.3	13.3	3.63	37.2	0.77	7.9	4.05	41.5	9.75	0.36
250 mS/m										
Cl	0.52	8.2	2.76	43.7	0.19	3.0	2.84	45.0	6.31	-0.11
Na	0.26	9.0	1.07	37.2	0.13	4.5	1.42	49.3	2.88	0.18
K	9.17	63.6	1.89	13.1	0.77	5.3	2.59	18.0	14.42	0.84
Ca	0.81	3.9	12.80	62.3	1.24	6.0	5.7	27.7	20.55	0.64
Mg	1.51	24.6	3.07	50.0	0.29	4.7	1.27	20.7	6.14	0.02
350 mS/m										
Cl	0.68	11.8	2.64	45.7	0.22	3.8	2.24	38.8	5.78	-0.17
Na	0.48	17.3	1.08	39.0	0.16	5.8	1.05	37.9	2.77	0.11
K	4.01	55.5	1.27	17.6	0.34	4.7	1.6	22.2	7.22	0.39
Ca	0.52	4.4	6.14	52.1	0.82	7.0	4.3	36.5	11.78	0.83
Mg	0.76	16.5	2.71	58.9	0.25	5.4	0.88	19.1	4.6	0.04

At the end of the 1994/95 season the largest part of the total amount of Cl for all the treatments were either lost through leaf fall, 43,5% (25 mS/m treatment) or remained in the permanent parts, 43.9% (25 mS/m treatment). The rest were lost through harvest and pruning. It is important to note that as shown earlier, the mass of the different organs decreased with salinity, but in spite of this decrease the mass of Cl per vine removed through the harvest and leaf fall increased with salinity. All the treatments showed a loss of Cl in the permanent parts during the 1994/95 season. For example the 25 mS/m treatment lost 0.77 g/vine; 250 mS/m treatment lost 0.11 g/vine and 350 mS/m treatment lost 0.17 g/vine (Table 5.8). The fact that the vines of the higher salinity treatments did not accumulate any Cl was surprising and the reason is not quite clear. It can either be that the permanent parts were already saturated with Cl taken up during the previous four years *(1994/95 was the fourth season of irrigation with saline water)*. It can also mean that the vines got rid of some of the Cl present at the beginning of the season by other unknown and unmeasured means. The correct explanation is probably a combination of these two factors. Respectively 43.8%, 45.0% and 38.9% of the Cl that was in the vines of the 25 , 250 and 350 mS/m treatments at the beginning of the 1994/95 season remained in the permanent parts at the end of the season.

The largest amount of potassium that was in the vine at the end of the season was removed by the harvest. The more saline irrigation treatments lost more K through the harvest. An appreciable amount remained in the permanent parts at the end of the season and the rest were lost through leaf fall and pruning. Respectively 2.56, 0.84 and 0.39 g K per vine accumulated in the permanent parts and trunk during the season for the 25, 250 and 350 mS/m treatments.

Very small amounts of Ca were lost through harvest and pruning. Most of the Ca was lost either through leaf fall or remained in the permanent parts. Calcium also accumulated in the

permanent parts during the season, and more so in the 25 mS/m treatment than in the 250 mS/m and 350 mS/m salinity treatments The amounts were respectively 1.41, 0.64 and 0.83 g for the three treatments.

For the 25 mS/m treatment 41.5% of the Mg remained in the permanent parts, 37.2% were lost through leaf fall and the rest 13.3% and 7.9% were lost through harvest and pruning. For the 250 and 350 mS/m ,50.0% and 58.9% were lost respectively through leaf fall with a smaller amount 20.7% and 19.13% remaining in the permanent parts. During the season, 0.36 g Mg accumulated in the vine with very small accumulations in the 250 and 350 mS/m treatments. Our results therefore indicate that the nutrients K, Ca and Mg accumulated in the permanent parts of all the treatments during the season, but more so for the lowest salinity treatment.

5.3.3 Leaf water potential and stomatal conductance

Robertson typically has cold nights and hot, dry, windy and cloudy days. These conditions limit days that are suitable for measurements of stomatal conductance and leaf water potential. On many occasions leaves were wet early in the morning because of dew whilst overcast conditions stopped midday measurements prematurely. Stomatal conductance integrates climatic conditions, soil water and salinity status and leaf ontogeny. The climate at Robertson can change from late morning clouds and late dew to very hot, dry and high radiant conditions. Therefore the midday measurements of stomatal conductance in 1992/93 show large fluctuations with a general decreasing trend during the season (Figure 5.19). Only small differences in stomatal conductance between the 25 and 250 mS/m treatments and lower conductance values for the 500 mS/m treatment were recorded over the entire season. Similar observations were made in 1993/94.

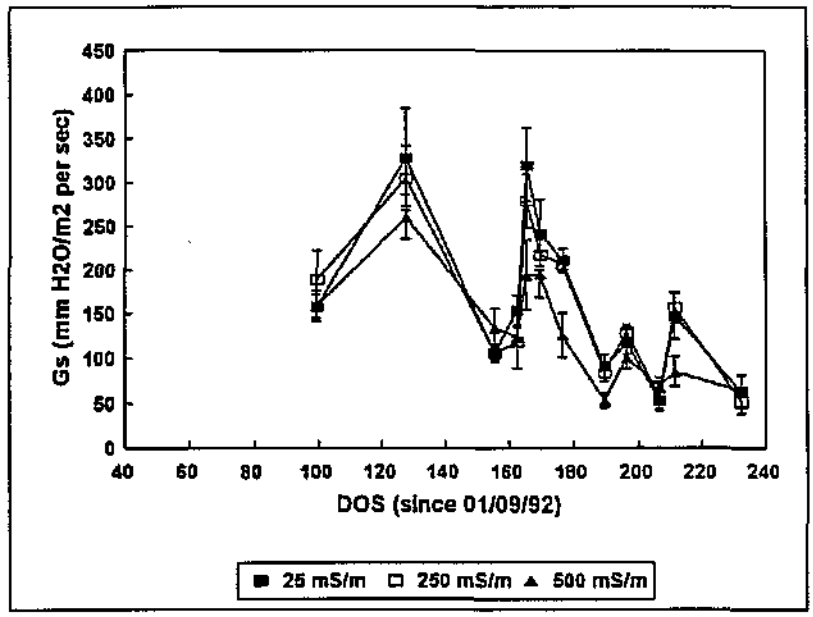

Figure 5.19 Salinity effect on the seasonal midday stomatal conductance of Colombar grapevine leaves at Robertson, 1992/93

The early morning leaf water potential (LWP) of treatments 1 (25 mS/m), 4 (75 mS/m) and 6 (500 mS/m) in 1992/93 decreased slightly over the season with the treatment means ranging between -338 kPa and -662 kPa (Fig. 5.20a). The measurements of DOS 92 and DOS 207 were 6 days and 23 days after the last irrigation respectively and on these two dates treatment 6 had a lower, but statistically insignificant, LWP than treatment 1. Significant reduction in early morning LWP under water stress was reported previously (Van Zyl 1984). The midday

LWP's of treatments 1, 4 and 6 in 1992/93 were about -800 to -900 kPa till day 77 (which is the beginning of rapid increase in fruit volume) and decreased linearly to about -1300 to -1400 kPa on DOS 112 (Fig. 5.20b). It then fluctuated between -1000 to -1400 kPa till the harvest on 207 DOS, followed by an increase after the harvest. Such seasonal responses are well documented (Smart and Coombe 1983, Van Zyl 1984). Large post harvest irrigations could also contribute to the increase in LWP after DOS 207.

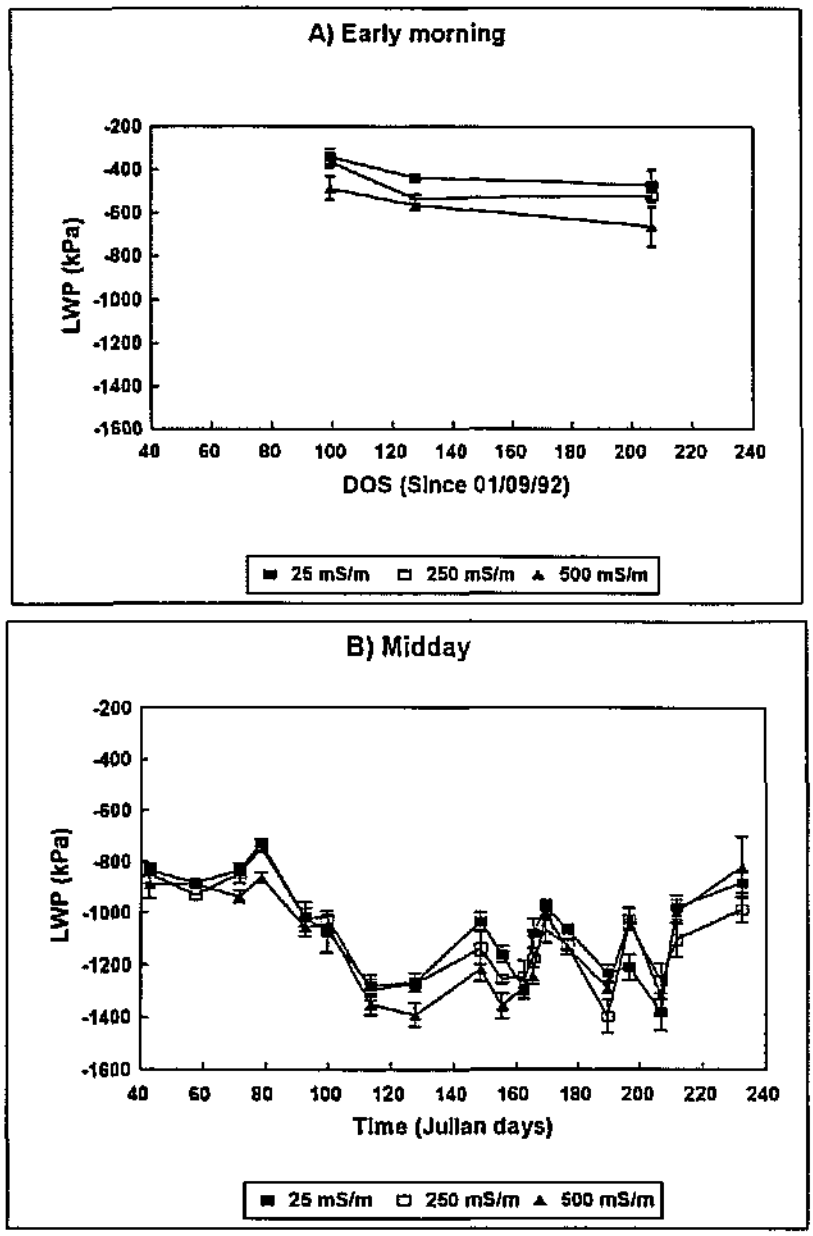

Figure 5.20 Salinity effect on the seasonal leaf water potential of Colombar grapes, 1992/93: a) Early morning measurements, b) Midday measurements

The diurnal measurements of 1992/93 and 1993/94 show a large temporal effect but a relatively small salinity effect (Fig. 5.21). In fact, measurements conducted over the season show only small seasonal effects on both stomatal conductance and leaf water potential and large effects of the time of day when the measurements were made. Leaf water potential decreased with time of the day till about 15h00. In the later afternoon, between 15h00 and 18h00 it started to increase again. At 18h00 the afternoon measurements stopped (Fig. 5.21). In order to minimise the effect of time of measurement in the statistical analysis of the salinity effect on leaf water potential, all observations from the different days were first combined and

then divided into the following three time groups: **early** (before 8 am), **transient** (from 8 am to 10h30 am) and **midday** (after 10h30 am).

For each time group the low salt water treatment had a higher LWP than the high salt water treatments (Table 5.9). Significant differences were found only in the early group and for all groups together. LWP decreased rapidly during the transient period and changed much less later. For all seasons, the time of day effect was much stronger than the salinity effect.

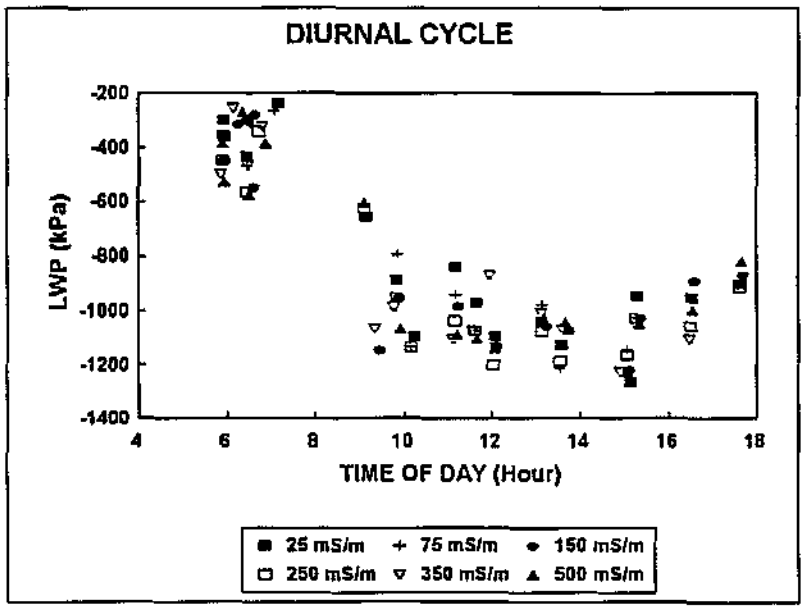

Figure 5.21 Diurnal changes in the leaf water potential (LWP) of Colombar grapes at Robertson, 1993/94

Table 5.9 ANOVA of effect of irrigation water salinity on leaf water potential (kPa) of Colombar grapevines at Robertson, 1992/93 to 1994/95

Time group	Salinity treatment (mS/m) 25	75	150	250	350	500	P
			1992/93				
All*	-979a			-1011a		-1024a	0.32
Early	-458a			-472a		-556a	0.15
Transient	-817a			-856a		-802a	0.65
Midday	-1074a			-1105a		-1113a	0.34
			1993/94				
All	-720a	-725a	-823b	-769ab	-818b	-772ab	0.01
Early	-329a	-364ab	-398ab	-400ab	-384ab	-426b	0.27
Transient	-812a	-775a	-1049a	-828a	-1025a	-826a	0.29
Midday	-1016a	-1036a	-1024a	-1083a	-1043a	-1052a	0.52
			1994/95				
All	-258a	-258a	-283a	-318ab	-385b	-334ab	0.06

* All = combined data of all time groups over season
Early = before 08h00
Transient = 08h00-10h30
Midday = 10h30-15h00

** Means separation within rows by LSD Multiple Range Test at the 5% level

P Probability level

The combined data set of 1993/94 for stomatal conductance show an inconsistent salinity effect but strong time of day effect. The differences in the stomatal conductance of treatments 1, 2, 3 and 6 are statistically significant at the 5% level (Table 5.10). However, although there are differences between treatments 1, 4 and 5, they are not statistically significant (Table 5.10). The time-of-day effect is more emphasised with the differences between the early morning, transient and midday groups being highly significant (Table 5.10). Only a limited number of the early morning measurements are available for stomatal conductance since the leaf blades were wet on many mornings. Stomatal conductance at this time was about 214 mm m^{-2} s^{-1} and uniform among treatments. Later in the day the differences for a given hour in the day were large with few conductance values larger than early in the morning.

Table 5.10 ANOVA of effect of irrigation water salinity and time on stomatal conductance (mm m^{-2} s^{-1}) of Colombar grapevines during 1993/94 at Robertson

Time group		Salinity treatment (mS/m)						
		1(25)	2 (75)	3 (150)	4 (250)	5 (350)	6 (500)	P
All*	185a	153b	154b	161ab	160ab	151b	0.17	
Transient	158a	126b	129b	134ab	125b	130b	0.16	
		Time of day						
	Early		**Transient**		**Midday**			
	214a		152b		116c		0.0001	

* All = combined data of all time groups over season
Transient = 08h00-10h30
** Means separation within rows by LSD Multiple Range Test at the 5% level
P Probability level

5.4 Discussion

Irrigation with saline water affected vegetative growth and yield. The salinity effect of the previous year advanced budburst of the higher salinity treatments and therefore, early in the season the higher salinity treatments had longer shoots than the low salinity control treatment. However, later in the season, e.g. from day 34 of the 1994/95 season, (with 1 September as day one) both the shoot length and elongation rate of the control exceeded that of the high salinity treatments. Dry mass of plant organs and pruning mass were decreased with increasing salinity treatment.

Petiole and lamina Cl and Na increased during the season, with the higher salinity treatments at a more rapid rate. Sodium levels were always lower than Cl. As in the study of Hoffman *et al.* (1989) the lamina Cl accumulated to a certain maximum before Na moved into the laminae. When the lamina Cl reached a concentration of between 5.12-5.80 g/kg, the Na concentration was between 0.71 and 1.03 g/kg and then started to increase more rapidly.

The K concentration of lamina, petioles and shoots decreased over the season with the K concentration of the 25 mS/m the highest and the 350 mS/m treatment the lowest. This is indicative of a sodium-potassium antagonism, i.e. in the presence of high sodium concentrations, potassium uptake is surpressed.

In all three seasons a large part of the shoot and leaf expansion growth as measured by shoot and leaf elongation and increase in leaf area, took place early in the season, i.e. before day 90. Our estimate of the time of first noticeable effect on expansive growth of shoots and leaves in 1992/93 was about day 35 and in 1993/94 at about day 20. In this study the salinity management includes winter leaching with fresh water followed by small amounts of saline water according to the low water use of the plants in the spring. Under such management soil

salinity in the spring is relatively low (*see Table 4.8*). In the 1992/93 season the first saline irrigation was given on day 72 (after the first day of recorded salinity damage). This leave us with two possible explanations for the early salinity effect observed for example in 1992/93:

i) early in the spring, after the winter leaching, expansive growth is sensitive even to low soil salinity.
ii) growth conditions in one season have a large influence on the growth during the following season, especially if salt accumulates in the permanent parts.

The first explanation is supported by the results of Prior *et al.*, (1992c) who concluded that soil salinity levels (ECe) at the end of winter should be maintained below 100 mS/m in order to keep yield losses, due to salinity, below 10%. The carry-over of the effects can be associated with the level of the development of the buds that produce the growth and yield of the following year or with carrying over of matter. Metabolites, nutrients and salts are carried over from one season to another in the spurs, cordons, trunks and roots which are the perennial parts of the plants.

A mass balance of salt in the plant system in the 1994/95 season (Table 5.8) show that Na and Cl and the nutrients K, Ca and Mg all accumulated in the permanent parts of the grapevine. In the case of Chloride 44% (control treatment), 45,0% (treatment 4 and 38,8% (treatment 5) that were present in the plant at the beginning of the season remained in the permanent parts at the end of the season. i.e. will be carried over to the next season..

The salinity effects on the growth of shoots and leaves also manifests itself in growth in thickness of and metabolite deposition in leaves. In this regard the parameters to investigate are the specific fresh and dry mass of the leaves and the fresh and dry weights of the internodes. Metabolite deposition continues after volume expansion has stopped (Williams & Matthews, 1990). The change in leaf specific weight show that for leaves this deposition continued at least to day 170. Leaf specific fresh weights were not sensitive to salinity or age while the internode fresh weights were smaller in the saline treatments. The specific dry weight of leaves increased with age more in the low than in the high salt treatments. The result is a larger effect of salinity on the mass than on the length of the internodes. Alternatively, it indicates an increase in metabolite deposition in the leaves and decreased metabolite transport to the internodes - a change that can be the result of salinity interference to the metabolite export from the leaves. Metabolite availability did not limit the leaf growth but could limit the internode growth. The reduction in metabolite transport to the shoot under saline conditions, may also imply a reduced build-up of metabolite storage in the perennial plant organs. An additional cause for the reduced rate of metabolite reserves in perennial organs, is the early damage of salinity to the leaves as recorded in the plant score. Leaf drop reduced the photosynthetic area and stimulate new leaf development on laterals and main shoot apex. These leaves were small and had a short life span with a consequent large use of carbohydrate for the growth of the new leaves with no or very little return for the rest of the plant.

Leaf water potential (LWP) and stomatal conductance measurements in 1993/94 and 1994/95 were not intensive. More intensive work during the 1992-3 season show that differences in LWP between salinity treatments are best shown before the stomata control transpiration (see Appendix II). The 1992/93 data also show that stomatal closure occur earlier in the day in the saline treatments. This means salinity treatment effects on LWP will most likely only be detected with pre-dawn measurements. Unfortunately, at Robertson, leaves are often wet at that time of day which means that stomatal conductance cannot be measured simultaneously. Comparison of salinity treatment effects during the transient period when rapid changes in LWP and stomatal conductance occur, will require a large team of people measuring LWP and stomatal conductance simultaneously at different positions in the vineyard.

In this study the minimum LWP was about -1100 kPa which is much higher than the minimum potentials reported from other irrigation studies, e.g. Van Zyl (1984) and Myburgh & Moolman (1991). In spite of the relatively high leaf water potentials, damage to growth and yield was significant (see also Chapter 6). Salinity damage to leaves may be the result of accumulation of salts in the apoplast. If this is the case the pressure chamber technique does not measure the total leaf water potential of grapevine and perhaps also not the hydrostatic component of the xylem water potential. It measures the difference between the vacuole water potential and the apoplast osmotic potential. Growth was related to two water status parameters which are leaf turgor (appendix II) or leaf water potential and both may be interpreted wrongly from pressure chamber readings if the apoplast water contain a significant concentration of salt.

5.5 Conclusions

i) Salinity has a negative effect on shoot growth, leaf area and pruning mass with the first negative effects, although not always visible, occurring early in the season. Intensive measurements of shoot growth in 1992/93 and 1994/95 revealed damage on day 20 of the 1992/93 season and day 35 of 1994/95. This suggests that the negative effects occur earlier in the growing season as exposure to saline conditions continues.

ii) Early in spring vegetative growth is sensitive even to low soil salinity. In this study the depth weighted mean soil salinity in terms of electrical conductivity of the extract of a saturated soil paste (ECe) in September were in most cases less than 100 mS/m, the maximum being 152 mS/m (Treatment 6, Sept. 1994: (Table 4.8).

iii) The early response to salinity can in part be attributed to a carry-over effect of exposure to saline conditions in a previous year. Salt, specifically Na and Cl accumulates in the permanent parts of the grapevine, i.e. the trunk and roots. Most of the salt taken up during a season is stored in the roots while leaf fall is the main mechanism by which the plant rids itself of the accumulated salt.

iv) Salinity has a negative effect on shoot growth, but more so on the mass of the internodes than on length. One possible explanation is an increase in metabolite deposition in the leaves and a decrease in metabolite transport to the shoots.

v) Sodium and chloride levels at which leaf damage started were about 1.7 g/kg (0.17%) and 6 g/kg (0.6%) respectively.

vi) The salinity damage to grapevine leaves reduces the photosynthetic active area of the plant, which stimulate new leaves on the lateral shoots, but the large use of carbohydrates may have a negative effect on the rest of the plant.

vii) Leaf water potential does not seem to be very sensitive to salinity. Consequently it is not a good parameter to use in detecting early signs of salinity stress. The salinity effect on leaf water potential are best shown by pre-dawn measurements (i.e. early in the morning). However, salinity damage to the leaves may be the result of salt accumulation in the apoplast, which if true, means that leaf water potential measured with the pressure chamber technique may be interpreted wrongly.

CHAPTER 6
SALINITY EFFECTS ON THE YIELD, REPRODUCTIVE GROWTH AND FRUIT AND WINE QUALITY OF COLOMBAR GRAPES

6.1 Introduction

One of the main objectives of this study is to determine the salt tolerance of grapevines. Prior to this study however, there was little quantitative information on the yield responses of grapevines to salinity in irrigation water. This is specifically true for reproductive growth and yield of grapevine cultivated under actual field conditions. Maas and Hoffman (1977) classified grapevines as moderately salt-sensitive, but according to Prior *et al.* (1992b) most of the Maas and Hoffman information was derived from published results of short-term growth studies of potted vines in sand or solution culture. Some work has been done on the effect of different rootstocks on grapevine performance under saline conditions e.g. Southey & Jooste (1991) and Bernstein *et al.* (1969). Most of what appears in literature seems to have been inferred indirectly from studies that were not primarily designed to investigate the effect of saline conditions on the vegetative and reproductive growth of grapevines. Prior *et al.* (1992a,b) published results on a six year field experiment in Australia in which the effects of salinity on yield, ionic composition, growth and physiology of field-grown sultana were studied. They concluded that sultana grapevines are more sensitive to salinity than previously thought.

In our study conducted at Robertson, irrigation with the different salinity treatments started midway through the 1991/92 season. Grapevines are perennial plants and the effect of salinity will be cumulative with time. The reproductive growth of grapevines includes the number of bunches, number of berries per bunch, size of berries and must quality. As with most perennial crops, floral differentiation for the current year's crop takes place during the preceding year. The differentiation of fruit buds begins early in the growing season the year preceding the development of flowers (Winkler *et al.*, 1974). Each cluster can produce many flowers, a fraction of which might mature as harvested berries. Thus, the potential number of bunches per *vine* and berries per bunch are determined early in spring of the year preceding the current year's harvest. The realisation of this potential in number, size and quality of berries depends on conditions later during the season of bud formation and during the harvest season. In this study the differential salinity treatments started on 19/12/91, which was after the potential number of berries for the 1992/93 yield had been initiated. Therefore, even if the grapevine during the berry initiation stage is sensitive to salinity, the length and timing of exposure to salinity during the second season (1992/93) would have had little, if any, effect on bunches per vine or number of berries per bunch in that year. However, the size of berries and the composition of the must are determined within the season of harvest. The first long-term effect of salinity on reproductive growth can only be expected in the third and fourth year, which in the present study is 1993/94 and 1994/95. In this chapter the results of four years of differential salinity treatments on the yield, yield components, reproductive growth, must and wine composition of Colombar grapes are presented.

6.2 Material and Methods

6.2.1 Yield and yield components

The Colombar grapevine cultivar is known to be a late variety, i.e. it has a long growing season and the grapes only reach maturity and required sugar content for wine making towards the end of March. This was found to be true in all, except the last year (1994/95) of this study. Different procedures for deciding when to harvest were followed during the course of this study. During the first season, 1991/92, the decision when to harvest was made by the manager of the experimental farm and all the grapes were harvested on the same day, i.e. 25/03/92. The harvesting proceeded irrespective of possible differences in the sugar and acid content of the different plots and treatments. During the 1992/93 and 1994/95 seasons a different procedure was followed. The sugar and acid content of the grapes were monitored frequently (see 6.2.2 below) and the plots were harvested according to the degree of ripeness. Two norms were used to determine when the grapes should be picked: i) sugar content > 18° Balling and ii) acid < 8 g/L. The motivation for this procedure was to determine whether the various salinity treatments had any effect on the number of days required to reach maturity. The final harvesting of the grapes in 1992/93 was done in three stages on 15/03/93, 22/03/93 and 25/03/93 (during the period DOS 195 to 205). Two plots of treatment 6 (ECi=500 mS/m) did not reach the level of 18% sugar and were harvested on 25/03/93, which was the final day allowed by the cellar. In order to harvest at the optimum time, the frequency of monitoring the must composition was increased when the first grapes approached maturity.The initial berry sampling scheme was designed to take care of the variability between bunches on different positions of the plant as well as the variability between berries situated on different positions of the bunch. A composite sample of individual berries taken from different positions on the outside of both sun-exposed and shaded bunches was made. Later during the season, the must composition of this composite sample of individual berries was compared with data from the must of whole bunches that were sampled on the same day (Table 6.1). It was found that the must of samples consisting of whole bunches had a significantly higher sugar and acid content than that of the composite sample. Since wine is made of whole bunches all subsequent sampling in 1992/93 and the following years, including those used to decide when to harvest, was conducted on whole bunches. The analytical results used further in this chapter, also refer to the must composition of whole bunches.

In 1993/94 a procedure similar to that of 1992/93 was followed but only two dates were required to harvest all 24 plots of the vineyard, namely 12 plots on 03/03/94 and the balance on 15/03/94. During the last season, 1994/95, there was little difference in the rate of sugar accumulation between the treatments and or plots and the whole vineyard was harvested on 28/02/95.

In all years the 240 experimental plants were harvested individually and the yield per plant determined by weighing. At harvest four bunches of each plot were selected randomly, weighed and the number of berries per bunch counted. A sub sample of the berries was then oven dried and the mean fresh- and dry mass per berry of each plot determined. The results were statistically evaluated by ANOVA using the *Statgraphics 6 Plus* statistical software package and by expressing the yield of the ten experimental plants as the mean yield per plot. Approximately one month before harvest, the number of bunches and shoots per plant were counted.

Table 6.1 Comparison of the must composition from berries using different sampling methods: I, Individual berries; II, Whole bunches (Data of 2 March 1993)

	Acid (g/L)	Sugar (Balling)	Sugar/acid
Method			
I	7.82b[1]	16.63b	2.17
II	8.48a	18.76a	2.25
Treatment			
1	7.94	17.54	2.24
2	8.06	17.79	2.24
3	8.44	17.76	2.15

1) different letter = significant difference

6.2.2 Monitoring of reproductive growth

Pruning is a procedure that is used to manipulate the vegetative and reproductive growth of vines. In this study the annual pruning of the vines were always done in August using the spur-pruning method. This particular method of pruning result in the growth of two shoots per spur and about two bunches per shoot. The time scale used in this study is the day of season (DOS) which starts on September 1st. The main reproductive stages in each of the last three seasons according to this scale (to the nearest week) are listed in Table 6.2.

Table 6.2 Main reproductive growth stages of Colombar grapevines at Robertson in terms of day of season, DOS, for the 1992/93 to 1994/95 seasons

Growth stage	1992/93	1993/94	1994/95
Flowering	57	57	61
Pin head size	71		
Pea size berries	95	85	90
Veraison	127	126	132
Harvest	195-205	184-196	181

In 1991/92 only yield mass and must composition at harvest, DOS 206, was determined. For the 1992/93 season Dr. Avraham Meiri of the Volcani Institute in Israel joined the research team which enabled us to conduct a more detailed investigation on the physiological effects of salinity on reproductive growth. In that year the plants of treatments 1, 4 and 6 were used for a detailed continuous monitoring of the effects of salinity on the vegetative and reproductive growth. Bunches from plants in border rows were sampled 13 times during the period DOS 92-190 and again at harvest. In order to determine the effects of the full salinity range on the yield parameters of vines, bunches from treatments 2, 3 and 5 were sampled three times, namely on days 184 and 190 and at harvest. At each sampling stage the bunches from an upper shoot on a middle spur facing south-west and a lower shoot on a middle spur facing north-east were sampled. *(See also the sampling procedure for vegetative growth parameters described in Chapter 5).*

Measurements included the number of bunches per shoot, weight of the bunches, total number of berries and the mass and quality parameters of a subsample of berries. The berries were counted from the largest to the smallest and every fifth berry was included in a subsample for fresh- and oven dry mass determinations. The other berries were crushed and analysed for must composition. This sorting procedure provided a good estimate of the mean values for the different berry parameters.

6.2.3 Ionic composition of fruit and wine

After the berries were crushed (all sampling dates including harvest of all years), the must were immediately analysed for pH (*Metrohm*), acid content (potentiometric titration with a *Metrohm 702 SM Titrino*), sugar content (by refractomotory) and osmotic potential (micro-osmometer - *Precision Instruments*). After these determinations the must were kept frozen for further ion analyses. The frozen must was heated for 1-2 hours at 80°C to dissolve the potassium tartrate and analysed for chloride content by potentiometric titration with $AgNO_3$ (*Metrohm 702 SM Titrino*) and for Na, Ca and K by atomic absorption spectrophotomotory (*Varian AA 1275 and Varian AA 250+*). The must of the 1992/93 season was analysed (by the Department of Viticulture and Oenology, University of Stellenbosch), for the citric-, tartaric- and malic acid content as well as the free amino nitrogen concentration. These organic compounds all impact on wine quality.

6.2.4 Wine evaluation

The effect of salinity on wine quality was not evaluated during the first season (1991/92) and the entire harvest was sold to a commercial winery. From the 1992/93 and 1993/94 harvest, experimental wine (i.e. on a small scale) were made by using twenty four subsamples of the grapes (one per plot). The Department of Viticulture and Oenology of the University of Stellenbosch was involved in this part of the study and for each plot, using standard wine making procedures, six bottles (750 mL) of wine was made. After about four to five months a panel of judges evaluated the quality of the wine according to aroma and taste. The chemical composition of a sample of the must used for wine making was analysed as described above. In 1994/95, for logistical reasons and in view of the results of the previous two seasons, only six experimental wines were made. A composite sample of the six salinity treatments, consisting of a subsample from each replicate, was used. All other analytical procedures were the same as before.

6.3 Results

6.3.1 Yield

As can be deduced from the harvesting dates mentioned above, and compared to the first season, the required degree of ripeness for the grapes to be harvested, i.e. the sugar and acid contents of the berries, were reached progressively earlier in the season in 1993/94 and 1994/95, but within a particular year, salinity had no effect on time to reach maturity. The decrease in time to reach maturity observed during the last two seasons apparently is not related to salinity, because even treatment 1 (control) was harvested earlier.

The arithmetic mean yield per treatment for each year is shown in Figure 6.1 while relative yield, normalised with respect to the control is shown in Figure 6.2. In both cases

yield is expressed as a function of target treatment salinities. The response of Colombar to salinity, using other indices of salinity, is dealt with in a separate chapter.

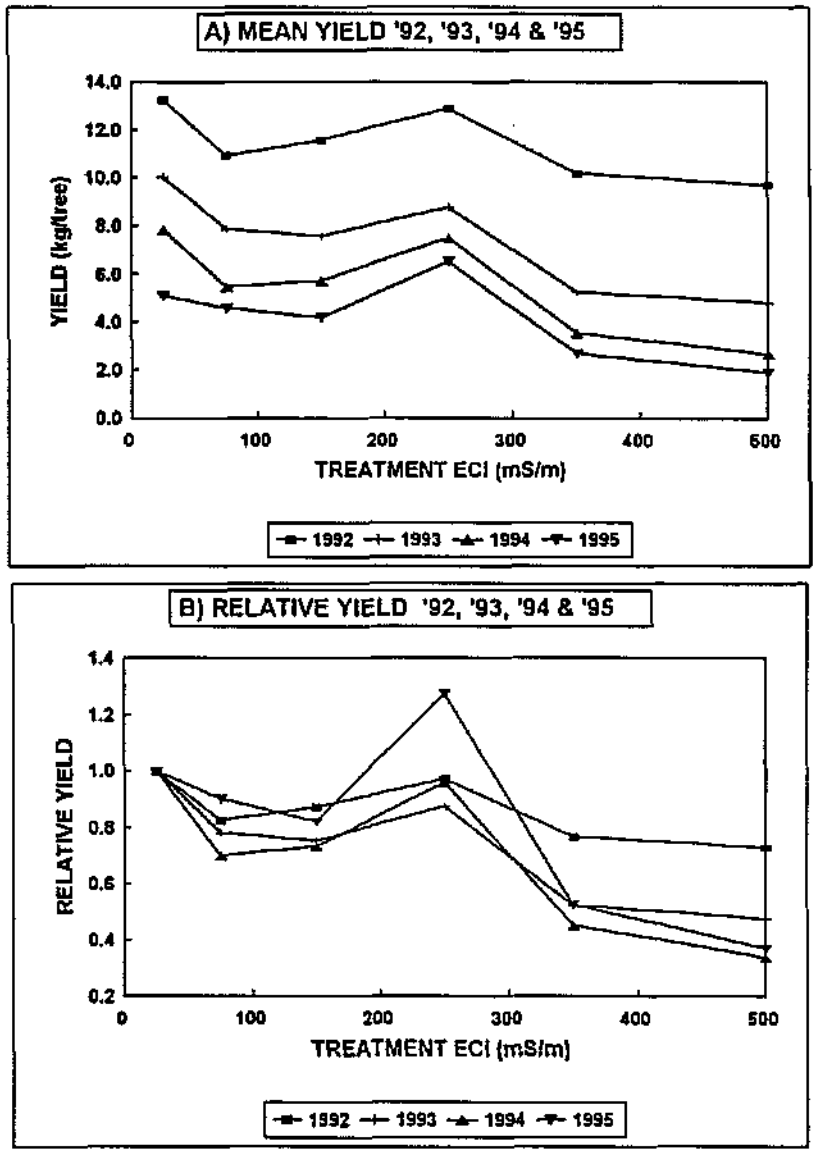

Figure 6.1 Yield per treatment as a function of the target ECi salinities for the seasons 1991/92 to 1994/95: a) arithmetic mean yield, b) relative yield

With respect to the results shown in Figure 6.1, the following can be concluded:

a) Yield decrease with salinity without any consistent trend. In all four years treatment 4 (ECi=250 mS/m) had higher yields than treatments 2 and 3 receiving less saline water. During the last season (1994/95), yield of treatment 4 was even higher than that of treatment 1. Our initial explanation for this is in terms of historical differences in plant size and growth vigour of the vines. However, more investigation and data analysis are necessary to fully explain this seemingly inconsistent result.

b) There is a large annual effect that apparently is not related to salinity. Since the first year, yield of the control treatment has continuously decreased. The viticultural extension officer at Robertson and other wineries in the Breede River Valley also reported the decrease in the yield of treatment 1 from 1991/92 to 1992/93 (Fig. 6.1a). A probable cause for this particular decrease

is unfavourable cold and wet conditions that prevailed at the flowering stage in October 1992. It is also known that a high yielding (above normal) year is often followed by a below normal yield the following season (Perold, 1926). However, yield of treatment 1 continued to decrease from 1992/93 to 1994/95 and this is not related to climatic conditions. Irrigation in this study used the soil water deficit as reference. This reference was reduced twice during this study. In December 1992 the wetted area was reduced from full surface wetting to 66% wetted area per plant. In September 1993 the assumed field capacity was reduced from 348 mm/1.20 m to 287 mm/1.05 m. It is important to find out whether these changes implemented to reduce unintended leaching during summer resulted also in higher water or salt stress in the root zone, even with treatment 1. The salinity profiles (Figure 4.6a) show an increase, though minor, in salt accumulation at the 0.3 to 0.9 m depths of treatment 1 from October 1991 to April 1994, with the biggest accumulation occurring in the 1992/93 season. It is unknown (but unlikely) whether this minor salt build-up could have been the primary cause for the marked yield decrease of treatment 1[4].

c) The detrimental effect of salinity on yield increases with time. For example, comparing the normalised yield of treatment 6 (ECi=500 mS/m) with treatment 1 (ECi=25 mS/m) on a relative scale, the progression of yield reduction from 1991/92 to 1994/95 were 27%, 52%, 66% and 63%. Treatments 2, 3 and 5 showed similar long term trends.

d) Yield seemingly was not affected by the irrigation water salinity levels of treatment 4, i.e. ECi=250 mS/m. This result should be treated with caution, because we are of the opinion that other factors such as vine size and more vigorous growth of the treatment 4 plants, even before this study started, are key determinants in the response of treatment 4 to salinity. The response to salinity also is somewhat different when expressed as a function of soil salinity in stead of irrigation water salinity (see Chapter 7).

e) In 1993/94 virtually all plants of treatment 6 started to show shoot die-back and severe leaf necrosis. By the end of that season, some plants were already dead. For this reason we decided to discontinue treatment 6 in 1994/95 and to replace the saline water with the low salinity canal water, equivalent to treatment 1. This was done to see if the damage can be reversed.

The yield results were statistically analysed with ANOVA. There was a very good relationship between yield mass per vine and plant size in terms of either trunk circumference or pruning mass, irrespective of salinity (Figure 6.2). We therefore decided to do the ANOVA with plant size as a covariate. Yield correlated well with both trunk circumference and with pruning mass of the current year and anyone of these two parameters could have served as a covariate. However, measurements of trunk circumference and pruning mass were both made after the start of the salinity experiment in December 1991 and it is uncertain to what extent these two plant parameters were

[4] It is important to note that this report deals with the results of 1990/91 to 1994/95. The project ended in June 1995 but was extended for another three years. In 1995/96 the downward trend in the yield of the control treatment was reversed with the yield increasing from 4.99 kg/vine in 1994/95 to 6.80 kg/vine in 1995/96). The yield of treatment 4 (ECi=250 mS/m), which in previous years was more than, or equal to, that of the control, also for the first time decreased from 6.53 in 1994/95 to 5.96 kg/vine in 1995/96.

influenced by the treatments. The only available index of plant size that was definitely not influenced by the salinity treatments was the shoot mass of August 1991, i.e. prior to any salinity treatment. Consequently were decided to use the pruning mass of August 1991 as covariate. Unfortunately, in August 1991 individual data of each vine were not recorded and only the combined shoot mass of all ten experimental plants per plot were determined. The result was expressed as the mean shoot mass per plot. Therefore, in the ANOVA all yield data were reduced to a mean value (in terms of kg/vine) per plot.

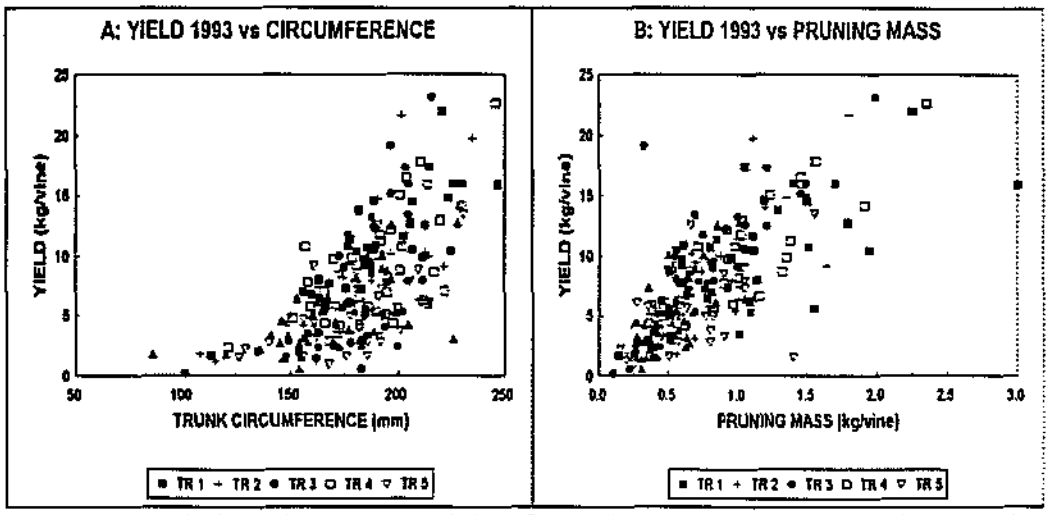

Figure 6.2 Relationship between yield of March 1993 and plant size irrespective of treatments: a) trunk circumference, b) pruning mass of August 1993

Another factor that played a role in the ANOVA is the skew frequency distribution of yield (Fig. 6.3) and other yield components (not shown). The distribution is typically log-normal and consequently, for the ANOVA all yield data were log-transformed. The treatment means resulting from the ANOVA were back transformed and are reported here as geometric means. Three types of means could therefore be used to express salinity effects and treatment differences, i.e. i) the untransformed arithmetic means without the inclusion of a covariate, ii) geometric means without the inclusion of a covariate, and iii) geometric means including the effect of shoot mass as a covariate. The arithmetic mean yield per treatment and the normalised yield data from 1991/92 to 1994/95 are shown in Figure 6.1. The results of the ANOVA with the untransformed- and log-transformed data, with and without pruning mass as a covariate, are summarised in Table 6.3.

The geometric means in all cases are lower than the arithmetic means (Table 6.3). Inclusion of shoot mass as covariate in the ANOVA had a substantial effect on the geometric mean yield. For example in 1993/94, adjustment for plant size reduces the geometric mean yield of treatment 4 in by 0.92 kg/vine (from 6.43 kg/vine to 5.51 kg/vine), while the yield of treatments 3, 5 and 6 increases by respectively 0.19 kg/vine, 0.58 kg/vine and 0.11 kg/vine. This illustrates the role of plant size in the salt tolerance of grapevines. It also confirms that the apparent higher tolerance of treatment 4 to irrigation water salinity was at least in part caused by plant size.

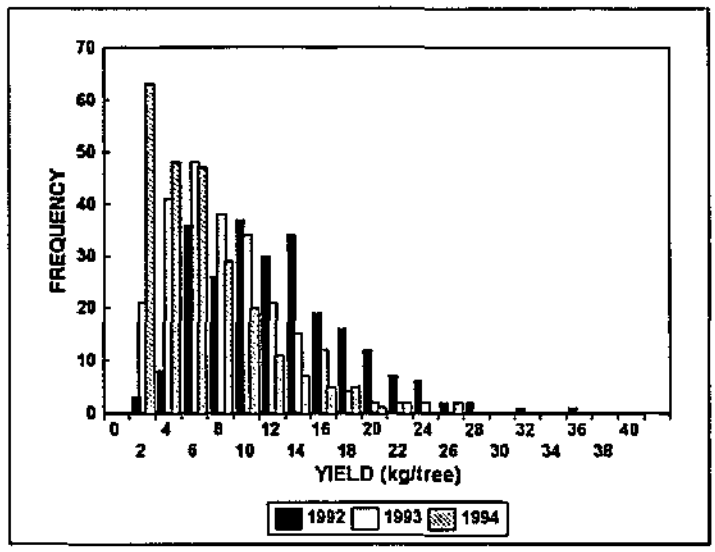

Figure 6.3 Frequency distribution of the yield per vine for the 1991/92, 1992/93 and 1993/94 seasons

Table 6.3 Results of an ANOVA using mean data per plot, on the effect of saline irrigation water on the yield of Colombar grapes over four years

Year	Salinity treatment (mS/m) 25	75	150	250	350	500	P
Arithmetic Mean Yield (fresh weight, kg/vine)							
1992	13.28a*	10.95ab	11.65ab	12.90ab	10.19ab	9.72b	0.137
1993	10.05a	7.86ab	7.56abc	8.78a	5.26bc	4.81bc	0.009
1994	7.83a	5.49ab	5.73ab	7.51a	3.54b	2.68b	0.019
1995	4.99ab	4.61ab	4.20abc	6.53a	2.69bc	1.91c	0.012
Geometric Mean Yield (fresh weight, kg/vine)							
1992	13.12a*	10.41ab	10.39a	12.35ab	9.63b	9.42b	0.146
1993	9.99a	7.41ab	6.33bc	8.14ab	4.95c	4.38c	0.068
1994	7.43a	4.80ab	4.08bc	6.43a	2.71bc	2.48c	0.009
1995	4.58ab	4.39ab	3.75bc	5.95a	2.55c	1.70d	0.001
Geometric Mean Yield with Shoot Mass (1991) as Covariate (fresh weight, kg/vine)							
1992	12.46a	10.40ab	10.60ab	11.60ab	10.43ab	9.59b	0.335
1993	9.52a	7.40ab	6.44bc	7.68ab	5.33bc	4.56c	0.012
1994	6.54a	4.78ab	4.27ab	5.51a	3.29bc	2.59c	0.010
1995	4.43a	4.38a	3.88ab	5.34a	2.93b	1.76c	<0.001

* Means separation within rows by LSD Multiple Range Test at the 5% level
P Probability level

6.3.2 Yield components

The yield components at harvest, i.e. shoot- and bunch number per plant and bunch and the fresh and dry berry mass, given as the respective treatment means at time of harvest, are listed in Table 6.4. although the data have not been statistically analysed (ANOVA) or the means adjusted for plant size, the following trends are discernible:

a) With the exception of treatment 6 in 1994/95, the number of shoots per plant was not influenced by salinity nor was there a consistent change in the number of shoots over the years, although there were more shoots per plant in

1993/94 compared to the other two seasons. This does not seem to be a salinity effect.

b) The bunch number decreases with salinity in all seasons, especially at the higher salinity levels, e.g. 56 for treatment 1 and 40 bunches per plant for treatment 6 in 1993/94. All treatments experienced a considerable decrease in bunch number over the seasons, which again was accentuated at the higher levels of salinity.

c) Bunch mass on a fresh basis decreased as salinity increased, but within a season, the trend was not consistent with treatment 4 both in 1992/93 and 1994/95 having a larger mass than treatment 3. For all treatments the maximum bunch mass was measured in 1992/93. A large decrease in fresh mass occured at treatment 5 (EC_i=350 mS/m) and in the dry mass at treatment 6 (EC_i=500 mS/m).

d) There is no consistent salinity effect on the number of berries per bunch, or on the fresh mass per berry. In all seasons the berry dry mass decreased with salinity.

e) The yield decrease of treatment 1 from 1993/94 to 1994/95 seems to be the result of less shoots per plant and therefore a reduced bunch number, and not because of a reduced bunch- and berry fresh mass, or less berries per bunch. No explanation for the smaller number of shoots per plant in 1994/95 could be found, especially as the pruning method used in August 1993 and August 1994 was the same.

6.3.3 Berry size and growth

Figure 6.4a-c presents the seasonal gain in berry size during the 1992/93 season expressed in terms of fresh and dry mass and dry matter content for the three salt levels of treatments 1, 4 and 6. The first berries were sampled 35 days after flowering (DOS 92). All three treatments followed the classical growth rate stages of grape berries (Winkler *et al.* 1974, Williams and Matthews 1990). These different stages can best be seen in the 25 mS/m treatment: Phase I to DOS 102 rapid growth (not shown in full on graph), phase II to DOS 130 slow, Phase III to DOS 150 rapid gain in fresh and dry weights. The berry fresh mass during Phase IV till harvest was more or less constant, but dry mass continued to increase. All treatments also show the lag in the gain of dry- compared to fresh mass and an increase in dry matter fractions during phases III and IV. Differences between the 25 and 500 mS/m treatments in fresh mass were already noticeable on day 92 and increased over the season. The differences between the 25 and 250 mS/m treatments were much smaller but became more accentuated from day 155.

Before day 130 salinity reduced only the gain in fresh mass, but after this day salinity also started to affect the gain of dry mass. From DOS 150 the effect of salinity on dry mass was larger than the effect on fresh mass gain. These changes in fresh and dry mass gains show up in the ratio of dry (DW) to fresh mass (FW) (Figure 6.4c) which indicate a higher dry matter content in the high salt treatment early in the season (ratio DW/FW for treatment 6 > treatment 1) and in the low salt treatment late in the season (ratio of treatment 6 < treatment 1).

6.3.4 Ionic composition of berries, must and wine

The seasonal changes in the acid and sugar contents of the must of treatments 1, 4 and 6 along the 1992/93 season are given in Figure 6.5. Similar trends were observed in the other seasons and consequently are not shown here. Both sugar and acid in all treatments

show the normal seasonal changes with a rapid increase in sugar content and decrease in acids after veraison. No consistent salinity effects on the acid content and pH, (not shown) were found. Before DOS 170, the salinity effects on the sugar content were also small, especially when compared to the normal developmental stage effects. High salinity reduced the sugar accumulation after this day when the rates of sugar accumulation became slower in all treatments. The lower rate of sugar accumulation shown for the mean of the high salt treatment (EC_i=500 mS/m) was mainly the result of two plots. In these plots the sugar content stabilised at less than 17% and could not reach the 18% target before the last day allowed for harvesting by the cellar. These two plots of treatment 6 were replicates with a more vigorous vegetative growth and higher yield load. The other two replicates of this treatment had less vegetative growth and lower yield and could accumulate sugar to the required level for harvesting. This indicates that the high level of salinity disturbed the balance between the shoot source and the fruit sink when the fruit load was heavy.

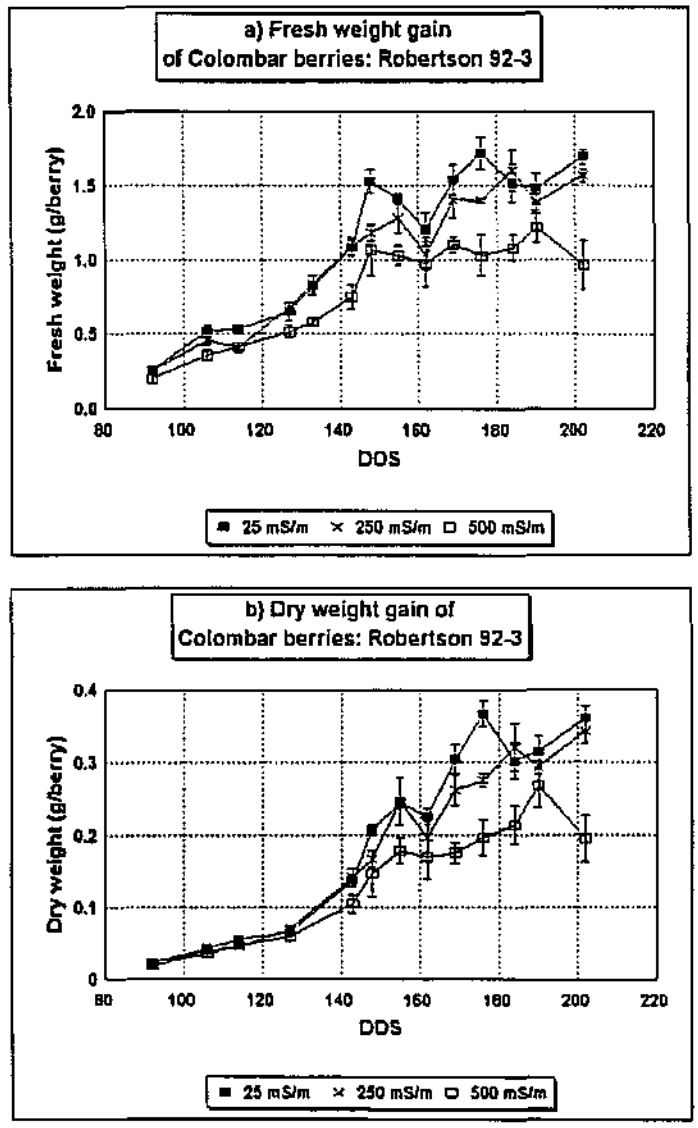

Figure 6.4 Salinity effect on seasonal gain of Colombar berries in a) fresh-, b) dry mass, and c) dry matter content, Robertson 1992/93

On day 132 the leaves in the high salt treatment started to deteriorate and most leaves in this treatment, including the two replications with the large canopy, were dropped before

harvest. This resulted in unbalanced conditions in the two replications with the high sugar requirement, i.e. high yield but not enough healthy leaves to produce the sugar. When the means of all 6 treatments are compared (not shown) the differences in sugar content, like the differences in the acid content and pH of the must, were not statistically significant.

Table 6.4 Untransformed treatment mean data of the yield components: shoots, bunches, and berries of Colombar grapes, 1992/93 to 1994/95

Component	Tr 1 25 mS/m	Tr 2 75 mS/m	Tr 3 150 mS/m	Tr 4 250 mS/m	Tr 5 350 mS/m	Tr 6 500 mS/m
1992/93						
Shoots per plant	38.2	36.6	36.5	36.3	37.8	36.1
Bunches per plant	61.7	56.5	53.6	56.4	52.3	49.2
Bunch mass, fresh (g)	198.7	224.9	226.9	225.1	131.3	141.7
Berries per bunch	114.3	139.0	149.4	138.3	102.9	154.4
Berry mass, fresh (g)	1.70	1.60	1.48	1.57	1.24	0.97
Berry mass, dry (g)	0.36	0.34	0.29	0.34	0.25	0.20
1993/94						
Shoots per plant	43.4	42.7	42.1	40.0	42.8	41.5
Bunches per plant	56.1	47.1	44.6	49.1	38.9	39.7
Bunch mass, fresh (g)	128.6	137.2	154.7	162.8	114.8	104.9
Berries per bunch, (g)	79.8	87.8	95.8	110.1	94.3	97.4
Berry mass, fresh (g)	1.55	1.55	1.47	1.32	1.16	1.04
Berry mass, dry (g)	0.27	0.26	0.27	0.24	0.19	0.19
1994/95						
Shoots per plant	34.7	32.9	27.7	32.3	27.9	24.5
Bunches per plant	37.5	34.0	29.8	37.7	26.7	17.1
Bunch mass, fresh (g)	121.3	149.2	118.1	165.3	95.2	71.2
Berries per bunch	105.0	125.3	134.3	128.0	99.5	74.1
Berry mass, fresh (g)	1.61	1.40	1.23	1.36	1.10	1.21
Berry mass, dry (g)	0.44	0.28	0.30	0.31	0.31	0.28

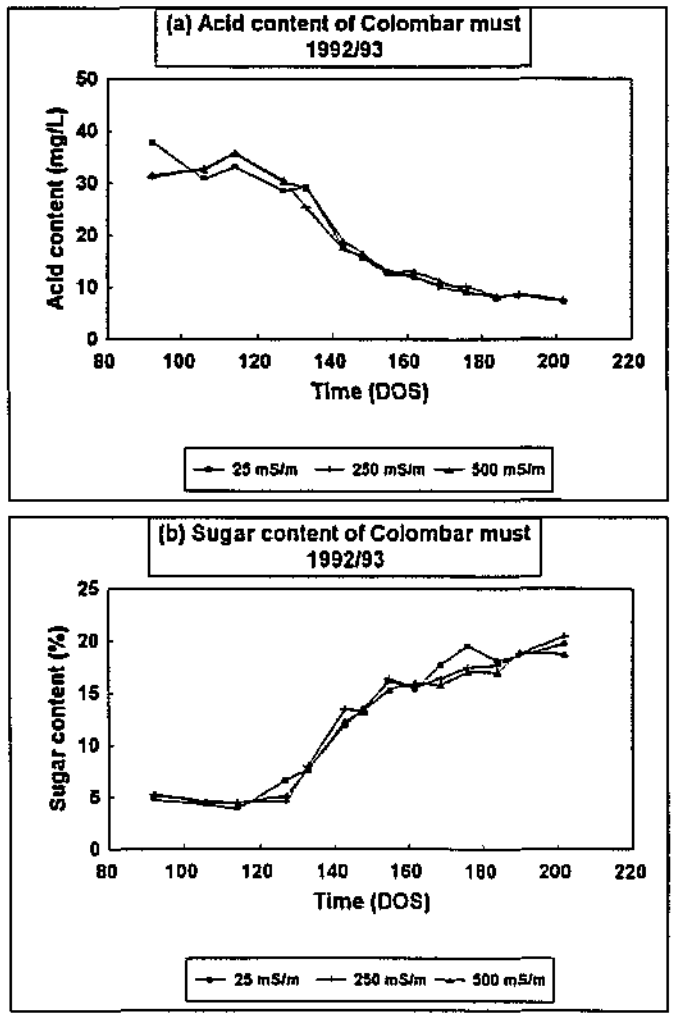

Figure 6.5 Salinity effect on the seasonal changes in must composition of Colombar grapes at Robertson 1992-3, for treatments 1, 4 and 6: (a) acid, and (b) sugar

Figure 6.6 presents the seasonal changes in the Cl and Na concentration of the must of treatments 1, 4 and 6 for 1992/93 and for all treatments in 1993/94. The berries were first sampled at the pea size fruit stage (DOS 105) up to harvest (DOS 205). Although the sampling frequency in 1992/93 was more intense than in 1993/94, the temporal trends in both years were the same. The changes in Cl and Na content were very similar. The differences between the two in 1992/93 on DOS 190 are probably the result of experimental error (Fig. 6.6a & c). In 1992/93 the concentration of these two ions in the must increased until DOS 155. During this period the increase was rapid in the 500 mS/m treatment and much slower in the 250 mS/m treatment. After day 155 the concentration of Na and Cl remained stable in the two saline treatments.

In 1993/94 the uptake of Cl and Na continued right up to harvest without reaching a plateau value (Fig. 6.6b & d). The concentration of Cl and Na increased very little below ECi 350 mS/m, with the salinity effect becoming larger with the progress of the season. Calcium was higher at higher salinities on all sampling days (data not shown) which can be explained in terms of the $CaCl_2$ that was used to salinize the irrigation water. Potassium was decreased, but in most cases non-significant, with the increase in salinity. Must Cl and Na in 1993/94 reached somewhat higher levels than in the 1992/93 season mainly as a result of continuos accumulation to harvest.

It is interesting to note that the curves that describe the changes in the chloride and sodium contents in the must of 1992/93 were similar to the curves that describe the gain in fresh weights of the berries (Fig 6.4). The close agreement between volume expansion and the increase in Cl and Na content in the must indicate that there is a significant change in the salt transport to the fruit when growth in volume stops. This is also the time when the import of nutrients to the fruits decreases or stops (Conradie 1981). The increase in concentration of Cl and Na while the fruits grow indicate to a larger import of salts than the retained water volume.

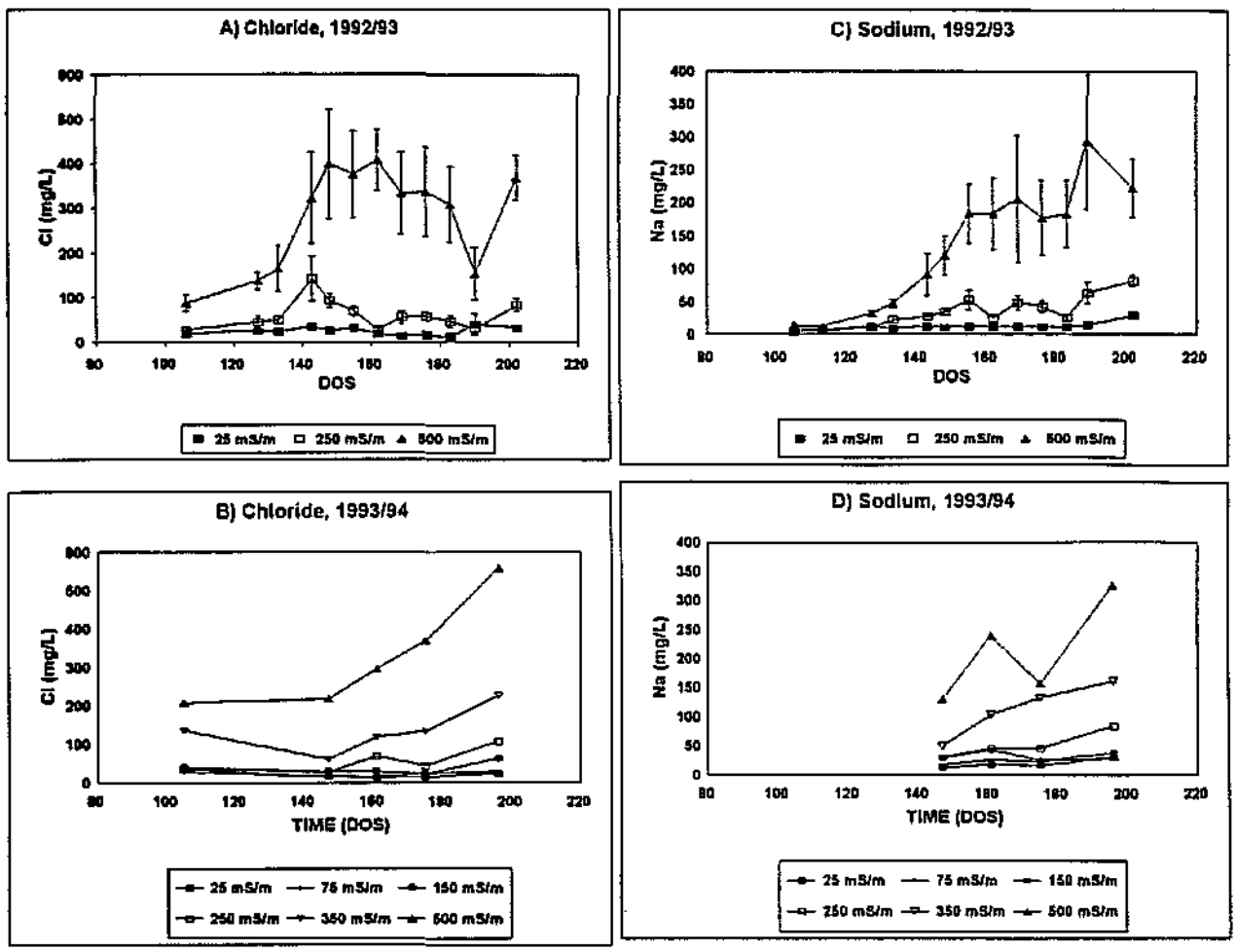

Figure 6.6 Salinity effect on the seasonal changes in the ion content of Colombar must at Robertson: a) Cl in 1992/93, b) Cl in 1993/94, d) Na in 1992/93 and c) Na in 1993/94

The temporal trend in the uptake of Na and Cl in 1992/93, when after day 155 there was no salt deposition in the must, suggest that irrigation with saline water from the end of January (150 DOS) or even earlier, with quantities sufficient to salinize the root zone, will not result in import of salt to the fruit. However, a second flush of nutrient uptake and root growth occurred immediately after harvest, which might be negatively effected if the root zone is saline. Also, this pattern did not repeat itself the following season. Nevertheless, this interesting result calls for further investigation.

The sugar and acid content and the pH of the must at harvest for all years and treatments are shown in Figure 6.7. The sugar content of the must was not influenced by salinity in any consistent or clear way. According to ANOVA there is no treatment effect. The

annual differences were larger than the treatment differences within a year. Sugar content was maximal in 1993/94 and minimum in 1992/93. Acid content and pH were also not influenced by salinity (Fig. 6.7).

Table 6.5 Salinity effect on the treatment mean ionic composition of the must of Colombar grapes at harvest for the period 1991/92 to 1994/95

	Treatm 1 25 mS/m	Treatm 2 75 mS/m	Treatm 3 150 mS/m	Treat 4 250 mS/m	Treatm 5 350 mS/m	Treatm 6 500 mS/m
	1991/92					
Cl (mg/L)	12	16	16	19	46	75
Na (mg/L)	29	27	29	33	39	41
Ca (mg/L)	44	46	45	45	49	52
K (mg/L)	589	655	619	678	591	631
	1992/93					
Cl (mg/L)	32	27	56	83	153	368
Na (mg/L)	25	31	46	77	111	221
Ca (mg/L)	86	88	102	91	115	140
K (mg/L)	1355	1303	1371	1311	1271	1283
	1993/94					
Cl (mg/L)	25	30	64	108	228	560
Na (mg/L)	30	26	44	77	155	303
Ca (mg/L)	90	99	118	105	132	140
K (mg/L)	815	1007	1095	712	940	829
	1994/95					
Cl (mg/L)	41	16	33	68	212	165
Na (mg/L)	26	21	34	46	184	168
Ca (mg/L)	94	78	91	89	125	103
K (mg/L)	2063	1840	1689	1735	1679	1871

The ionic composition of the must in terms of Cl, Na, K, and Ca are summarised as treatments means in Table 6.5. The citric-, tartaric- and malic acid contents and free amino nitrogen in the must of 1992/93 were also determined and are shown in Table 6.6. The salinity effect on the Na and Ca content in 1991/92 was only marginal, but there was a substantial increase in Cl with salinity, especially with treatments 5 (ECi 450 mS/m) and 6 (ECi=600 mS/m). Since 1992/93 the absolute Na, Cl and Ca contents (Table 6.5) increased and K content decreased consistently at irrigation water salinities higher than 75 mS/m. The increase in Na and Cl was very pronounced at the higher salinities. Chloride, calcium and sodium were added to the irrigation water at a chemical equivalent ratio of 4:2:1. In the must of treatment 6 the ratio of the increase in these ions were 1.48 : 1.37 : 1 in 1992/93 and 1.19 : 0.53 : 1 in 1993/94. (*Treatment 6 was irrigated with non-saline water in 1994/95*). The decrease in the K content of the must was smaller than the increase in Na. It is also important to note that the Na content in the must of treatment 6 is above the permissible level by the French and German standards (Amarine and Ough, 1980) and also above the South African standard of 100 mg/L (S.A. Government Gazette 12558, 1990). There is a general trend for potassium to increase with time (Table 6.5). For example, the potassium content of 1993 is about double the 1992 values. There is a good relationship between sugar, acid (and pH) and K of must.

Potassium increases with sugar and pH, and decreases with acid (Saayman, personal communication). All these factors imply a higher K content in 1992/93 and 1994/95. Because of the continuous decline in yield over the years, some of the increase in K with time might be attributed to a volume dilution effect.

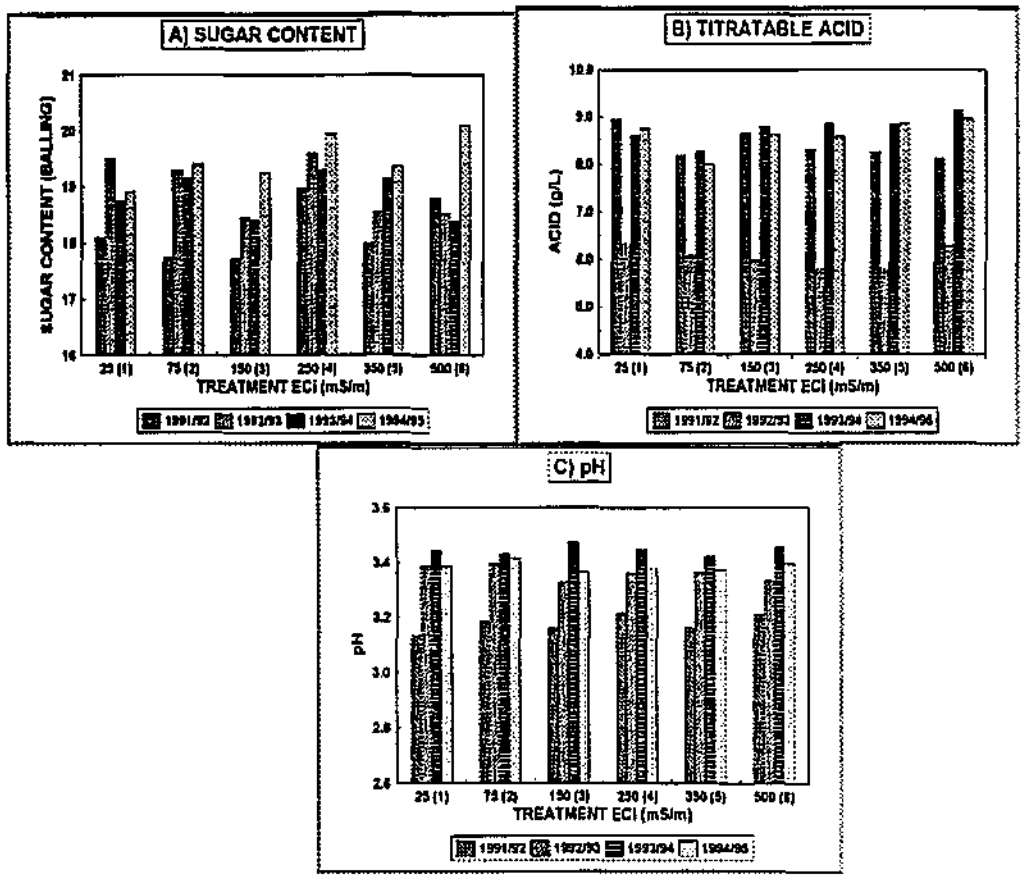

Figure 6.7 Salinity effects on the treatment mean sugar and acid content and pH of the must of Colombar grapes at Robertson from 1992/93 to 1994/95

The mean organic acid and free amino nitrogen (FAN) contents were determined only in 1992/93 and the treatment means are summarised in Table 6.6. Malic acid and FAN are the only two variables that show a trend with salinity, malic acid decreasing and FAN increasing with salinity. According to Prof. Van Wyk (Dept. of Viticulture and Oenology, University of Stellenbosch; personal communication), these differences are too small to have any real effect on wine quality. Free amino nitrogen apparently has an effect on the fermentation of the must with 42,6 mg/L FAN per degree Balling (sugar content) being a minimum value that is required for good and total fermentation of the must. This value was exceeded at all salinity levels.

6.3.5 Wine quality

Wine of the 1992/93 and 1993/94 seasons was bottled and matured for about four to six months before the Cl, Ca, Mg, K and Na contents were determined. The results were not subjected to an ANOVA and only the means per treatment are shown in Figure 6.8. Some unknown aromatic compound (or compounds) in wine interferes with the potentiometric determination of chloride. Consequently the record of the Cl-content of the matured wine is incomplete, especially at the higher levels of salinity. Nevertheless,

the results of those treatments and years for which it was possible to determine the Cl-content, indicate a marked increase in the Cl and Na concentration in the wine as salinity increases. Chloride, for example, in the wine of the control treatment in 1994 was 25 mg/L, 162 mg/L in treatment 4 (250 mS/m) and 560 mg/L in treatment 6 (500 mS/m). Sodium in the same year was 340 mg/L (treatment 1), 77 mg/L (treatment 4) and 311 (treatment 6). Calcium did not show any salinity effect, which in view of the fact that the vines were irrigated with Ca-enriched water was surprising. In contrast, magnesium had a small but consistent increase with salinity, the increase from treatment 1 to 6 being 20 mg/L and 40 mg/L in 1992/93 and 1993/94 respectively. The wines of treatment 5 and 6 in both years contained less potassium than those of treatments 1 to 3.

Table 6.6 Salinity effect on the treatment mean citric-, tartaric- and malic acid contents and free amino nitrogen of the must of 1992/93

Treatment	Citric (g/L)	Tartaric (g/L)	Malic (g/L)	FAN * (mg/L)
1 (25 mS/m)	0,29	4,52	3,62	986
2 (75 mS/m)	0,27	5,30	3,07	842
3 (150 mS/m)	0,27	4,79	3,41	930
4 (250 mS/m)	0,26	4,59	3,23	982
5 (350 mS/m)	0,25	4,97	2,99	996
6 (500 mS/m)	0,33	5,28	2,69	1088

* FAN = free amino nitrogen

Sodium is sometimes used in wine processing (in ion-exchange resins) and it is also of importance to people on low sodium diets. South Africa (S.A. Government Gazette, 12558, 1990) and other countries of the European Community (Amarine and Ough, 1980) have imposed a legal limit on the Na content of wine. In view of this we further investigated the relationship between Na in the must and the equivalent concentration in wine (Fig. 6.9). As is to be expected there is a very good 1:1 relationship with no increase in the Na content of the wine due to wine processing. This indicates that the must can serve as a good index of the natural Na content of wine. It also means that elevated levels of Na in wine will be proof of unnatural Na additions during wine processing. In August 1994 the wine of the 1992/93 and 1993/94 harvests were evaluated by a panel of twelve wine judges. It is important to note that at the time of evaluation there was a one year difference in the age of the two sets of wine. This age difference therefore suggests that the salinity effect on ageing could also be evaluated. However, as was shown in Table 6.6, there was considerable difference in the ionic composition of the must at harvest between these two yield years and it would be difficult, if not impossible, to distinguish between age and salinity effects.

The wine was evaluated by ranking the four replicates of treatments 1, 4 and 6 in decreasing order of quality according to aroma and taste. The 12 wines were grouped into four batches, with each batch consisting of the three treatments from a particular replicate (or block, Fig. 3.2). A rank order number of 1 implied the best of the three wines within a batch, 2 the second best, etc., i.e. a rank number of 3 indicated the poorest wine in a particular batch.

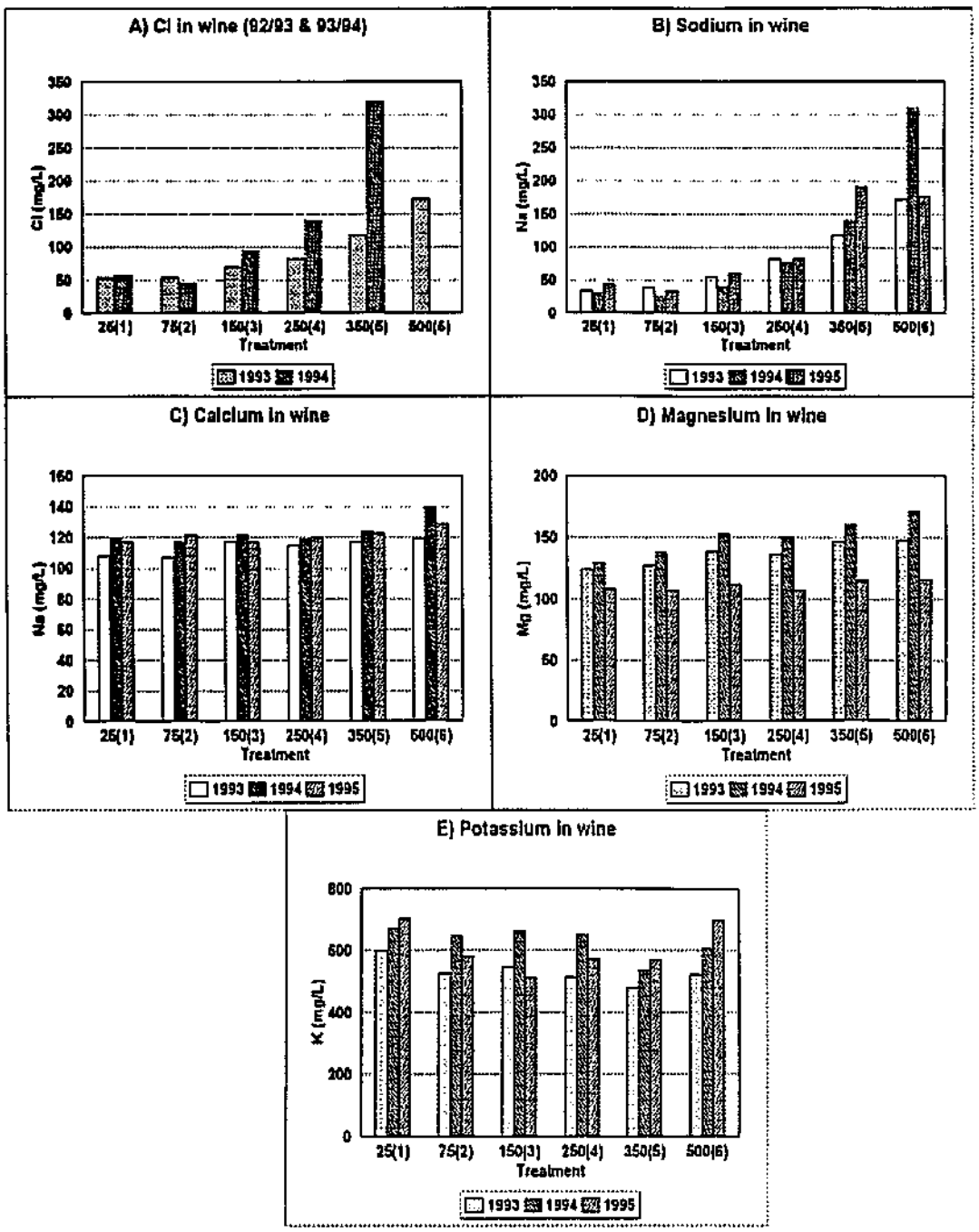

Figure 6.8 Salinity effect on the treatment mean ionic composition of the wine of Colombar grapes of 1992/93 and 1993/94 harvest: a) Cl, b) Na, c) Ca, d) Mg and e) K.

Each wine was also scored on a scale of 1 to 6 in terms of general quality, with a higher score indicating a better quality of wine. The results have not been statistically analysed in any great detail but the mean score per wine for quality, aroma and taste as function of Na content, for example, are shown in Figure 6.10. Because of the good correlation between Na and Cl in the wine and the small variability in the K content of the different treatments, only Na is shown. The visual representation of the results suggests that there is no relationship between Na-content and aroma or taste.

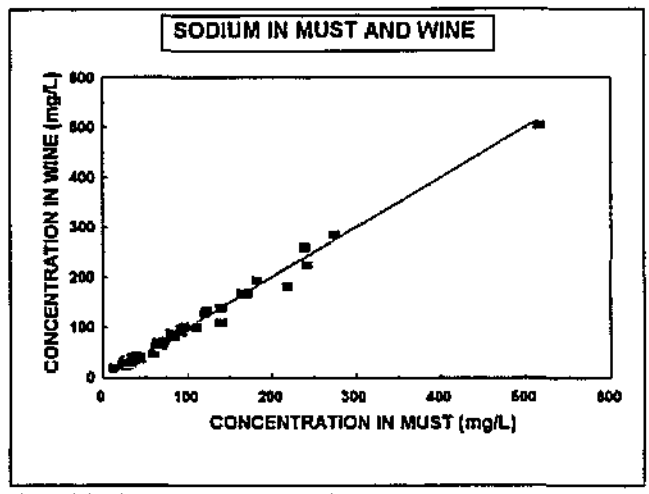

Figure 6.9 Relationship between the sodium content of must and wine of Colombar grapes irrigated with saline water ($Na_{wine} = 0.976Na_{must}+2.961$; $R^2=0.988$, n=47)

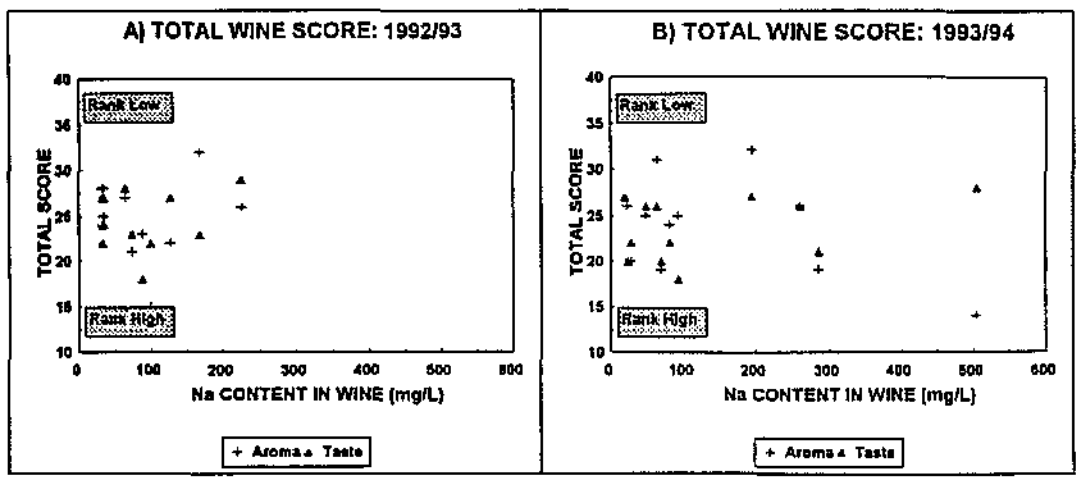

Figure 6.10 Relationship between the sodium content and total cumulative rank order score for the aroma and taste of Colombar wine: a) 1992/93 and b) 1993/94 vintages.

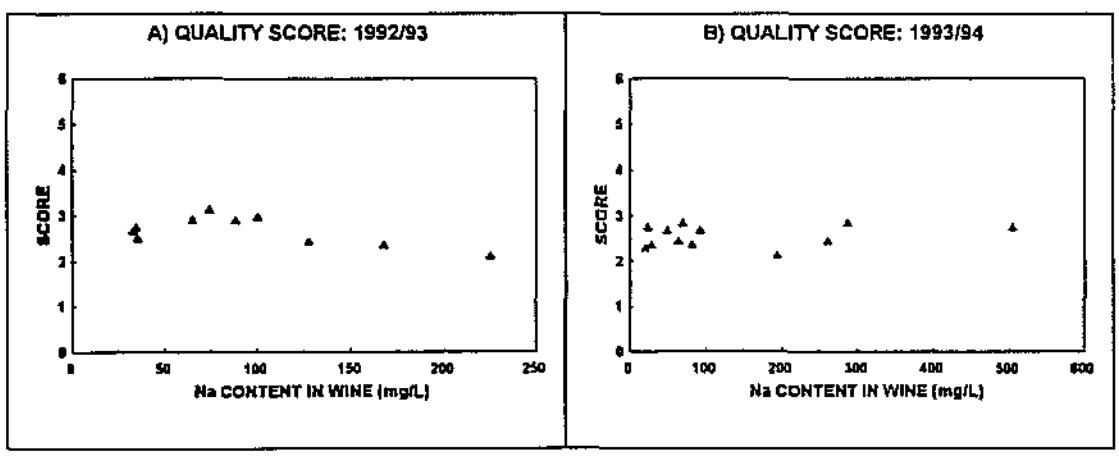

Figure 6.11 Relationship between sodium content and the mean score for the quality of Colombar wine allocated by a panel of twelve wine judges, with a larger score indicating a better quality wine: a) 19922/93 and b) 1993/94 yield years

A similar conclusion can be drawn from the relationship between Na-content and the mean score for wine quality (Fig. 6.11). The scores in general ranged between 2.5 and 3.2 for the 1992/93 vintage and between 2 and 3 for the 1993/94 vintage, irrespective of Na which ranged from < 50 mg/L to > 500 mg/L in the individual wines. In view of this, it seems as if Na had no influence on wine quality and it is doubtful whether a more rigorous statistical analysis will lead to a different conclusion. A possible explanation for this result is the general mediocre quality of the Colombar wine which could have masked any salinity effect.

6.4 Discussion and Conclusions

The number of shoots and bunches per plant for the first two seasons, 1991/92 and 1992/93, were initiated before the salinity treatments began. The main influence of the saline water during these two seasons therefore was the impact on the ripening process and berry growth. The first full effect of the salinity treatments on the yield and berry growth became visible in the third season. Even during the first two seasons, the saline irrigation water through the process of berry growth, ripening and must composition had a significant effect on yield of March 1992 and March 1993.

The berry weight and yield of 1992/93 and 1993/94 showed a significant salinity effect without any clear threshold salt tolerance value. An organoleptic evaluation of the wine did not reveal any salinity effect on wine quality, aroma or taste. In view of the substantial differences in, for example the Na and Cl content of the wine, this was a rather surprising result. However, there are so many factors in wine processing that determine wine quality, that a statistical quantification of the effect of salinity on wine quality, seems very remote. At best, the effect of salinity on wine quality will have to be based on chemical analysis of the must.

Salinity had a severe effect on yield with a yield decrease of 60% at the ECi 500 mS/m salinity level. Yield was negatively influenced even at the intermediate salinity levels of 75 and 150 mS/m. A better understanding of the effect of salinity on the yield and reproductive growth of Colombar grapes is complicated by the fact that during the first four years of this study an irrigation water salinity of 250 mS/m seemingly had little effect on yield. Quantifying the effect of salinity on yield was further hampered by the progressive decrease in the yield on the control treatment. It seems that plant vigour and size are key determinants that influence the response of Colombar grapes to salinity. Despite these two complicating factors, the results of this experiment indicate that grapevines are more sensitive to salinity than previously thought, and that the threshold salinity value of 150 mS/m as reported by Ayers and Westcott (1985) is too high. Our results are more in line with the limiting value of 100 mS/m reported by Prior *et al.* (1992).

CHAPTER 7
INDICES TO DESCRIBE THE SALT TOLERANCE OF THE COLOMBAR GRAPEVINE CULTIVAR

7.1 Introduction

One of the aims of the study is to investigate and report on indices that describe how grapevines, specifically wine grapes respond to salinity. Literature reveals that more is known about the salinity response of annual crops than for perennial crops (see Chapter 2). Also, as shown in the previous two chapters, although interdependent, salinity effects on vegetative and reproductive growth are not necessarily the same. Prior *et al.* (1992a) concludes that there is "*little quantitative information on the yield response of grapevines to salinity in irrigation water, soil or plant tissue*". Ayers and Westcott (1985) classify grapevines as moderately salt-sensitive. According to Walker (1994) the salt tolerance data for grapevines used by Ayers and Westcott were based on an earlier publication by Maas and Hoffman (1977) which in turn were based on reported responses of grapevines to salinity. Furthermore, most of the work on salt tolerance of grapevines involved application of mixed salts and were based on growth rather than yield. The piece-wise response function [7.1] of Van Genuchten and Hoffman (1984) contains two independent parameters: the salinity threshold c_t, being the maximum soil salinity without yield reduction, and the slope s of the response function between c_t and c_0 where c_0 is the concentration beyond which the yield is zero. The slope of the curve determines the fractional decline per unit increase in salinity beyond the threshold.

$$Y_r = \begin{cases} 1 & 0 \le c \le c_t \\ 1 - s(c - c_t) & c_t < c \le c_0 \\ 0 & c > c_0 \end{cases} \qquad [7.1]$$

According to Ayers and Westcott (1985) the salinity threshold of grapevines is 150 mS/m with a yield decrease of 1% per 10 mS/m increase above the threshold. In Australia, Prior *et al.* (1992a) evaluated the effect of salinity (mostly NaCl) in the range 37 to 347 mS/m on the yield of 20-year old own-rooted Sultana vines and concluded that there is no single yield decrement to directly compare with the data of Ayers and Westcott (1985). Prior *et al.* (1992a) found that the yield response of Sultana grapevines was well described by a generalised logistic function:

$$y = D\,[1 + (EC_i/EC_{ih})^{\alpha}]^{-1} \qquad [7.2]$$

where y is yield, EC_i is the salinity of the irrigation water, D is the theoretical yield at $EC_i=0$, EC_{ih} is the half effect *Eci*, (i.e. *the ECi at which a 50% yield reduction occurs)*, and α is the shape parameter. They furthermore concluded that soil texture, and more specifically silt plus clay content, affects the salinity response via an effect on *ECih* and on α (Prior *et al.* 1992a). In their experiment they made provision for five silt plus clay classes at the 0.6 to 0.9 m depths with the midpoints of the classes being 19, 20, 22, 25 and 28%. This is a very narrow textural range and is outside the silt plus clay range of the soil of the Robertson vineyard (Table 3.2). The half effect ECih decreased with

increasing silt plus clay, i.e. the salt sensitivity (with respect to yield) increases with silt plus clay. Their model accounted for 76.2% of the variance in yield. In another paper Prior *et al.* (1992c) found that yield was correlated more strongly with soil salinity, ECe, averaged over three years (r=-0.72) or four years (r=-0.79) than with ECe measured on any one occasion (*r* between -0.24 and -0.69). However, the soil salinity relationship was not as good as with plant salinity levels. In order to keep yield losses (due to salinity) below 10% they recommended that soil salinity (ECe) levels at the end of winter should be maintained below 100 mS/m.

The grapevine is a perennial plant and as found by Prior *et al.* (1992c) the effect of salinity is likely to be cumulative with time. As was shown in our Chapter 6, reproductive growth parameters, such as the number of buds and bunches per tree, are determined during the previous year. It is therefore quite likely that short-term responses are transitional and that the full impact of saline water on perennial crops will only materialise in the longer term. In an experiment where mature plum trees were irrigated with saline water Hoffman *et al.* (1989) and Catlin *et al.* (1993) found significant reductions during the second year when irrigated with water having an electrical conductivity of 800 mS/m. The lower salinity treatments (0, 100, 200 and 400 mS/m) did not suffer measurable yield losses in the first three years of the study (Hoffman *et al.*, 1989). However, there were indications that the intermediate salt treatments were beginning to damage the trees. After five years the yield of the 200 mS/m treatment started to decline. Their eventual salt tolerance model for mature plum trees was based on a time integrated depth weighted mean soil salinity of two successive irrigation seasons.

The experiments of Prior *et al.* (1992a, b, c) and Hoffman *et al.* (1989) involved application of uniform concentrations of saline water throughout the growing season. However, the salinity response of vines and other perennial fruit crops might be altered if saline water is alternated with good quality water, the better quality water being applied during the more critical growth phases e.g. flowering. This kind of crop response and salinity management is well documented for annual crops. In this chapter we investigate several approaches that describe the yield response of Colombar grapes to various indices of salinity. It is important to note that the original experiment was not designed to investigate the effect of salinity at different growth stages on the overal seasonal performance of the Colombar grapevine.

7.2 Methods

In our study the indices to describe the effect of salinity on the yield of Colombar were grouped into two categories namely i) the effect of soil salinity, and ii) sodium and chloride on yield. The first category involves osmotic effects on yield while the second category is a specific ion effect. Different scenarios were investigated. The scenarios were (for better reading the difference between the scenarios are underlined):

a) correlating arithmetic and geometric mean yield of each of the four seasons (Table 6.3) with the volume weighted seasonal mean salinity of the irrigation water and rain of that particular year, i.e. current year, (see Chapter 4, section 4.2.2.1 and Table 4.4);

b) same as a) but using the time integrated depth weighted mean soil salinity (ECe) of the same year, i.e. a one year time integration (Chapter 4, section 4.2.2.4e, Table 4.10);

c) same as b) but using geometric mean yield, with a covariate adjustment for plant size (Table 6.3);
d) same as c) but with a two year time integration (Table 4.4); and
e) same as c) but with a three year time integration.
f) normalised, covariate adjusted treatment mean yield (the data of all yield years were combined) as a function of the chloride and sodium content in the leaves at harvest;
g) leaf chloride content at harvest as a function of the chloride content of the irrigation water;
h) leaf chloride content at harvest as a function of the depth weighted, time integrated seasonal mean ECe;
i) same as h) but with a two year time integration for soil salinity.

In all cases the treatment mean yields were normalised with respect to the control value. The depth weigthing was done for a range of soil depths from a 0-0.3 m to a 0-1.2 m combination but because the results were very similar, we report on the 0-0.6 m and 0-1.2 m depth combinations only. As proposed by Hoffman *et al.*, (1989), the integrated values were calculated using the soil salinity data of the previous two or three years, but excluding the months when the vines are dormant (May to August). It is assumed that this time period accounts for the influence of salinity on shoot growth which contributes to bud formation the year prior to harvest (Hoffman *et al.*, 1989). In order to include the yield results of 1991/92 and 1992/93 in the response models involving the two- and three-year time integration of soil salinity we required information on the soil salinity that prevailed in 1989/90, i.e. before the start of the experiment. The only information available was the analytical results of samples collected at Robertson in April 1990 (Table 3.2). We used the appropriate ECe values for each plot and assumed that, because the vineyard was not irrigated with saline water, the soil salinity values would not have changed much and that the data of April 1990 are representative of conditions that prevailed in 1990/91, i.e. the season immediately before the start of our experiment.

In all of the above cases and as a first approach, we used only linear regression curve fitting techniques to obtain the appropriate salinity-yield response model that fits our data. The following four types of equations were evaluated:

a) linear model: $y = a + bx$
b) multiplicative model: $y = ax^b$
c) exponential model: $y = exp(a + bx)$
d) reciprocal model: $1/y = a + bx$

where in all cases y refers to the normalised yield and a and b the intercept and slope respectively. The terms "linear", "exponential", etc. listed above and the mathematical description of each was taken from the *Statgraphics* Ver. 6 User's Manual.

7.3 Results

For the sake of brevity, selected results only are presented here. Also, it is important to note that throughout this chapter, geometric means, adjusted for plant size are used. As a first attempt and in view of the result of Prior *et al.*. (1992a), the yield of each particular plot and for each year separately, was normalised with respect to the maximum yield (of the 24 plots) for that particular year. The normalised yields were then plotted as a function of the profile weighted (0-1.2 m) silt plus clay contents but only for those plots where soil texture was analytically determined, i.e. no inter- or extrapolation were used. (Prior *et al.* (1992a) extrapolated their available textural data to all plots by using the

relationship between silt plus clay and saturation percentage of the saturated soil paste). The results are shown in Figure 7.1. We interpret the significant variability and the absence of a clear pattern in the data as sufficient proof that for this particular case, the textural differences between the 24 experimental plots did not have any strong influence in the salinity response. Also, in our case we were dealing with a considerably smaller data set (6 treatments x 4 replicates = 24 plots) compared to the 80 plots (= 4 treatment x 20 replicates) of Prior *et al.* (1992a).

The effect of the volume weighted irrigation water salinity of each season on the normalised, covariate-adjusted yield is shown in Figure 7.2. All four models were fitted to the data but the best one was the linear model. However, although being the best, it could account for only 16.9% of the variance. Yield seems to decrease continuously with increasing ECi without any salinity threshold.

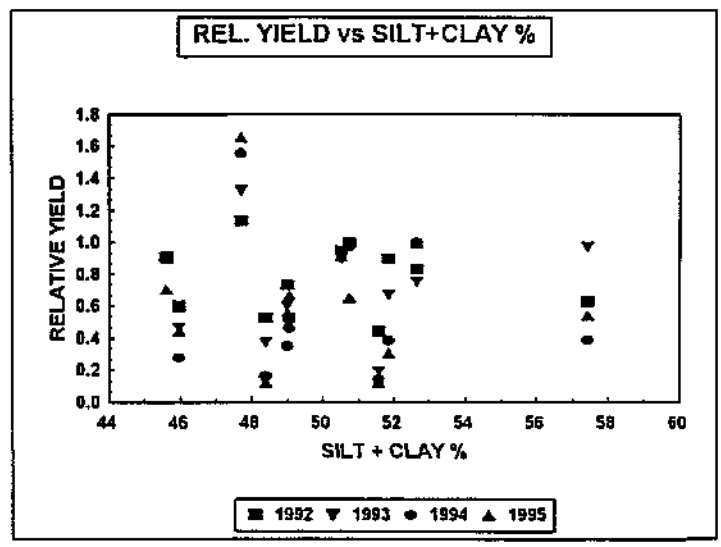

Figure 7.1 Normalised yield per year as a function of the profile weighted (0-1.2 m) mean silt plus clay contents of twelve plots at the Robertson vineyard where the textural composition was analytically determined

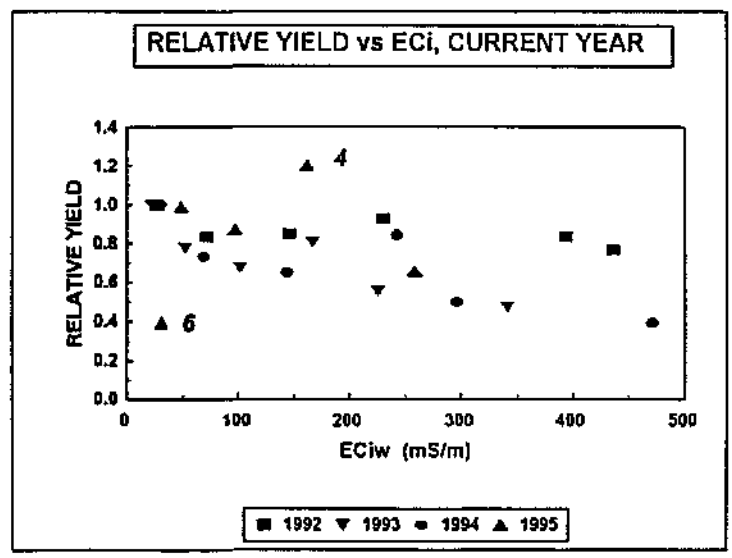

Figure 7.2 Relationship between normalised yield per year and the volume weighted irrigation water salinity, ECi, of the particular year: best response function: y = 0.858 - 0.0004ECi, R^2=16.9. (*The labels 4 and 6 refer to the 1995 yield of treatment 4 and 6*).

The relationship between time integrated soil salinity, as indicated by the electrical conductivity of the extract of a saturated soil paste, ECe, and normalised geometric mean yield is shown in Figure 7.3. Five different indices are shown: a one and two year time integration of soil salinity for the 0-1.2 m depth (Fig 7.3a & c) and 0-0.6 m depth (Fig. 7.3b & d) involving the yield of all four seasons, and a three year time integration of soil salinity for the 0-0.6 m depth with the yield of 1993/94 and 1994/95 only. The regression statistics of two of the most appropriate response models, namely a linear and exponential model, which can be fitted to the data, are summarised in Table 7.1.

Table 7.1 Parameter estimates of the linear [$y = a + bx$] and exponential [$y = exp(a + bx)$] yield response models quantifying the effect of soil salinity (x = ECe, mS/m) on the normalised, covariate (plant size) adjusted geometric mean yield (y) of 20-year-old Colombar grapevines

Model	x (=ECe) (and depth)	Time integration	a	b	R^2	F-Ratio ANOVA	Comment
Linear*	ECe(1.2)	1 year	1.093	-0.002	29.0	9.00	All yield data
Exponential**	ECe(1.2)	1 year	0.191	-0.003	33.6	11.1	All yield data
Linear	ECe(1.2)	2 year	1.108	-0.020	27.9	8.5	All yield data
Exponential	ECe(1.2)	2 year	0.240	-0.003	35.9	12.3	All yield data
Linear	ECe(1.2)	3 years	1.108	-0.003	22.9	4.9	All yield data
Exponential	ECe(1.2)	3 years	0.256	-0.004	31.3	7.3	All yield data
Linear	ECe(0.6)	1 year	1.071	-0.002	31.5	10.1	All yield data
Exponential	ECe(0.6)	1 year	0.148	-0.003	35.1	11.9	All yield data
Linear	ECe(0.6)	2 year	1.096	-0.003	32.8	10.7	All yield data
Exponential	ECe(0.6)	2 year	0.211	-0.004	40.6	15.0	All yield data
Linear	ECe(0.6)	3 years	1.091	-0.002	25.3	5.4	All yield data
Exponential	ECe(0.6)	3 years	0.222	-0.000	33.7	8.1	All yield data
Linear*	ECe(1.2)	2 year	1.208	-0.003	60.0	31.5	Only yield data ≤ 1.2
Exponential*	ECe(1.2)	2 year	0.366	-0.005	62.2	34.6	Only yield data ≤ 1.2
Linear*	ECe(0.6)	2 year	1.165	-0.003	63.3	36.3	Only yield data ≤ 1.2
Exponential* (Fig. 7.3d)	ECe(0.6)	2 year	0.297	-0.004	65.0	39.1	Only yield data ≤ 1.2

* rejected normalised yield >1.2 (i.e. yield of treatment 4 of 1994/95)

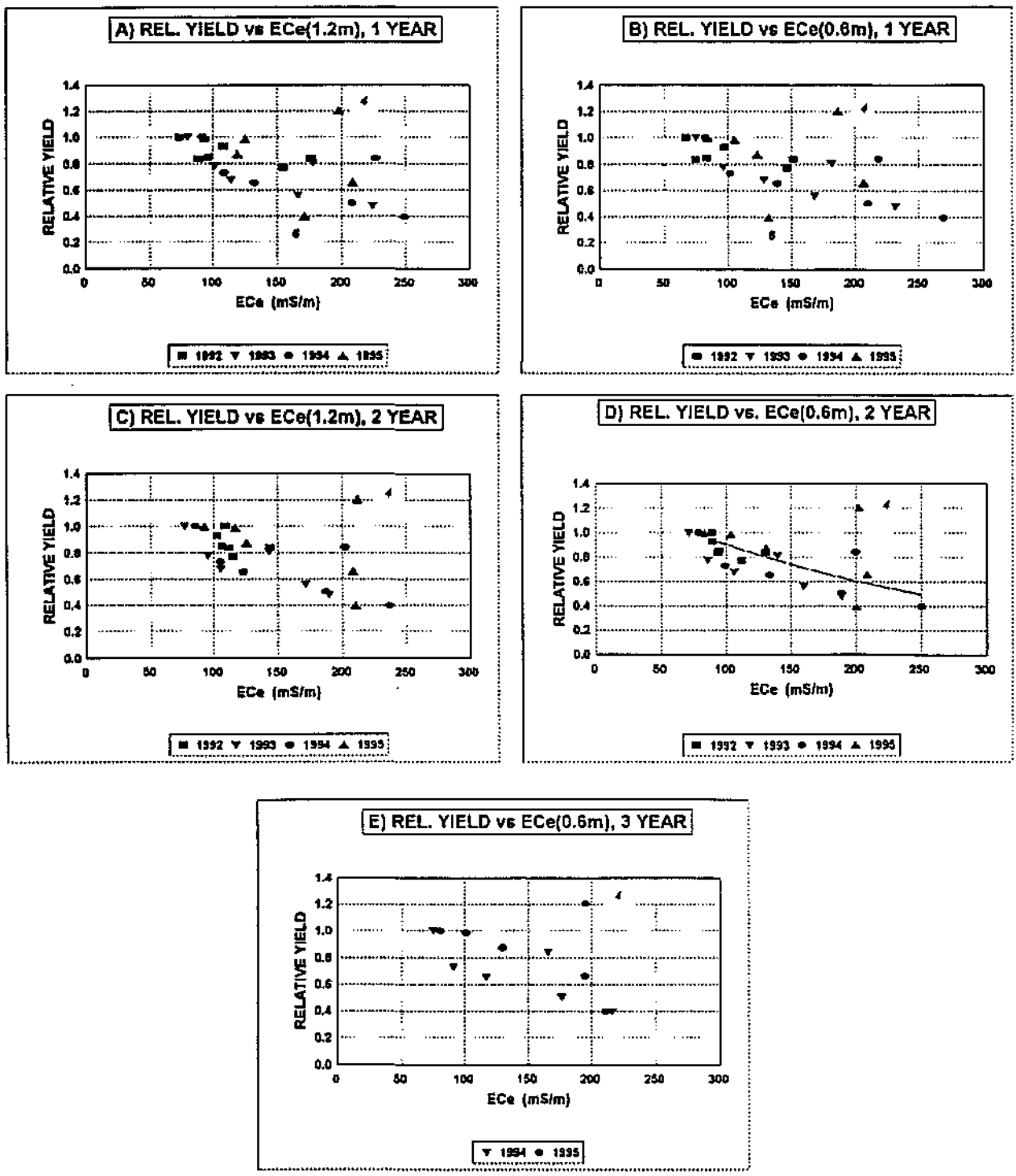

Figure 7.3 Relationship between normalised yield per year and time integrated soil salinity, ECe: a) one year integration, 0-1.2 m depth, b) one year integration, 0-0.6 m depth), c) two year integration, 0-1.2 m depth, d) two year integration, 0-0.6 m depth (with exponential model fitted), and e) three year integration, 0-0.6 m depth. *The labels 4 and 6 refer to the 1994/95 yield of treatments 4 and 6.*

The relationship between soil- and irrigation water salinity and normalised yield can be summarised as follows:

i) The linear model in general accounts for about 23 to 29% of the observed variance, while the exponential model can account for 31 to 41% of the variance, i.e. a slight improvement.

ii) When the yield of treatment 4 of 1994/95, with a normalised yield >1.2, is excluded from the regression analysis, R^2 increases to 62% and 65% for the 1.2 m and 0.6 m depths respectively.

iii) For both models, soil salinity of the 0-0.6 m depth is a better descriptor of yield response than the 0-1.2 m depth although the improvement in the coefficient of determination, R^2, is only marginal (2-3%).

iv) A two year time integration of soil salinity in general improves the response model, but a three year time integration weakens both the linear and the exponential model for both depths.

v) Soil salinity describes better the effect of salinity on the yield response of Colombar grapes than irrigation water salinity.

The exponential model and a two year time integration for soil salinity in the 0-0.6 m depth, is shown in Figure 7.3d. The full statistics and ANOVA for the linear and exponential yield response models for the two year time integration of soil salinity in the 0-0.6 m depth is given in Table 7.2

Table 7.2 Regression analysis and ANOVA of the linear and exponential models describing the yield response of Colombar grapevines to a two year time integration of soil salinity in the 0-0.6 m depth (yield of treatment 4, 1994/95 not included in data set)

A: Linear model: Y = a+bX

Regression analysis

Parameter	*Estimate*	*Standard error*	*t value*	*Probability level*
Intercept	1.165	0.0711	16.37	0.00000
Slope	-0.0030	0.0005	-6.02	0.00001

Analysis of Variance

Source	*Sum of Squares*	*Df*	*Mean Square*	*F-Ratio*	*Prob. Level*
Model	0.5272	1	0.5272	36.3	0.00001
Residual	0.3051	21	0.0145		
Total (Corr.)	0.8322	22			

Correlation Coefficient = -0.80 R^2 = 63.34 percent Stnd. Error of Est. = 0.121

B: Exponential model: Y = exp(a+bX)

Regression analysis

Parameter	*Estimate*	*Standard error*	*t value*	*Probability level*
Intercept	0.297	0.1031	2.88	0.00889
Slope	-0.0045	0.0007	-6.25	0.00000

Analysis of Variance

Source	*Sum of Squares*	*Df*	*Mean Square*	*F-Ratio*	*Prob. Level*
Model	1.1934	1	1.1934	39.07	0.00000
Residual	0.6424	21	0.0305		
Total (Corr.)	1.8348	22			

Correlation Coefficient = -0.81 R^2 = 65.04 percent Stnd. Error of Est. = 0.174

The effects of leaf chloride content on yield and the relationship between soil and water salinity on leaf chloride content are shown in Figures 7.4 and 7.5 with the regression statistics summarised in Table 7.3. The chloride content in the leaves at harvest generally seems to be a better descriptor of salinity effects on yield reduction than soil salinity (i.e. ECe) can account for between 52% and 65% of the observed variance, depending on whether a linear or exponential response function is used (Table 7.3). The corresponding values for soil salinity ranged from 23% to 65% (Table 7.1), but similar to soil salinity, no threshold for leaf chloride content is apparent (Fig. 7.4). The sodium content of the leaves at harvest accounts for 51% of the variance, i.e. more or less similar to the chloride effect (data not shown). Although the chloride- and sodium (not shown) content in the leaves correlate well with the chloride content of the irrigation water (R^2 = 62.4 and 65.9% for the linear and exponential models respectively, Table 7.3), the best predictor of chloride accumulation in the leaves is one- and two year time integrated soil salinity (ECe). Unlike irrigation water chloride content as parameter, time integrated soil salinity accounts for both the level of salinity as well as duration of saline conditions. This explains the improved R^2 when using soil, instead of irrigation water salinity.

According to our data, leaf chloride concentrations of 1.5 g/kg and 4 g/kg suggest yield losses of 10 and 20% respectively (Figure 7.4 and Table 7.3). Figure 7.5 (c) show these leaf chloride levels are equivalent to time integrated ECe's that range from about 90 mS/m to 140 mS/m and irrigation water chloride concentrations that vary between 40 mg/L and 150 mg/L. However, it must be stressed that in our study, the foliage was not wetted and leaf damage was primarily the result of chloride uptake by the roots. The asymptotic relationship between ECe (and/or chloride content of the irrigation water) and chloride uptake by the leaves, show that the rate of chloride accumulation in the leaves is accelerated at high levels of soil salinity. This suggests damage to cell membranes with a concomitant decreasing ability of the roots to exclude chloride (and sodium) from the transpiration stream.

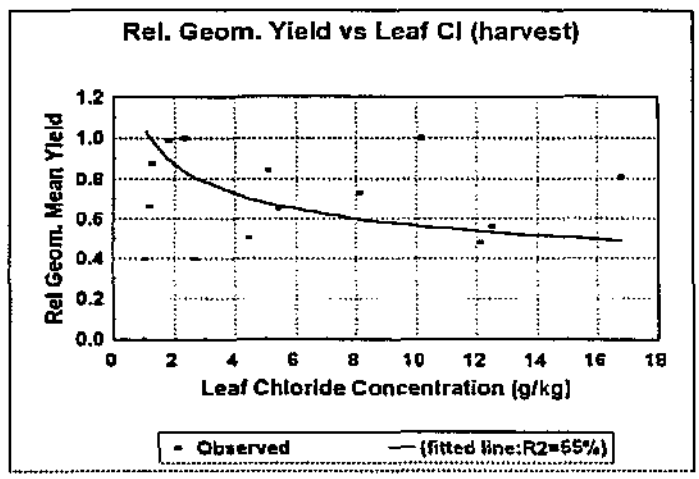

Figure 7.4 Relationship between normalised yield over years and chloride content in leaves at harvest [Rel. Yield = exp(-0.025-0.049*leaf Cl), R^2=55.0%)]

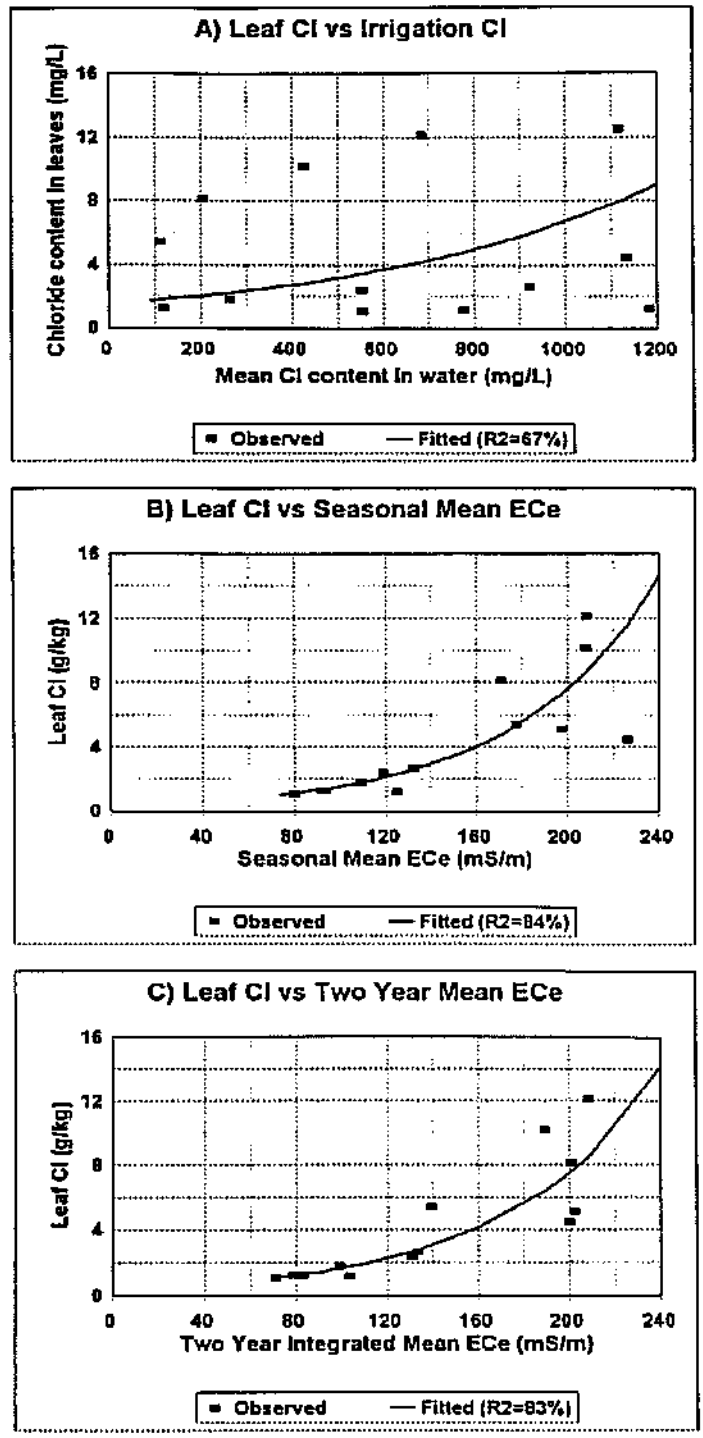

Figure 7.5 Relationship between chloride content in leaves at harvest and a) the volume weighted seasonal mean chloride content of the irrigation water, b) the depth weighted (0-0.6 m) seasonal mean ECe and c) two year time integrated, depth weighted (0-0.6 m) mean ECe

Table 7.3 Parameter estimates of the linear [$y = a + bx$] and exponential [$y = exp(a + bx)$] relationships between normalised, covariate adjusted yield and leaf chloride content, and between soil and irrigation water salinity and leaf chloride content.

Model	y	x	Time integration	a	b	R^2	F-Ratio ANOVA	Comment
Linear	rel. yield	leaf Cl.	NA	0.968	-0.034	51.6	13.8	All yield data
Exponential	rel. yield	leaf Cl	NA	-0.025	-0.049	55.0	15.9	All yield data (Fig. 7.4)
Exponential*	rel. yield	leaf Cl.	NA	0.297	-0.005	65.0	39.1	Yield > 1.2 not included
Linear	leaf Cl	irrig. Cl	NA	0.802	0.008	62.4	21.5	
Exponential	leaf Cl	irrig. Cl	NA	0.401	0.002	65.9	25.1	(Fig. 7.5a)
Exponential	leaf Cl	ECe(0-0.6)	1 year	-1.175	0.016	83.4	65.4	(Fig. 7.5b)
Exponential	leaf Cl	ECe(0-0.6)	2 year	-0.988	0.015	81.6	57.8	(Fig. 7.5c)

* rejected normalised yield >1.2 (i.e. yield of treatment 4 of 1994/95)

7.4 Evaluation of irrigation water quality criteria of the Breede River

The water quality guidelines for the Breede River Irrigation Scheme and operational curve used to manipulate the salt content of the river (Fig. 3.1), show that 50% of the water diverted into the Zanddrift canal should have an electrical conductivity of less than 70 mS/m. Thirty percent of the water may have salt contents ranging from ECi 70 to 120 mS/m but should never exceed 120 mS/m. Between 1 June 1992 and 27 July 1995 the Department of Soil and Agricultural Water Science (University of Stellenbosch), in conjunction with the Zanddrift Irrigation Board, has been monitoring the salt content and ionic composition of the water in the canal on a continuous basis (Figure 7.6). The total salt content was below the target of 70 mS/m most of the time. However, 70 mS/m is equivalent to approximately 120 mg/L chloride, which, in view of our results can lead to a 2 g/kg chloride content in the leaves (Fig. 7.5a). Even if wetting of foliage is avoided, this leaf chloride concentration can cause a yield decrease of about 10-15%. Wetting of foliage will exacerbate the salinity damage with a concomitant decrease in yield.

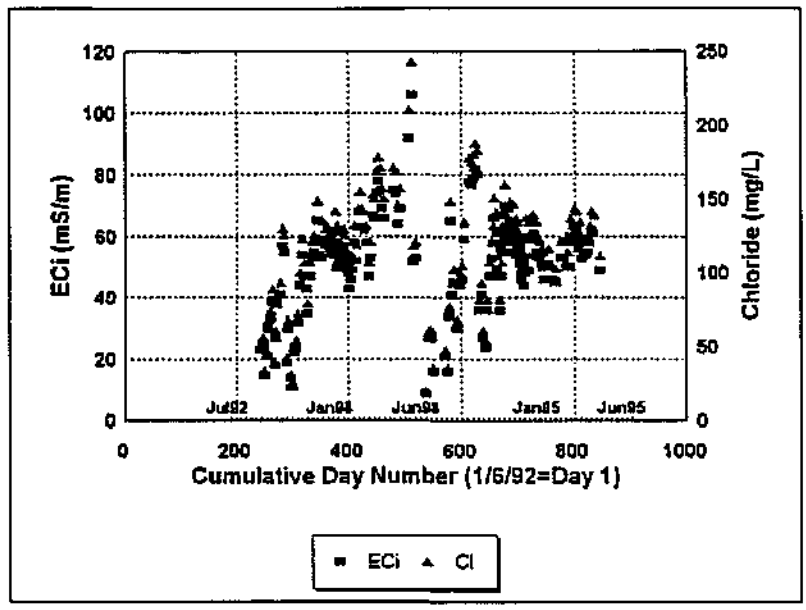

Figure 7.6 Time series of the electrical conductivity (ECi) in mS/m and equivalent chloride content of the Zanddrift canal between 1 June 1992 and 27 June 1995 [Cl, (mg/L)=2.30ECi (mS/m)-0.42, R^2=0.997, n=504)]

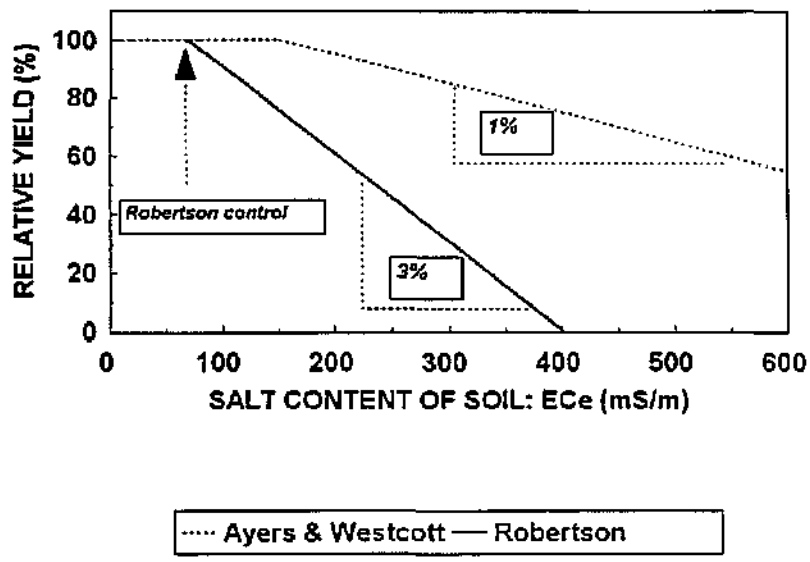

Figure 7.7 Simplified graphical comparison of the salt tolerance curve for grapevine of Ayers & Westcott (1985) and the Robertson experimental data for Colombar winegrapes.

7.5 Conclusion

Our data show no threshold salinity ECe value and yield decreased progressively above ECe = 75 mS/m. According to both the linear and exponential models, the rate of yield

decrease is 3% per 10 mS/m which is three times more than the rate of decrease reported by Ayers and Westcott (1985). The comparison in a more simplified form is shown in Figure 7.7. It is important to note that the minimum time integrated soil salinity of 75 mS/m was attained by irrigating with the Robertson canal water. The volume weighted ECi of the canal water for the four respective years (without adjustment for rainfall during the growing season) were 29, 26, 34 and 32 mS/m (Table 4.4). This result has important practical implications, because as was calculated in Chapter 4, the leaching fraction of treatment 1 ranged between 0.11 and 0.15 (Table 4.14). This means that if a soil salinity less than 75 mS/m is aimed for (to avoid any yield loss), and if the existing salinity levels of the Robertson canal remain the same, leaching must be increased. This in turn will increase the irrigation return flow with the concomitant elevated levels of salinity in the Breede River. Any increase in the existing salt content of the Robertson canal will also lead to increased soil salinity which in turn will reduce yields at a rate of 3% per 10 mS/m increase in ECi. The target ECi of 70 mS/m used by the Department of Water Affairs and Forestry to control water releases from the Brandvlei Dam is equivalent to treatment 2 of our study with a volume weighted seasonal mean ECi that ranged from 58 mS/m (1994/95 season) to 78 mS/m (1991/92 season) (see Table 4.4). Irrigation with this water was associated with yield losses that ranged from 10 to 30% during the course of this study (Figure 6.1). However, it must be remembered that we irrigated with water enriched with NaCl and $CaCl_2$, Consequently the yield losses and salinity damage will be a combined result of osmotic and specific ion effects. It is therefore possible that irrigation with water with a similar total salt content (i.e. 65 mS/m) but with a lower chloride content (e.g. more sulphate) will be less damaging to the crop.

Chloride content in the leaves is a good index of salinity damage and in this study, concentrations at harvest of 1.5 to 4 g/kg were associated with yield reductions of 10 to 20% respectively. Our results show that a chloride level of 1.5 g/kg in the leaves were reached by irrigating with water with a chloride concentration as low as 40 mg/L (Figure 7.5a, Table 7.3). Consequently, our conclusion is that the existing ECi target of 70 mS/m set by the Department of Water Affairs and Forestry for managing salinity in the lower reaches of the Breede River Irrigation Scheme is not too conservative. In fact, for optimum grape yields, the target of 70 mS/m and 140 mg/L chloride[5] might be too liberal.

[5] Document GB/A/88/2: "Hersiene kriteria vir besproeiingswater in die Breërivier", (*Revised criteria for irrigation water quality in the Breede River*, Soil and Irrigation Research Institute), 1988.

CHAPTER 8
EFFECTS OF SUPPLEMENTAL IRRIGATION WITH SALINE WATER ON THE PERFORMANCE OF WEISSER RIESLING GRAPES

8.1 Introduction

One of the objectives of this study was to investigate the effect of climate on the salt tolerance of the grapevine. In order to achieve this the salinity treatments applied at Robertson was used also at Stellenbosch. The way in which the research was conducted, and the variables that were monitored, and the methodology used at Stellenbosch were the same as at Robertson. The main difference between the two studies was that viticulture in the Stellenbosch region is practised using supplemental irrigation in contrast to Robertson where viticulture relies entirely upon irrigation.

The Weisser-Riesling vineyard at Stellenbosch was established during the spring of 1989, specifically for this study. Initially it was planned to install the drainage system in the winter of 1990 and to start with the salinity treatments in December 1991. However, because of a very wet winter in 1990 accessibility to the vineyard was difficult and installation of the drainage system could not start before the summer of 1990/91. The extent of soil disturbance not only had a severe effect on the growth of the vines but it also increased the spatial variability. By December 1991, the vines were still too small (many of them still so small that most of the foliage were below the outlets of the micro-sprinklers). The risk of losing many of the vines because of severe leaf burn and salinity stress was considered to be too great. Consequently it was decided to postpone the onset of the treatments until the 1992/93 season. By September 1992 plant size was still highly variable. After consulting with viticulturists it was decided not to irrigate with saline water but rather to take corrective steps to reduce the variability in plant size. This was done by selectively removing the fruit (bunches) of the 1992/93 season from the vines according to their size. The vegetative growth of the smaller plants were stimulated more by removing all their bunches. This had the desired homogenising effect and the salinity treatments were started the following season (1993/94).

8.2 Soil water and salinity regimes: 1993-1995

8.2.1 Irrigation water salinity

The irrigation water serving the experimental farm at Stellenbosch is winter runoff that is stored in several dams on the farm. The vineyard was irrigated three times during the 1993/94 season of which only the last irrigation was with saline water. This particular irrigation was applied on 02/02/94, about three weeks before the grapes were harvested. The salinity levels were similar to the 1992/93 treatments used at Robertson and were as follows: treatment 1, dam water (ECi ~ 35 mS/m), treatment 2, 75 mS/m; treatment 3, 150 mS/m; treatment 4, 250 mS/m; treatment 5, 350 mS/m and treatment 6, 500 mS/m. The irrigation started with a 30 minute application during which time the salt injection system was calibrated. The saline water was applied for a period of five hours (32 mm) followed by a 30 minute irrigation with fresh water. This was necessary to wash off the saline water from the leaves. Due to wind and canopy structure, leaf contact with the saline water cannot be avoided. During the course of the irrigation, the ECi values tended to drift and continuously had to be adjusted. In 1994/95, the vineyard was irrigated three times with saline water. Prior to harvest the vineyard received water on

13/12/94 and 30/01/95. The post-harvest irrigation of 21/02/95 was also done with saline water. The volume-weighted seasonal mean ECi values for the 1994/95 season and the ECi of the one irrigation when saline water was used in 1993/94, are listed in Table 8.1.

Table 8.1 Volume weighted seasonal salt contents, given in terms of the electrical conductivity of the irrigation water applied during 1993/94 and 1994/95 to the experimental vineyard at Stellenbosch

Treatment and target ECi	ECi 1993/94* (mS/m)	ECi 1994/95 (mS/m)	Salt load 1994/95 (kg/m^2)
1 (control)	46	45	0.031
2 (75)	46	93	0.064
3 (150)	85	141	0.097
4 (250)	171	204	0.141
5 (350)	273	333	0.230
6 (500)	452	492	0.341

* 1993/94 data refer to one irrigation only, i.e. not volume weighted

8.2.2 Soil water content

Soil water content was measured with a neutron probe to a depth of about 1 m. As described in Chapter 3, each of the 24 experimental plots is equipped with a neutron access tube situated within the vineyard row in the wetted zone of the microsprinklers. Water content was monitored weekly throughout the irrigation season, starting early in September. Water content was also measured during winter on an *ad hoc* time basis. During summer water content was measured immediately before and immediately after the individual irrigation events and expressed as mm/1.05 m. The time course of total soil water content in the root zone for the 1993/94 and 1994/95 seasons are presented in Figure 8.1.

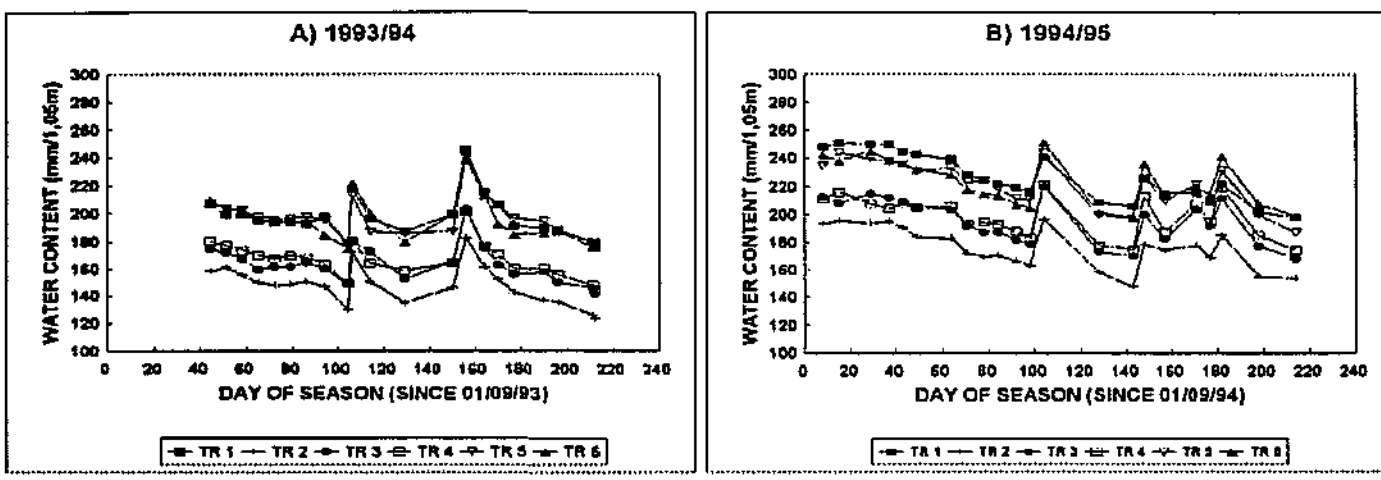

Figure 8.1 Time course of soil water content of the Stellenbosch experimental vineyard, expressed as mean per treatment: a) 1993/94 and b) 1994/95

The results are expressed as means per treatment. For both seasons the change in water content from before, to immediately after the irrigation events, are clearly visible. The time variation in total water content ranged from a minimum of

140 mm/1.05 m to a maximum of 240 mm/1.05 m. No particular trend between the different salinity treatments was observed other than treatment 2 which always was the driest of the six treatments.

The seasonal mean and associated standard error of the water content for 1994/95 is shown in Figure 8.2. There seems to be a slight increase in the water content from treatment 2 to 6, i.e. as salinity increases. However, this increase is not statistically significant and we do not believe that this is a true treatment effect.

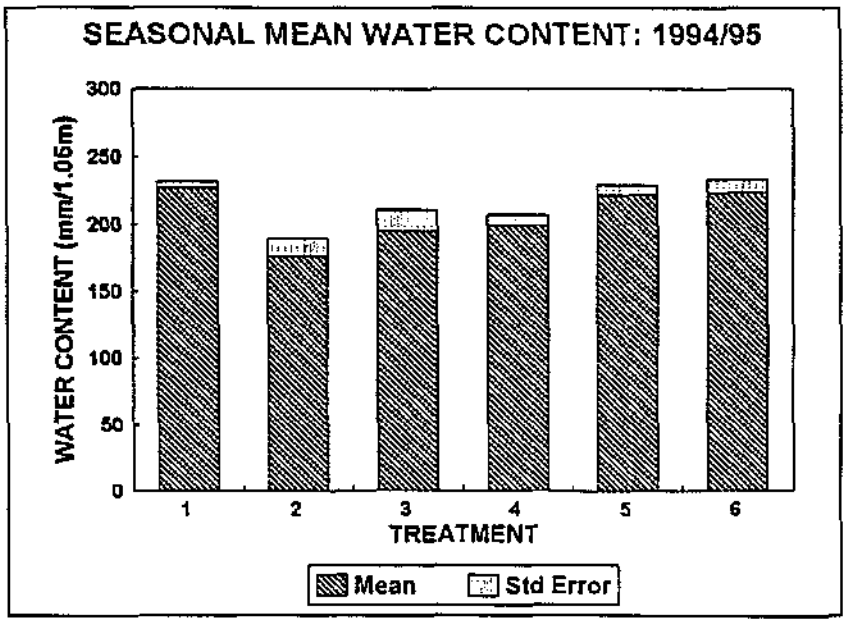

Figure 8.2 Seasonal means and associated standard error of the total soil water content per treatment for the 1994/95 season at Stellenbosch

8.2.3 Soil salinity

Soil samples were taken with a soil auger at the beginning (September) and end (March) of the growing season. One site on each of the 24 experimental plots was sampled using five depth increments: 0-0.15 m, 0.15-0.30 m, 0.30-0.6 m, 0.6-0.9 m and 0.9-1.2 m. The sampling and analytical procedures were the same as at Robertson (see section 4.2.1.3) In both seasons the limited amount of saline water applied to the vineyard had a substantial effect on the salt content of the soil and is shown in Figure 8.3 for treatments 1, 4 and 6. This is especially true for the 0.15 and 0.30 m depths. Also shown in Figure 8.3 are the ECe values of the last winter sampling before the start of the salinity treatments, i.e. September 1992. In September 1992 ECe in all cases and at all depths were less than 40 mS/m. The one irrigation of 1993/94 with saline water shortly before harvest, yielded ECe's at the 0.15 m depth that, in March 1994, ranged from 70 mS/m (treatment 1) to 165 mS/m (treatment 6). The three saline water irrigations of 1994/95 had a more dramatic effect and in March 1995 ECe at the 0.15 m and 0.30 m depths ranged from 40 mS/m to 560 mS/m. The increase in the ECe of the control treatment from September to March is a natural cyclic phenomenon that happens every year from the end of winter to the end of summer, even when low salinity water is used for irrigation. When the data of March 1995 are plotted on the same axis, the differences in soil salinity between the six treatments become more evident (Figure 8.4).

An intriguing result is the increase in the ECe of the topsoil (0-0.3 m) at Stelenbosch compared to Robertson (Fig. 8.5). Considerably less saline water, and therefore a smaller salt load, was used in 1994/95 at Stellenbosch compared to, for example, the 1992/93 season at Robertson, the respective loads being 0.34 kg/m^2 (Stellenbosch) and 1.47 kg/m^2 (Robertson). *The loads are expressed in terms of the area per plant and not wetted area.* Yet the ECe of the 0.15 m depth at Stellenbosch was substantially more saline (550 mS/m vs. 350 mS/m)! At the 0.30 m depth the ECe of Stellenbosch was comparable to that of Robertson. It is only deeper than 0.6 m that the soil at Robertson is more saline than at Stellenbosch, which can be explained in terms of the greater flux of water at Robertson (926 mm, Table 4.6), compared to Stellenbosch (113 mm). The slope of the ECe-TDS relationship at Robertson is 5.68 (R^2=0.98, n=120) and 4.80 for Stellenbosch (R^2=0.94, n=120). This indicates that for the same ECe the actual salt content at Robertson will be higher than at Stellenbosch. Put in a different way, the soil solution at Stellenbosch contains substances that have different transference numbers (Barrow, 1966, p677) compared to the Robertson soil solution. The transference number gives the fraction of the total current carried by each ion, i.e. the fraction of the total conductance that each ion contributes. For example, at infinite dilution the transference number of hydrogen (H^+) is 6.98 times larger than that of sodium (Na^+) and 4.26 times larger than that of chloride (Cl^-). Therefore, if the soil at Stellenbosch is more acidic and have a greater concentration of hydrogen in solution, a similar ECe value at Robertson will not necessarily indicate the same level of salinity. The pH of the soil solution at Stellenbosch is slightly lower than at Robertson, but the difference is not sufficient to explain the large difference in the ECe response of the soil at Stellenbosch. A more detailed investigation is required to better explain this observation. This was not possible within the time frame of this project.

8.3 Salinity effects on yield, pruning mass and must composition

8.3.1 Yield

The yield of the experimental plants was determined individually by weighing. The treatment mean and the ANOVA of yield of the Weisser-Riesling grapes for the 1993/94 and 1994/95 seasons are given in Table 8.2. Differences between treatments are minor and no statistically significant salinity effect is present. The yields of treatment 2 and 3 are statistically different at P=5%, but we do not believe that this is related to salinity. The yield of the Weisser-Riesling cultivar at Stellenbosch is considerably less than the yield of Colombar at Robertson. Because of different soil and climatic conditions yield in the Stellenbosch area is normally less than in the Breede River Valley. This particular result is also related to the younger age of the plants and a different trellising system. Also shown in Table 8.2 are the relative yields normalised with respect to the control treatment.

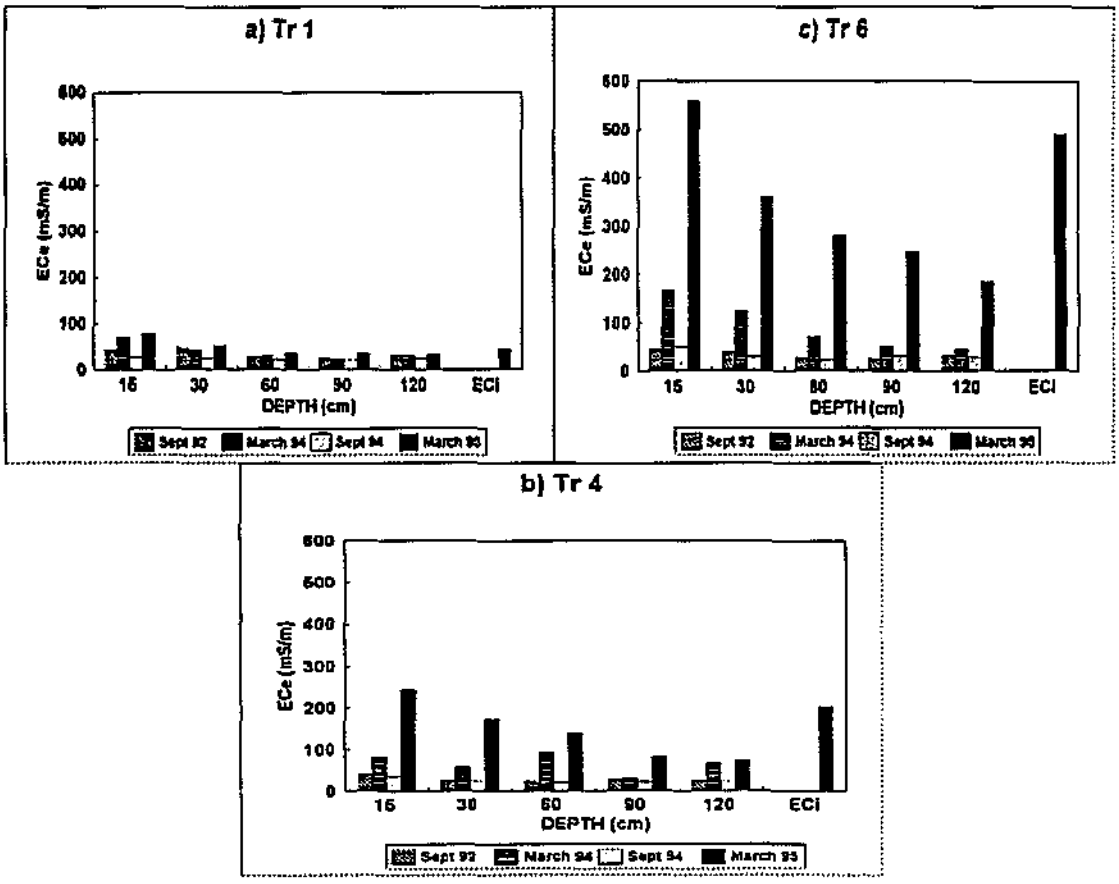

Figure 8.3 Time course of treatment mean salt content of treaments 1 (35mS/m), 4 (250 mS/m) and 6 (500 mS/m) expressed in terms of the ECe, from September 1992 to March 1995

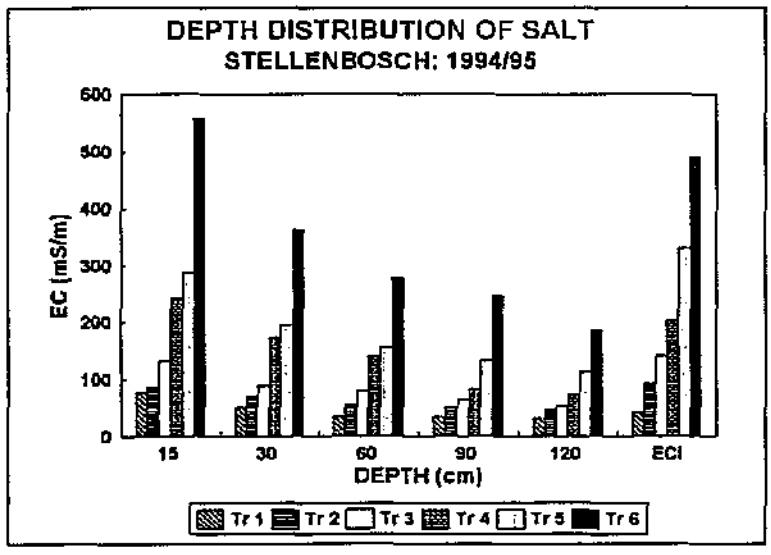

Figure 8.4 Salt distribution with depth in the vineyard at Stellenbosch at the end of the 1994/95 season

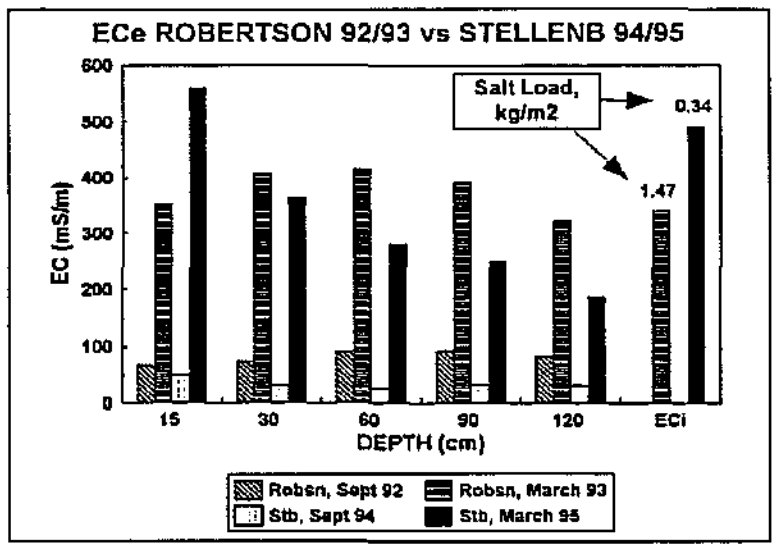

Figure 8.5 Comparison of ECe per depth after one season of irrigation with saline water at Robertson (1992/93) and Stellenbosch (1994/95), as a function of seasonal mean ECi and salt load of the irrigation water.

Table 8.2 Treatment mean yields and of Weisser-Riesling grapes for the 1993/94 and 1994/95 seasons

Year	Salinity treatment (mS/m)						
	0	75	150	250	350	500	P
Treatment means, fresh mass (kg/vine)							
1994	2.53a*	2.93a	2.70a	2.44a	2.38a	2.57a	0.420 NS
Rel. Yld	1.00	1.16	1.07	0.96	0.94	1.01	
1995	2.13ab	2.69b	1.90a	2.09ab	2.18ab	2.20ab	0.260 NS
Rel. Yld	1.00	1.26	0.89	0.98	1.02	1.03	

* Means separation within rows by LSD Multiple Range Test at the 5% level
NS Not significant
P Probability level

8.3.2 Pruned shoot mass

The experimental vines were pruned in July 1994 and August 1995 and the pruning mass per vine determined individually by weighing. The pruning mass of 1995 is about 0.20 to 0.25 kg/vine more than was the case in 1994 and can be explained by normal vine growth and larger plants in 1995 (Figure 8.6). Differences between treatments are small and no salinity effect is evident.

8.3.3 Composition of must

At harvest the berries of a composite sample of each plot, consisting of one bunch per experimental vine, were crushed and the must analysed. In 1993/94 the analysis was restricted to a determination of chloride, sugar and acid content. In 1994/95 the must was also analysed for Ca, Mg, Na and K. The sugar content of the must at harvest was determined by refractomotory, the chloride content by potentiometric titration with $AgNO_3$ (*Metrohm 702 SM Titrino*) and the Ca, Mg, Na and K content by atomic

absorption spectrophotometry (*Varian AA 250+)*. The treatment mean sugar content of the 1993/94 yield varied between 19.7° and 20° Balling and in 1994/95 between 21.7° and 24.3° Balling with no salinity treatment effect visible (Fig. 8.7).

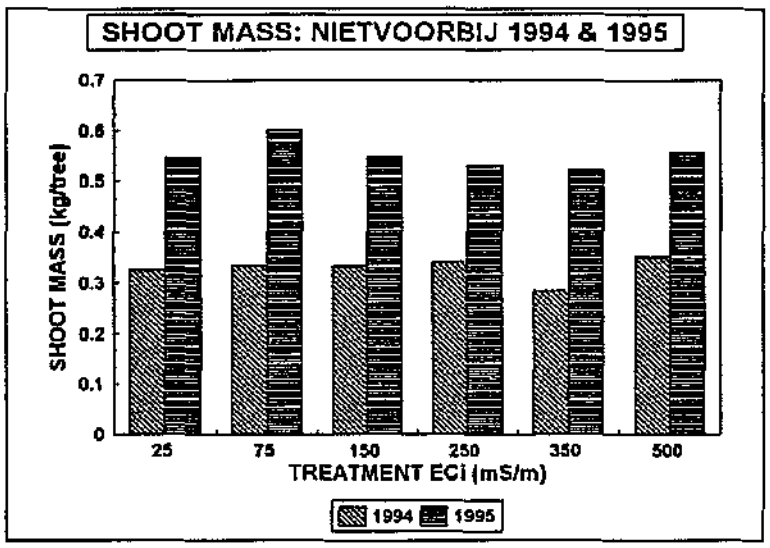

Figure 8.6 Salinity effect on the treatment mean pruning mass of Weisser-Riesling grapes at Stellenbosch for the 1993/94 and 1994/95 seasons.

The chloride content in the must of 1994/95 for all treatments was below the 10 mg/L detection limit of the Metrohm Titrino endpoint titrator. The 1993/94 treatment means data suggest that the one irrigation with saline water did increase the chloride content of the must (Fig. 8.8a), but the differences are not statistically significant. The sodium content in the must of 1993/94 and 1994/95 was also not effected by the little irrigation with saline water applied before harvest (Fig. 8.8b). Similar to chloride, the sodium content of 1994/95 is lower than that of the previous year. The calcium, magnesium and potassium content of the must of 1994/95 was higher than the sodium content but no treatment salinity effect was found (data not shown).

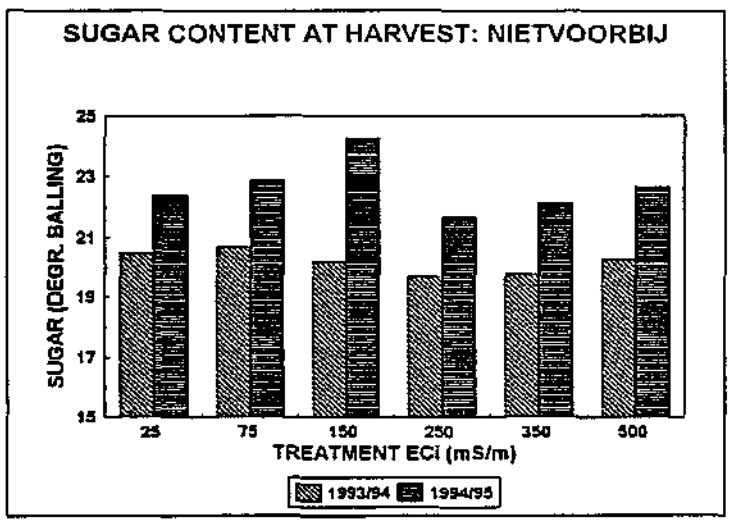

Figure 8.7 Salinity effect on the sugar content of must of Weisser-Riesling grapes for the 1993/94 and 1994/95 seasons.

8.3.4 Plant water relations

Leaf water potential (LWP) was measured before 6 am (pre-dawn) on five occasions during the 1993/94 and 1994/95 seasons. In February 1994 the dates were chosen relative to the timing of the one irrigation with saline water, i.e. one day prior to the irrigation (01/02/94) and one- (09/02/94), two- (17/02/94) and three weeks (21/02/94) after the saline water was applied. Unfortunately, because of heavy dew on the morning of 01/02/94 (i.e. immediately before the irrigation) the leaves were all wet and the LWP of all plants were within 10 kPa of each other with a global mean of approximately -100 kPa. The data of this measurement are therefore rather meaningless because it is not a true reflection of soil water conditions. The difference in the water potential of treatment 1 (-285 kPa) and 6 (-380 kPa) one-week after the irrigation were statistically significant (Table 8.3). Twelve days later, on 21/02/94, LWP of all treatments had decreased to values ranging from about -460 kPa to -640 kPa. However, the apparent salinity effect between treatments had disappeared. No tensiometer data are available, but it is speculated that the influence of soil matric potential on the plant water status was greater than the osmotic effect. Leaf water potential of the six salinity treatments early in the 1994/95 season (02/11/94) were not statistically different (Table 8.3). The measurements were taken before the first irrigation with saline water at a time when soil salinity of all treatments was low.

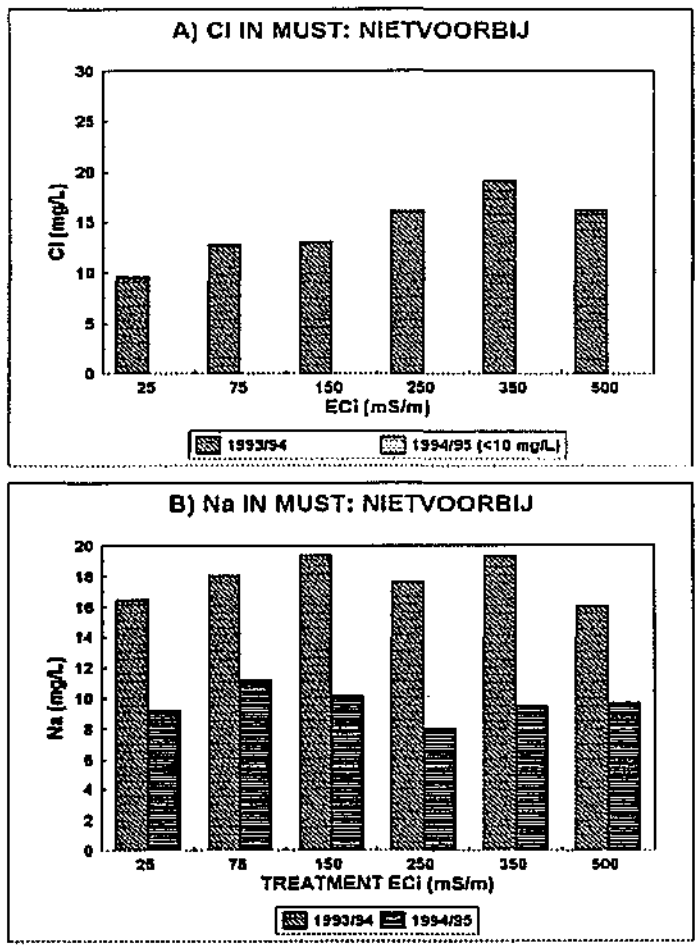

Figure 8.8 Salinity effects on a) the chloride and b) sodium content of the must of Weisser-Riesling grapes in 1993/94 and 1994/95 (*the chloride content of 1994/95 was below the detection limits of the Metrohm end-point titrator*).

The second measurement of LWP (13/01/95), taken about one month after the first irrigation with saline water, ws also not statistically different between the six salinity treatments. Pre-dawn leaf water potential one day after harvest (09/02/95) however was strongly influenced by salinity with LWP decreasing consistently with increasing salinity (Table 8.3).

Table 8.3 Statistical significance of the salinity effect on the treatment mean pre-dawn leaf water potential of Weisser-Riesling grapes in 1993/94 and 1994/95

Year	Salinity treatment (mS/m)						
	0	75	150	250	350	500	P
Treatment means (kPa)							
09/02/94	-279a*	-333abc	-325abc	-303ab	-348bc	-386c	0.037
21/02/94	-465a	-529a	-473a	-640a	-490a	-570a	0.361 NS
02/11/94	-508a	-518a	-463a	-548a	-515a	-757a	0.331 NS
13/01/95	-430a	-348a	-333a	-392a	-355a	-365a	0.282 NS
09/02/95	-253a	-299b	-318bc	-340cd	-360d	-373d	0.0001

* Means separation within rows by LSD Multiple Range Test at the 5% level
NS Not significant
P Probability level

8.4 Summary and conclusions

Although yield and must composition of Weisser-Riesling grapes were not influenced by the limited amount of saline water applied in 1993/94 and 1994/95, soil salinity at the higher levels of saline irrigation water (e.g. treatments 4 to 6), was significantly increased. It will be interesting to see what the residual effects of the salinity exposure of 1994/95 will have on the future growth and yield of the grapes. In contrast to the Robertson experiment where salinity had little effect on leaf water potential, the leaf water potential measurements at Stellenbosch towards the end of the 1994/95 season showed a very strong treatment effect with leaf water potential decreasing with increasing salinity. A possible explanation is the higher relative humidity of the atmosphere which at Stellenbosch might result in less stomatal control over transpiration. However this aspect was not investigated any further. In this particular vineyard and climate leaf water potential might be an early indicator of salinity stress.

The research at Stellenbosch could only start towards the end of the second last year of this five-year research project. At Robertson production of wine grapes is fully dependent on irrigation and it was found that salinity effects are cumulative with time. Some negative effects only manifested itself after two to three years of salinity exposure. At Stellenbosch supplemental irrigation is used to produce wine grapes, which means that less salt is added to the soil. It is reasonable to assume that salinity effects on grapevine performance at Stellenbosch not only will be different to those observed at Robertson, but also that the negative effects will take longer to become measurable and visible.

CHAPTER 9
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

9.1 Introduction

The main objective of this research project was to investigate the effects of salinity on grapevines and to evaluate the salinity criteria used to manage salinity levels in the Breede River. Six salinity treatments, ranging in electrical conductivities of the irrigation water (ECi) from *ca.* 25 mS/m to 500 mS/m, replicated four times were used to investigate the long term effects of salinity on *Vitis vinifera* L.

The research was conducted at Robertson (33° 46'S, 19° 46'E) under conditions of intensive irrigation, (i.e. weekly irrigations) and Stellenbosch (33° 58'S, 18° 50'E) where supplemental irrigation was used (i.e. two to three irrigations per season). The vineyard at Robertson is planted with Colombard grafted on 99 Richter rootstock and was established in 1974. The vineyard at Stellenbosch was established in 1989 and is planted with Weisser Riesling, also on 99 Richter rootstock. In both vineyards the soil water and soil salinity regimes of all 24 experimental plots was monitored continuously using a neutron probe and suction cup samplers. Vegetative and reproductive growth and the ionic composition of different plant organs and must were monitored either throughout the season or at selected phenological growth stages. *Ad hoc* measurements of plant water relations were made. At the end of each season, yield of all 240 experimental plants was determined individually. The effect of salinity on wine quality was evaluated using Colombard grapes (Robertson) from the 1992/93, 1993/94 and 1994/95 seasons.

The following target salinities of the irrigation water (ECi) were used at Robertson and Stellenbosch:

treatment 1 (control):	ECi 25-50 mS/m
treatment 2:	ECi=75 mS/m
treatment 3:	ECi=150 mS/m
treatment 4:	ECi=250 mS/m
treatment 5:	ECi=350 mS/m
treatment 6:	ECi=500 mS/m

The first irrigation with saline water at Robertson was applied in December 1991 and at Stellenbosch in February 1994. Based on the results of four seasons of intensive irrigation with saline water at Robertson and two seasons of supplemental irrigation with saline water at Stellenbosch, our conclusions can be summarised as follows:

9.2 Conclusions

i) Despite different irrigation scheduling techniques that were used between the different years, the soil water regime in the Robertson vineyard during the course of this four-year study was very similar. The maximum inter-annual difference in the seasonal mean soil water content for any treatment was 29 mm/1.05 m.

ii) Contrary to expectation, seasonal mean soil water did not increase in any consistent or significant way as soil- or irrigation water salinity increased. This is probably due to the relatively high frequency of irrigation (once per week), good

internal drainage properties of the soil and the way in which soil water balances were calculated. However, after extended periods of drying when no irrigation was applied (such as prior to harvest) water content did increase with increasing soil salinity and is indicative of reduced water uptake at the higher levels of salinity. This conclusion is confirmed by the soil water content measured outside the directly wetted zone (of the microsprinkler irrigation system) of treatments 1, 4 and 6 which increased as salinity increased.

iv) Irrigation with the saline water led to a significant salt accumulation in the root zone during the irrigation season, reaching maximum levels just before harvest in March, but the salt accumulation was not proportional to the salt load of the salinity treatments. This is explained in terms of accentuated leaching due to reduced soil water uptake at the higher levels of salinity.

v) At Robertson it requires about 275-300 mm of water during winter to reduce ECsw of the topsoil (0-0.3 m) from 300 mS/m to 100 mS/m. To reach the same target ECsw of 100 mS/m at the 0.9 m depth and for the same antecedent condition, about 700 mm of rain and irrigation is necessary.

vi) The Sodium Adsorption Ratio (SAR) of the soil solution of the Robertson vineyard fluctuated significantly from summer to winter. Over the longer term there was a gradual increase in SAR with time and depth. By April 1995 the SAR of all treatment and at all depths, including the control treatment, had increased to levels higher than the antecedent conditions of October 1991.

vii) The salt- and water balance, and all other inferences made from them, are strongly influenced by the choice of sampling sites and assumptions concerning the size of, and redistribution of water and salt within the wetted area. Leaching fractions derived from the salt balance were disappointing. A study of spatial variability within the zone of influence of one microsprinkler showed that one sampling point per microsprinkler (or plant) is insufficient to obtain a water and salt balance from which evapotranspiration and leaching can be inferred. The leaching fractions calculated from the ratio of ECi/ECsw ranged from ca. 0.14 for the control to 0.70 for treatment 6 with a general increase as salinity increased. These leaching fractions suggest substantial deep percolation losses, as much as 70% at the higher levels of irrigation water salinity, compared to irrigation management strategies that are based non-saline, non-stressed conditions for plant water uptake .

viii) As the duration of salinity conditions increases the first noticeable negative effect of salinity on expansive growth of shoots and leaves occurs earlier. At Robertson this was on day 35 of the 1992/93 season and day 20 of the 1993/94 season. Our data suggest that early in the spring, expansive growth is sensitive even to low soil salinity (as low as 100 mS/m) and that saline growth conditions in one season have a large influence on the growth during the following season.

ix) Leaf specific fresh weights were not sensitive to salinity or age while the internode fresh weights were smaller in the saline treatment. The specific dry weight of leaves increased with age more in the low than in the high salt treatment from which we infer that salinity has a larger effect on the mass than on the length of the internodes. Alternatively, it indicates an increase in metabolite deposition in the

leaves and decreased metabolite transport to the internodes - a change that can be the result of salinity interference on the metabolite export from the leaves. The reduction in metabolite transport to the shoot under saline conditions, may also imply a reduced build-up of metabolite storage in the perennial plant organs.

x) Leaf water potential (LWP) and stomatal conductance measurements in 1992/93 show that differences in LWP between salinity treatments are best shown before the time of day when the stomata start to control transpiration. The 1992/93 data also show that stomatal closure occur earlier in the day in the saline treatments. This means salinity treatment effects on LWP will most likely only be detected with pre-dawn measurements.

xi) The minimum recorded LWP at Robertson was about -1100 kPa, which is much higher than the minimum potentials reported from other irrigation studies. In spite of the relatively high leaf water potentials damage to growth and yield was significant. We speculate that salinity damage to grapevine leaves may be the result of accumulation of salts in the apoplast which means that the pressure chamber technique does not measure the total leaf water potential and perhaps also not the hydrostatic component of the xylem water potential of vines. Rather, it measures the difference between the vacuole water potential and the apoplast osmotic potential.

xii) At Robertson the first full effect of the salinity treatments on the yield and berry growth became visible in the third season. Even during the first two seasons, the saline irrigation water, through the process of berry growth, ripening and must composition had a significant effect on yield.

xiii) An organoleptic evaluation of the wine did not reveal any salinity effect on wine quality, aroma or taste. In view of the substantial differences in, for example the Na and Cl content of the wine, this was a rather surprising result. However, there are so many factors in wine processing that determine wine quality, that a statistical quantification of the effect of salinity on wine quality, seems very remote. At best, the effect of salinity on wine quality will have to be based on chemical analysis of the must.

xiv) Salinity had a severe effect on yield with a yield decrease of 60% at the irrigation water salinity ECi level of 500 mS/m. Yield was negatively influenced even at the intermediate irrigation water salinity levels of 75 and 150 mS/m. However, a better understanding of the effect of salinity on the yield and reproductive growth of Colombar grapes is complicated by the fact that during the first four years of this study an irrigation water salinity of 250 mS/m seemingly had little effect on yield. Quantifying the effect of salinity on yield was further hampered by the progressive decrease in the yield on the control treatment. It seems that plant vigour and size are key determinants that influence the response of Colombar grapes to salinity. Despite these two complicating factors, the results of this experiment indicate that grapevines are more sensitive to salinity than previously thought, and that the threshold soil salinity (ECe) value of 150 mS/m as reported by Ayers and Westcott (1985) is too high. Our results are more in line with the limiting value of 100 mS/m reported by Prior *et al.* (1992).

xv) Our data show no threshold salinity ECe value and yield decreased progressively for ECe > 75 mS/m, at a rate of about 3% per 10 mS/m. This is three times more than the rate of decrease reported by Ayers and Westcott (1985) and previously by Maas & Hoffman (1977). In our study the minimum time integrated soil salinity of 75 mS/m was attained by irrigating with the Robertson canal water with a electrical conductivity of 25-35 mS/m. If a lower soil salinity is to be achieved to avoid any yield loss, and if the existing salinity levels of the Robertson canal remain the same, leaching must be increased. This in turn will increase the irrigation return flow with the concomitant elevated levels of salinity in the Breede River. Any increase in the salinity of the Robertson canal will also lead to increased soil salinity values, which in turn will reduce yields. The target ECi of 70 mS/m used by the Department of Water Affairs and Forestry to control water releases from the Brandvlei Dam is equivalent to treatment 2, which in our study, resulted in a volume weighted seasonal mean ECi that ranged from 58 mS/m (1994/95 season) to 78 mS/m (1991/92 season). Irrigation with this water was associated with yield losses that ranged from 10 to 30% during the course of this study. However, in this study irrigation water enriched with NaCl and $CaCl_2$ was used. Consequently the yield losses and salinity damage observed with Colombar at Robertson will be a combined result of osmotic and specific ion effects.

xvi) Chloride content in the leaves is a good index of salinity damage and we found that concentrations at harvest of 1.5 to 4 g/kg were associated with yield reductions of 10 to 20% respectively.

xvii) Sodium and chloride levels at which leaf damage started were about 1.7 g/kg (0.17%) and 6 g/kg (0.6%) respectively.

xviii) Also, chloride levels of *ca.* 1.5 g/kg in the leaves were reached by irrigating with water with a chloride concentration as low as 40 mg/L. Consequently, our conclusion is that the existing ECi and Cl target levels set by the Department of Water Affairs for managing salinity in the lower reaches of the Breede River Irrigation scheme is not too conservative. In fact, from the producer's perspective and to achieve optimum grape yields, the target of 70 mS/m for the total salt content, and 140 mg/L chloride, might be too liberal. However, this conclusion is made without an economic analysis of the cost to maintain the salinity and chloride levels of the Breede River below 70 mS/m and 140 mg/L respectively.

xix) Intensive measurements of shoot growth during two seasons reveal that the earliest measurable sign of salinity damage occurred on day 35 and 20 of the 1992/93 and 1994/95 growing seasons respectively. This was at a stage when the depth-weighted mean soil salinity in most cases was still < 100 mS/m, the maximum measured salinity being 152 mS/m (treatment 6, Sept 94/95, Table 4.8).

xx) Sodium and chloride concentrations in the wine increased as treatment salinity increased. Na ranged from 34 mg/L in the control treatment to 173 mg/L in the 500 mS/m treatment for the 1992/93 wine and from 30 mg/L in the control to 311 mg/L in the 500mS/m treatment for the 1994/95 wine. Chloride concentrations in wine always exceeded that of sodium and ranged from 53 mg/L (control) to 173 mg/L in the 500 mS/m treatment in 1992/93, and from 25 mg/L

to 560 mg/L (500 mS/m treatment) in the wine of 1994/95). The combined data of the 1992/93 and 1994/95 wines show a 1:1 relation between Na in the must and Na in the wine.

xxi) Despite large differences in the Na and Cl concentrations of the wine, an organoleptic evaluation suggest that salinity apparently did not influence wine quality.

xxii) The research at Stellenbosch only started towards the end of the second last year (1993/94) of this five-year research project. Although yield and must composition of Weisser-Riesling grapes were not influenced by the limited amount of saline water applied in 1993/94 and 1994/95, soil salinity at the higher levels of saline irrigation water (e.g. treatments 4 to 6), was significantly increased but had no detrimental effect on yield. It is expected that the residual effects of the salinity exposure of 1994/95 will materialise only during the 1995/96 season.

xxiii) Contrary to the results from the Robertson experiment, the leaf water potential of Weisser-Riesling grapes at Stellenbosch showed a very strong treatment effect with leaf water potential decreasing with increasing salinity. A possible explanation for this apparent anomaly is the differences in climate. Stellenbosch has a higher relative humidity than Robertson does. At Stellenbosch the higher relative humidity might point towards less stomatal control over transpiration.

xxiv) At Robertson, (i.e. the Breede River Valley) production of wine grapes is fully dependent on irrigation and it was found that salinity effects are cumulative with time. Some negative effects were only manifested after two to three years of salinity exposure. At Stellenbosch supplemental irrigation is used to produce wine grapes which means that less salt is added to the soil during the irrigation season. It is reasonable to assume that salinity effects on grapevine performance under conditions of supplemental irrigation not only will be different to those observed under full scale, intensive irrigation, but also that the negative effects will take longer to become measurable and visible.

9.3 Success in achieving the research objectives

Only one of the research objectives was not successfully addressed. Time and manpower constraints prevented us from investigating how (and if) computer simulation models can be used to predict the dynamics of water and solute movement within the root zone of micro-irrigated vineyards. Also, because the study at Stellenbosch only started in 1993/94, insufficient data were available to investigate the role of climate on irrigation water quality criteria. The results from the Robertson experiment showed that the results of at least three years are required to measure the full impact of salinity on grapevines. This suggest that the data of Stellenbosch which cover two seasons only, are not sufficient to do an in-depth investigation of how climate alters the salt tolerance of winegrapes. Although we failed to meet these two research objectives, all other objectives were addressed successfully and represent a substantial improvement in our knowledge of salinity injury to winegrapes under field conditions.

The results of this research can be used by the Department of Water Affairs and Forestry to improve the salinity management of the Breede River and to better plan and manage

irrigation expansion along the Breede River. The report can also be used locally and internationally to provide improved guidelines for irrigation water salinity criteria under conditions of full-scale, as well as supplemental irrigation.

9.4 Recommendations

a) Determine the effect of saline water on the evapotranspiration rate and irrigation water requirements of grapevines, with specific emphasis on transpiration.

b) Evaluate alternative on-farm management strategies such as high frequency- and subsurface drip irrigation that can be used to enhance the use of saline water for the irrigation of perennial crops.

c) Investigate the interactions between plant growth, different growth stages and temporal and spatially changing salinity in the root zone and evaluate how this knowledge can be used to enhance the use of saline water to irrigate fruit and vine crops.

d) Determine the effect of alternating cycles of fresh and saline irrigation water on the surface properties of the soils of the Breede River Valley (e.g. soil crusting and infiltrability).

d) Investigate the role of climate on salinity damage to fruit and vine crops.

e) Use the six-year database of the Robertson experiment to evaluate how and whether hydrosalinity simulation models can be used to predict and manipulate salt accumulation in the root zone of vineyards irrigated with saline water.

f) Establish methodology to calculate the salt and water balance of vineyards under conditions of partial surface wetting, with specific emphasis on minimum data requirements.

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APPENDIX I

USING A SUNFLECK CEPTOMETER TO MONITOR PLANT CANOPY DEVELOPMENT UNDER STRESS CONDITIONS

USING A SUNFLECK CEPTOMETER TO MONITOR PLANT CANOPY DEVELOPMENT UNDER STRESS CONDITIONS

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Light intercept by the leaves is the primary factor that determines transpiration (T) and photosynthesis. Salinity that reduces the leaf area will in accordance reduce the light intercept. In a salt water irrigation experiment, funded by the Water Research Commission in an experimental vineyard near Robertson, R.S.A., we used a *Decagon Sunfleck Ceptometer* to measure the light intercepted by the plants of the different saline treatments. The data were also used to estimate a leaf area index (LAI) for each plot. Estimated LAI was then compared with the LAI derived from physical measurements of leaf area by using destructive as well as non-destructive methods on a few shoots per plot. A correlation was found which proves a ceptometer as an easy and less time consuming instrument for determining LAI and monitoring treatment effects on leaf area.

1.1 Introduction

Light intercept by leaves is the primary factor that determines transpiration and photosynthesis. Salinity that reduces the growth rate of leaf area, maximal leaf area per plant and accelerates leaf defoliation, will reduce light intercept. The salinity effects may change over time. Therefore, seasonal integration and time differentiation of salinity effects requires closer studies of the changes in light intercept and leaf area. The *Decagon Sunfleck Ceptometer* provided the data of light intercepted by the plants in the different salinity treatments. The ceptometer data can provide good estimates of LAI after appropriate adjustment for the canopy characteristics of the plants. Models that estimate the LAI from ceptometer data are available for cover crops (Lang et al, 1992) and single trees (Lang et al, 1992). We are not aware of a suitable model for a canopy with characteristics similar to that of the Colombar grapevine used in the Robertson salinity experiment. The unique features of the canopy are the 3m spacings between vine rows with orientation of 303° and a trailing structure with a south-westward dip (factory roof type trellising system). Adjustments to existing models consequently had to be made. To be able to relate the LAI to various other plant physiological parameters that were measured over the same period, one must however be sure about the validity of sunfleck ceptometer derived LAI. If a good correlation was to be found, the use of the ceptometer implies a less destructive and less time consuming method for monitoring the impact of saline irrigation water on the phenology of the plant. Verification of the ceptometer estimates of LAI, could be made by comparing them with the LAI calculated from measurements of the leaf area on a few shoots per plot, using non-destructive or destructive methods.

I.2 Theory

The ceptometer registers the size of the gaps in the canopy that is penetrated by sun rays passing through the canopy to the plane of measurement. Figure I.1 present a diagram of a cross-section perpendicular to one vine row with 270° orientation, showing the position of the sun at about 11h00.

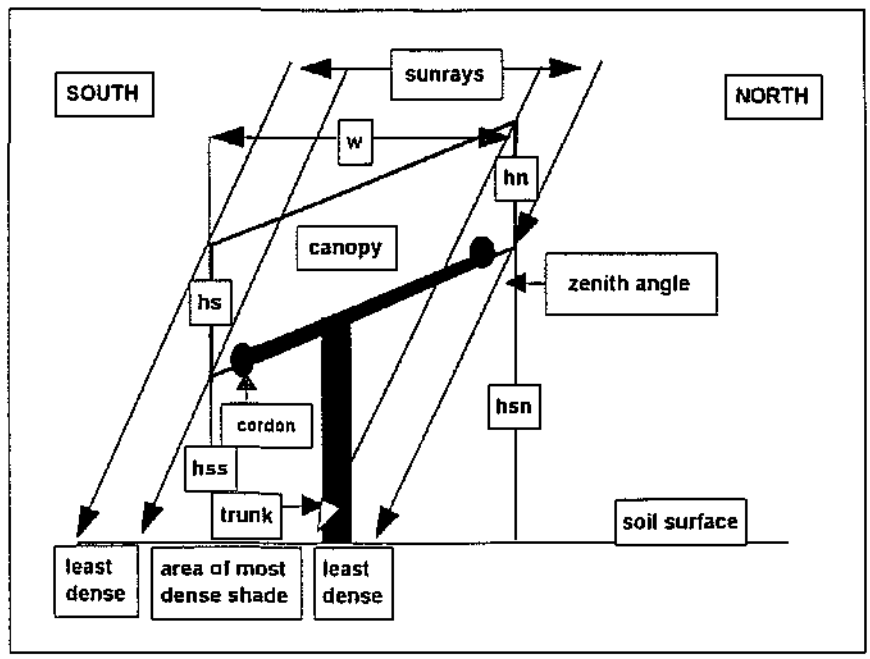

Figure I.1 Diagram of a cross-sectional view of the vine row indicating the measured parameters on the vines. The parallelogram is a crossection of the monoclinic body used to determine non translucent body shade. With respect to Fig. I.1 the following dimensions can be defined: h_s = height of vine above south cordon, h_{ss} = height of south cordon above soil (which was taken as a horizontal surface), h_{sn} = height of north cordon above soil, h_n = height of vine above north cordon and w = width of the vine.

As shown in Figure I.1, the shade boundaries are determined by the sun elevation and orientation, canopy width, height and canopy inclination. Ceptometer measurements for a row crop like vineyard are valid for the time of day when there is no overlapping of shades from neighbouring rows.

Measurements on different times of day varies according to the zenith angle of the sun and therefore need to be corrected for sun angle. This angle determine the size of the shade and the length of the sunbeam path through the canopy for different times of day. The increase of this length for a given gap between leaves, reduces the chances for an open path oriented to the sun that produce sunfleck. Therefore this angle influence also the density of the shade.

Sun angle, row orientation and canopy inclination's effect on the size of the shaded area, are best described by the shade of a theoretical non-translucent body with similar dimension to that of the vine row. Relating the ceptometer shade data (1-sunfleck) to this theoretical shaded area for the same sun angle, gave an estimate of the shade density. The shaded area was estimated by using the same zenith angle as the time at which ceptometer readings were taken.

Some of the existing formulas to determine the elevation angle of the sun from the zenith, θ, had to be adjusted for the southern hemisphere and were calculated from (all angles in radians)

$$\theta = \arccos(\sin L \sin D + \cos L \cos D \cos(0.2618(t-t_0))) \quad [1]$$

where L is the latitude for the place in question, D the solar declination, t the time and t_0 is the time of solar noon. The declination (D) can be calculated from

$$D = \arcsin(0.39785 \sin(4.869 + (\pi/180)J + 0.03345 \sin(6.224 + (\pi/180)J)) \quad [2]$$

where J is the Julian day.

The time of solar noon is calculated from

$$t_0 = 12 - LC - ET \quad [3]$$

where LC is the longitude correction and ET the equation of time. The Robertson experimental farm is situated at 19 degrees and 54 minutes east and therefore

$$LC = (19.9-30)/15 \quad [4]$$

(Data of the temporal statistics of the sun's position relative to the Robertson vineyard, were obtained from List (1966)).

The equation of time represents a 15 to 20 minute correction depending on the time of year and is given by

$$ET = (-104.7\sin\phi + 596.2 \sin 2\phi + 4.3 \sin 3\phi - 12.7 \sin 4\phi - 429.3 \cos\phi - 2 \cos 2\phi + 19.3 \cos 3\phi)/3600 \quad [5]$$

where ϕ is

$$\phi = (279.575 + 0.986J)\pi/180 \quad [6]$$

To be able to correct the sunfleck data for row orientation and for the varying sun angle, the canopy dimensions of the plants at the point of sunfleck measurements were

used to calculate the maximum or total possible shaded area. The cross-sectional surface of a plant through the row (perpendicular) was taken as a parallelogram and a correction equation, X, was determined where

$$X = ((h_s + h_{ss} - h_{sn})\,\zeta \tan\theta + w) \qquad [7]$$

and

$$\zeta = |\sin\lambda - (-\cos D \sin(\pi/12(t-t_0))/\sin\theta)| \qquad [8]$$

where λ is the row orientation measured from north.

When ζ is 0, i.e. when the azimuth of the sun is equal to the azimuth of the row, X becomes

$$X = w \qquad [9]$$

In the last instance where the azimuth of the row is smaller negative than the azimuth of the sun, i.e. when the sun has crossed the row, X becomes

$$X = ((h_n + h_{sn} - h_{ss})\,\zeta \tan\theta + w) \qquad [10]$$

Canopies with similar size and leaf area will produce varying size shades at different times of day and seasons due to changes in the sun position with respect to the row. Figure 1.2 illustrates the effects of row orientation and canopy inclination on the size of a shaded area of the non-translucent body (equations 7-10) on DOS 113 (December 21) the day with the smallest sun angle from zenith at noon. Figure 1.2 shows the effect on the shade of the row orientation alone, as well as the effect of both row orientation and canopy inclination. It also compares the shades of two rows where the cordons are on the same as well as different heights from the soil (horizontal). One row orientation is 270° (the sun never crosses it) and the other is 303°. The latter produces the largest shade over the entire day. In the first instance w=18 dm (*decimeter*), h_n and h_s=9 dm. For the last, h_n=95, h_{ns}=15.7 dm and h_{ss} 13.5 dm was used.

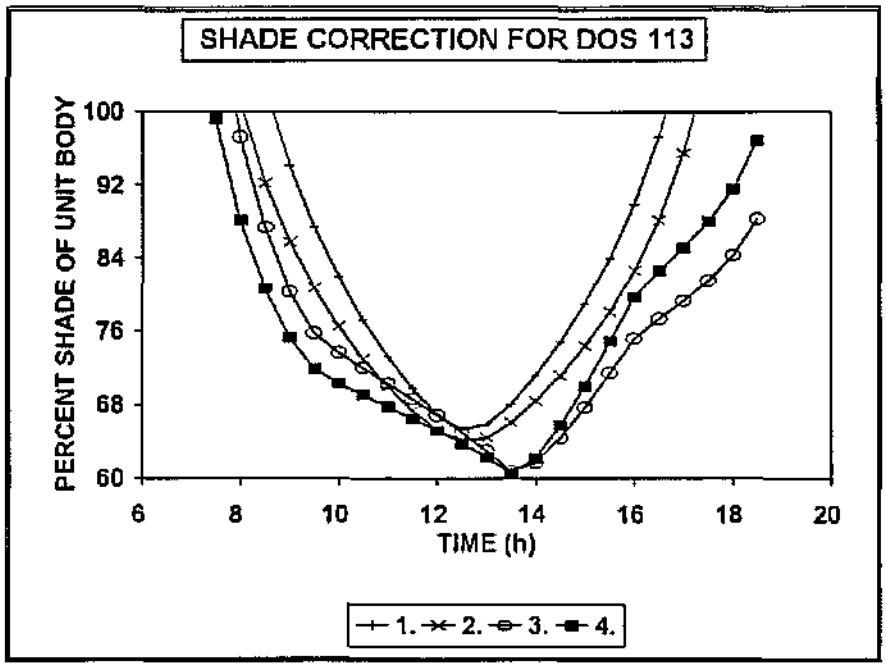

Figure 1.2 Shade correction for a non-translucent body: 1) row at 270° from north and horizontal canopy, 2) row at 270° and inclined canopy, 3) row at 303° and horizontal canopy and 4) row at 303° and inclined canopy.

The non-translucent body produces the maximum shade (X in eqns. 7, 9 and 10) that can possibly be measured for a certain θ. The measured shade from the ceptometer divided by the result X now gives a shade density per area (d_1). This shade density per area d_1, has a certain relation with the shade density per area for conditions where the zenith angle of the sun is zero. The relation between the two, or for any other zenith angle, can be modelled for a whole day. This was approached by Campbell (1986) as an ellipsoidal gap fraction model (eqn 13).

Various models for the leaf extinction coefficient or the resultant gap fraction was proposed by Campbell (1986), Norman and Campbell (1989), Welles and Norman (1991), and Lang (1992). The general approach is to use a spherical model in absence of long day measurements or to use the ellipsoidal model when reliable full day measurements exists.

According to Campbell (1986) and Lang (1992) the LAI can be calculated by

$$L\bar{G} = -\cos\theta \ln\overline{\tau} \qquad [11]$$

where L is the LAI, G represents the gap fraction and τ is the sunfleck reading when dealing with a range of sun angles, θ, encompassing 1 radian. The gap fraction is analogous to transmittance and depends on the foliage orientation, foliage density and the path length through the canopy. The left side of the equation must be regressed

upon θ and then the slope B and constant A must be used as follows to produce L (or LAI)

$$L = 2(A + B) \quad [12]$$

This however result in a LAI that is not corrected for either the inclined structure of the vine trellis or the row orientation. Therefore the correction similar to equation X must also be introduced here. The proposed gap fraction G for an ellipsoid, can be modelled for a range of zenith angles by the following equation where

$$G = (x^2 + \tan^2\theta)^{0.5} / (x+1.774(x+1.182)^{-0.733} \quad [13]$$

and

$$x = \exp(-B/^{0.}4L) \quad [14]$$

The density per area of the shade (d_2) can also be calculated from the sunfleck data by determining the shaded area as the area where a sunfleck reading was encountered smaller than 100%. The shade fraction of the sunfleck data divided by the area, gives the density per area. A correction for the sunfleck data to remove the effect of the row orientation and sun angle or to normalize the data was done by determining C from

$$C/(w/300) = d \quad [15]$$

where C is the adjusted average measured shade, w/300 is the width of the plant as a fraction of the row spacing and d is the density of the measured shade per area. This however do not adjust for gap fraction in all cases, but presents an easy solution to determining LAI when the gap fraction need not be taken into account.

1.3 Methods

Data were collected with a *Decagon Sunfleck Ceptometer* which consists of an $^{0.}$8 m long probe and a recording unit. The instrument records the PAR, sunfleck percentage and time of measurement simultaneously. A 3 m long measure was prepared with $^{0.}$15 m spaced markings. It was placed across the interrow space with the 0 and 3 m marks of the measure, in two adjacent rows and in the centre of 2 x 1.5 m spaced vines (Figure 1.3). The instrument was then moved perpendicularly over the measure, parallel to the vine rows, to each mark where a reading was taken. Forty measurements were taken over this area in a 2 x 20 configuration between four fixed plants. The plants were similar in size and representative of the mean of the plot. Measurements

were only taken when clear and stable sky conditions prevailed and the same procedure was followed at all measuring sites at all times.

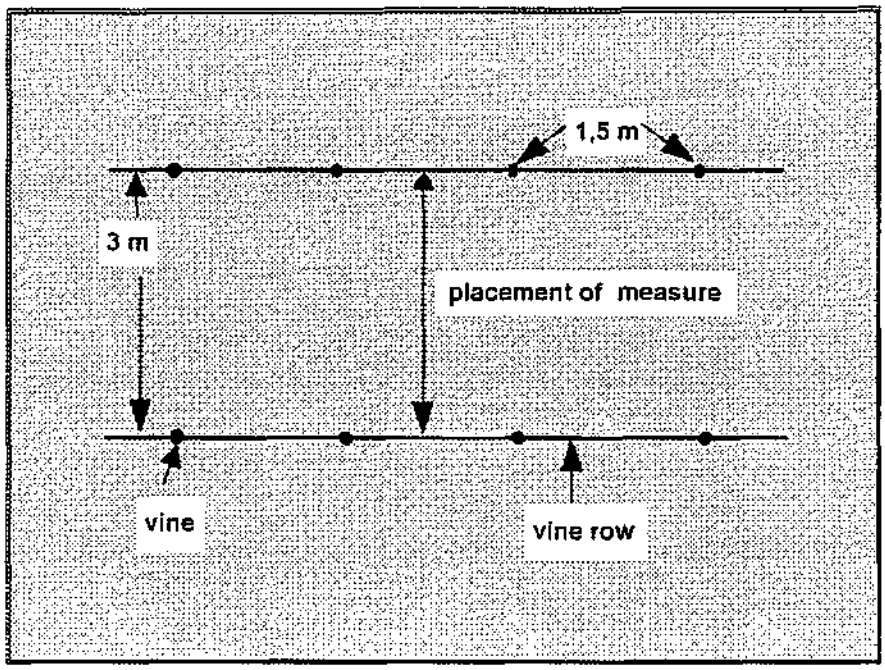

Figure 1.3 Schematic site diagram showing the position where the 3m measure was put to take readings at accurate intervals

Several sets of data were taken over all treatments together with shoot samples for destructive measurements. The canopy dimensions were also determined, i.e. the height of the cordons from the soil, the height of the canopy above the cordons and the width of the plant across the row. Each vine has an effective soil surface area of 1.5 x 3 m. Since one plant canopy occupies more or less a third of this space at midday, care was taken not to sample data when the shades of two plants were overlapping later or earlier in the day.

Destructive measurements of leaf area where also conducted at the same time as the Ceptometer readings but on different plants in the same treatment. Shoots were sampled and the area of the leaves measured with a Licor leaf area meter. The number of shoots per vine were counted and a total leaf area thus approached. The LAI was calculated as

$$LAI = LA_s * N_{sp}/SA_p \qquad [16]$$

with LA_s the leaf area per shoot, N_{sp} the number of shoots per plant and SA_p the soil surface area per plant (4.5m2).

1.4 Results and discussion

Figure 1.4 shows the sunfleck data measured at plot 1 in the Robertson vineyard. The two areas around the cordons, which are the most dense part and accordingly produces the most dense shade, can clearly be seen. Since these measurements were taken on the morning of 20 April 1993 (DOS 232) at 10h05, the results represent only the shade of the northern row. The inclination of the sun do have an effect on the shade density. The graph can therefore be divided into three segments namely, a top line which is 100 percent sun, parallel to this a baseline which represents the most dense shade and the rest of the graph which represents the transition between these two lines. To be able to determine density, one has to determine the area to relate the averaged or totalled sunfleck value to. The first problem here is to decide where the cut-off point or the perimeter of the shaded surface must be.

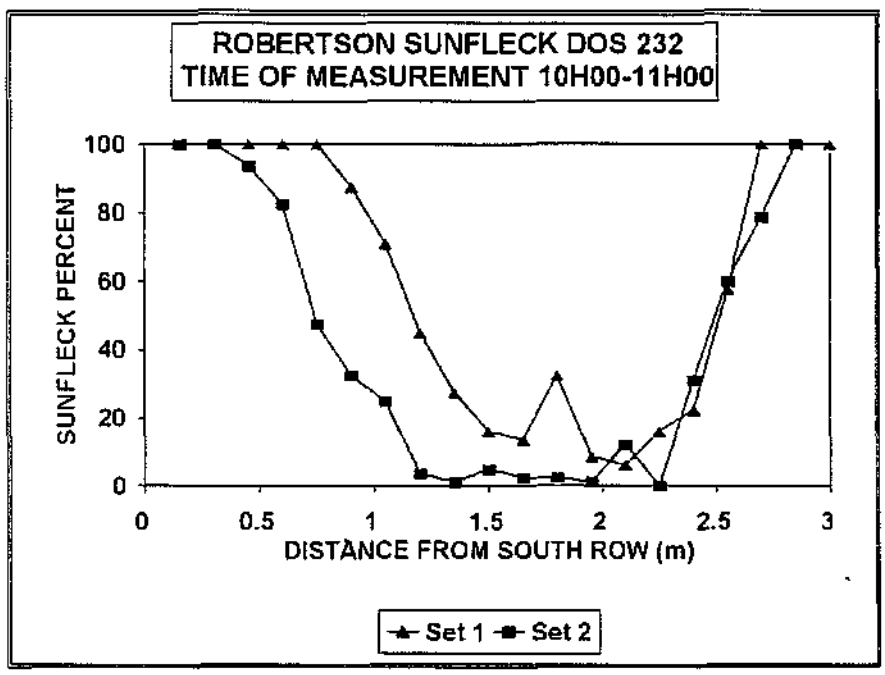

Figure 1.4 The raw sunfleck data of plot 1 in Robertson showing two transects from the south to the north row, set 1 measured west of the trunk and set 2 measured east of the trunk

There can be three scenarios.

i) The first is to decide to include the maximum surface, thus the drip line surface.

ii) The second is to decide to use only the area of the most dense shade.

iii) The third is to use 50 percent sunfleck as the cut-off point or to determine the point where the surfaces of the area above and below the line will be equal (which will be in the vicinity of 50 percent).

The last seems to produce the best estimate but since we wanted to relate the results to the measured canopy results (solid body shade), we used the first approach as this represents best the canopy measurements we took by hand.

The means of the four replicates of treatments 1, 4, 6 and the field mean of all 24 plots of one day's measurements, are shown in figure 1.5. The mean values for all treatments are presented in Table 1.1. These results show a large variation between replicates of the same treatment, a result similar to most of the other plant parameters that were measured. However, it is clear that treatment 6 represents the area with least shade and treatment 1, the area with the widest but not the most dense shade. From the baseline data shown in figure 1.5 it can be inferred that salinity effected the leaves and shoots of treatment 4 in such a way that it produced a very dense, but not necessarily large, shade. To a certain extent this was substantiated by measurements of root and leaf elongation rates. Also evident from

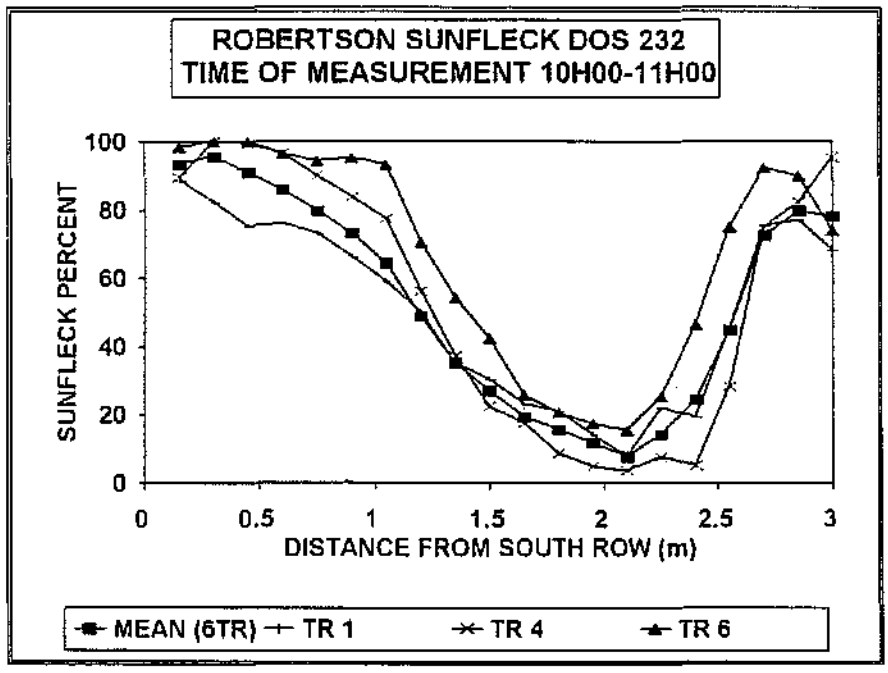

Figure 1.5The mean sunfleck data for treatments 1, 4 and 6 together with the overall mean of all six treatments

the diagram is that the higher the salt treatment, the narrower and higher the V-shape of the graph. The low sunfleck values of treatment 3 shown in Table 1.1, which suggest a large and dense leaf area, correlates with the observation that it had the lowest soil water status throughout the 1992/93 season. The larger leaf area will lead to higher transpiration rates and a greater rate of soil water depletion. However, this analogy between sunfleck data, leaf area and soil water status does not hold for the other treatments.

Table 1.1 Treatment mean sunfleck data measured on 20/04/93 (DOS 241)

Treatment	ECi	Sunfleck (%)
1	30	50.6
2	75	44.2
3	150	42.2
4	250	54.2
5	350	61.6
6	500	66.4

100% = full sun, no shade

In Figure 1.6 the calculated shade (equations 7 to 10) of the vineyard as a non-translucent body, is compared with the averaged shade (1 - sunfleck) measurements made at the same zenith angle of the sun. When the sunfleck readings are divided by the calculated values, the shade density of the plants in the vineyard, which is in a certain relation to their leaf density, are obtained. Therefore the difference between the two sets of data account for the leaf density. This difference increased with an increase in salinity. These calculations were made for a day, late in the season, when salinity-induced leaf drop was significant. When the sunfleck readings are divided by the corrected values, the shade density of the plants in the vineyard (which is in a certain relation to their leaf density) are obtained. The correlation between the measured shade and the solid body shade, calculated according to the procedure described above, i.e. for the same time of day when the measurements were made (eqn. 7), is presented in Figure 1.7. The regression equation, $SHADE_{ceptometer} = {}^{0.}69 * SHADE_{theoretical} + 32.$ is also presented. The offset is the point of minimum true (ceptometer measured) shade. This linear relationship has a R^2 of $^{0.}90$. The offset can be interpreted as the cordon and shoot skeleton dimensions with no leaves. The slope >1 indicate higher leaf density in larger plants. This can be the result of initial higher density or less leaf drop at lower salinities. Calculations of these ratios along the growing season can illuminate this point and provide information on shoot and leaf growth. The results presented in figure 1.7 is a very significant result in that either one of the two sets of data can be predicted by the other.

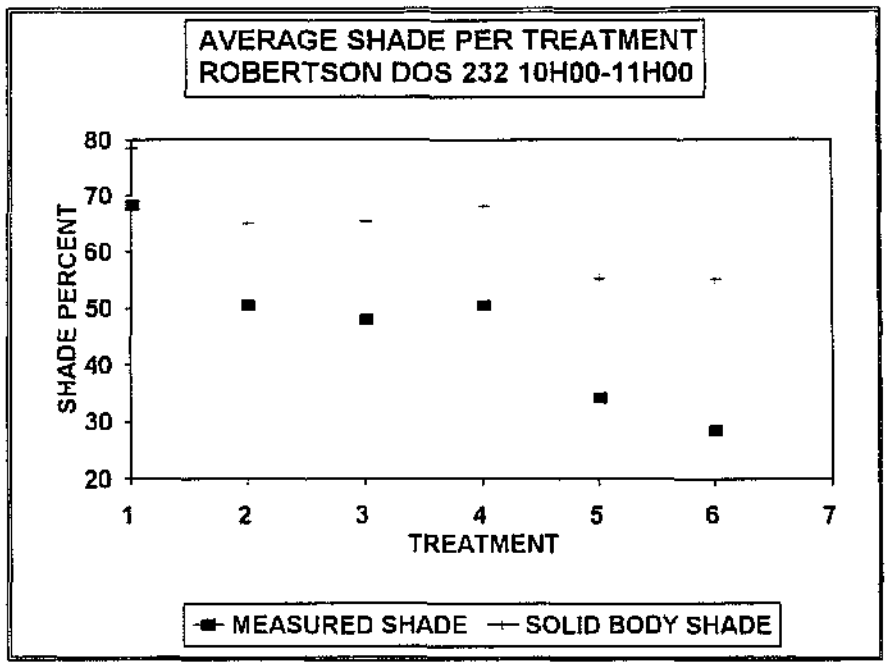

Figure 1.6 The calculated shade per treatment for the X (eqns. 7-10) corrected non transparent body, and the measured shade percent per treatment

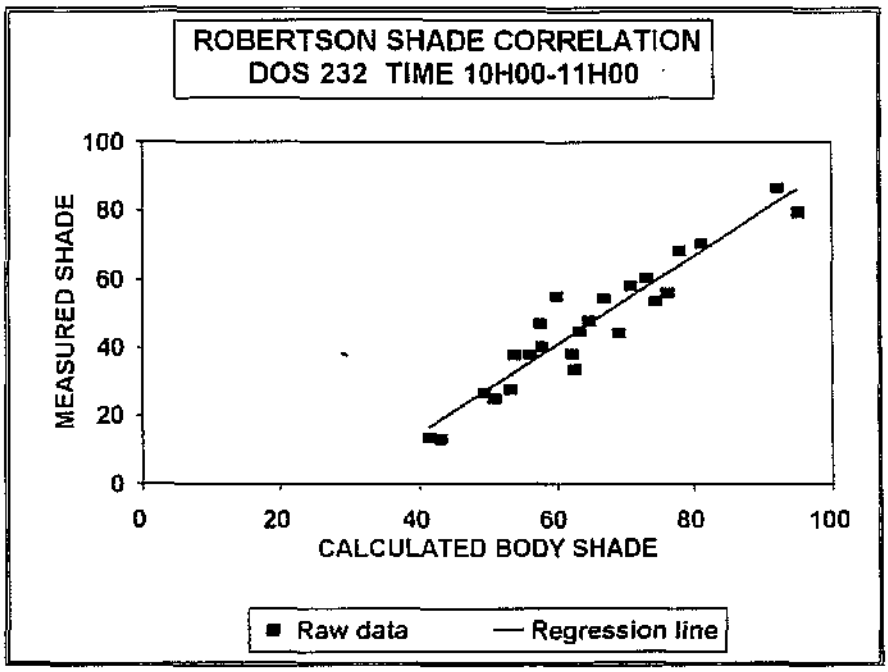

Figure 1.7 Relationship between measured and theoretical body shade

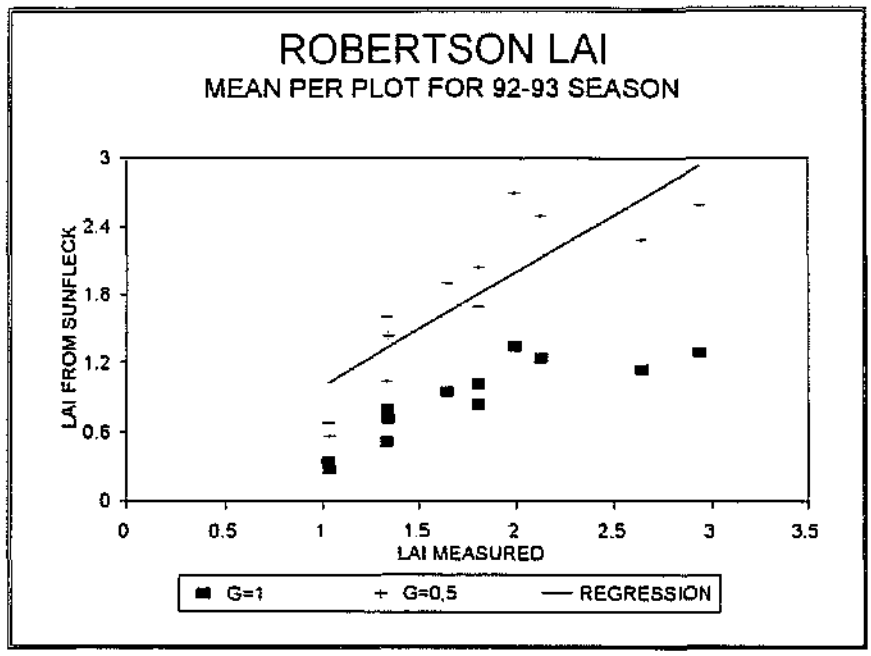

Figure 1.8 Comparison between the leaf area index (LAI) measured from physical plant analysis and the LAI derived from sunfleck ceptometer data using different values for G in eqn (11)

In the next step, averaged seasonal leaf area index (LAI) data per plot, obtained from measuring leaf area per shoot and the LAI derived from shadefleck data, were compared. The comparison between the measured and ceptometer derived data was done by using four approaches.

i) The ceptometer data was converted to LAI using eqn. 11 with G=1 and compared with destructive LAI;

ii) The same as i) but assuming a spherical model with $G=^{0}.5$;

iii) The same as i) but assuming an ellipsoidal model with G varying between $^{0}.42$ and $^{0}.919$ for the different treatments;

iv) Predicting ceptometer LAI from the ceptometer data using the regression statistics of the comparison of i) with destructive data.

The calculation using the G=1 (no leaf extinction model) agreed well with the measured $LAI_{ceptometer}$ and the regression results can be used to predict the true (destructive) leaf area index.. In the second approach the correlation between these two sets of data presented a useful result. with a correction of $LAI_{predicted}=^{0}.92*LAI_{ceptometer}+^{0}.57$. With a slope of almost one, the need to correct for the gap fraction diminishes.

The ellipsoidal model in the third approach also presented a result not worth discussion. With the fourth approach which is similar to the first approach, one uses

the best regression equation by using all available data and formalises it to be used for future calculation of LAI.

With a $LAI_{ceptometer}$ above 2.5 the increase in LAI did not affect the sunfleck readings as this is the value where 100 percent shade exists. The interpretation of this curve is that at $LAI_{ceptometer}$ of 2.5 the canopy approaches characteristics of a non-translucent body. Also as the shoots become longer, they tend to fall over and rest on the support system. For cover crops this point is at about LAI=4 (Welles et al.1991). Using the ratio of maximal canopy width of 1.8 m to row spacing as a conversion factor to find this point for the vineyard (1.8m/3m*4LAI=2.4LAI) result in similar LAI. The little larger threshold in the vineyard may be the result of sunfleck at the canopy sides where path length is shorter.

Bearing in mind that the foregoing discussion was based on readings that were taken during the same time of day for different days over the season, thus minimising the effect of sun position, a model was developed after the analysis of full day measurements on specific plants. Therefore as a result of full day measurements on single plants, we discovered that measurements taken in the afternoon are subjected to very rapid and large change not only over the afternoon but also over the season. Instead we propose to model $LAI_{ceptometer}$ at or around the time when the sun angle with the row is perpendicular and represents to smallest seasonal effect (Figure 1.10).

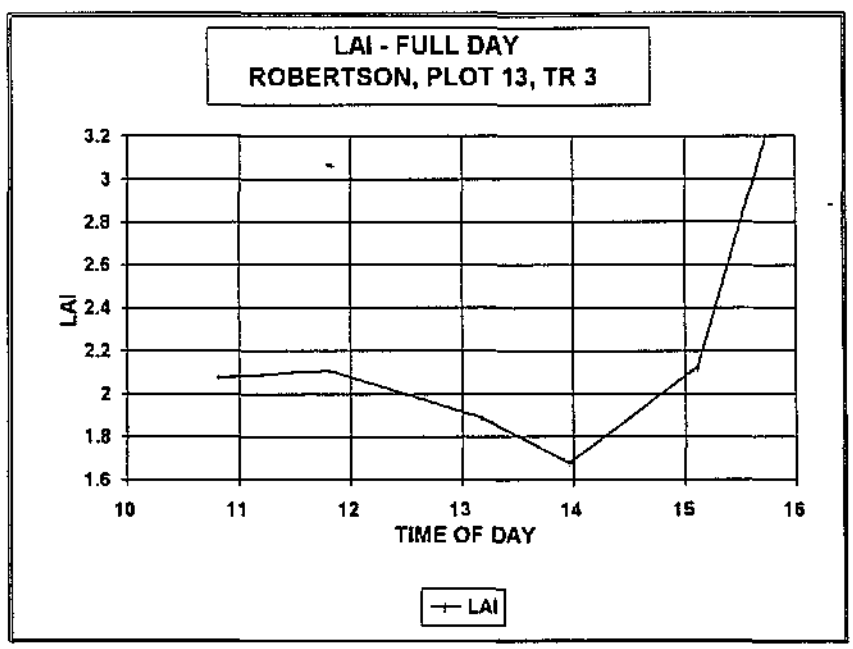

Figure 1.9 Full day measurements of one plant to demonstrate the rapid change after 12h00.

Calculation of LAI can be simplified if a good relationship between shade fraction of ceptometer readings and LG (eqn. 11) exists. If this is true, LAI can be obtained from the measurements of the shade fraction, using an empirical G value that was not derived from an spherical or ellipsoidal model . Using all the sunfleck ceptometer data of the 1992/93 season, LG (equation 11) was determined and compared with corrected shade (equation 15). In both cases the gap fraction and/or leaf extinction coefficient were ignored. The results are presented as Figure 1.9 and the regression was LG=-0.008+2.54(shade fraction), R^2=0.76.

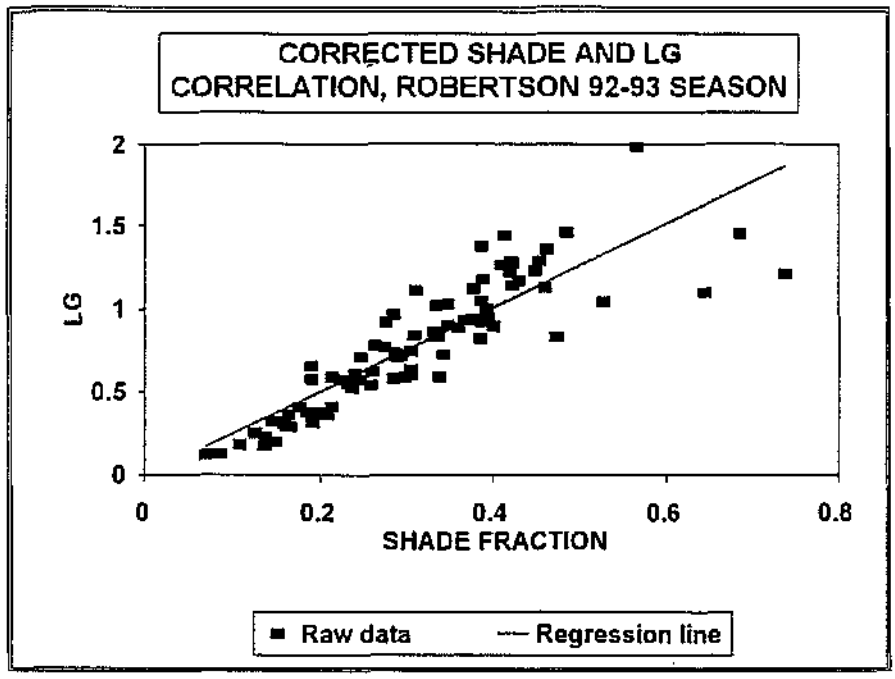

Figure 1.10 Relationship between LG (eqn 11, with G=1) and corrected shade data (eqn 12.) based on all the sunfleck ceptometer data of 1992/93

With the exception of a few points at the upper end of the curve (i.e. shade fraction>0.6), the relationship is very good.

The seasonal trend of the treatment mean sunfleck data are shown in Figure 1.11. It is clear that treatments 1 and 4 showed a upward trend over the season. Treatment 6 was more or less stable during the middle part of the season followed by a downward trend towards the last part of the season, which is the result of salinity-induced defoliation. It is important to note that the LAI results portrayed by Figure 1.11, was done for a G-value of one.

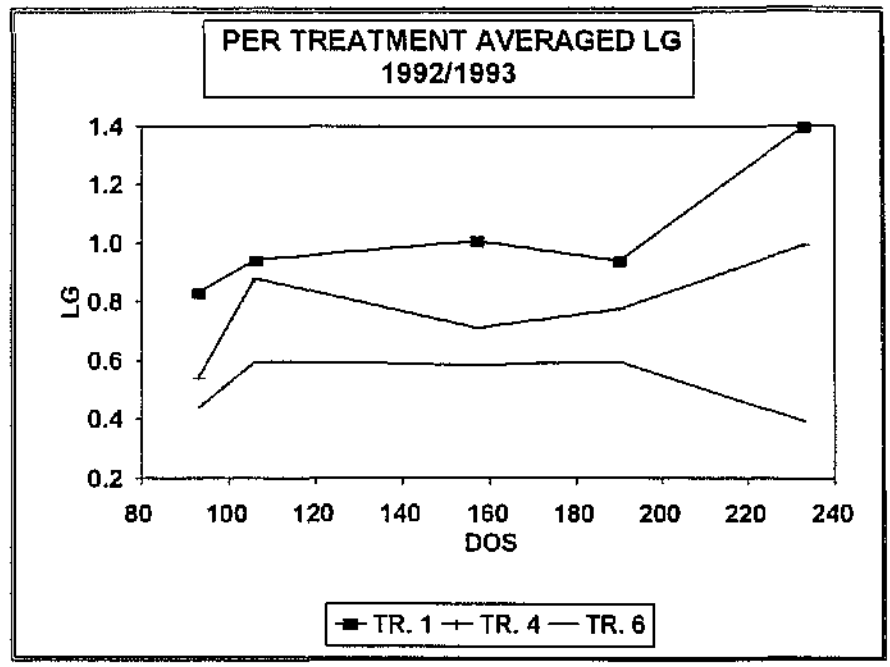

Figure 1.11 Seasonal changes in average LG for treatments 1, 4 and 6.

To summarise, the dimensions of the plants were taken and a potential maximum shade was determined. Taken into account was the time of day, day of year etc. to determine the zenith angle of the sun for a specific time in the year, i.e. for a specific reading in the year. Then equation 11 according to Campbell was determined for each plant. The gap fraction (G) was calculated by means of a regression analysis for data taken at the same sun time of day. Since the path of the sun over the plant does not follow a symmetrical shape, we could not define a good model for the gap fraction for the whole day. It was however possible to derive a model for the morning to noon period (Figure 1.11) but this also proved to be a long procedure with no real gain. It however proved that our initial approach to take readings during the late morning was indeed the right one as changes during this period was minimal. This correlation proved extremely successful and an easy way out.

1.5 Conclusions

Experience gained during the 1992/93 and 1993/94 seasons confirms the usefulness of the sunfleck ceptometer as an instrument to measure LAI of row crops such as grapevine. A sound theoretical basis for correcting the ceptometer data according to row orientation, canopy and trellising structure, time of day and year, have been established. A good correlation between the adjusted ceptometer data and LAI measured destructively and non-destructively from the leaves of individual shoots,

were found. The biggest utility of the instrument in the present study is that it can be used to monitor the effect of salinity on canopy development and leaf area non destructively and that a great number of measurements can be taken in a short time.

Full day measurements was modelled during the 1993-1994 season and the result showed that

Based on the experience gained in using the ceptometer in a vineyard, the following recommendations can be made:

i) For row structures in an east to west orientation readings must be taken when the sun rays is perpendicular to the row. For rows in a north south orientation a time of day must be decided upon, to minimise the fact that the effect of neighbouring plants on the readings. The best time to take readings is when the sun angle is at 57 degrees from the horizontal (Campbell 1986).

ii) Take readings parallel to the row direction at a constant interval (10-15 cm), so that one can describe the whole canopy in this direction. To do this gives you two advantages, namely, to be able later to successfully interpret point readings and secondly for now to get an average of a full cross section of the plant.

iii) From the time of day that readings were taken, determine theta (the zenith angle of the sun) for use in equation 11.

iv) Correlate LG with $LAI_{destructive}$ and use the regression equation to calculate $LAI_{ceptometer}$.

The greater the symmetry of the plant to be measured the easier the solution. In our case, when measuring the vine in a row in which they inter grow, the strike of the row presents a problem as to the time of day best suited to take readings. Furthermore, the inclined trellising system in use add to the problem as it accounts for a rapid enlargement of the shade as well as the longer path length of the suns rays through the canopy during part of the day.

The results are presented in Figure 1.11 and it is clear that the LAI from only one reading per day without some compensation for the time of day will be of no use. A general formula to correct the LAI for any time of day was attempted. The idea was abandoned as it is quite clear that readings in the afternoon is very sensitive to changes in the sun position (Figure 1.9).

1.6 References

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APPENDIX II

SALINITY EFFECTS ON LEAF WATER POTENTIAL, STOMATAL CONDUCTANCE AND OTHER LEAF WATER COMPONENTS OF THE COLOMBAR GRAPEVINE

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9.1 Introduction

The mechanisms of salinity damage to crops are divided between osmotic and specific ions effects. The osmotic effects on expansive growth are explained by changes in plant water potentials, osmotic potentials and plant turgor. Salinity by way of its impact on the components of water potential or root stress signals, can reduce the stomatal conductance and therefore transpiration and photosynthesis. The aim of this study was to obtain the effects of salinity on the seasonal and diurnal changes in the components of the water potentials present in *Vitis Vinifera L* (cv Colombar). The study was conducted during the 1992/93 season at the Robertson experimental farm.

9.2 Materials and methods

Information on the salinity effects on the leaf water relations of the Colombar grapevine was obtained by conducting all sets of measurement on the same leaves. The measurements concentrated mainly on treatments 1, 4 and 6 (control, 250 mS/m and 500 mS/m respectively) of the vineyard at Robertson. Leaf stomatal conductance measurements with a portable steady state porometer (*PP systems*) were followed by measuring the leaf water potentials (LWP) in a pressure chamber and fast freezing of the leaves in liquid nitrogen. The leaf sap was later defrosted and the osmotic potentials (LSOP) measured with a micro-osmometer (*Precision Instruments*). The total organic solute contents (LSRI) were determined with a refractometer. Over the period DOS 57 to 232, midday leaf measurements were conducted almost every week on the 6th day of a seven day irrigation interval. Measurements on days 196 and 206 were taken on the 12th and 22nd day of a long preharvest irrigation interval. Measurements of the stomatal conductance started on DOS 99, with DOS (Day Of Season) 1 being 1 September 1992. (Before this day a porometer was not available). Measurements of LWP started earlier in the season. In addition to the weekly midday measurements, on DOS 99 and 206, full diurnal cycles, on DOS 127 the pre-noon (AM), and on DOS 155 the post-noon (PM) half diurnal cycles were measured.

A fully developed, apparently healthy leaf which was about the 12th leaf from the main shoot tip, and in full exposure to the sun, was used for the measurements in treatments

1 (25 mS/m) and 4 (250 mS/m) throughout the season. The same applied to treatment 6 (500 mS/m) but after about day 150 these leaves (12th position on main shoot) in this treatment started to show necrotic symptoms and stopped growing. The procedure was then to select any fully developed healthy leaf exposed to the sun.

Details of the different measurements

a) Stomatal conductance

Stomatal conductances were measured with a steady state continuous flow porometer with adjustable inlet air flow rate and air humidity. The cuvette has a 2 cm^2 leaf exposure opening and can be clipped comfortably over any leaf. The instrument was held in such a way as not to disturb the natural orientation of the leaf. A suitable leaf for this measurement was defined as a leaf with a standard size, unscathed, fully developed, with full sun exposure and more or less in the twelfth position from the tip of the shoot but not lower or opposite the bunch. In most instances three leaves where measured with the median leaf being used for other measurements. A light sensor attached to the probe provides the light radiation intensity on surface parallel to the leaf surface in the PAR range (photosynthetic active radiation). A temperature sensor in the probe provides an equilibrium temperature of the cuvette and the leaf that is the ambient temperature. A microprocessor calculate the stomatal conductance using the airflow, air temperature, and change in air relative humidity between inflowing and outflowing air.

b) Leaf water potential (LWP)

After the determination of stomatal conductance the leaf was covered with aluminium foil before cutting it's petiole with a sharp knife (Meiri *et al* 1975, Turner & Long 1980). The covered leaf was inserted quickly into a pressure chamber and the air pressure increased at a rate of about 600 kPa/min (Turner 1981) to determine the equilibrium pressure.

c) Leaf sap collection

After the determination of the equilibrium pressure the petiole was removed and the leaf blade was sealed in the aluminium foil and frozen in liquid nitrogen. The frozen leaves were stored in a freezer. Later they were defrosted and pressed mechanically to collect their sap. The sap was centrifuged to separate any solid particles. A 50 µL sample was used for the osmometry and refractometry. If we had to store the sap in a freezer, the sap was stirred and centrifuged before taking the 50 µL samples.

d) Calculations

i) Leaf sap osmotic potential was calculated as: LSOP(kPa) = Xmiliosmols*224*298/273 (temperature correction for 25°C).

ii) Sap organic solutes contents were expressed as percentage sugar. Their contribution to the LSOP were calculated as:

LSOPorganic (kPa)=%sugar*8 .

iv) Since the turgor was not measured and its estimate may be not accurate we prefer the term apparent turgor. Leaf apparent turgor was calculated as

LAT (kPa)=LWP (kPa)+LSOP (kPa)

9.3 Results and Discussion.

a) Stomatal conductance

Stomatal conductance integrates climatic conditions, soil water and salinity status and leaf ontogeny. The climate at Robertson can change from late morning clouds and late dew to very hot, dry and high radiant conditions. Therefore the midday stomatal conductance shows large fluctuations with a general decreasing trend during the season (Figure 9.1). Only small differences in stomatal conductance between the 25 and 250 mS/m treatments and lower conductance values for the 500 mS/m treatment were recorded over the entire season.

The integrated effect of water availability and light on stomatal conductance is seen in the diurnal cycles of the data of days 92, 127, 155 and 206 (Figure 9.2a-d). Days 92 and 127 have similar sun hours while days 155 and 206 DOS are becoming shorter. The stomatal conductance data were plotted against time (Figures 92a-d), LAT (Figures 9.3a-d) and LWP (Figures 9.4a-d).

Observing the stomatal conductance changes with time show that the maximum daily stomatal conductance decreased as the season progressed. On DOS 92 all treatments showed about the same morning increase in stomatal conductance to a maximum at about 9h30 and a progressive earlier closure of the stomata as salinity increased. At 13h30 stomatal conductance values where similar in all treatments. On DOS 127 the stomatal conductance was highest at 13h30. On this day the 500 mS/m treatment had lowest stomatal conductance and the 250 mS/m treatment showed an earlier increase in stomatal conductance. On 155 DOS measurements started only at 11h00 and low conductance values were found in all treatments. On day 206 a definite decrease in stomatal conductance with salinity was recorded at 8h00 and 9h30. Later during the day the 500 mS/m treatment showed highest stomatal conductance.

Regarding the response of stomatal conductance to LWP and LAT during a diurnal cycle one must first consider the time of day when the measurements were made. On days 92, 127 and 206 the measurements started in the morning and the lines should be followed from the right side of Figures 9.3(a,b,d) and 9.4(a,b,d). On day 155 the measurements started at 11h00 and the lines should be followed from the left side of Figures 9.3c and 9.4c. In all four days the LWP range was similar (-300 to -1400 kPa), with LAT increasing from 100 to 900 kPa on the first day, to 500 to 2200 kPa on the last day. These differences are discussed later.

The difficulty of defining the response of stomatal conductance to LWP or LAT and identifying threshold values for stomatal closure can be demonstrated with the data of DOS 92 (Figs.9.3a & 9.4a)). The data show a clear hysteresis effect with different stomatal conductances for a given leaf water potential (LWP) or apparent turgor (LAT). Measurements were taken between 6h30 and 18h00 and the stomatal conductance show only one maximum before noon which is in contradiction with Archer (1992) who reported both pre- and afternoon maxima. The first measurements in the morning with low stomatal conductance and high LWP and LAT were taken before the light induction caused the stomates to open. As the stomates opened, leaf dehydration, a result of faster transpiration than water uptake, resulted in rapid decrease in LWP and LAT to levels that caused stomatal closure. These levels were higher in the high salt than in the low salt treatments. The LWP levels on time of maximal stomatal conductance were -750 kPa in the 250 and 500 mS/m treatments and between -750 and -950 kPa in the 25 mS/m treatment. The lowest stomatal conductance was first recorded when the LWPs were -1100, -1040 and -950 kPa for the 25, 250 and 500 mS/m treatments respectively. Post noon increases in LWP to -700 kPa, a value similar to when the maximum stomatal conductance was measured in the morning, did not cause any increase in stomatal conductance. The maximum differences in the stomatal conductances of the three treatments were recorded when they all had LWP's of -900 kPa. The LAT levels at the time of maximal stomatal conductance were 550, 600 and 800 kPa in the 25, 250 and 500 mS/m treatments respectively. The corresponding LAT value at the time of the first minimum stomatal conductance, were 200, 250 and 600 kPa. The afternoon increase in LAT with a value of 600 kPa, also, did not result in an increase in stomatal conductance. It can be concluded that there was no single threshold value of LWP or LAT for stomatal conductance reduction. However, the increase in salinity did lead to a decrease in the stomatal conductance at higher leaf water potentials or apparent turgors.

Measurements on DOS 127 were taken between 6h00 and 14h00 (Figs. 9.3b & 9.4b). Before 8h00 it was cloudy and the leaves were wet which prevented early morning

stomatal conductance measurements. These climatic conditions, or the ageing of the leaves, were responsible for the slow pre-noon increase in stomatal conductance with no significant reduction in Stomatal conductance when the LWP of all treatments were in the range of -1300 to –1400 kPa and the LAT at 200 and 400 kPa in the 25 and 500 mS/m treatments. The 250 mS/m treatment show a small decrease in stomatal conductance when LWP was -1300 kPa and LAT was 380 kPa, values that are much lower than the ones on DOS 92.

On day 206 measurements were taken between 11h00 and 19h30 (Figs. 9.3d & 9.4d). Therefore the data cycle starts on the left side of the figure. On this day a decrease in stomatal conductance was noticed in the 25 and 500 mS/m treatments when the LWP values were -1100 and -1350 kPa and the LAT values were 700 and 1030 kPa respectively. Small increases in stomatal conductance were noticed during the afternoon. Measurements on DOS 155 (Figs. 9.3c & 9.4c) were taken between 8h00 and 16h30 when it started raining. On this day stomatal conductance decreased after the first measurement at 08h00.

Grapes have good stomatal control on transpiration and can close their stomata at relatively high LWP. Our data show the development of conditions that impose stomatal closure earlier in the day at later stages in the growing season. Soil salinity built-up can explain such response in saline treatments. The responses of the low salt treatment indicate an additional cause(s). Since soil moisture was always high it can not explain the stomatal closure. The only explanation is a change in the stomatal response with leaf ageing.

b) Leaf water potential (LWP)

The seasonal trend in the midday LWP are presented in Figure 9.5a. The midday LWP's, in all three treatments, were about -800 to -900 kPa till day 77 (which is the beginning of rapid increase in fruit volume) and decreased linearly to about -1300 to -1400 kPa on 112 DOS. It then fluctuated between -1000 to -1400 kPa till the harvest on 207 DOS, followed by an increase after the harvest. Such seasonal responses are well-documented (Smart and Coombe 1983, Van Zyl 1984). Large applications of irrigation at post harvest could also contribute to the increase in LWP after DOS 207.

The mean treatment LWP did not decrease below -1400 kPa and individual measurements did not decrease below -1700 kPa. Differences between salinity treatments were not larger than 200 kPa. The 25 mS/m treatment had the highest LWP over most of the season. Exceptional was the period between DOS 197 and 207, which are days 12 and 22 of the pre-harvest drought stress. During this period the 25

mS/m treatment had the lowest LWP. The 250 and 25 mS/m treatments had similar LWP before 127 DOS (veraison stage). During the period 127-167 DOS the 250 mS/m treatment LWP was between the 25 and 500 mS/m treatments. After 187 DOS the 250 mS/m treatment had lower LWP than the 500 mS/m one. The 500 mS/m treatment had lowest LWP before 167 DOS, intermittent LWP during the period 167-187 DOS and highest LWP after 187 DOS. The morning LWP was highest for the 25 mS/m treatment and lowest for the 500 mS/m treatment throughout the season (Fig 9.5a).

The early morning LWP decreased slightly over the season (Fig 9.5a). Measurements on DOS 92 were 6 days, and on DOS 207 23 days since the last irrigation. LWP was lower in the 500 mS/m treatment from DOS 92 and in the 250 mS/m treatment from DOS 127 than in the 25 mS/m treatment. Significant reduction in early morning LWP under water stress was reported previously (Van Zyl 1984). The maximum differences of 50 and 200 kPa, between the saline and fresh water treatments, correspond to electrical conductivity (EC) of 150 and 600 mS/m (USDA Handbook 60). The differences in mean soil salinity of treatments 1, 4 and 6 were 150 and 350 mS/m on day 92, and 600 and 800 mS/m on day 210 respectively.

The diurnal LWP cycles are given in Figure 9.6a-d. Daily minima were observed after 14h00 on all four measuring days. Treatment 1 (25 mS/m) consistently had the highest LWP in the mornings. This treatment also show the highest minimum on DOS 92 (Fig 9.6a) and lowest minimum on DOS 207 (Fig 9.6d). The pre-noon decrease in LWP became faster at later during the season. The post noon recovery was not completed before dark and additional recovery took place during night which is in accordance with the results of Archer (1992).

The changes of the saline- as compared to the control LWP during the season and specifically the change of the 25 mS/m treatment to have the lowest and the 500 mS/m treatment the highest leaf water potential after day 190 can be explained by:

i) A stronger response of the highly transpiring plants to the long pre-harvest drying cycle (the measurements of DOS 197 and 207 were taken 12 and 22 days respectively after the last irrigation).
ii) Deterioration of the cell membranes in the saline treatments that resulted in solute leaking and therefore a too low pressure end point.
iii) Solute accumulation in the apoplast to different levels in the different salt treatments.

c) Osmotic potential (LSOP)

Both morning and midday LSOP values decreased continuously through the growing season (Figure 9.7a,b). The osmotic potentials were highest in the 25 mS/m treatment and lowest in the 500 mS/m treatment. Differences between salinity treatments were smaller in the mornings than at middays. The seasonal change in LSOP from -1000 to -2400 kPa is about 2.5 times the change in the LWP between -800 and -1400. This leads to a significant seasonal increase in the apparent turgor obtained by the calculation of T=LWP+LSOP. The LSOPs in the diurnal cycles were lower later in the season (Figures 9.8a-d). In all cycles, lowest LSOP values were recorded during midday or early afternoon hours. Such daily patterns are expected in response to the daily cycles in tissue hydration. An additional cause can be the result of changes in solute, mainly organic, content as a result of diurnal cycles of metabolic activity.

d) Organic solute content in leaf sap - leaf sap refractive index (LSRI)

The organic solute content measured as the leaf sap refractive index (LSRI's) are shown in Figures 9.9a,b. The midday and morning values increased from 8% to 15%, sugar equivalent units, over the season which are smaller relative changes than the changes in LSOP. The morning data does not show clear differences between treatments. However, the midday data show differences between treatments with a seasonal interaction. Early in the season the 25 mS/m had lowest and the 500 mS/m the highest LSRI. The reverse was found later in the season. During the period DOS 162-187 treatments 25 mS/m and 250 mS/m switched maxima. The LSRI value range in the diurnal cycles increased during the growing season (Figures 9.10a-d). Within a given day, there was a trend to maxima around midday. The daily changes were large on DOS 92 and small on DOS 127. On DOS 99 the daily increase in LSRI was similar in the different treatments while on DOS 127 it was largest in the 250 mS/m and minimal in the 25 mS/m treatment. The magnitude of the daily amplitude decreased over the season when the absolute LSRI increased. This can be interpreted as changes in synthesis and translocation of metabolites over the season.

e) Organic component of leaf sap osmotic potential - leaf sap refraction index (LSRIF)

The relative smaller seasonal increase in LSRI than in LSOP indicates reduced contribution of organic solute to the LSOP (Figures 9.11a,b). The organic solute contribution to LSOP was calculated as

OP(kPa)=80*(% sugar) (Shimshi and Levine 1967, Meiri and Poljakoff-Mayber 1969)

The organic solute fraction was largest, 70% to 60%, in the 25 mS/m treatment and smallest, 60% to 50%, in the 500 mS/m one. The diurnal changes in the relative contribution of organic solute to LSOP (Figures 9.12a-d LWR) are similar to the diurnal changes in solute organic content. Largest diurnal changes where found on 92 DOS, when leaves had wider open stomates (see stomatal conductance), and probably more photosynthesis.

f) Apparent turgor (AT)

The apparent turgor (AT) in all treatments increased over the season from 800 to 1800 kPa and from 300 to 1400 kPa during morning and midday respectively (Figures 9.13a,b). The diurnal cycles show the highest AT in the mornings and lowest AT between 14h00 and 16h00 (Figures 9.14a-d). The AT was lowest in the low salt treatment in the midday and diurnal measurements. It is important to remember that the AT is a calculated and not a measured value. Either LSOP or LWP, the two measured values in the calculation, can cause these results. The seasonal increase in AT is mainly the result of the decrease in LSOP since the midday LWP was rather stable. However, midday turgor values of up to 1300 or 1500 kPa and even higher values in the more saline treatments, are unlikely. We propose the solute compartmentation in the leaf cells as a more likely explanation. Good agreement between the AT, calculated with the above model, and the real T (turgor), requires low solute content in the apoplast. This is also the requirement for the reported agreement between LWP values obtained by the pressure chamber and the thermocouple psychrometer methods. This requirement is probably met early in the season in all treatments and for a longer period in the low salt treatment. During this period (in our study before day 127), the midday AT in the 25 mS/m treatment was in the range of 100-200 kPa and in the saline treatments somewhat higher. These higher values may indicate some apoplastic content of solute. Rapid accumulation of solute in the apoplasts of all treatments, after DOS 127, can explain high AT when the real T is lower, as we believe. The accumulation of solute in the apoplast can also explain the large seasonal changes in the response of the stomata to LWP or AT.

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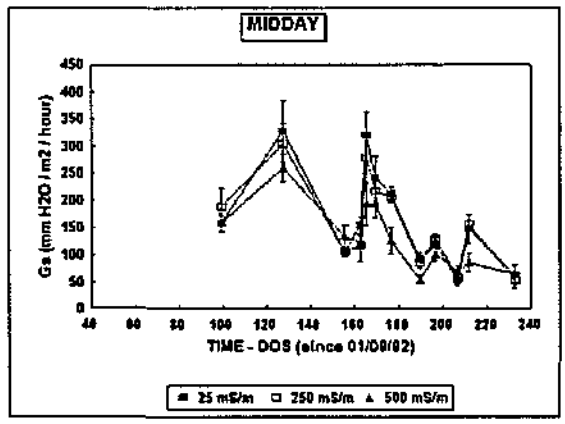

Figure 9.1 Salinity effect on the seasonal midday stomatal conductance of Colombar grapes, Robertson 1992-93

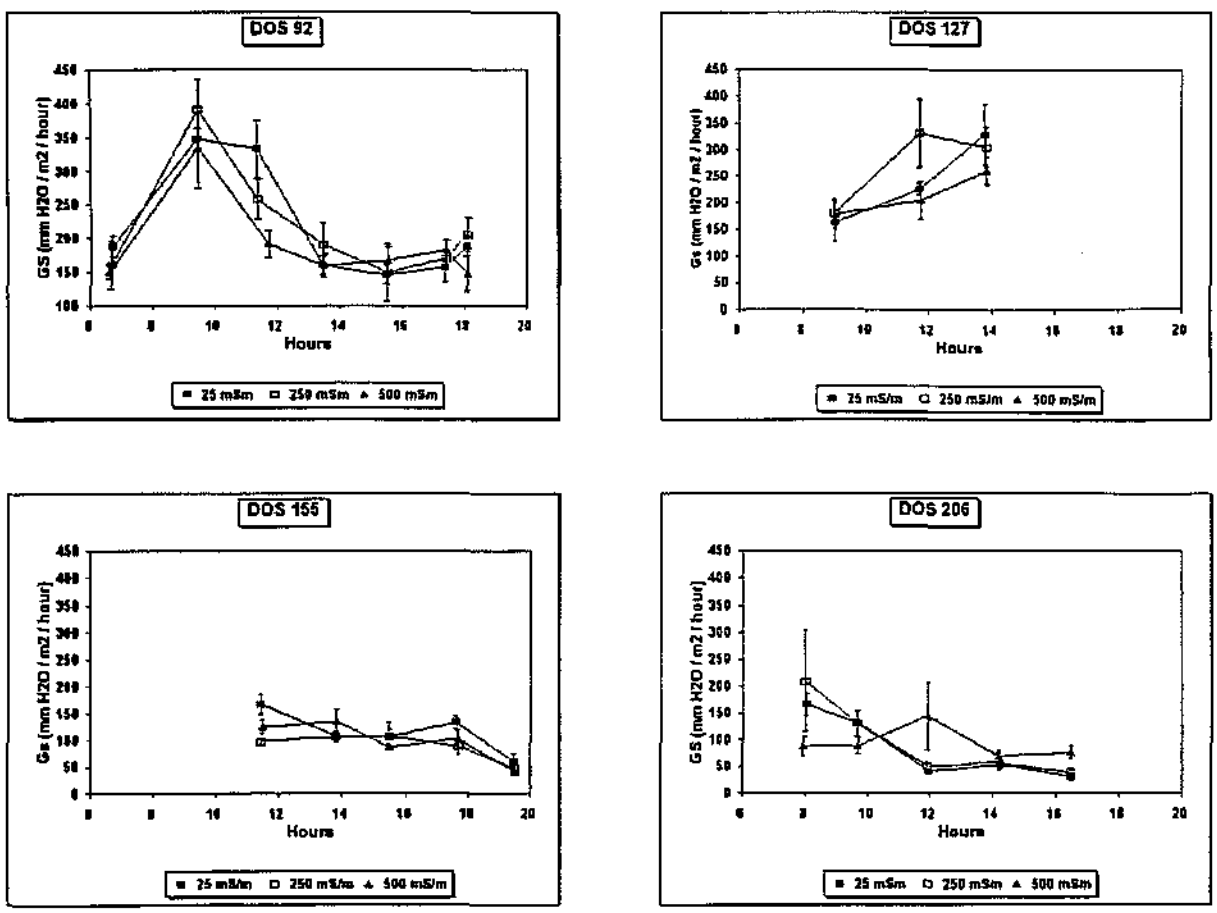

Figure 9.2 The salinity and seasonal effect on the diurnal changes of the stomatal conductance of Colombar grapes a) DOS 92, b) DOS 127, c) DOS 155, d) DOS 206 Robertson 1992-3.

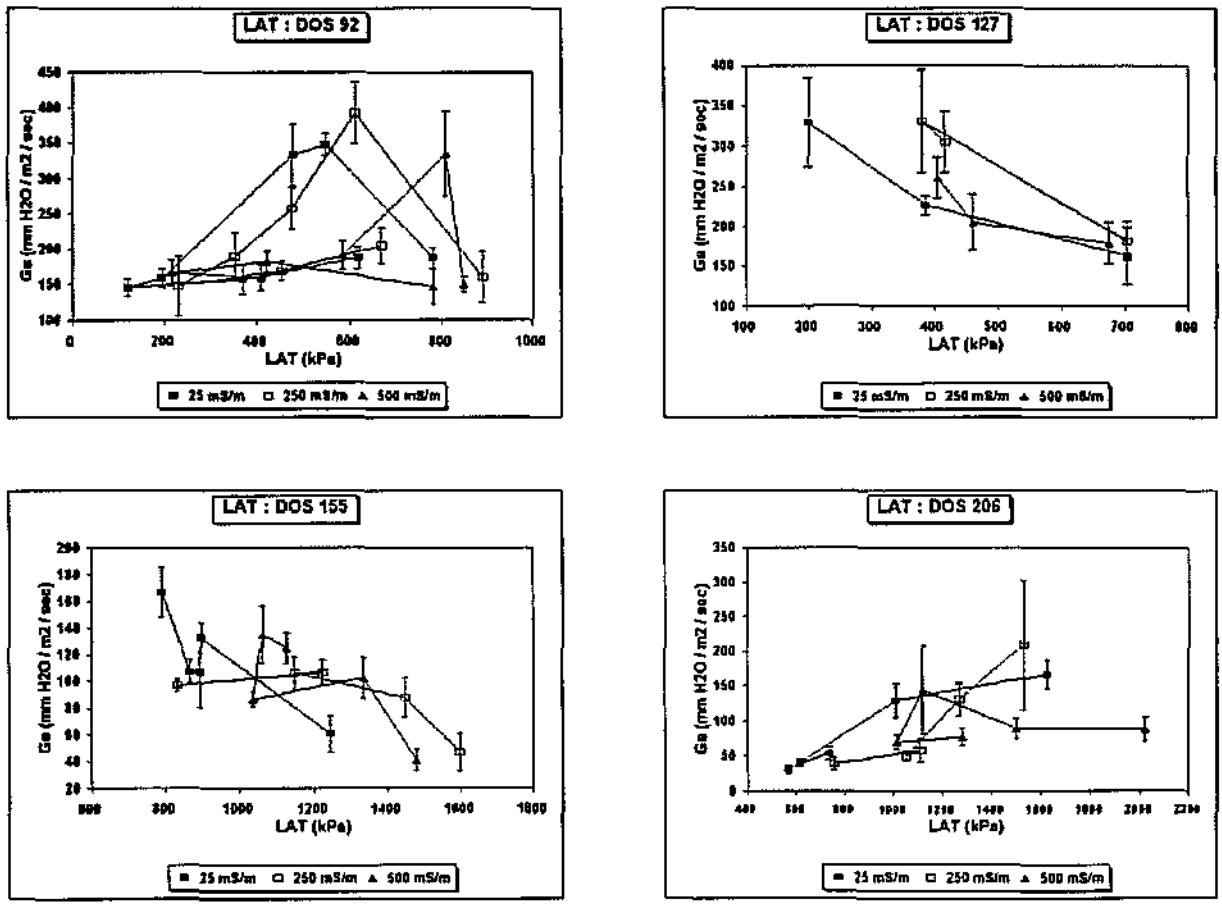

Figure 9.3 The salinity and season effect on the diurnal responses of the stomatal conductance of Colombar grapes to the apparent leaf turgor a) DOS 92, b) DOS 127, c) DOS 155, d) DOS 206, Robertson 1992-3

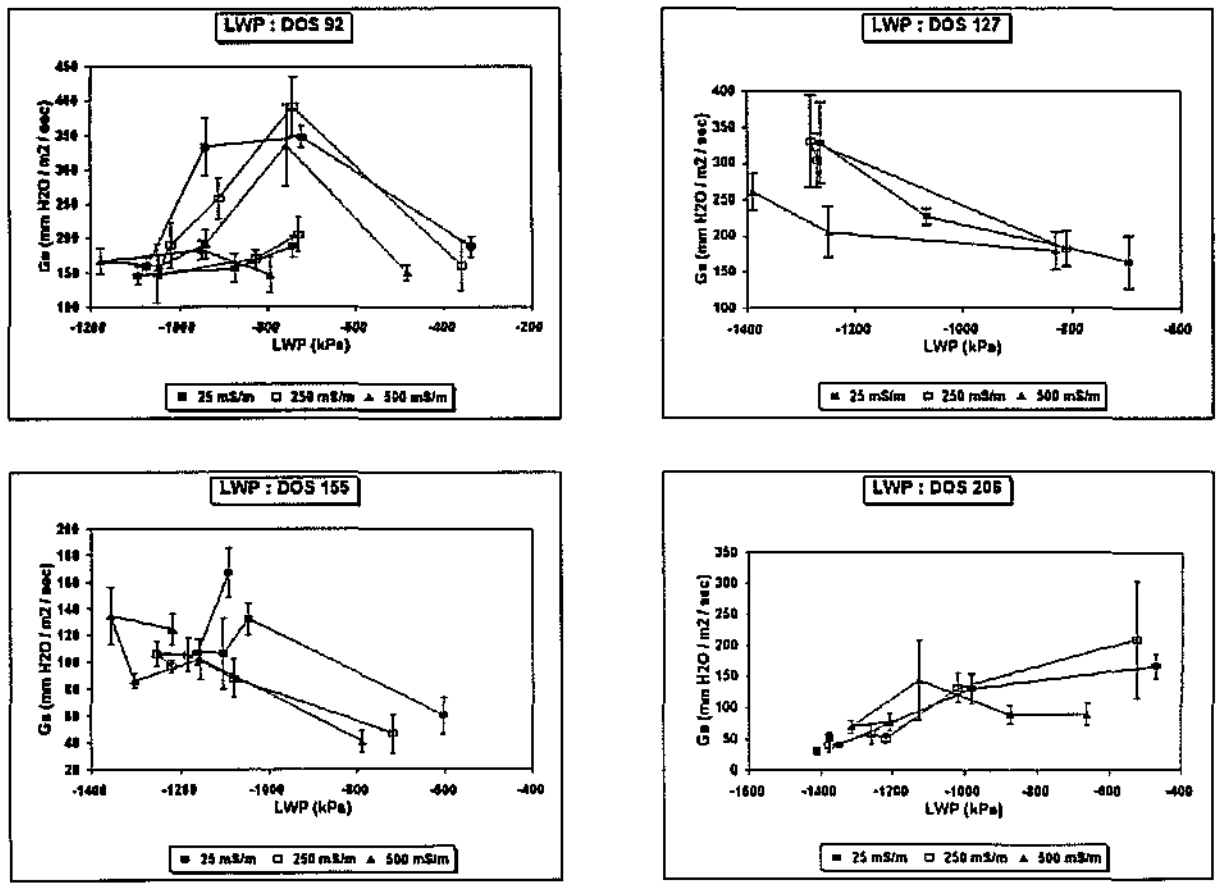

Figure 9.4 The salinity and seasonal effect on the diurnal responses of the stomatal conductance of Colombar grapes to the leaf water potential a) DOS 92, b) DOS 127, c) DOS 155, d) DOS 206, Robertson 1992-3

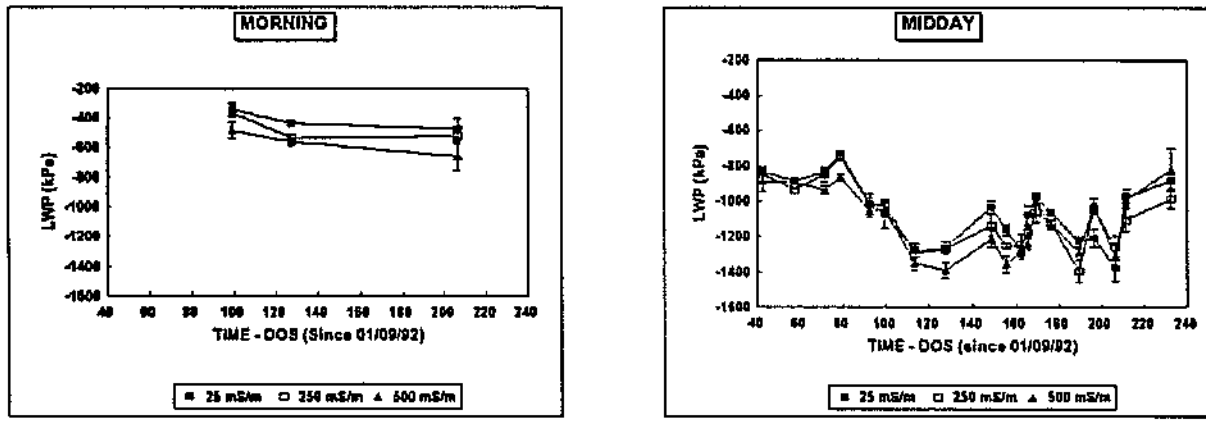

Figure 9.5 Salinity effect on the seasonal a) morning and b) midday leaf water potentials of Colombar grapes, Robertson 1992-3

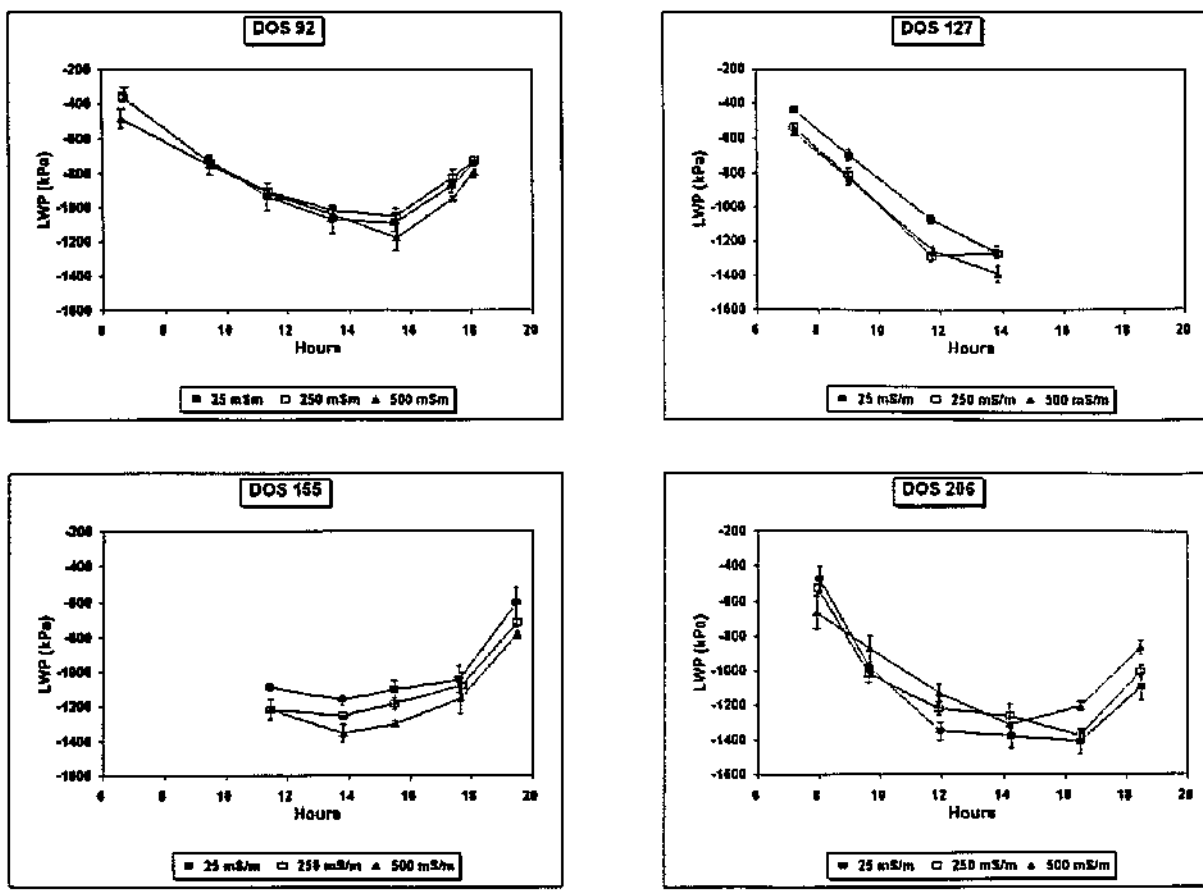

Figure 9.6 The salinity and seasonal effect on the diurnal changes of the leaf water potentials of Colombar grapes a) DOS 92, b) DOS 127, c) DOS 155, d) DOS 206, Robertson 1992-3

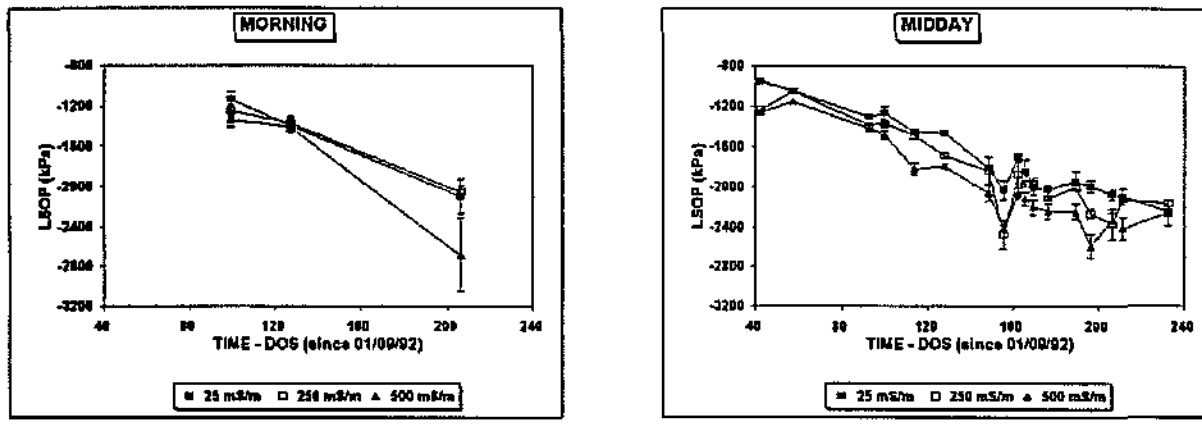

Figure 9.7 Salinity effect on the seasonal a) morning and b) midday osmotic potentials of leaf sap of Colombar grapes, Robertson 1992-3

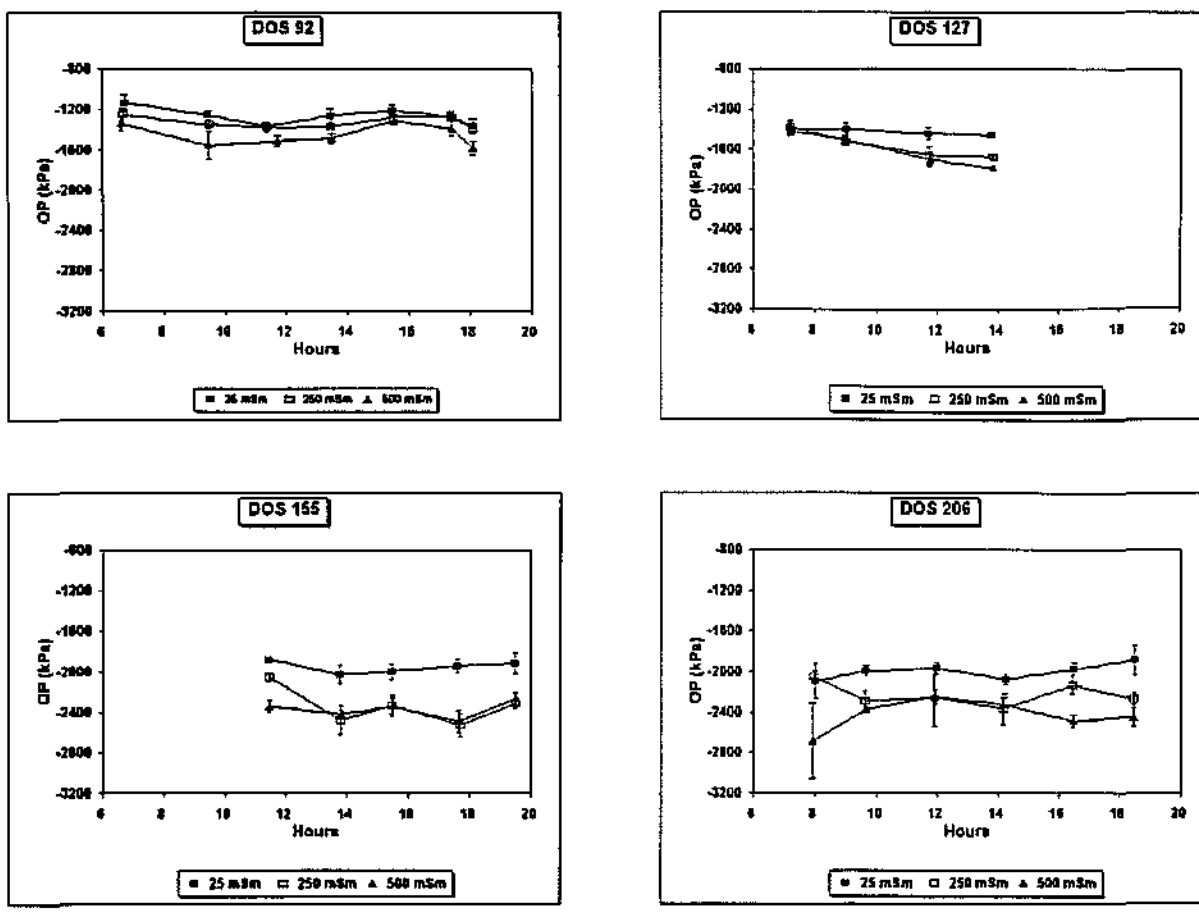

Figure 9.8 The salinity and season effect on the diurnal changes of the osmotic potentials of leaf sap of Colombar grapes a) DOS 92, b) DOS 127, c) DOS 155, d) DOS 206, Robertson 1992-3

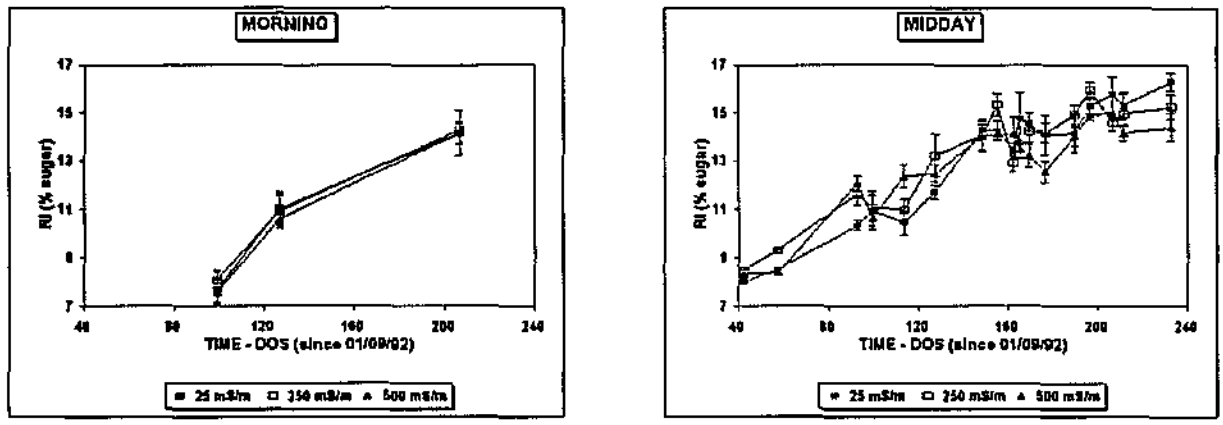

Figure 9.9 Salinity effect on the seasonal a) morning and b) midday refractive index of leaf sap of Colombar grapes, Robertson 1992-3

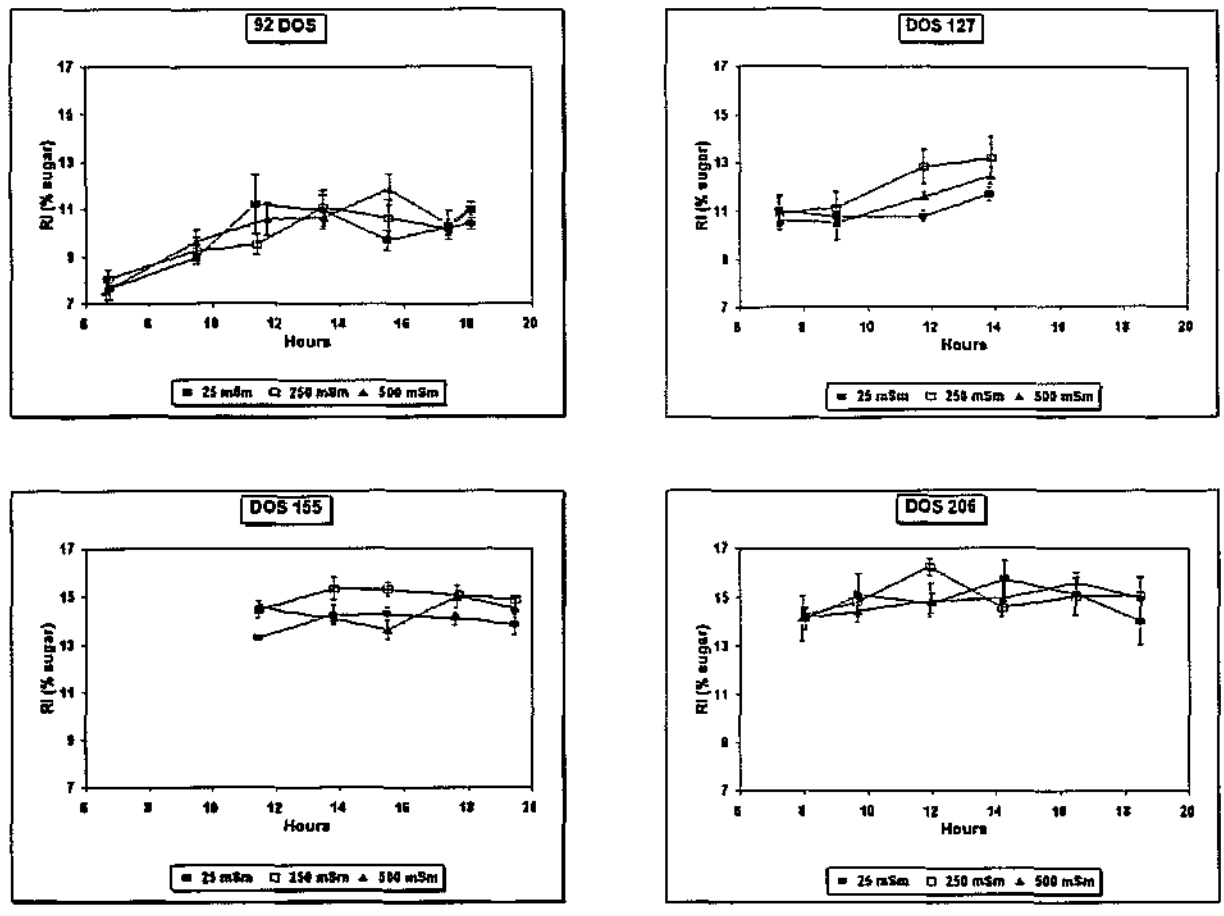

Figure 9.10 The salinity and season effect on the diurnal changes of the refractive index of leaf sap of Colombar grapes a) DOS 92, b) DOS 127, c) DOS 155, d) DOS 206, Robertson 1992-3

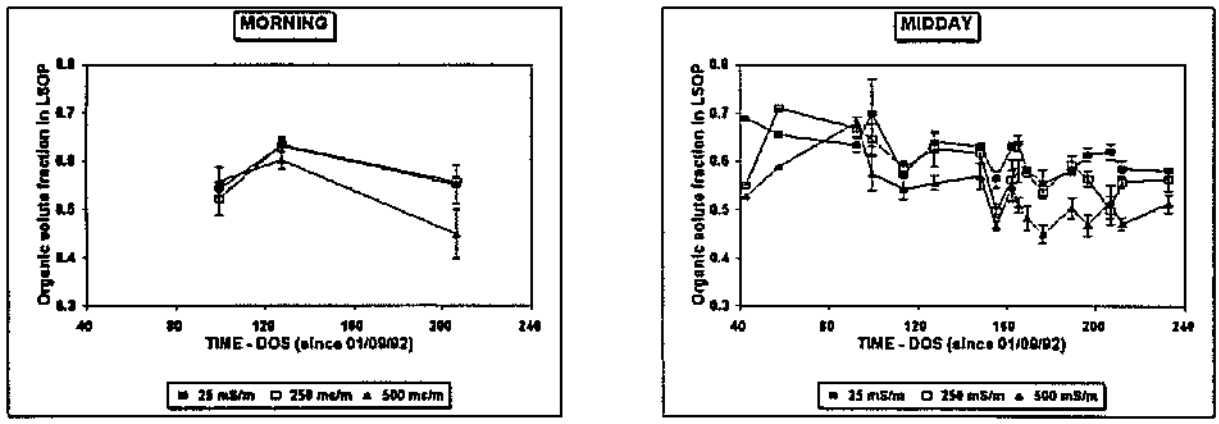

Figure 9.11 Salinity effect on the seasonal a) morning and b) midday contribution of organic solute to the osmotic potential of the leaf sap of Colombar grapes, Robertson 1992-3

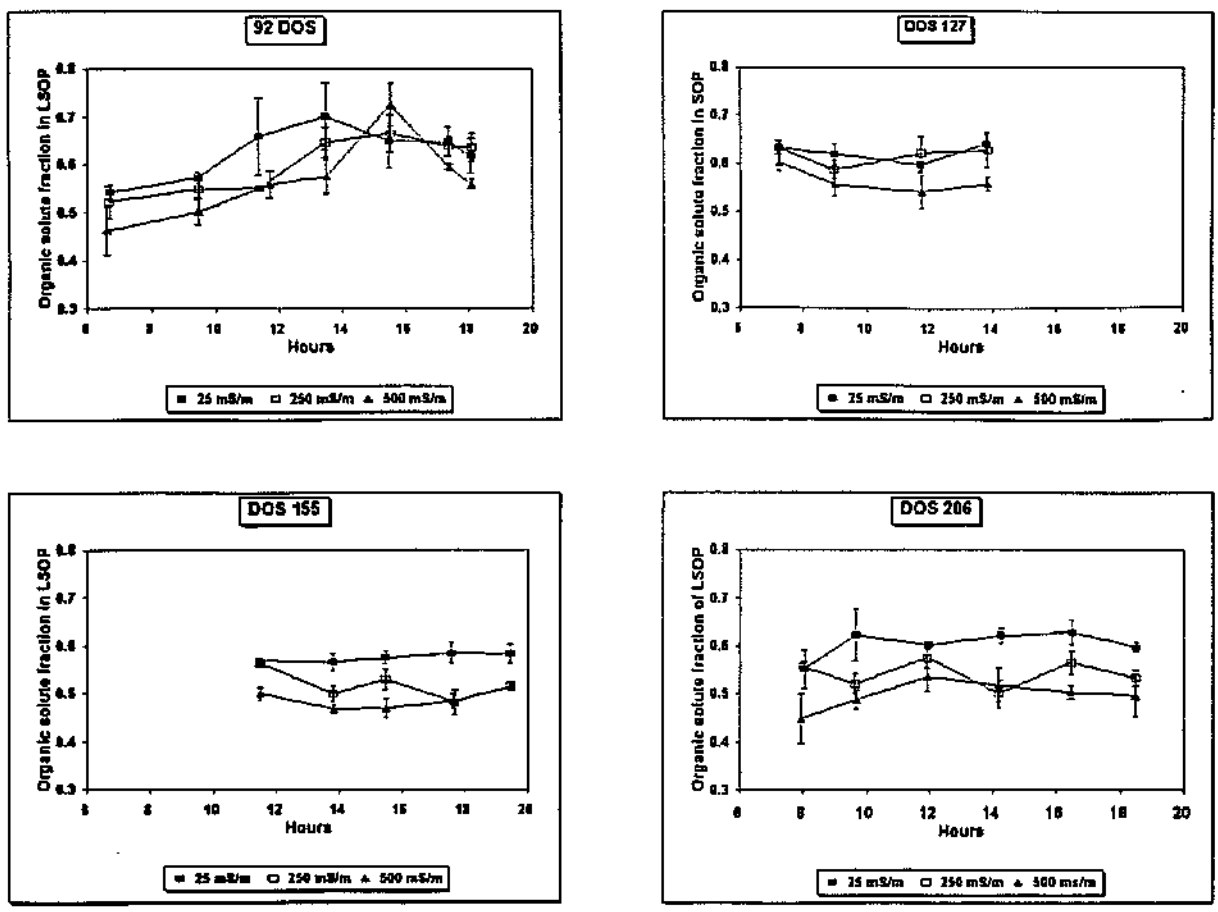

Figure 9.12 The salinity and season effect on the diurnal changes in the contribution of organic solute to the osmotic potentials of leaf sap of Colombar grapes a) DOS 92, b) DOS 127, c) DOS 155, d) DOS 206, Robertson 1992-3

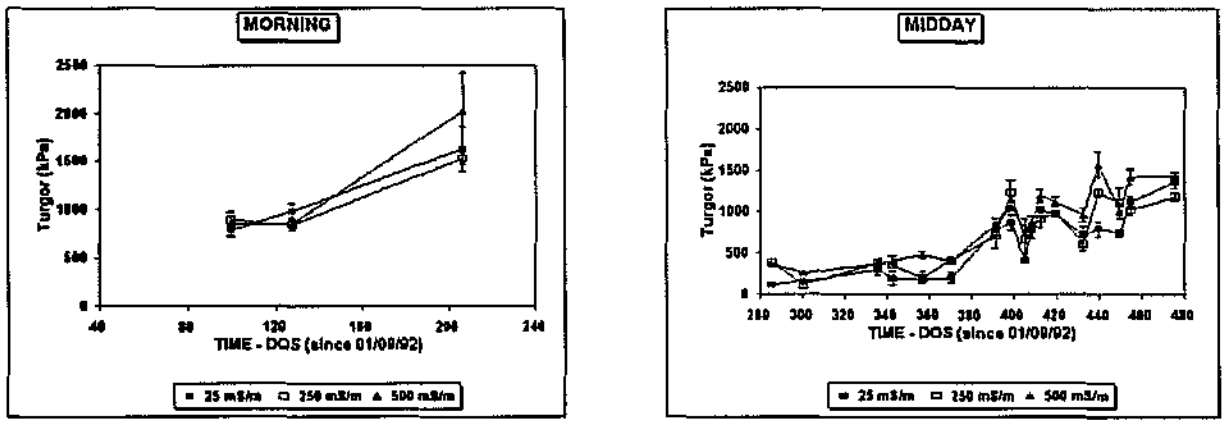

Figure 9.13 Salinity effect on the seasonal a) morning and b) midday apparent turgor of the leaves of Colombar grapes, Robertson 1992-3

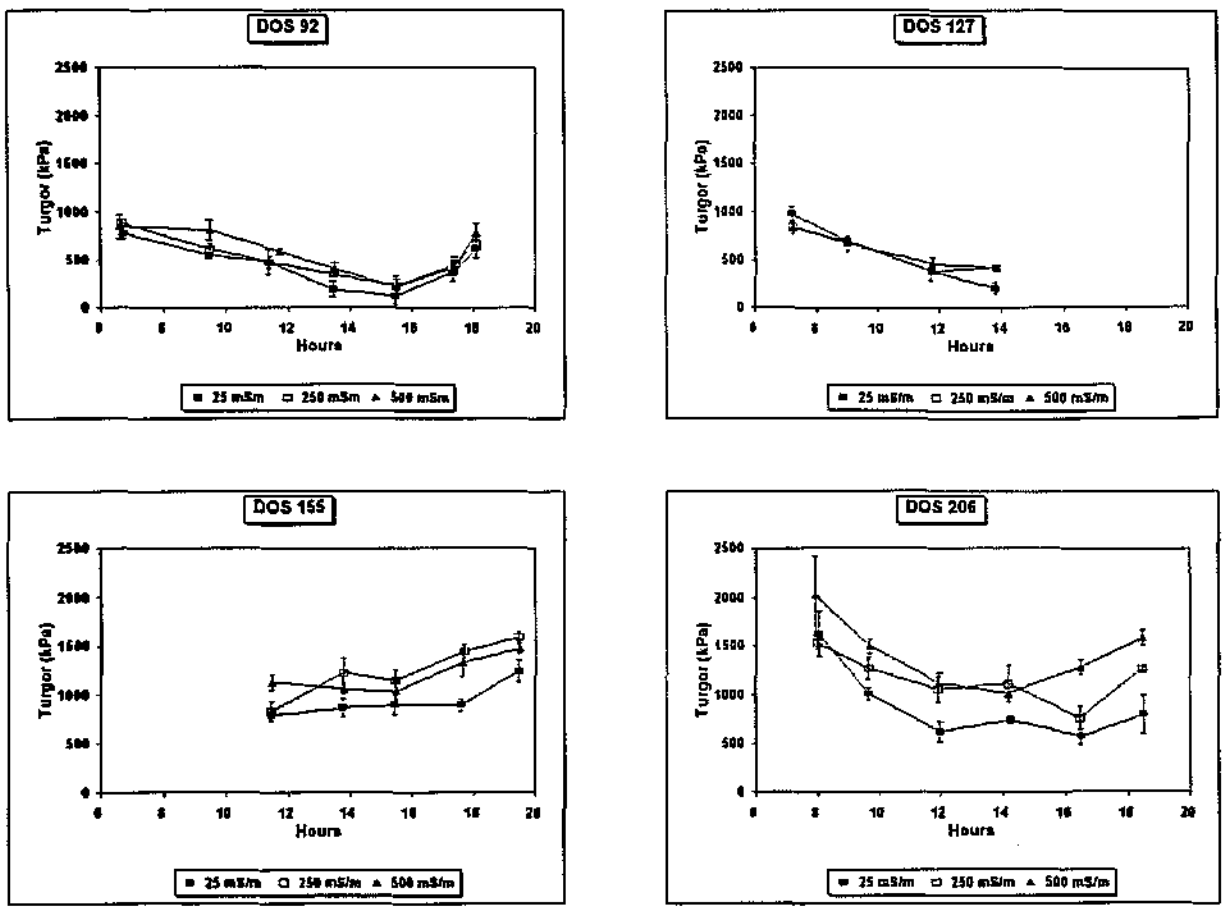

Figure 9.14 The salinity and season effect on the diurnal changes in the apparent turgor of the leaves of Colombar grapes a) DOS 92, b) DOS 127, c) DOS 155, d) DOS 206, Robertson 1992-3

APPENDIX III

LONG TERM TRENDS IN THE SPATIAL DISTRIBUTION OF SOIL SALINITY AND DRAINAGE RATES IN A MICRO-IRRIGATED VINEYARD

Conclusion

As a result of the initial irrigation practice and thorough soil preparation, a considerable amount of salt was leached from the profile since 1986 up to 1990. From 1990 the situation almost reversed in that the soil accumulated almost $2m^3$ salt per hectare. The amount of salt lost from the profile, as was calculated above, does not account for the total movement of salt through the profile but only accounts for the status since the start of measurement. The soil was therefore dependent on the irrigation management practices, soil management practices and rainfall each year and still in some years a salt build-up was experienced. The results indicate the possibility of a higher water table and a decreasing infiltration capacity. The results also show redistribution of salt in the profile. Since the 1994 sampling was not done in the same time of year than the 1986 sampling, it is also possible that a seasonal effect was observed.

The fact remains however that this system operated on a lower salt movement rate than what was started off with in 1986. Its contribution to the salt load of the Breede River therefore declined over the last 4 years. Smaller irrigations and/or a decreased efficiency of the drainage system will however result in the natural salinisation of this soil as a result of its position as a wetland and increased irrigation activity upstream of the Klaas Voogds River.

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APPENDIX IV

EXAMPLES OF DATA
(AVAILABLE ON CD-ROM)

After careful consideration it was decided not to include long lists and tables with data but rather to include all data on a CD-ROM disc. The disc will be made available to the Water Research Commission but will not be included with each copy of the final report. The normal reproduction cost per disc is in the vicinity of R50.00 each. Discs can be obtained from either the WRC or the University of Stellenbosch directly. The disc can also be made available to be viewed over Internet on request.

The disc contains the full text of the final report.

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APPENDIX V

TECHNOLOGY TRANSFER
LIST OF PAPERS PUBLISHED READ AT CONFERENCENCES, LECTURES OF AN INFORMAL NATURE, AND POSTGRADUATE STUDIES THAT EMANATED FROM THIS RESEARCH

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1 Papers published in the proceedings of international conferences

1.1 Moolman., J.H., W.P. De Clercq, W.P.J. Wessels, A. Meiri, & H.M. Du Plessis. Salinity effects on *Vitis Vinifera* L (cv Colombar) grapevine. Microirrigation for a changing world: p123-128. In: Conserving resources/preserving the environment. Proceedings of the Fifth International Microirrigation Congress, Orlando, Florida, U.S.A. April 1995

1.2 Moolman, J.H., & W.P. De Clercq. Using the probability density function of soil water content to locate representative soil water monitoring sites in a drip irrigated vineyard. p81-87 In Proceedings of the Southern African Irrigation Symposium (June 1991), Durban, South Africa. 1995:

1.3 Wessels., W.P.J., Steyn, W.H., & J.H. Moolman. Automatic microirrigation and salt injection system for research and commercial applications. Microirrigation for a changing world: Conserving resources/preserving the environment. p116-122 In Proceedings of the Fifth International Microirrigation Congress, Orlando, Florida, V.S.A. 1995.

1.4 Moolman., J.H., W.P. De Clercq, W.P.J. Wessels, & H.M. du Plessis. Salinity effects on yield and the Sodium and Chloride content of must and wine of *Vitis Vinifera* L. cv. Colombar grapevine. p108-110 In: P.G. Goussard, E. Archer, D. Saayman, A. Tromp, & C.J. Van Wyk, C.J. (Eds). Proceedings of the first SASEV International Congress, 8-10 November, 1995, Cape Town, South Africa,.

1.5 Moolman., J.H., W.P. De Clercq, & F.H. Knight. Macropore flow and drainage rates: A case study in two micro-irrigated vineyards. p.193-205 In: Proceedings of the Workshop on Micro-Irrigation Worldwide, 15th Congress of the International Commission on Irrigation and Drainage, The Hague, The Netherlands, July, 1993

2 Papers published in the proceedings of national conferences

2.1 De Clercq., W.P. J.H. Moolman, & W.P.J. Wessels. An automated sample retrieval system for soil water samples. Pages 31-32 in: Proceedings of the 18th Congress of the Soil Science society of South Africa. Potchefstroom, January 1994.

2.2 De Clercq., W.P, J.H. Moolman, & A.Meiri. Estimating the leaf area index of trellised *Vitis vinifera* L. (cv. Colombar) with a sunfleck ceptometer. p30-30 In Proceedings of the 19th Congress (Joint Congress) of the Soil Science Society of South Africa. Stellenbosch, Jan. 1995.

2.3 Van Zyl., E., J.H. Moolman. Seasonal distribution of salt in the organs of *Vitis Vinifera* L. (cv. Colombar) irrigated with saline water. Proceedings of the 20th Congres of the Soil Science Society of South Africa, Bloemfontein, July 1996.

2.4 Du Toit., S.F., J.H. Moolman,. Spatial variability in the salt accumulation of a vineyard irrigated with saline water. p 43-43 In Proceedings of the 19th Congres (Joint Congress) of the Soil Science Society of South Africa, Jan. 1995, Stellenbosch.

2.5 Moolman., J.H., W.P. De Clercq, & F.H. Knight. Relationship between irrigation and drainage rates in two micro-irrigated vineyards. Proceedings of the 18th Congress of the Soil Science society of South Africa. Potchefstroom, January 1994.

2.6 Moolman., J.H., W.P. De Clercq, W.P.J. Wessels, & A. Meiri. Initial results of the effect of saline irrigation water on the performance of *Vitis vinifera* L. (cv. Colombar) grapevines. p 95-957 In Proceedings of the 19th Congress (Joint Congress) of the Soil Science Society of South Africa. Jan. 1995 Stellenbosch, South Africa.

2.7 Moolman, J.H. & W.P. De Clercq. Water Balance studies in a drip irrigated vineyard in the Breede River Valley, p. 4-4.1 to 4-4.6 In: Proceedings of the 17th Congress of the Soil Science Society of South Africa, Jan. 1992 Stellenbosch, South Africa.

2.8 Wessels., W.P.J. W.H. Steyn,& J.H. Moolman. An automated system for the accurate control of dosing irrigation water with soluble salts. Proceedings of the 18th Congress of the Soil Science Society of South Africa. Potchefstroom South Africa, January 1994.

3 Informal adresses delivered at farmer's meetings

3.1 De Clercq., W.P. Effect of saline irrigation water on vine production, North west Agricultural Development Centre. 12th June 1996, Vredendal, South Africa

3.2 Moolman, J.H. Scheduling of drip irrigation on saline soil. Ashton Irrigation Day. Dec. 1989, Ashton, South Africa

3.3 Moolman., J.H. The future of irrigation in the Breede River Valley (Cogmanskloof Irrigation Board, March 1995, Ashton, South Africa)

3.4 Moolman, J.H., W.P. De Clercq, W.P.J. Wessels, A. Meiri. & C.G. Moolman, C.G. Effect of saline irrigation water on the grapevine performance: Results after four years of research with Colombar winegrapes. KWV Irrigation study group. Robertson & Montagu Farmers Association. August 1995, Montagu, South Africa

3.5 De Clercq., W.P. Effect of saline irrigation water on grapevine. General Meeting of Kynoch Fertiliser Company. June 3rd 1996, Robertson, South Africa

3.6 Moolman., J.H. South African Irrigation Institute. General Meeting, Worcester. Using saline water to irrigate grapevine. Research Results 8th Nov. 1993

4 Theses & Degrees

4.1 Du Toit., S.F. Temporal and spatial changes in the chemical composition of a vineyard soil irrigated with saline water. MSc. Agric, University of Stellenbosch, December 1995(158 pp).

4.2 Van Zyl., E. Seasonal Distribution of salts in the plant organs of *Vitis vinifera* L. (cv Colombar) irrigated with saline water. MSc. Agric., University of Stellenbosch, March 1997. (78pp)

4.3 Lanz., J. Influence of spatial variability of soil water content within the wetted zone on the water balance of a micro-irrigated vineyard soil. B.Sc. Agric., (Junior Thesis) University of Stellenbosch, June 1995